Science-based environmentally friendly new layout for floating PV

Deliverable 1.1: Guidelines for Standardized FPV Monitoring for Inland Water Bodies and Nearshore

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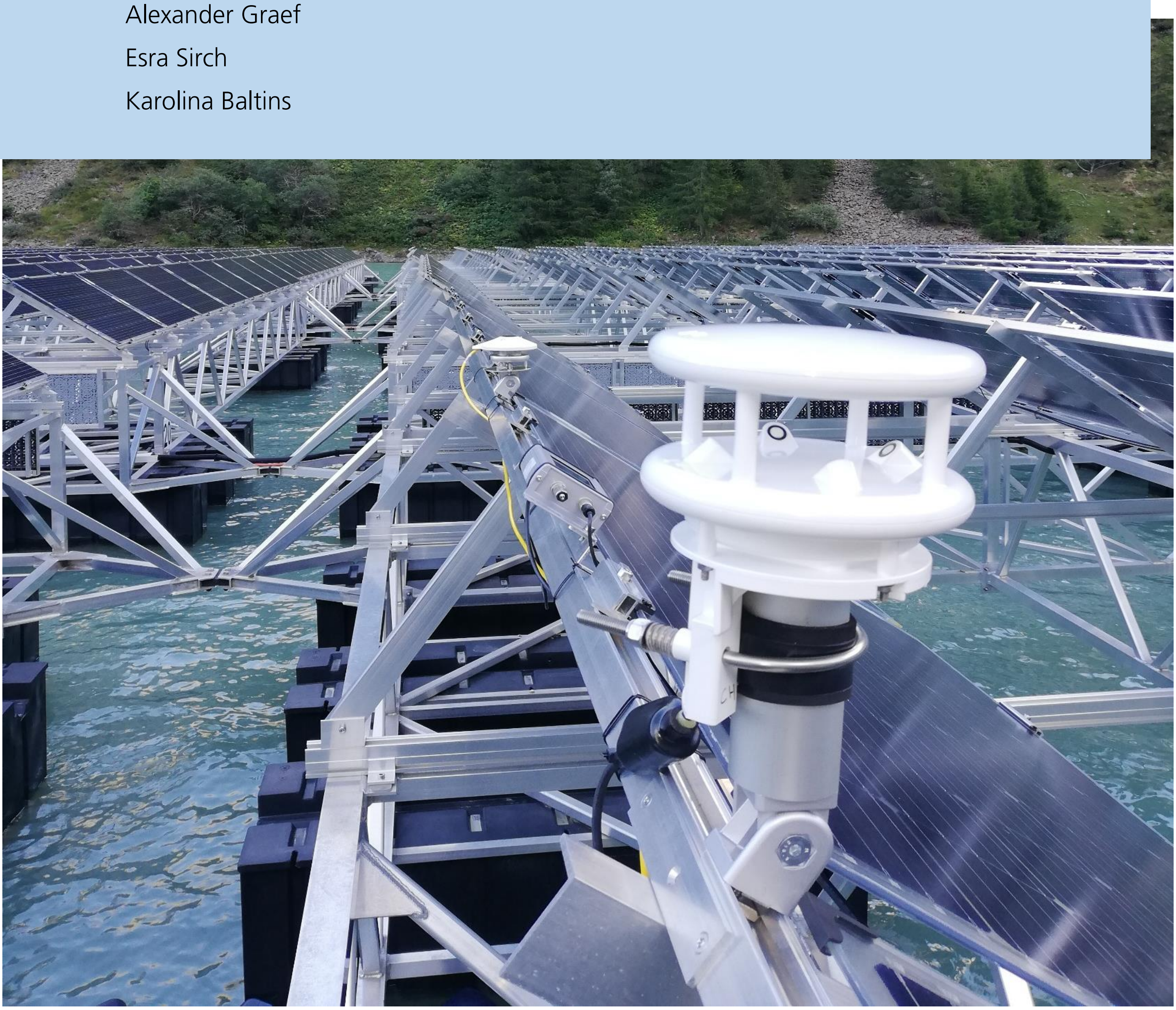

Purpose of this Guideline

Due to the wide range of FPV designs, differing approval procedures, and varying environmental regulations across EU member states, a common monitoring approach is essential. This guideline presents a unified framework for the standardized monitoring of floating photovoltaic (FPV) systems on inland waters (e.g. lakes and reservoirs) and in nearshore coastal environments. It defines how FPV systems should be monitored in a systematic and comparable way across sites, focusing on energy production, structural integrity, and environmental impacts on the physical, chemical, and biological components of aquatic ecosystems. The guideline proposes three monitoring tiers, allowing the level of effort and detail to be adapted to site sensitivity, project scale, and available resources, while providing a comparative perspective across inland and nearshore FPV installations. A harmonized framework enables comparable datasets, supports consistent evaluation of technical performance and environmental effects, and improves cross-border coordination. In addition, standardized monitoring enhances transparency for authorities, project developers, stakeholders, and the public, while increasing regulatory and investment certainty for FPV projects.

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Executive Summary

Floating photovoltaic (FPV) systems are increasingly deployed worldwide as a land-efficient renewable energy technology. In Europe, FPV is gaining strategic importance within the energy transition and initiatives such as REPowerEU, which aim to accelerate renewable electricity generation. At the same time, FPV installations interact with aquatic environments and may influence physical, chemical, and biological processes in water bodies. Combined with heterogeneous regulatory frameworks and approval procedures across EU member states, this highlights the need for a harmonized monitoring approach.

This guideline provides a standardized framework for monitoring FPV systems on inland water bodies (e.g. lakes and reservoirs) and nearshore coastal environments. It aims to ensure comparable monitoring practices across sites while supporting reliable assessment of system performance and environmental effects. The framework integrates technical monitoring of FPV installations with eco-hydrological monitoring of aquatic ecosystems, thereby addressing both engineering and environmental perspectives.

A central element of the framework is a **tiered monitoring concept** that balances scientific depth with practical feasibility. Three monitoring tiers are defined:

- **Basic Tier:** baseline characterization and early detection of trends using a limited set of key physical and chemical parameters.
- **Extended Tier:** additional parameters and improved spatial resolution to support process-oriented environmental assessment.
- **Advanced Tier:** high-resolution interdisciplinary monitoring suitable for sensitive sites, pilot projects, or research installations.

Monitoring activities are structured along the **project lifecycle**, including a baseline phase prior to installation, an early operational phase during the first years of operation, and a later operational phase where monitoring intensity may be adjusted based on observed system behaviour and environmental responses.

To support the selection of an appropriate monitoring level, the guideline introduces **FPV-MASI (Multi-Axis Sensitivity Index)** as a diagnostic tool. FPV-MASI combines system characteristics, lake properties, climatic conditions, and external pressures into a sensitivity profile that helps identify sites where FPV impacts are more likely to be detectable.

By harmonizing monitoring practices across inland and nearshore FPV installations, the framework enables comparable datasets, supports consistent evaluation of technical performance and environmental effects, and improves cross-border coordination. Standardized monitoring also enhances transparency for authorities, project developers, researchers, and stakeholders while increasing regulatory clarity and investment certainty for FPV projects.

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Glossary and Abbreviations

Term / Abbreviation	Definition
ADCP – Acoustic Doppler Current Profiler	Instrument used to measure water current velocity profiles using the Doppler effect of sound waves.
Baseline Monitoring	Monitoring conducted prior to FPV installation to establish reference environmental conditions for later comparison.
Benthic	Referring to organisms or ecological processes associated with the bottom sediments of a water body.
Biofouling	Accumulation of aquatic organisms such as algae, mussels, or barnacles on submerged FPV structures.
Buoyancy	Upward force exerted by water that enables floating structures such as FPV platforms to remain afloat.
CFD – Computational Fluid Dynamics	Numerical modelling approach used to simulate fluid flow, turbulence, and hydrodynamic processes.
Chlorophyll-a	Pigment used as an indicator of phytoplankton biomass and primary productivity in aquatic ecosystems.
Dissolved Oxygen (DO)	Concentration of oxygen dissolved in water, essential for aquatic organisms and ecosystem functioning.
DOC – Dissolved Organic Carbon	Fraction of organic carbon dissolved in water, originating from biological processes or terrestrial inputs.
Epilimnion	The upper, well-mixed layer of a stratified lake.
FPV – Floating Photovoltaics	Solar photovoltaic systems installed on floating platforms on water surfaces such as lakes, reservoirs, or sheltered coastal waters.
FPV-MASI – Floating Photovoltaic Multi-Axis Sensitivity Index	Diagnostic tool used to estimate the sensitivity of a water body to FPV impacts and guide the selection of monitoring intensity.
Hydrodynamics	Movement and circulation of water within a water body, including mixing processes and currents.

Term / Abbreviation	**Definition**
Hypolimnion	Deep, colder, and typically less mixed layer of a stratified lake located below the metalimnion. Oxygen concentrations may decline during prolonged stratification.
Inland FPV	Floating photovoltaic systems installed on freshwater bodies such as lakes, reservoirs, or artificial basins.
Lake Morphology	Physical characteristics of a lake such as size, shape, depth distribution, and shoreline configuration.
Lake Stratification	Vertical separation of water layers in a lake caused by differences in temperature and density.
LiDAR – Light Detection and Ranging	Remote sensing technology using laser pulses to measure distances and generate high-resolution spatial data.
Metalimnion	Intermediate layer of a stratified lake located between the epilimnion and hypolimnion, typically characterized by a strong temperature gradient (thermocline).
Mixing Regime	Characteristic pattern of vertical mixing in a lake (e.g. polymictic, dimictic), influencing temperature and oxygen distribution.
Natura 2000	Network of protected areas across the European Union established under the Birds and Habitats Directives to conserve biodiversity.
Nearshore Floating PV (NFPV)	Floating photovoltaic systems deployed in sheltered coastal environments such as ports, lagoons, or nearshore marine waters.
O&M – Operation and Maintenance	Activities required to ensure reliable operation of FPV systems, including inspection, cleaning, and repair.
PAR – Photosynthetically Active Radiation	Portion of the light spectrum (400–700 nm) used by photosynthetic organisms for photosynthesis.
Pelagic	Referring to the open-water zone of a lake or sea, away from the bottom and shoreline.
Primary Production	Formation of organic matter by photosynthetic organisms such as algae and aquatic plants.

Term / Abbreviation	Definition
Shading Effect	Reduction of solar radiation reaching the water surface beneath FPV modules due to panel coverage.
Significant Wave Height	Statistical measure of wave height defined as the average height of the highest one-third of waves in a wave record.
Soiling	Accumulation of dust, pollen, bird droppings, or salt deposits on PV modules that can reduce energy yield.
Structural Integrity	Ability of FPV structures and mooring systems to withstand environmental loads such as wind, waves, and currents.
Turbidity	Measure of water clarity determined by the concentration of suspended particles such as sediments or plankton.
WFD – Water Framework Directive	European Union Directive (2000/60/EC) establishing ecological objectives and monitoring requirements for surface waters.
Wind Attenuation	Reduction of wind speed at the water surface caused by physical barriers such as FPV arrays.
Wind Load	Mechanical force exerted by wind on floating structures and photovoltaic modules.

1. Introduction

Floating photovoltaics (FPV) have become an important part of global solar energy. FPV systems are being installed in many countries around the world and are contributing to the expansion of renewable electricity generation. FPV is also gaining importance in the European Union, supported by political initiatives to accelerate the energy transition. In this context, FPV is a promising solution for utilizing existing water areas and diversifying energy production.

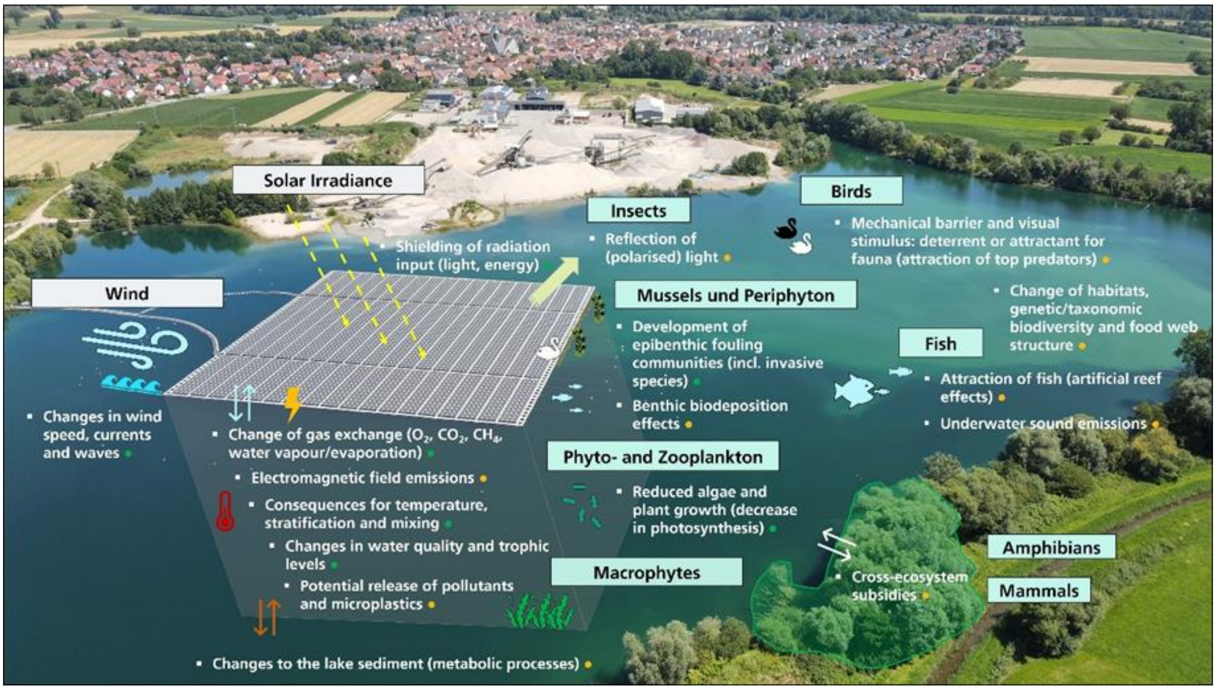
FPV is embedded in the European framework for the energy transition. The European Commission's REPowerEU program gives solar energy a leading role in reducing dependence on fossil fuels. To support these goals, the use of renewable technologies will be further promoted, with new forms of solar power generation to be expanded on suitable land (European Commission, 2025a). The revision of the Renewable Energy Directive (RED) aims to establish clear support mechanisms for innovative technologies and emphasizes the need for reliable approval procedures, coordinated approval processes with water authorities, and the disclosure and publication of environmental parameters. A cross-sectoral dialogue should enable a common EU approach to FPV sites. Clear guidance on site selection, water and land use, and water management systems is needed, as ownership and legal frameworks vary from country to country (SolarPower Europe, 2024).

The EU's environmental and legal frameworks play a central role in FPV projects (de Rijk et al., 2025a). The Environmental Impact Assessment (EIA) establishes EU-wide standardized procedures for assessing potential environmental impacts, public participation, and transparency (European Parliament and the Council, 2012). In addition, the Water Framework Directive (WFD) sets out the ecological objectives for water bodies and requires measures to achieve good ecological status, including monitoring of water quality indicators related to FPV operations and water bodies (European Commission, 2025b). Natura 2000 requires projects to assess in advance the potential impacts on protected species and habitats in order to avoid negative effects (European Commission, 2025c).

Given the heterogeneous design variants, different approval processes, and diverse environmental requirements in the EU, a uniform monitoring concept is essential. It creates comparable data bases across onshore and offshore FPV variants, enables consistent assessment of performance and environmental impacts, facilitates cross-border cooperation, and supports fast, reliable decisions for planning, operation, and regulation. At the same time, standardized monitoring increases transparency for stakeholders, promoters, and the public and strengthens planning security for investments in FPV projects.

1.1 FPV Interaction on Inland Water Bodies

FPV systems on inland water bodies are increasingly deployed as a land-efficient renewable energy technology, yet their environmental implications extend beyond energy production. By partially covering the water surface and introducing artificial structures, FPV systems modify radiative, thermal, and aerodynamic boundary conditions at the air–water interface. These physical alterations can cascade through processes, such as gas exchange, stratification, and nutrient dynamics, and ultimately affect biological communities and ecosystem functioning (de Rijk et al., 2025a). As illustrated in Figure 1, potential FPV-induced impacts span multiple ecosystem compartments, from changes in light availability and mixing regimes to responses of plankton, macrophytes, fish, and higher trophic levels. However, empirical evidence for many of these effects remains limited and highly context dependent, reflecting differences in climate, lake typology, and FPV system design. This highlights the need for standardized, integrative monitoring concepts to robustly quantify FPV impacts across sites and scales, supporting both scientific assessment and operational environmental management of FPV installations on inland waters.



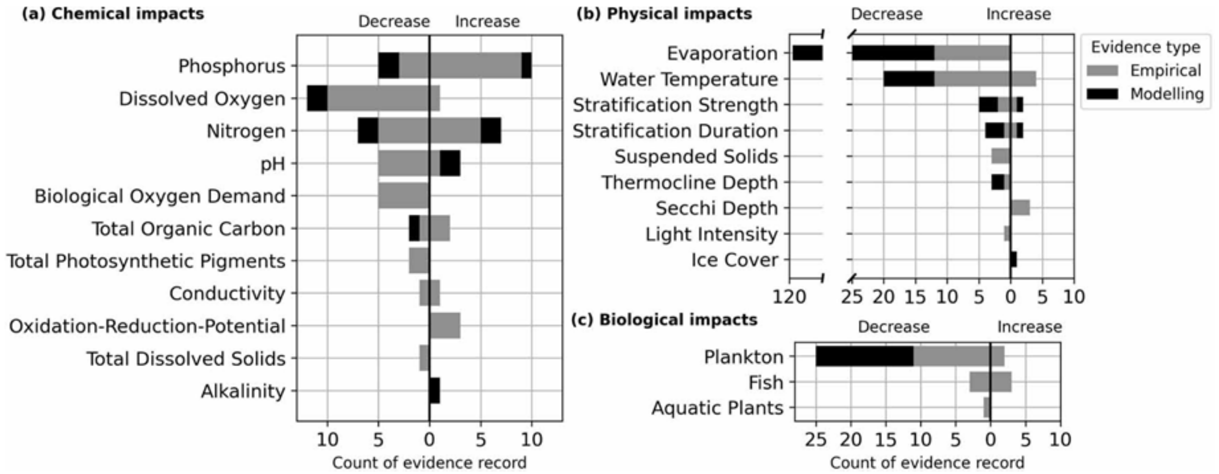


Figure 1. Top: Potential ecological interactions of floating photovoltaic (FPV) systems with lake ecosystems, illustrating physical, chemical, and biological processes potentially affected (Ilgen, 2025). Effects range from empirically supported (●) to likely but with limited empirical evidence (●), synthesized from Nobre et al. (2023), Benjamins et al. (2024), Mehl et al. (2024), and own findings (Ilgen, 2026). Bottom: Reported numbers of physical, chemical, and biological FPV impacts, differentiated by evidence type and direction. Values refer to individual pieces of evidence from the literature, including multiple coverage scenarios from empirical studies and model-based assessments (Rocha et al., 2024).

1.2 FPV interaction on Nearshore Water

For inland freshwater FPV systems, interactions between the installation and the aquatic environment have already been investigated in considerably greater detail. For these systems, first robust findings are available regarding impacts on water quality, thermal stratification, oxygen dynamics, and selected biological components. As a result, research in this domain increasingly shifts towards integrated ecological and socio-economic assessment and life-cycle based evaluation.

In contrast, for nearshore floating PV (NFPV) in coastal environments, the primary research focus to date lies less on ecosystem-level impacts and more on the technical performance of the systems under marine boundary conditions. Key questions concern the detailed characterization of site-specific loads in coastal settings—such as waves, currents, tides, salinity, corrosion processes, and biofouling—as well as the derivation of appropriate design criteria. The overarching aim is to enhance structural and electrical robustness and long-term operational reliability through targeted technical adaptations and coastal-specific system design, including material selection, mooring and buoyancy concepts, and cable and connector configurations.

From a technical perspective, coastal environments are highly variable and require careful site-specific assessment of meteorological and oceanographic conditions. In sheltered nearshore settings, typical operational significant wave heights range between 0.2 and 1.0 m, while storm conditions may generate wave heights of 1.5 to 3.0 m depending on basin exposure. Wave periods are generally shorter than offshore swell conditions. Wave action influences platform motion, including heave, pitch, and roll, induces fatigue in structural connections, and affects mooring line tension. Although port infrastructure often attenuates wave energy, extreme storm events, typically defined by 50-year return period conditions, must be incorporated into structural design.

Wind loading frequently represents the governing design parameter for nearshore FPV systems. In European coastal areas, mean annual wind speeds typically range from 5 to 9 m/s, strong storm winds from 20 to 25 m/s, and extreme gusts associated with 50-year return periods from 30 to 40 m/s. Wind generates aerodynamic uplift forces on the panels, contributes to wave formation within basins, and increases mooring tension. Design approaches commonly align with IEC standards or established offshore engineering practices.

Hydrodynamic conditions vary depending on geographic location. Tidal ranges may be minimal, below 1 m, or significant, exceeding 5 m. Floating systems must accommodate vertical movement associated with tides, and mooring configurations require sufficient slack and adjustability. In high-tidal regions, anchoring and mooring design complexity increases substantially. In estuaries and river mouths, current velocities can reach 1 to 3 m/s, sediment transport and scour processes may occur, and ship wakes can introduce dynamic loading. These factors directly influence anchor selection and mooring system configuration.

Marine environments further introduce durability challenges, including saltwater corrosion, ultraviolet exposure, and biofouling due to marine growth on structural components. Materials must therefore be corrosion-resistant, for example marine-grade metals or high-density polyethylene, protected through appropriate coatings or cathodic systems, and designed for operational lifetimes of approximately 20 to 25 years.

Environmental considerations are equally relevant. Coastal ecosystems may comprise bird habitats, fish spawning areas, benthic communities, and protected marine zones. Environmental impact assessments are often required, particularly under European marine spatial planning and environmental protection regulations.

2. Monitoring Concepts and Parameters for inland FPV

This chapter looks at the environmental assessment of FPV systems on lakes and other inland waters. It focuses on:

- a step-by-step (tiered) concept for environmental monitoring,
- measurement methods and sensor systems that can be used over long periods,
- the integration of observations across physical, chemical, and biological compartments
- the main processes through which FPV systems can affect the environment.

2.1 Tiered monitoring concept

The tiered monitoring concept was developed to address the inherent trade-off between scientific depth and practical feasibility in environmental monitoring of FPV systems on inland water bodies (Tab. 1). While comprehensive, high-resolution monitoring programs provide valuable mechanistic insights into FPV–ecosystem interactions, they are often resource-intensive in terms of costs, infrastructure, and data management. As a result, such approaches cannot be realistically implemented at every FPV project without potentially compromising economic viability.

At the same time, there is a growing need for robust empirical evidence on the environmental effects of FPV installations, both to advance scientific understanding and to inform regulatory decision-making. The tiered framework therefore enables systematic participation of all FPV projects in evidence generation, while allowing monitoring intensity and complexity to be scaled according to site sensitivity, project scope, and available resources. The different tiers are defined as follows:

- **Basic Tier – Baseline characterization and trend detection**

  The Basic tier is designed for commercial FPV installations at less vulnerable sites, as identified through site-specific environmental risk assessments. Its primary purpose is to establish reference conditions and enable early detection of possible long-term trends during the initial operational phase. Monitoring focuses on a limited set of key physical and chemical parameters, typically measured continuously using robust, low-maintenance sensors. The Basic tier is intentionally structured to require minimal additional effort and cost, ensuring broad applicability without compromising project feasibility, while still enabling commercial installations to contribute to empirical evidence generation.

- **Extended Tier – Process-oriented assessment**

  The Extended tier is intended for FPV installations at moderately vulnerable sites, where environmental sensitivity or regulatory requirements warrant a more detailed assessment of FPV-induced effects. It builds on the Basic tier by extending parameter coverage, spatial resolution, and temporal detail. In addition to core physical and chemical measurements, the Extended tier may include selected water quality variables, periodic biological observations, and expanded meteorological monitoring. This tier supports the analysis of dominant physical and biogeochemical processes and provides a balanced compromise between monitoring effort and explanatory power, suitable for environmentally relevant but operationally constrained projects.

- **Advanced Tier – High-intensity, research-driven monitoring**

  The Advanced tier is designed for highly sensitive sites, pilot installations, or dedicated research locations where process-based, causal understanding of FPV–ecosystem interactions is required. It involves high-resolution, interdisciplinary monitoring, covering physical, chemical, and biological compartments in detail. This tier may include measurements of hydrodynamics, stratification dynamics, benthic and pelagic biological communities. Due to its complexity and resource demands, the Advanced tier is typically implemented within research-driven projects, generating transferable insights that support model validation, cross-site synthesis, and evidence-based guidance for FPV deployment in sensitive environments.

Table 1. Tiered environmental inland FPV monitoring framework with parameters structured into basic, extended, and advanced levels across physical, chemical, and biological domains.

	FPV monitoring approach		
Parameter	**Basic**	**Extended**	**Advanced**
Physical and atmospheric forcing			
Light conditions + Secchi depth	X	X	X
Wind conditions	X	X	X
Water level	X	X	X
Surface heat fluxes		X	X
Wind-driven wave dynamics			X
Flow velocity			X
Hydrochemistry and water quality			
Water temperature	X	X	X
Dissolved oxygen	X	X	X
pH	X	X	X
Conductivity	X	X	X
Turbidity	X	X	X
Nutrients (NO_3, PO_4)		X	X
Dissolved organic carbon		X	X
Pollutants and microplastics			X
Morphology and substrates			
Shoreline structure	X (qualitative)	X (detailed)	X (detailed)

Sediments		X	X
Primary producers and basal indicators			
Chlorophyll-a	X	X	X
Aquatic macrophytes and phytobenthos	X (presence/cover)	X (quantitative)	X (quantitative)
Phytoplankton		X	X
Benthic diatoms		X	X
Consumers and higher trophic levels			
Zooplankton		X	X
Macrozoobenthos (e.g. mussels)		X	X
Birds		X	X
Insects (e.g. dragonflies)			X
Fish and cyclostomes			X
Mammals (e.g. bats)			X

2.2 Adaptive Timing of the FPV Monitoring Framework

The monitoring framework is divided into three phases: **baseline, early operation, and late operation** (Fig. 2). Prior to FPV installation, a one-year baseline survey is conducted to establish reference conditions for subsequent assessments. This baseline survey is mandatory for Extended and Advanced monitoring tiers, whereas for Basic monitoring it is not obligatory but may be required by the permitting authority on a case-by-case basis.

After completion of the baseline survey, the FPV installation is implemented and the monitoring framework is re-assessed. Where site-specific evidence indicates potential risks, additional parameters may be incorporated at this stage. Monitoring then continues into the early operation phase, which is accompanied by further evaluation and adjustment. This phase is particularly critical, as immediate ecological responses to the installation are most likely to occur during this period, especially with respect to key parameters such as water quality and hydrodynamics. While direct effects may become apparent shortly after installation, the propagation of impacts through the trophic pyramid, for example to higher levels of the aquatic food web, typically requires more time.

Accordingly, the early operation phase is designed to extend over three years in order to capture both short-term responses and intra-annual variability, as well as to identify early indications of impact propagation within the ecosystem. At the end of this period, a comprehensive re-evaluation is conducted. Monitoring results are interpreted in their site-specific context, including the consideration of potential positive effects, to determine whether individual parameters require continued observation or whether monitoring efforts can be reduced without compromising ecological safeguards.

The subsequent late operation phase generally involves a gradual reduction in eco-hydrological monitoring once early-phase impacts have been sufficiently characterized. Under Extended monitoring, selected parameters may optionally be maintained where site-specific conditions justify continued observation or where uncertainties remain too high to support discontinuation. This is particularly relevant for sensitive or highly variable systems under Advanced monitoring, where delayed or cumulative effects cannot be ruled out. Even in such cases, monitoring may be restricted to the most relevant parameters to maintain project feasibility while ensuring adequate ecological protection.

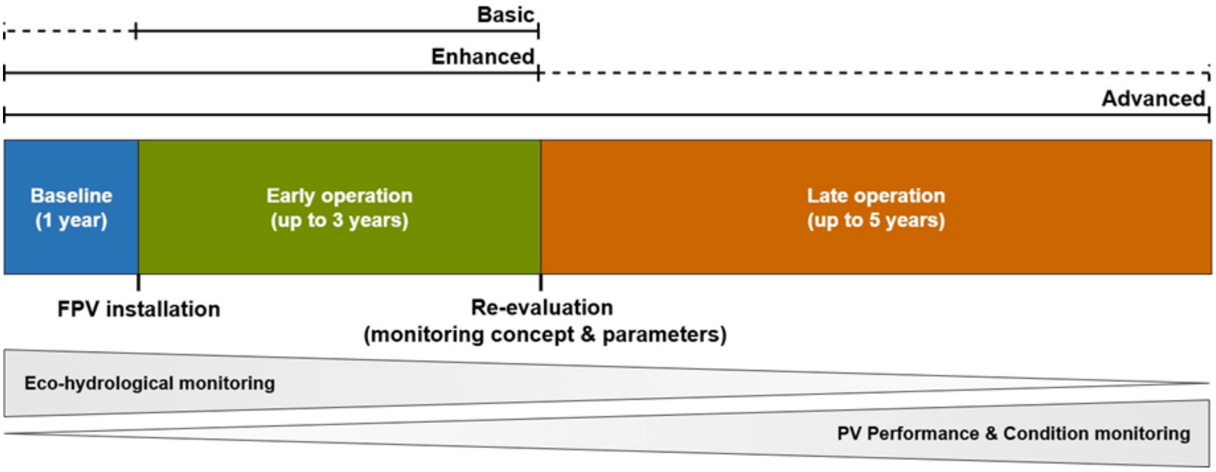


Figure 2. Allocation of monitoring tiers (Basic, Extended, Advanced) along the FPV project timeline (Ilgen, 2026).

Over the project lifetime, the emphasis of monitoring is expected to shift progressively from eco-hydrological parameters towards PV system performance and condition. Nevertheless, both dimensions remain closely interconnected. The long-term durability of FPV systems is not yet well understood, and potential degradation processes, such as material ageing, leaching, or pollutant release, may directly affect aquatic ecosystems. For this reason, system condition assessments should increase in importance as installations age and, to ensure transparency and credibility, should preferably be conducted by neutral and independent institutions. Ideally, these assessments are embedded within an interdisciplinary monitoring framework, in which technical findings inform decisions on whether eco-hydrological monitoring should be partially reactivated or refocused. This integrated approach ensures that technical reliability and ecological safeguards are evaluated jointly rather than in isolation.

2.3 Selection of monitoring tier: FPV-MASI

To support the selection of an appropriate monitoring intensity for FPV installations on inland water bodies, the FPV-MASI (Multi-axis Sensitivity Index; Ilgen, 2026) as a pragmatic screening and prioritization tool can be applied (Fig. 3). FPV-MASI integrates key characteristics of FPV systems, lake properties, climatic forcing, and external pressures into a consolidated sensitivity profile, allowing an initial assessment of where FPV-induced effects are more likely to be detectable.

The approach follows recent methodological developments (Ilgen, 2026) and is intended to provide a transparent and operationally feasible basis for scaling monitoring effort, particularly in early project phases or in contexts where detailed pre-construction assessments are not available. FPV-MASI does not replace comprehensive site-specific risk assessments; rather, it offers a structured way to guide decisions on monitoring scope under practical constraints.

In principle, monitoring tier selection may also be based on detailed preliminary assessments, expert judgement, or hydrodynamic and eco-hydrological modelling, either as alternatives or in combination with FPV-MASI. Such approaches can reduce uncertainty, especially for sensitive sites or novel FPV designs, but are not always feasible for all projects. FPV-MASI therefore represents a practical compromise between scientific robustness and real-world applicability.

Importantly, FPV-MASI is a diagnostic indicator of potential sensitivity rather than a predictive tool for ecological outcomes. Higher scores reflect an increased likelihood that FPV-induced effects are detectable, but do not imply whether such effects are beneficial, neutral, or adverse for lake ecosystems. Accordingly, FPV-MASI should be used solely as a decision-support tool for selecting an appropriate monitoring tier, while the ecological relevance and interpretation of observed changes must be derived from targeted monitoring results and site-specific assessment.

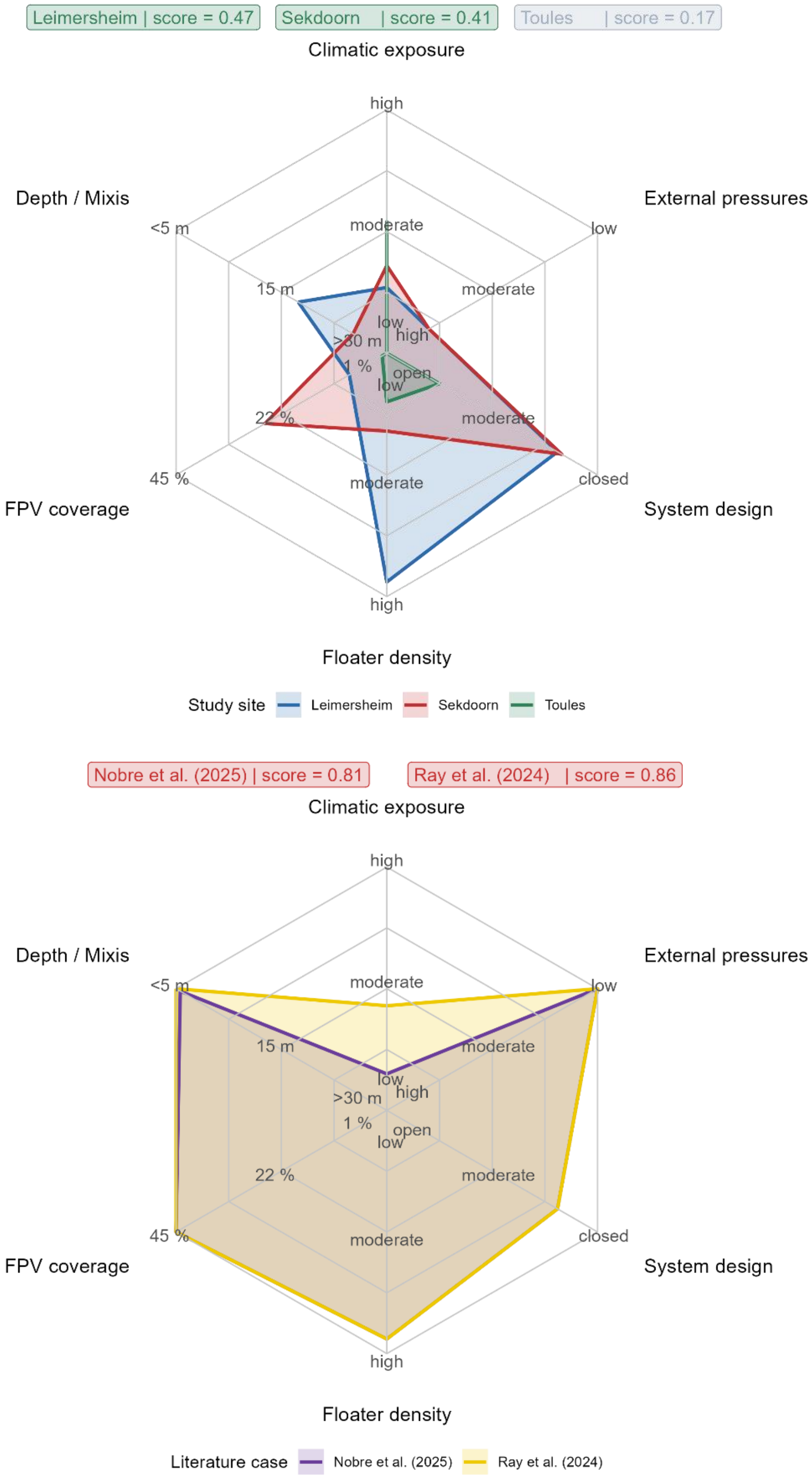


Figure 3. FPV-MASI radar plots showing relative sensitivity profiles of FPV installations. Upper panel: study sites analyzed in Ilgen (2026). Lower panel: contrasting literature cases (Nobre et al., 2025; Ray et al., 2024). MASI-score (0–1) indicates cumulative sensitivity.

Based on comparative analyses of multiple FPV installations and contrasting literature cases, FPV-MASI scores can be used to indicatively guide the selection of monitoring intensity as follows:

- **FPV-MASI < 0.25 – Very low sensitivity**
  FPV-induced effects are unlikely to be measurable or are largely overridden by external drivers.
  → Dedicated environmental **monitoring is not required**.
- **FPV-MASI 0.25–0.50 – Low to moderate sensitivity**
  FPV-induced effects may become detectable under specific meteorological conditions or during certain seasonal states.
  → **Basic Tier** monitoring is recommended, focusing on baseline characterization and long-term trend detection.
- **FPV-MASI 0.50–0.75 – Moderate to high sensitivity**
  FPV-induced effects are likely to be measurable and may influence dominant physical and biogeochemical processes.
  → **Extended Tier** monitoring is appropriate to resolve key drivers and seasonal dynamics.
- **FPV-MASI 0.75–1.00 – High sensitivity**
  Strong FPV–ecosystem interactions are expected due to the combined influence of system design, lake morphology, climatic exposure, and low external pressure.
  → **Advanced Tier** monitoring is recommended and may be complemented by modelling-based assessments.

2.4 Overview of Methods and Sensor Types

Light Conditions & Euphotic Zone Depth

Methodological Principles

Floating PV systems substantially reduce photosynthetically active radiation (PAR, 400–700 nm) at the water surface beneath the installation (Prandini et al., 2025). As water attenuates different wavelengths unevenly (red light near the surface, blue light penetrating deeper), shading primarily affects primary production, oxygen generation, and light-dependent habitats of phytoplankton, macrophytes, and phytobenthos within the euphotic zone (Tanabe et al., 2019). Light attenuation also interacts with lake heat balance and stratification dynamics (Exley, 2022).

To adequately capture these effects, light conditions should be measured at spatially high resolution (Prandini et al., 2025). Measurements should be combined with simple optical clarity indicators (Secchi depth) to derive the euphotic depth and to enable an ecologically meaningful interpretation of impacts on the trophogenic zone (Golubkov et al., 2024; Mehl et al., 2024).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X	X	X

System Layout

Basic, Extended, Advanced:

PAR sensors above and below FPV modules

- One sensor above the modules as a reference for incoming radiation
- Minimum of three sensors below the modules at different positions
- Recommended locations include module edges and the central module area
- Due to module tilt and orientation, PAR may differ between the upper and lower module edges

Secchi depth measurements

- Conducted below FPV installations and at reference locations
- Used to estimate euphotic depth and spatial differences in light availability

Sampling Period and Frequency

Photosynthetically Active Radiation:

- Continuous measurements
- Recommended sampling interval: 15 minutes

Secchi depth:

- Four measurements during the vegetation period (regular intervals, e.g. every two months)
- One additional measurement during the circulation period

Data Evaluation and Expected Insights

- Quantification of FPV-induced light reduction relative to reference conditions
- Determination of changes in euphotic depth beneath FPV installations

- Assessment of spatial heterogeneity in light availability caused by module layout and tilt
- Interpretation of potential impacts on primary production, macrophyte distribution, and phytobenthic habitats
- Contextualization of light effects in relation to thermal structure and stratification dynamics

Wind conditions

Methodological Principles

Wind conditions play a key role in both the structural design and the operational performance of FPV systems (Selj et al., 2025). Wind loads are among the dominant environmental forces acting on FPV installations and directly affect mechanical stability, anchoring systems, and long-term durability. Computational Fluid Dynamics (CFD) studies demonstrate that wind speed, wind direction, turbulence intensity, and array configuration strongly control the spatial distribution of loads across FPV systems (Joo et al., 2023).

Load maxima typically occur at the leading rows of PV modules under forward wind conditions. Under backward or oblique wind directions, the highest loads may shift to trailing or lateral rows. This spatial variability can induce differential stress, deformation, and fatigue if not explicitly accounted for in design and operation. In addition, wind-driven surface shear interacts with thermal stratification and mixing processes in the water body, thereby influencing gas exchange, heat fluxes, and near-surface hydrodynamics (Choi et al., 2023).

Consequently, wind conditions should be monitored in a spatially resolved manner above and below FPV installations and systematically linked to hydrodynamic and thermal measurements. This integrated approach supports both structural safety assessments and eco-hydrological interpretation.

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X	X	X

System Layout

Basic, Extended, Advanced:

- Deployment of 2D or 3D ultrasonic anemometers above and below the FPV modules.
- Three measurement positions are recommended:
    - One integrated within the on-site climate station.
    - One directly above the PV modules at module height.
    - One beneath the modules, directly above the water surface.
- Measured variables include wind speed and direction, turbulence parameters, and where applicable vertical wind components.

Sampling Period and Frequency

- Continuous, year-round monitoring with a multi-year perspective to capture seasonal and extreme-event variability.
- High temporal resolution measurements, typically 1 to 10 Hz for wind speed, direction, and turbulence parameters, to adequately resolve gusts and short-term load fluctuations.
- Aggregation of high-frequency data to standardized 15 min intervals for statistical analysis, model input, and comparison with meteorological and hydrodynamic datasets. Aggregated variables should include mean wind speed and direction, maximum gusts, standard deviation, and turbulence intensity.
- Regular maintenance, cleaning, and functional checks, particularly after storms, high-wave events, or ice formation.
- Strict time synchronization and consistent measurement heights across all stations, with uniform data acquisition rates.

Data Evaluation and Expected Insights

- Quantification of spatial and temporal wind load distributions across FPV arrays under different wind regimes.
- Identification of critical wind directions and speeds associated with peak structural loads and fatigue risks.
- Assessment of turbulence characteristics and their role in dynamic loading and anchoring performance.
- Analysis of wind-driven air–water interactions, including effects on thermal stratification, mixing depth, and gas exchange.
- Improved parameterization of wind forcing in coupled structural, hydrodynamic, and ecological models for FPV systems.

Water level

Methodological Principles

FPV systems are explicitly distinguished by the behavior of the water surface (Du et al., 2024). While some concepts are intended for shallow or regulated water bodies with relatively stable water levels, dedicated water level variation systems are designed for reservoirs with pronounced fluctuations, such as pumped-storage reservoirs. At the same time, all floating structures require mooring and anchoring systems to maintain their target position, limit horizontal and vertical movement, ensure minimum distances between arrays, and safely accommodate water level changes (Kanotra et al., 2022). Variable water levels are therefore a central challenge for FPV mooring design, as highlighted by Bossi et al. (2024).

In this context, information on the magnitude, rate, and temporal dynamics of water level variations constitutes a fundamental boundary condition for site classification, FPV concept selection, and the evaluation of mooring and anchoring performance. Systematic water level monitoring is thus an integral component of the overall monitoring concept, as it documents the actual hydraulic conditions to which the FPV structure and its mooring system are exposed over time, including seasonal variability and extreme drawdown or filling events (Lian et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X	X	X

System Layout

Basic, Extended:

- **Gauge measurement:**
    - A measuring stick or staff gauge fixed at a stable reference point.
    - Water level is determined by reading the water height relative to the scale.
    - Suitable for basic monitoring and visual validation.

Advanced:

- **Pressure sensor measurement:**
    - Submerged pressure transducers installed at a fixed depth and referenced to atmospheric pressure.
    - Enables continuous, high-resolution recording of water level fluctuations.
    - Recommended for Extended and advanced monitoring, especially at sites with rapid or large water level changes.

Sampling Period and Frequency

Basic:

- Discrete water level readings during regular site visits.
- Typical frequency of 4 to 6 measurements per year for lakes or reservoirs with low water level variability.

Extended:

- Regular gauge readings during site visits, with increased visit frequency if moderate water level fluctuations are expected.
- Seasonal coverage recommended to capture characteristic high- and low-water conditions.
- Optional short-term deployment of automatic loggers for targeted campaigns.

Advanced:

- Continuous, year-round monitoring using pressure sensors with a multi-year perspective.
- High temporal resolution measurements, typically at 1 to 10 min intervals.
- Aggregation of raw data to standardized 15 min intervals for analysis, synchronization with meteorological and FPV operational data, and long-term statistics.
- Regular inspection, calibration, and maintenance of sensors, particularly after rapid drawdown, refilling, storm events, or ice conditions.

All levels:

- Consistent referencing of all measurements to a fixed vertical datum.
- Documentation of site visits, reading times, and hydrological conditions to support data interpretation.

Data Evaluation and Expected Insights

- Characterization of typical water level states and seasonal high- and low-water conditions relevant for FPV deployment.
- Quantification of water level variability ranges supporting site classification and FPV concept selection.

- Identification of water level change rates and extreme events affecting mooring geometry and anchoring loads.
- Support for the interpretation of thermal stratification stability, external pressures as well as inflow and outflow regimes of the water body.
- Validation of design assumptions and long-term exposure conditions through combined analysis with wind, wave, and operational data.

Surface heat fluxes

Methodological Principles

Surface heat flux measurements quantify the exchange of thermal energy at interfaces affected by FPV installations. Heat-flux sensors measure the total surface heat flux as the sum of incoming and outgoing convective and radiative components, while embedded thermocouples simultaneously record surface temperature (Rueda et al., 2025). Positive fluxes indicate heat gain by the surface, whereas negative fluxes indicate heat loss. Applied to FPV systems, these measurements allow direct assessment of how PV modules modify surface heat exchange, shading effects, and near-surface thermal conditions, with implications for module performance, microclimate, and water temperature dynamics (Cannon and Vasel-Be-Hagh, 2024; Nobre et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	X	X

System Layout

Extended, Advanced:

Heat flux sensors attached below the modules

- Heat-flux sensors attached directly to the underside of PV modules.
- At least three sensors installed at different locations:
    - One at the module center.
    - Two near opposing module edges.
- Spatial differences in measured heat flux are expected due to module tilt, shading patterns, and varying distance to the water surface.
- Sensors should be securely mounted, thermally well-coupled to the module surface, and protected against moisture and mechanical stress.

Sampling Period and Frequency

- Continuous measurements during system operation with a multi-year perspective.
- High temporal resolution sampling at typically 1 to 10 Hz to resolve diurnal cycles and short-term variability.
- Aggregation of high-frequency data to standardized 15 min intervals for analysis and synchronization with meteorological, hydrodynamic, and FPV performance data.

- Regular sensor inspection and recalibration, particularly in advanced monitoring, to ensure long-term data quality.

Data Evaluation and Expected Insights

- Quantification of FPV-induced modifications of surface heat exchange compared to ambient conditions.
- Assessment of spatial variability in heat flux across module surfaces.
- Analysis of diurnal and seasonal heat flux patterns beneath FPV arrays.
- Improved understanding of feedbacks between thermal conditions, module efficiency, and near-surface air and water temperatures.
- Support for interpreting FPV impacts on local energy balance and thermal stratification processes.

Wind-driven wave dynamics

Methodological Principles

Measuring wind-driven wave dynamics is essential to quantify how FPV installations modify wind–wave interactions, surface drag, and the transfer of momentum and energy at the air–water interface (Denis et al., 2025). FPV arrays partially shelter the water surface, reduce effective fetch, and alter wave growth and dissipation, thereby redistributing turbulent stresses and locally modifying the atmospheric boundary layer.

The resulting attenuation of wave energy beneath and downstream of FPV systems affects near-surface turbulence, vertical mixing, and air–water exchange (Rueda et al., 2025). Reduced wave breaking and bubble entrainment can weaken mixing and increase thermal stratification stability, while strong gradients at array edges may induce localized zones of Extended turbulence. Capturing wind-driven wave dynamics is therefore critical for assessing FPV-induced changes in mixing regimes and thermal properties of the water body.

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
		X

System Layout

Advanced:

- Deployment of wave measurement systems in open-water areas representative of FPV exposure conditions.
- Suitable instruments include wave buoys, pressure-based wave sensors, or ultrasonic wave gauges mounted on fixed structures.
- Sensors should be positioned both within and upstream of FPV arrays where feasible, to capture modifications of the wave field by the installation.
- Co-location with wind sensors is recommended to enable direct analysis of wind–wave coupling.

Sampling Period and Frequency

- Continuous monitoring during system operation, preferably year-round with a multi-year perspective.
- High temporal resolution sampling, typically 1 to 5 Hz, to resolve wave spectra, groupiness, and breaking events.
- Aggregation to standardized 15 min intervals for statistical analysis and synchronization with wind, water level, and FPV operational data.
- Regular maintenance and calibration, particularly after storm events or periods of high wave activity.

Data Evaluation and Expected Insights

- Quantification of wave climate characteristics, including significant wave height, dominant period, and wave direction.
- Assessment of wind–wave coupling strength and its variability under different wind regimes.
- Identification of conditions leading to Extended surface drag, wave breaking, and intensified near-surface turbulence.
- Evaluation of wave-induced loads and motions relevant for FPV structural integrity and mooring design.
- Improved interpretation of wind-driven mixing, air–water exchange, and thermal processes in FPV-affected water bodies.

Flow velocity

Methodological Principles

Measuring water flow velocity is essential because hydrodynamic drag acting on FPV structures depends on the Reynolds number and therefore directly on flow speed (Xu et al., 2024; Graham & Li, 2024). Increasing flow velocity leads to higher drag forces and amplifies the influence of draft depth on resistance (Arora et al., 2023). Flow velocity also controls the pressure field around FPV elements, with increased positive pressure on the inflow side and Extended negative pressure in the wake region, resulting in expanded entrainment and reflux zones (Debnath et al., 2025a). These effects govern vorticity generation and wake development (Nair et al., 2025). In FPV arrays consisting of multiple floating bodies, shielding effects and flow obstruction could lead to non-uniform velocity and pressure distributions along the flow direction. As a result, hydrodynamic loads and resistance vary spatially within the array (Friel, 2024). Quantifying flow velocity is therefore critical for assessing FPV-induced modifications of local circulation patterns, wake interactions, and their implications for structural loading, mixing processes, and transport pathways, consistent with the findings of Denis et al. (2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
		X

System Layout

Advanced:

- Deployment of flow velocity sensors such as Acoustic Doppler Velocimeters (ADV) or Acoustic Doppler Current Profilers (ADCP).
- Profilers can be installed in an upward-looking configuration beneath FPV arrays as well as in adjacent open-water areas to quantify FPV-induced flow modification relative to undisturbed conditions.
- Sensors positioned upstream, within, and downstream of FPV arrays to capture flow alteration, shielding effects, and wake development.
- Measurements at multiple depths to resolve vertical velocity profiles, shear, and turbulence characteristics.
- Co-location with water level and wind measurements to support integrated hydrodynamic interpretation.

Sampling Period and Frequency

- Continuous monitoring during system operation, preferably year-round to capture a range of hydrological and operational conditions.
- High temporal resolution sampling, typically 1 to 10 Hz, to resolve turbulence, velocity fluctuations, and wake dynamics.
- Aggregation of high-frequency data to standardized 15 min intervals for analysis and synchronization with meteorological, wave, and FPV operational data.
- Regular sensor inspection and calibration, particularly after high-flow or extreme events.

Data Evaluation and Expected Insights

- Quantification of ambient and FPV-modified flow velocity regimes.
- Identification of wake structures, velocity deficits, and Extended shear zones associated with FPV arrays.
- Assessment of hydrodynamic loads and spatial variability in resistance acting on floating structures.
- Improved understanding of FPV-induced changes in circulation, mixing intensity, and transport processes.
- Support for validating hydrodynamic and structural models used in FPV design and risk assessment.

Water temperature

Methodological Principles

Water temperature is a fundamental limnological variable for assessing whole-lake processes and energy balance (Wetzel, 2001). In FPV settings, temperature dynamics are directly affected by reduced shortwave irradiance at the water surface due to shading and by modified near-surface wind flow caused by the FPV structure. Both mechanisms influence heat fluxes, vertical mixing, and the development and stability of thermal stratification. Continuous temperature–depth profiles are therefore required to resolve diurnal variability, thermocline depth and strength, and seasonal stratification dynamics (Read et al., 2011).

From these profiles, stability metrics such as Schmidt stability, mixed-layer depth, and internal heat content can be derived (Idso, 1973). These metrics are essential for calibrating and validating hydrodynamic models, for example the General Lake Model, and for testing FPV coverage and climate scenarios. As thermal impacts of FPV systems remain insufficiently constrained but are highly relevant for environmental assessment, licensing, and approval procedures, water temperature monitoring constitutes a core element of FPV monitoring concepts (Ilgen et al., 2023).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
x	x	x

System Layout

Basic:

Water temperature chains installed at two locations:

- **FPV location**: in the central area of the FPV array, positioned at the locally deepest feasible point beneath the installation.
- **Reference (REF) location**: in open water at the deepest available point that is simultaneously as far away as possible from the FPV array to avoid shading and hydrodynamic influence. If the deepest point of the lake is located directly at or near the FPV array edge, a sufficient horizontal distance should be maintained and the reference chain placed at the next deepest undisturbed location.

- **Sensor placement**:
  - First sensor at 1 m below the water surface.
  - Last sensor at 1 m above the lake bottom.
  - One intermediate sensor positioned at an intermediate depth between surface and bottom, representing the mid-water column.
- Suitable for capturing seasonal temperature differences and coarse vertical stratification patterns.

Extended, Advanced:

- High-resolution water temperature chains installed at the same two locations (FPV center and REF open water) following the same spatial criteria as above.
- **Sensor placement**:
  - One sensor directly below the water surface.
  - Sensors at 0.5 m intervals from the surface down to 10 m depth to resolve the epilimnion and thermocline.
  - In higher depths (hypolimnion), larger spacing is acceptable, with sensors at 5 m intervals down to the lake bottom.
- This configuration enables detailed resolution of diurnal temperature dynamics, thermocline structure, and FPV-induced modifications of vertical mixing.

Sampling Period and Frequency

- Continuous, year-round monitoring with a multi-year perspective.

- Direct measurement at standardized 15 min intervals
- Synchronization of temperature data with meteorological, hydrodynamic, and FPV operational datasets.
- Regular inspection, cleaning, and recalibration of sensors to ensure long-term data quality and stability.

Data Evaluation and Expected Insights

- Quantification of FPV-induced changes in surface and subsurface water temperatures.
- Assessment of thermocline depth, strength, and seasonal evolution beneath FPV arrays compared to reference conditions.
- Derivation of thermal stability metrics and heat storage changes relevant for ecological processes.
- Improved understanding of FPV effects on mixing regimes and internal lake dynamics.
- Calibration and validation of hydrodynamic models to support impact assessment and scenario testing.

Dissolved oxygen

Methodological Principles

Dissolved oxygen (DO) is a key variable for assessing FPV impacts on aquatic systems, as FPV installations can modify oxygen dynamics through multiple interacting pathways (Kalff, 2002). Shading by FPV reduces shortwave radiation and photosynthetically active radiation, potentially suppressing primary production and altering phytoplankton biomass and community composition. At the same time, wind shielding by FPV arrays can reduce surface reaeration and vertical mixing, limiting oxygen exchange between the atmosphere and the water column (Cole & Caraco, 1998). The resulting DO response is not binary but may vary across diurnal, seasonal, and spatial scales, depending on meteorological forcing, FPV layout, and site-specific hydrodynamic and ecological conditions (Winslow et al., 2018). Given the relevance of lakes and reservoirs for drinking water supply and biodiversity, continuous DO monitoring is essential for detecting FPV-induced changes in limnological functioning and ecosystem health (Prandini et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X	X	X

System Layout

Basic, Extended, Advanced:

- Dissolved oxygen sensors installed at two locations:
    - **FPV location**: below the FPV array, preferably in the central area of the installation.
    - **Reference (REF) location**: in open water, sufficiently distant from the FPV system to represent undisturbed conditions.

- Discrete vertical sensor placement:
    - First sensor at 1 m below the water surface.
    - One intermediate sensor at mid-depth of the water column.
    - Last sensor at approximately 1 m above the lake bottom.
- Sensors should be co-located with temperature measurements to support stratification-aware interpretation.

Sampling Period and Frequency

- Continuous, year-round monitoring with a multi-year perspective.
- Measurement at standardized 15 min intervals, sufficient to capture diurnal oxygen dynamics and longer-term trends.
- Synchronization with water temperature, meteorological, and FPV operational data.
- Regular sensor cleaning, calibration, and maintenance to prevent biofouling and signal drift.

Data Evaluation and Expected Insights

- Detection of FPV-induced changes in near-surface and deep-water oxygen concentrations.
- Assessment of vertical oxygen gradients and hypolimnetic oxygen depletion under FPV influence.
- Interpretation of diurnal and seasonal oxygen dynamics in relation to shading, stratification, and mixing regimes.
- Evaluation of potential ecological risks, such as hypoxia, relevant for water quality and ecosystem functioning.
- Support for integrated assessment of FPV impacts on lake metabolism and biogeochemical processes.

pH

Methodological Principles

pH is a central indicator of aquatic biogeochemical conditions and ecosystem functioning (Stumm & Morgan, 1996). In FPV systems, pH dynamics may be indirectly affected by reduced photosynthetically active radiation, altered primary production, modified CO_2 uptake and release, and changes in mixing and gas exchange caused by wind shielding (Verschoor et al., 2017). These processes influence the balance between photosynthesis, respiration, and carbonate chemistry, leading to spatial and temporal pH variability. Monitoring pH is therefore essential to detect FPV-induced shifts in metabolic regimes, acid–base balance, and potential implications for nutrient availability, metal solubility, and aquatic organisms (Hanson et al., 2003).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X	X	X

System Layout

Basic, Extended, Advanced:

- pH is measured using a **multiparameter probe** deployed at two locations:
    - **FPV site**: at the deepest feasible point centrally beneath the FPV array.
    - **Reference (REF) site**: at the deepest available point in open water, located as far as possible from the FPV installation.
- Vertical profiling across the full water column with measurements at **0.5 m depth intervals**.
- pH measurements conducted simultaneously with temperature, dissolved oxygen, and other water quality parameters to enable integrated interpretation.
- Where total water depth differs between FPV and REF sites, profiles should extend to comparable relative depths, ensuring consistent evaluation of vertical gradients.

Sampling Period and Frequency

Basic

- At least four profiles during the vegetation period at regular intervals.
- One additional profile during full circulation.
- Total: **5**

Extended

- Six profiles during the vegetation period and two profiles during circulation periods.
- Total: **8**

Advanced

- Monthly depth-resolved profiling throughout the year.
- Total: **12**

Data Evaluation and Expected Insights

- Identification of FPV-induced shifts in vertical pH gradients relative to reference conditions.
- Interpretation of pH variability in relation to primary production, respiration, and stratification dynamics.
- Assessment of seasonal differences in metabolic balance beneath FPV arrays.
- Support for evaluating FPV impacts on biogeochemical processes and water quality conditions.

Conductivity

Methodological Principles

Electrical conductivity is a proxy for the concentration of dissolved ions and thus reflects catchment inputs, groundwater influence, evaporation–dilution dynamics, and internal mixing processes. In FPV settings, conductivity is not typically altered directly by the installation, but it can change indirectly through modified mixing and stratification (wind shielding), altered inflow and outflow patterns, and spatial differences in evaporation and heat balance beneath the array (Exley et al., 2021; Ilgen et al., 2023). Depth-resolved conductivity profiles therefore support the interpretation of water mass structure, mixing regimes, and the transport of dissolved substances, and they help distinguish FPV-related effects from hydrological forcing (Cagle, 2023; de Rijk et al., 2025b).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X	X	X

System Layout

Basic, Extended, Advanced:

- Conductivity is measured using a **multiparameter probe** deployed at two locations:
    - **FPV site**: at the deepest feasible point centrally beneath the FPV array.
    - **Reference (REF) site**: at the deepest available point in open water, as far as possible from the FPV installation.
- Full-depth profiling with measurements at **0.5 m depth intervals**.
- Conductivity recorded together with temperature, dissolved oxygen, and pH to support interpretation of stratification, mixing, and water mass differentiation.

Sampling Period and Frequency

Basic

- At least four profiles during the vegetation period at regular intervals.
- One additional profile during full circulation.
- Total: **5**

Extended

- Six profiles during the vegetation period and two profiles during circulation periods.
- Total: **8**

Advanced

- Monthly depth-resolved profiling throughout the year.
- Total: **12**

Data Evaluation and Expected Insights

- Identification of conductivity stratification and its temporal evolution under and outside FPV influence.
- Detection of water mass separation, mixing events, and inflow signatures (e.g., low- or high-conductivity intrusions).
- Support for interpreting changes in stratification stability and mixing regime when combined with temperature and DO.
- Context for assessing hydrological forcing (inflow/outflow, dilution, evaporation) versus FPV-related effects.

Turbidity

Methodological Principles

Turbidity (NTU/FNU) is a key water quality parameter in FPV impact assessment, as it reflects the concentration of suspended particles and directly influences underwater light availability and biological processes. Increasing turbidity reduces light transmission and thus limits photosynthetic activity. In FPV systems, surface forcing is modified through reduced solar radiation and altered wind excitation, which in turn affect thermal stratification, vertical mixing, and particle resuspension (Exley et al., 2021; Ilgen et al., 2023). These background processes must be considered when interpreting turbidity measurements. Previous studies have reported site-specific reductions in turbidity beneath FPV installations, in some cases linked to reduced algal biomass and altered primary production (Ilgen et al., 2025; de Rijk et al., 2025b).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
x	x	x

System Layout

Basic, Extended, Advanced:

- Turbidity is measured using a **multiparameter probe** deployed at two locations:
    - **FPV site**: at the deepest feasible point centrally beneath the FPV array.
    - **Reference (REF) site**: at the deepest available point in open water, as far as possible from the FPV installation.
- Full-depth profiling with measurements at **0.5 m depth intervals**.

Sampling Period and Frequency

Basic

- At least four profiles during the vegetation period at regular intervals.
- One additional profile during full circulation.
- Total: **5**

Extended

- Six profiles during the vegetation period and two profiles during circulation periods.
- Total: **8**

Advanced

- Monthly depth-resolved profiling throughout the year.
- Total: **12**

Data Evaluation and Expected Insights

- Identification of FPV-induced differences in turbidity between the FPV site and the reference location across the full water column.
- Interpretation of vertical turbidity gradients in relation to stratification, mixing intensity, and seasonal circulation.
- Assessment of reduced turbidity beneath FPV arrays associated with lower phytoplankton production and potential filtration or settling effects.

- Detection of Extended turbidity linked to resuspension processes during mixing events, inflow episodes, or at FPV edges where turbulence may be increased.
- Improved understanding of how FPV installations modify particle dynamics, underwater light climate, and related ecological processes.

Nutrients (NO_3, PO_4)

Methodological Principles

Dissolved inorganic nutrients, particularly nitrate (NO_3^-) and phosphate (PO_4^{3-}), are key drivers of primary production and trophic state in lakes and reservoirs (Goldman et al., 1996; Kennedy & Walker, 1990). In FPV systems, nutrient dynamics may be indirectly influenced by reduced photosynthetically active radiation, altered thermal stratification, and modified mixing regimes (Merino-Ibarra & Ramírez-Zierold, 2021; Sandrini et al., 2025). These changes can affect nutrient uptake by phytoplankton, vertical nutrient transport across the thermocline, and internal nutrient loading from deeper layers (Li et al., 2022; Engel & Fischer, 2017). Monitoring nutrients under FPV therefore supports the assessment of potential shifts in productivity, nutrient limitation, and biogeochemical cycling associated with FPV-induced physical changes (Exley, 2022; Vouhe et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	X	X

System Layout

Extended, Advanced:

- Nutrient concentrations measured using **depth-resolved water sampling** combined with laboratory analysis.
- Sampling conducted at two locations:
  - **FPV site**: at the deepest feasible point centrally beneath the FPV array.
  - **Reference (REF) site**: at the deepest available point in open water, located as far as possible from the FPV installation.
- Vertical sampling across the full water column, typically aligned with temperature and dissolved oxygen profiles, with representative depths in the epilimnion, metalimnion, and hypolimnion.

Sampling Period and Frequency

Extended

- Sampling during key phases of the vegetation period, typically four to six campaigns per year, complemented by one to two campaigns during circulation periods.

Advanced

- Monthly sampling throughout the year to capture seasonal transitions, stratification breakdown, and internal loading processes.

Data Evaluation and Expected Insights

- Comparison of nutrient concentrations and vertical distributions between FPV and reference sites.
- Assessment of FPV-related changes in nutrient availability linked to altered stratification and mixing.
- Identification of nutrient depletion in surface layers due to reduced primary production or enhanced settling.
- Detection of nutrient accumulation in deeper layers and implications for internal loading during mixing events.
- Support for interpreting FPV impacts on trophic state, productivity, and ecosystem functioning.

Dissolved organic carbon

Methodological Principles

Dissolved organic carbon (DOC) is a key component of aquatic carbon cycling and strongly influences light attenuation, microbial metabolism, and the transport of nutrients and trace substances (Cory et al., 2015; Minor & Oyler, 2023). In FPV systems, DOC dynamics may be indirectly affected by reduced photosynthetically active radiation (PAR), altered primary production, and modified mixing and stratification regimes (Vouhe et al., 2025). Changes in wind forcing and surface energy balance beneath FPV arrays can influence the vertical redistribution of DOC and its exposure to photodegradation at the surface (Brentrup, 2017). Monitoring DOC therefore supports the assessment of FPV-induced changes in carbon processing, light climate, and biogeochemical functioning.

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	X	X

System Layout

Extended, Advanced:

- DOC measured through **depth-resolved water sampling** with subsequent laboratory analysis, which provides the highest accuracy and reliability.
- Optionally, DOC (or CDOM as a proxy) can be measured using **multiparameter probes**, allowing higher spatial or temporal coverage; however, these measurements should be interpreted with caution and, where possible, validated against laboratory analyses.
- Sampling conducted at two locations:
    - **FPV site**: at the deepest feasible point centrally beneath the FPV array.
    - **Reference (REF) site**: at the deepest available point in open water, as far as possible from the FPV installation.

- Vertical sampling across the full water column, aligned with temperature and dissolved oxygen profiles, with representative depths in the epilimnion, metalimnion, and hypolimnion.
- Filtration (e.g. 0.45 µm) prior to laboratory analysis to ensure consistency of DOC measurements.

Sampling Period and Frequency

Extended

- Sampling during the vegetation period, typically four to six campaigns per year, and one to two campaigns during circulation periods.

Advanced

- Monthly sampling throughout the year to capture seasonal variability and mixing-driven redistribution.

Data Evaluation and Expected Insights

- Comparison of DOC concentrations and vertical distributions between FPV and reference sites.
- Assessment of FPV-related changes in surface DOC linked to reduced photodegradation under shading.
- Evaluation of DOC accumulation or depletion patterns associated with altered mixing and stratification.
- Improved understanding of FPV effects on carbon cycling, light attenuation, and microbial processes.

Pollutants and microplastics

Methodological Principles

Pollutants and microplastics represent emerging and site-specific water quality concerns in lakes and reservoirs. FPV installations may influence their distribution and fate indirectly by modifying hydrodynamic conditions, mixing intensity, and particle settling processes (Sharip et al., 2025). Reduced wind-driven mixing beneath FPV arrays can promote the accumulation or settling of particulate pollutants and microplastics, while enhanced turbulence at array edges may increase resuspension (Mancini et al., 2024).

In addition, FPV systems may act as a local source of microplastics through mechanical abrasion, material fatigue, and weathering of floats, cables, and auxiliary components (De Carvalho et al., 2025). Long-term exposure to UV radiation, temperature fluctuations, and biofouling can further contribute to material degradation and particle release (Błotnicki et al., 2025). Monitoring microplastics is therefore essential to distinguish between background inputs, hydrodynamically driven redistribution, and potential FPV-related emissions, supporting risk assessment for water quality, drinking water safety, and aquatic ecosystems (Exley, 2022).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
		x

System Layout

Extended, Advanced:

- Sampling conducted at two locations:
    - **FPV site**: centrally beneath the FPV array at the deepest feasible point.
    - **Reference (REF) site**: in open water at the deepest available point, as far as possible from the FPV installation.
- Collection of water samples at representative depths, typically near the surface, mid-water column, and close to the lake bottom.
- For microplastics, use of contamination-controlled sampling protocols and appropriate filtration methods.
- Pollutant analysis performed using laboratory-based analytical techniques suited to the target substances.

Sampling Period and Frequency

Extended

- Targeted sampling campaigns, typically two to four times per year, aligned with periods of stratification and circulation.

Advanced

- Regular or annual monitoring, with increased frequency where FPV materials, sensitive water uses, or regulatory requirements apply.

Data Evaluation and Expected Insights

- Identification of potential differences in pollutant and microplastic concentrations between FPV and reference sites.
- Assessment of accumulation, settling, or resuspension patterns linked to FPV-induced changes in mixing and flow.
- Evaluation of potential contributions from FPV materials or operational activities.
- Support for risk assessment related to water quality, drinking water abstraction, and ecosystem health.

Shoreline structure

Methodological Principles

Shoreline structure reflects the long-term interaction between hydrodynamic forcing, sediment transport, and biological stabilization processes (Knighton, 1998; Gurnell et al., 2001). FPV installations can indirectly influence shoreline morphology by modifying wind fetch, wave energy, and nearshore circulation patterns (Attar et al., 2025; Haas et al., 2020). Reduced wave exposure behind FPV arrays may decrease erosion and promote sediment accumulation, while wave reflection or redirection at array edges can locally enhance erosion (Trapani, 2014).

In addition, shoreline structure must also be considered during the installation phase, as construction activities, temporary access routes, anchoring works, and material handling can directly affect shoreline stability and riparian vegetation (Ibrahim et al., 2024). Monitoring shoreline structure therefore supports the assessment of both short-term installation-related impacts and long-term operational effects on erosion, sediment dynamics, and habitat conditions (Ogles, 2021).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
X (qualitative)	X (detailed)	X (detailed)

System Layout

Basic

- Baseline visual surveys of shoreline structure documenting vegetation cover, erosion features, bank stability, and sediment deposits.
- Photographic documentation from fixed reference points to ensure consistent comparison before installation, during construction, and throughout operation.
- Historical map and aerial image analysis (orthophotos, satellite imagery) to identify long-term shoreline trends and provide pre-installation reference conditions.

Extended, Advanced

- Geodetic shoreline surveys using GPS or total stations to obtain accurate horizontal positions and elevation profiles of the shoreline.
- LiDAR surveys to generate high-resolution digital elevation and surface models of the shoreline and adjacent nearshore zone.
- Vegetation surveys of the shoreline, documenting dominant plant communities, species composition, and coverage, with particular attention to riparian and emergent macrophyte species.
- GIS-based spatial analysis integrating all datasets to quantify shoreline position changes, erosion and deposition rates, and spatial patterns over time.

Sampling Period and Frequency

Basic

- Visual surveys and photographic documentation conducted before installation, shortly after installation, and one to two times per year during operation.
- Additional surveys following major storm, high-water, or construction-related disturbance events.

Extended

- Geodetic surveys conducted prior to installation and annually thereafter, with additional surveys before and after major hydrodynamic events where feasible.
- Vegetation surveys conducted annually during the growing season.

Advanced

- LiDAR surveys and detailed GIS analyses conducted pre-installation and at multi-year intervals during operation, or following significant system modifications or extreme events.
- Repeated vegetation surveys at one- to two-year intervals, enabling detection of longer-term shifts in species composition and habitat structure.

Data Evaluation and Expected Insights

- Identification of shoreline segments affected by construction activities, erosion, or sediment accumulation.
- Assessment of changes in shoreline vegetation cover and species composition in relation to FPV installation and operation.
- Separation of short-term installation-related impacts from long-term operational effects on shoreline morphology and habitats.
- Evaluation of FPV-induced changes in wave exposure and hydrodynamic forcing and their combined geomorphological and ecological effects.
- Support for impact assessment, mitigation planning, and adaptive shoreline and habitat management.

Sediments

Methodological Principles

Sediments integrate physical, chemical, and biological processes over time and provide an archive of environmental conditions in lakes and reservoirs. In FPV systems, sediment dynamics may be altered by modified hydrodynamic forcing, reduced wave energy, and changes in mixing beneath and around the arrays, affecting sedimentation rates, grain size, organic matter accumulation, and nutrient storage and release (Vouhe et al., 2025; Ilgen et al., 2025).

In addition, FPV structures promote biofouling and biocolonization (e.g. mussels), and the fall-off of biomass, shells, and biodeposits can locally enhance organic matter input and influence redox conditions and nutrient cycling (Sandrini et al., 2025; Attar et al., 2025). Altered suspension and resuspension patterns, with reduced particle mobilization under sheltered areas and potentially increased resuspension at array edges, further affect particulate nutrient transport and internal loading (Denis et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	x	x

System Layout

Extended, Advanced:

- **Sediment traps (particularly relevant for FPV):**
    - Install traps beneath the FPV array (centrally, at the deepest feasible point) and at a reference (REF) site in open water at comparable depth and as far as possible from the installation.
    - Optionally deploy additional traps at the FPV edge to capture gradients between sheltered and more turbulent zones (shallow lakes).
    - Purpose: quantification of current particle fluxes, including effects of shading, altered mixing and resuspension, and biodeposition or biofouling fall-off (e.g. mussels).
- **Sediment sampling (grab/core):**
    - Collection of surface sediments (0–5 cm) at FPV and REF sites to assess organic matter accumulation, nutrient storage, and redox-sensitive processes.
    - Short sediment cores where longer-term trends or before–after comparisons are required.
- **Choice of sampling devices:**
    - Sediment traps for time-resolved deposition rates.
    - Gravity corers or Kajak corers for intact cores, and Ekman or grab samplers for surface sediments, depending on sediment type and study objectives.

Sampling Period and Frequency

Extended

- Sediment sampling conducted **once per year**, preferably during stable stratification or low-flow conditions.

Advanced

- **Repeated sediment sampling** at multi-year intervals to detect trends in sediment accumulation, composition, and contaminant loads.
- Additional sampling following major hydrodynamic events or substantial changes in FPV layout.

Data Evaluation and Expected Insights

- Comparison of sediment properties beneath FPV arrays and at reference locations, including spatial patterns of deposition.
- Detection of FPV-related changes in sedimentation, including increased organic matter accumulation potentially linked to biofouling fall-off and biodeposition.
- Assessment of altered nutrient storage and mobilization, including the potential for increased internal loading under low-oxygen conditions.
- Evaluation of changes in suspension and resuspension dynamics that affect particulate nutrient transport and turbidity.
- Support for linking benthic changes to water column responses (oxygen, nutrients, stratification) and for assessing long-term ecological effects.

Chlorophyll-a

Methodological Principles

Chlorophyll-a is a widely used proxy for phytoplankton biomass and primary productivity in lakes and reservoirs (Wetzel, 2001; Reynolds, 2006). In FPV systems, chlorophyll-a dynamics may be affected by reduced photosynthetically active radiation (PAR) due to shading, altered thermal stratification, and modified mixing regimes resulting from wind shielding (Bossi et al., 2024; Sandrini et al., 2025). These changes can influence phytoplankton growth rates, vertical distribution, and community structure (Falkowski & Raven, 2007; Attar et al., 2025). Monitoring chlorophyll-a is therefore essential for assessing FPV impacts on primary production, trophic state, and associated biogeochemical and ecological processes (Zhao et al., 2023).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
x	x	x

System Layout

Basic, Extended, Advanced:

- Chlorophyll-a measured at two locations:
  - FPV site: centrally beneath the FPV array at the deepest feasible point.
  - Reference (REF) site: in open water at the deepest available point, as far as possible from the FPV installation.
- Depth-resolved measurements across the water column:
  - Either using multiparameter probes with chlorophyll-a fluorescence sensors, or
  - Through water sampling followed by laboratory analysis (e.g. extraction and fluorometric or spectrophotometric determination), which provides higher accuracy and calibration reference.
- Vertical resolution adapted to the monitoring level, with finer resolution in the upper water column where phytoplankton biomass is highest.

Sampling Period and Frequency

Basic

- Depth-resolved measurements during regular site visits, typically four times during the vegetation period and once during circulation.
- Total: **5**

Extended

- Six measurements during the vegetation period and two during circulation periods, synchronized with temperature and nutrient profiling.
- Total: **8**

Advanced

- Monthly depth-resolved measurements throughout the year, with optional high-frequency fluorescence logging where continuous sensors are deployed.
- Total: **12**

Data Evaluation and Expected Insights

- Quantification of phytoplankton biomass differences between FPV and reference sites.
- Assessment of vertical chlorophyll-a distribution and potential deep chlorophyll maxima.
- Interpretation of seasonal and FPV-induced changes in primary production linked to shading, stratification, and mixing.
- Support for evaluating FPV impacts on trophic state, ecosystem functioning, and water quality.

Aquatic macrophytes and phytobenthos

Methodological Principles

Aquatic macrophytes and phytobenthos play a key role in shallow-water ecosystem functioning by structuring habitats, stabilizing sediments, and regulating nutrient and oxygen dynamics (Gurnell et al., 2001; Jeppesen et al., 1998). FPV installations may influence these communities primarily through reduced light availability, altered wave exposure, and changes in nearshore hydrodynamics (Ilgen et al., 2025; Haas et al., 2020). Shading can limit macrophyte growth and shift species composition toward more shade-tolerant taxa, while modified wave energy and sediment dynamics may affect phytobenthic biomass and distribution (Sandrini et al., 2025). Monitoring macrophytes and phytobenthos is therefore essential for assessing FPV impacts on littoral habitats, biodiversity, and ecosystem processes (Vouhe et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
x (presence/cover)	x (quantitative)	x (quantitative)

System Layout

Basic:

- Qualitative assessment of macrophyte cover, focusing on spatial extent rather than species-level detail.
- Mapping of macrophyte presence and relative cover using acoustic methods (e.g. sonar/echosounder) and/or visual surface observations.
- Differentiation between areas beneath or adjacent to FPV installations and reference shoreline sections.
- Suitable for a coarse overview of macrophyte distribution and potential large-scale shading effects.

Extended, Advanced:

- Diver-based macrophyte and phytobenthos mapping following standardized transect-based methods in accordance with WFD (Water Framework Directive) protocols or comparable national standards.
- Quantitative assessment of species composition, percent cover, and depth distribution, and where feasible biomass.
- Surveys conducted along fixed transects at multiple locations:

    - Beneath or adjacent to FPV arrays where light reduction and hydrodynamic changes are expected.
    - At reference sites in unshaded littoral areas.
- Phytobenthos sampling using scraping techniques or artificial substrates to quantify benthic algal biomass and community structure.
- Georeferencing of transects and sampling points to enable spatial analysis and repeated long-term assessments.

Sampling Period and Frequency

Basic

- Surveys conducted once per year during peak vegetation growth.

Extended

- Annual surveys during the growing season, with repeated measurements at fixed transects.

Advanced

- Annual or biannual surveys over multiple years to detect long-term changes in species composition, coverage, and biomass.

Data Evaluation and Expected Insights

- Identification of FPV-related changes in macrophyte and phytobenthos presence, cover, and species composition.
- Assessment of light-driven shifts toward shade-tolerant species beneath FPV installations.
- Evaluation of changes in littoral habitat structure and benthic primary production.
- Support for biodiversity assessment, habitat management, and regulatory compliance.

Phytoplankton

Methodological Principles

Phytoplankton form the base of pelagic food webs and respond sensitively to changes in light availability, nutrient supply, and mixing regimes. FPV installations can influence phytoplankton dynamics by reducing photosynthetically active radiation (PAR) through shading, altering thermal stratification, and modifying vertical mixing due to wind shielding. These changes may affect phytoplankton biomass, species composition, vertical distribution, and bloom dynamics (Exley et al., 2022; Sandrini et al., 2025). Monitoring phytoplankton is therefore essential for assessing FPV impacts on primary production, trophic state, and ecological status of lakes and reservoirs (Vouhe et al., 2025; Cagle et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	x	x

System Layout

Extended, Advanced:

- Phytoplankton sampled at two locations:
    - FPV site: centrally beneath the FPV array at the deepest feasible point.
    - Reference (REF) site: in open water at the deepest available point, as far as possible from the FPV installation.
- Depth-integrated or depth-resolved water sampling covering the euphotic zone, aligned with temperature and chlorophyll-a profiles.
- Laboratory analysis for species identification, abundance, and biovolume, using microscopy or image-based methods.
- Optional use of in situ fluorometric sensors as supporting information, calibrated against laboratory measurements.

Sampling Period and Frequency

Extended

- **Two surveys per year during the vegetation period**, timed to capture key phases of phytoplankton development (e.g. early and peak summer).
- A **baseline survey prior to FPV installation** (or at the earliest feasible operational stage) is recommended, followed by repeated surveys in subsequent years.

Advanced

- **Four surveys per year during the vegetation period**, covering major succession phases (spring development, summer stratification, late-season conditions).
- A **baseline survey prior to FPV installation** (or at the earliest feasible operational stage) is required, followed by repeated multi-year monitoring.

Data Evaluation and Expected Insights

- Representative assessment of phytoplankton biomass and community composition under FPV and reference conditions.
- Detection of FPV-induced differences in phytoplankton biomass, species composition, and dominance structures.
- Identification of shifts toward shade-tolerant and low-light-adapted taxa beneath FPV installations.
- Analysis of seasonal phytoplankton dynamics and bloom development in relation to altered stratification, mixing, and nutrient availability.
- Improved separation of FPV-related effects from natural seasonal and interannual variability.
- Support for ecological status assessment, bloom risk evaluation, and overall FPV impact assessment.

Benthic diatoms

Methodological Principles

Benthic diatoms are sensitive indicators of light availability, nutrient conditions, and hydromorphological stability in littoral and shallow benthic zones (Round et al., 1990). FPV installations may influence benthic diatom communities indirectly through shading, altered wave exposure, and changes in sediment stability and near-bottom flow (Nobre et al., 2025; Sandrini et al., 2025). Reduced light beneath FPV arrays can shift diatom assemblages toward shade-tolerant taxa, while modified hydrodynamics may affect substrate availability and disturbance regimes (Ilgen et al., 2025). Monitoring benthic diatoms therefore provides a robust, integrative measure of FPV impacts on benthic primary producers and ecological status (Mancini et al., 2024).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	X	X

System Layout

Extended, Advanced:

- Benthic diatom sampling conducted at two locations:
    - FPV-influenced sites beneath or adjacent to FPV installations.
    - Reference (REF) sites in unshaded littoral areas.
- Sampling from standardized substrates (e.g. stones, artificial substrates, or sediment surfaces), following established protocols (e.g. WFD-compliant methods).
- Replicated sampling along fixed transects to capture spatial variability.
- Samples preserved and analyzed in the laboratory for species identification and index calculation.

Sampling Period and Frequency

- Sampling is conducted once per year during the vegetation period under stable hydrological conditions.
- A baseline survey prior to FPV installation (or at the earliest feasible operational stage) is required, with annual repetition to enable trend analysis.

Data Evaluation and Expected Insights

- Detection of FPV-related shifts in benthic diatom species composition and ecological indices.
- Assessment of shading and hydrodynamic effects on benthic primary production.
- Comparison of ecological status between FPV-influenced and reference sites.
- Support for regulatory assessment and long-term monitoring of FPV impacts on benthic habitats.

Zooplankton

Methodological Principles

Zooplankton plays a central role in pelagic food webs by linking primary producers to higher trophic levels and by contributing to grazing control of phytoplankton. Zooplankton communities respond sensitively to changes in light availability, temperature stratification, mixing intensity, and food quantity and quality. FPV installations may indirectly affect zooplankton through reduced photosynthetically active radiation, altered phytoplankton composition, and modified thermal and hydrodynamic conditions (Oliveira et al., 2025; Ilgen et al., 2023; Exley et al., 2022; Jeppesen et al., 2014; Vouhe et al., 2025). Monitoring zooplankton therefore supports the assessment of FPV impacts on pelagic ecosystem structure, trophic interactions, and energy transfer (Sandrini et al., 2025; Attar et al., 2025).

Monitoring Design

Monitoring level

Basic	Extended	Advanced
	x	x

System Layout

Extended, Advanced:

- Zooplankton sampling conducted at two locations:
    - FPV site: centrally beneath the FPV array at the deepest feasible point.
    - Reference (REF) site: in open water at the deepest available point, as far as possible from the FPV installation.
- Sampling using vertical net hauls (e.g. plankton nets with appropriate mesh size) covering the epilimnion or the full water column, depending on lake depth and stratification.
- Replicated samples to account for spatial variability.
- Samples preserved and analyzed in the laboratory for taxonomic composition, abundance, and size structure.

Sampling Period and Frequency

- **Two surveys per year during the vegetation period**, timed to represent early and peak summer conditions.
- A **baseline survey prior to FPV installation** (or at the earliest feasible operational stage) is recommended, followed by repeated annual surveys to detect long-term changes.

Data Evaluation and Expected Insights

- Assessment of zooplankton community composition, abundance, and size structure under FPV and reference conditions.
- Identification of FPV-related changes in grazing pressure and trophic interactions with phytoplankton.
- Interpretation of zooplankton dynamics in relation to food availability, thermal stratification, and mixing regimes.
- Detection of indirect FPV effects propagated through pelagic food-web interactions.
- Support for evaluating FPV impacts on pelagic ecosystem functioning and energy transfer.

Macrozoobenthos (e.g. mussels)

Methodological Principles

Macrozoobenthos integrates environmental conditions over longer time scales and responds sensitively to changes in sediment quality, organic matter availability, oxygen conditions, and hydrodynamics. FPV installations may influence macrozoobenthic communities indirectly through altered sedimentation patterns, biodeposition from biofouling organisms (e.g. mussels), reduced resuspension beneath sheltered areas, and modified oxygen and nutrient dynamics (Kristensen et al., 2012; Prandini et al., 2025; Attar et al., 2025; Langenheder et al., 2017; McGowan et al., 2023). Monitoring macrozoobenthos supports the assessment of FPV impacts on benthic habitats, biogeochemical processes, and food-web structure (Chen et al., 2021; Ilgen et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	x	x

System Layout

Extended, Advanced:

- Macrozoobenthos sampling at two locations:
    - FPV site: beneath the FPV array at the deepest feasible point.
    - Reference (REF) site: open-water site at comparable depth, as far as possible from the FPV installation.
- Sampling using standardized benthic methods (e.g. grab samplers or cores), following established protocols.
- Replicated samples to account for spatial variability.
- Laboratory analysis for taxonomic composition, abundance, and biomass.

Sampling Period and Frequency

- Sampling conducted once per year during stable conditions, preferably during late summer or early autumn.
- A baseline survey prior to FPV installation (or at the earliest feasible operational stage) is recommended, followed by annual repetition.

Data Evaluation and Expected Insights

- Assessment of FPV-related changes in benthic community composition and dominance patterns.
- Identification of effects linked to biodeposition, altered sedimentation, and oxygen conditions.
- Interpretation of macrozoobenthos responses in relation to sediment and nutrient dynamics. Support for evaluating FPV impacts on benthic ecosystem functioning.

Birds

Methodological Principles

Birds respond to FPV installations through changes in habitat availability, disturbance, collision risk, and altered foraging conditions. FPV systems may attract certain species (e.g. resting or roosting birds) while deterring others due to visual barriers or human activity. Monitoring birds supports the assessment of FPV impacts on species presence, abundance, behavior, and conservation-relevant sensitivities (de Jong et al., 2022; Zhou et al., 2023; Kiesecker et al., 2019; Johnson et al., 2020; Bellio et al., 2021).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
	x	x

System Layout

Extended, Advanced:

- Standardized bird surveys conducted at FPV and reference areas.
- Combination of visual counts, point counts, and transect surveys, depending on site characteristics.
- Recording of species presence, abundance, behavior (e.g. foraging, resting, flight paths), and seasonal use.
- Focus on waterbirds, shoreline-associated species, and sensitive or protected taxa.

Sampling Period and Frequency

- Surveys conducted multiple times per year, covering key periods:
    - breeding season,
    - migration periods,
    - wintering period (if relevant).
- A baseline survey prior to FPV installation is recommended, followed by repeated annual surveys.

Data Evaluation and Expected Insights

- Identification of FPV-related changes in bird presence, abundance, and spatial use.
- Assessment of attraction, avoidance, or displacement effects.
- Evaluation of potential disturbance or collision risks.
- Support for biodiversity assessment and compliance with nature conservation requirements.

Insects (e.g. dragonflies)

Methodological Principles

Aquatic and semi-aquatic insects, such as dragonflies (Odonata), are sensitive indicators of littoral habitat quality, vegetation structure, and microclimatic conditions (New, 2020). Floating photovoltaic (FPV) installations may indirectly affect insect communities by shading water surfaces, thereby influencing macrophyte development and thermal regimes, both critical for insect life cycles (Vouhe et al., 2025; Oliveira et al., 2025). Alterations of shoreline and nearshore habitats due to FPV-induced changes in light availability and wind dynamics may further impact oviposition sites and larval development zones (de Rijk et al., 2025b). Monitoring aquatic insects thus supports the assessment of FPV impacts on biodiversity and habitat integrity at the land–water interface, particularly given their key roles in trophic dynamics and ecosystem functioning (Lambert, 2022).

Monitoring Design

Monitoring level

Basic	Extended	Advanced
		X

System Layout

Advanced:

- Targeted insect surveys along shoreline sections adjacent to FPV installations and at reference sites.
- Standardized methods such as visual surveys, netting, and exuviae collection for dragonflies.
- Recording of species presence, abundance, and habitat associations.
- Georeferenced sampling locations to enable repeat surveys.

Sampling Period and Frequency

- Surveys conducted once per year during the main flight period.
- A baseline survey prior to FPV installation is recommended, followed by annual repetition.

Data Evaluation and Expected Insights

- Identification of FPV-related changes in insect species composition and abundance.
- Assessment of habitat alterations at the shoreline and littoral zone.
- Support for biodiversity assessment and evaluation of indirect FPV effects on nearshore ecosystems.

Fish and cyclostomes

Methodological Principles

Fish and cyclostomes integrate physical, chemical, and biological conditions across spatial and temporal scales. FPV installations may influence fish communities through altered light regimes, habitat structure, thermal conditions, and prey availability. Monitoring fish supports the assessment of FPV impacts on habitat use, community composition, and trophic interactions (Oliveira et al., 2025; Sandrini et al., 2025; Vouhe et al., 2025; Exley, 2022; Haas et al., 2020).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
		X

System Layout

Advanced:

- Fish surveys conducted at FPV and reference sites using appropriate methods (e.g. gill nets, hyroacoustics, or electrofishing, depending on site conditions and regulations).
- Recording of species composition, abundance, size structure, and habitat use.
- Alignment with existing fisheries or regulatory monitoring programs where possible.

Sampling Period and Frequency

- Surveys conducted once per year, preferably during stable thermal conditions.
- A baseline survey prior to FPV installation is required, followed by annual repetition.

Data Evaluation and Expected Insights

- Identification of FPV-related changes in fish community structure and habitat use.
- Assessment of indirect effects mediated through light, temperature, and prey availability.
- Support for ecological status assessment and fisheries management considerations.

Mammals (e.g. bats)

Methodological Principles

Mammals, particularly bats, may interact with FPV installations through altered foraging habitats, flight paths, and insect availability. Water surfaces often serve as important foraging areas for bats, and FPV installations may modify prey density, surface structure, and acoustic conditions. Monitoring mammals supports the assessment of FPV impacts on protected species and nocturnal ecosystem dynamics (Barré et al., 2024; Vouhe et al., 2025; Hernandez et al., 2025; Oliveira et al., 2025).

Study Design and Variables

Monitoring level

Basic	Extended	Advanced
		X

System Layout

Advanced:

- Bat monitoring using acoustic detectors deployed at FPV installations and reference shoreline locations.
- Recording of activity levels, species presence, and temporal patterns.
- Optional combination with visual observations or roost surveys where relevant.

Sampling Period and Frequency

- Monitoring conducted during the active season, with repeated recording nights.
- A baseline survey prior to FPV installation is required, followed by repeated annual monitoring.

Data Evaluation and Expected Insights

- Assessment of FPV-related changes in bat activity and species composition.
- Evaluation of potential impacts on foraging behavior and habitat use.
- Support for conservation assessment and compliance with species protection regulations.

2.5 Example monitoring and sensor setups across monitoring tiers

The following figures illustrate representative monitoring and sensor setups for FPV installations across basic, extended, and advanced monitoring tiers. All setups are based on a consistent conceptual framework comparing conditions at an open water reference (REF) site in open water with measurements conducted beneath the FPV array (Fig. 4). The examples demonstrate how increasing monitoring levels primarily reflect higher spatial and temporal resolution and improved process attribution, rather than fundamentally different parameter selections.

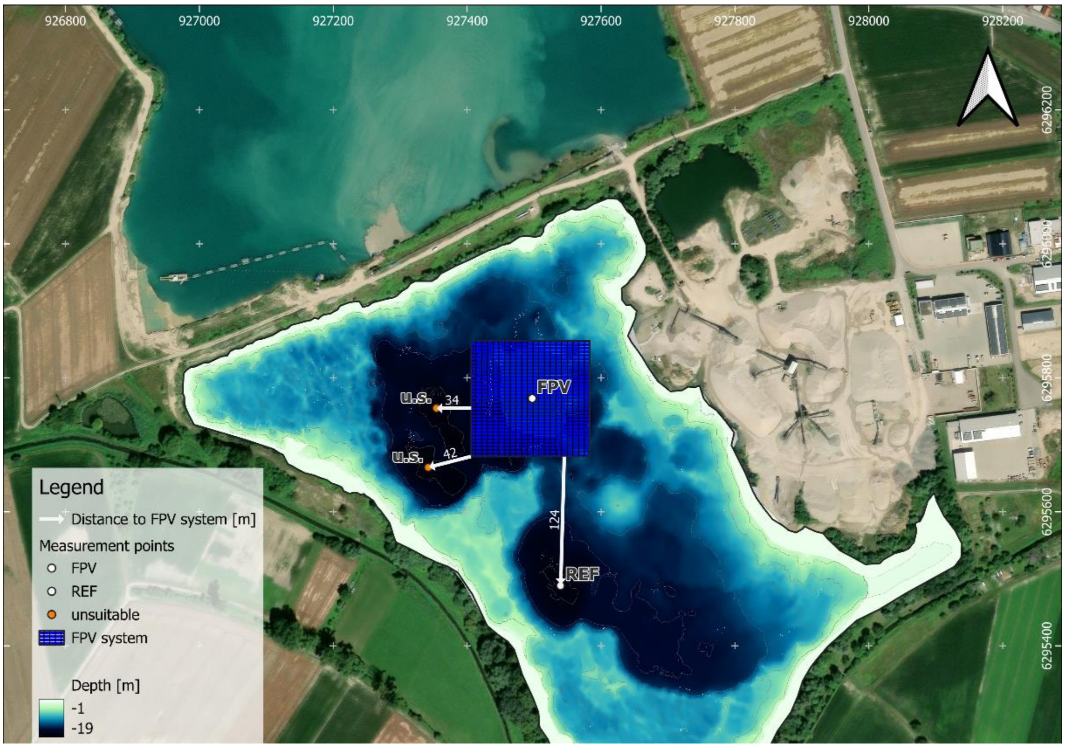


Figure 4. Selection of the open water reference measurement point (REF).

Figure 5 presents a Basic tier, focusing on point-based measurements at REF and FPV locations. The configuration relies on discrete depth profiling using a multiparameter probe combined with a Secchi disk and captures core hydrochemical variables such as temperature, dissolved oxygen, pH, conductivity, turbidity, and chlorophyll-a. This setup enables a first-order comparison between FPV-influenced and open-water conditions but resolves only coarse vertical gradients and limited temporal dynamics.

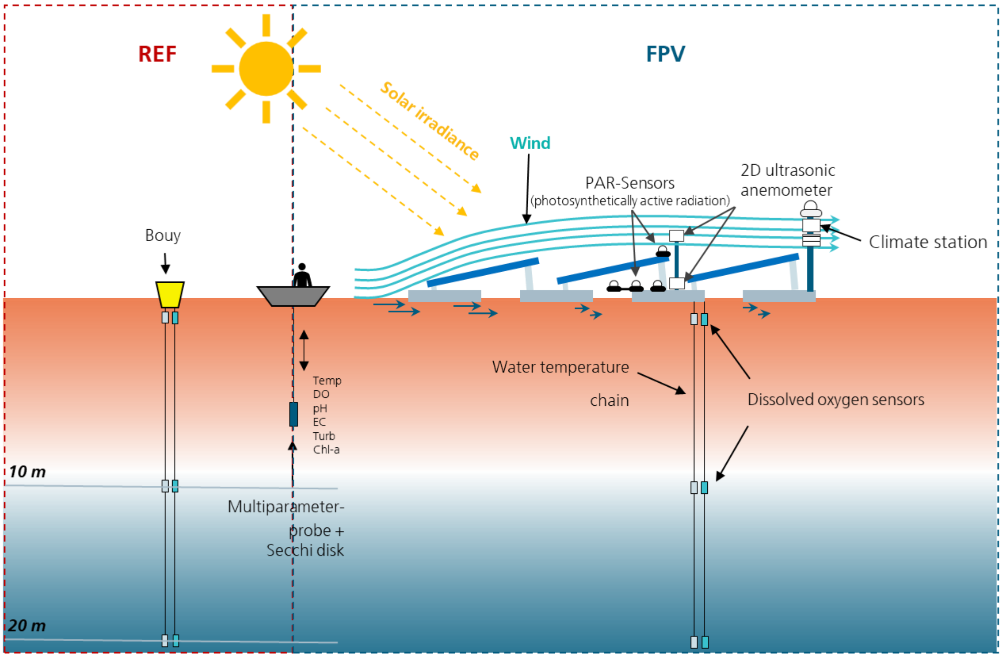


Figure 5. Setup for Basic tier with discrete multiparameter profiling at reference (REF) and FPV sites.

Figure 6 illustrates a setup for Extended tier, where discrete multiparameter profiling is complemented by continuous measurements from water temperature chains and distributed dissolved oxygen sensors beneath the FPV array. This configuration improves the resolution of thermal stratification, oxygen gradients, and near-surface responses to altered wind forcing and shading, while still maintaining comparability with the REF site.

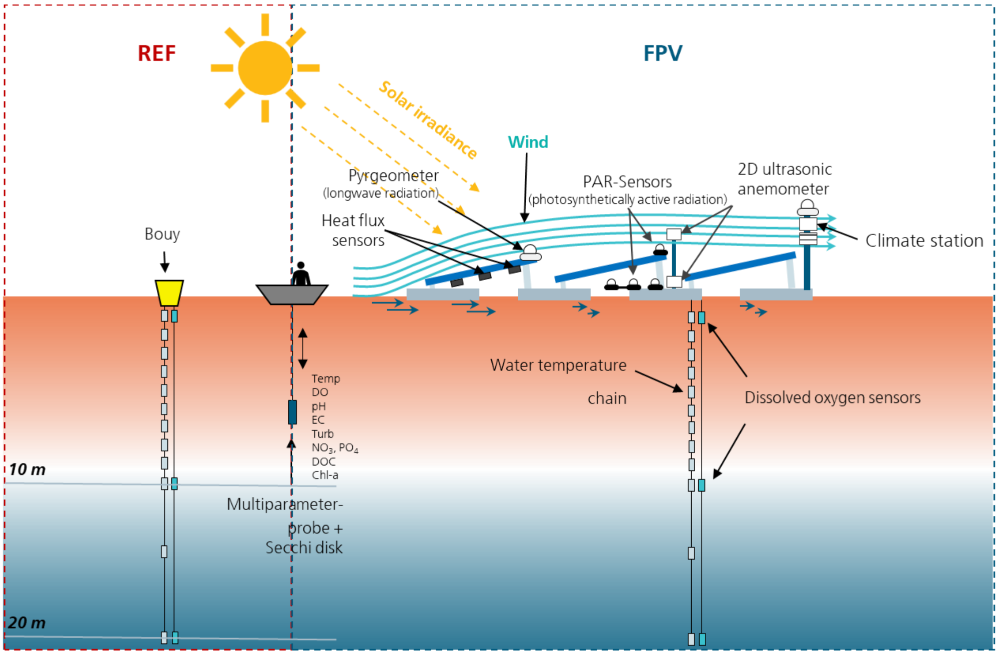


Figure 6. Setup for Extended tier combining multiparameter profiling with continuous temperature and dissolved oxygen measurements beneath the FPV array.

Figure 7 shows a monitoring setup for Advanced tier, integrating continuous high-resolution temperature and oxygen measurements with expanded multiparameter profiling that may include additional chemical variables (e.g. nutrients or dissolved organic carbon). The advanced configuration supports detailed analysis of FPV-induced changes in thermal structure, hydrochemistry, and the coupling between atmospheric forcing and water column processes, enabling robust process-based interpretation and long-term trend assessment.

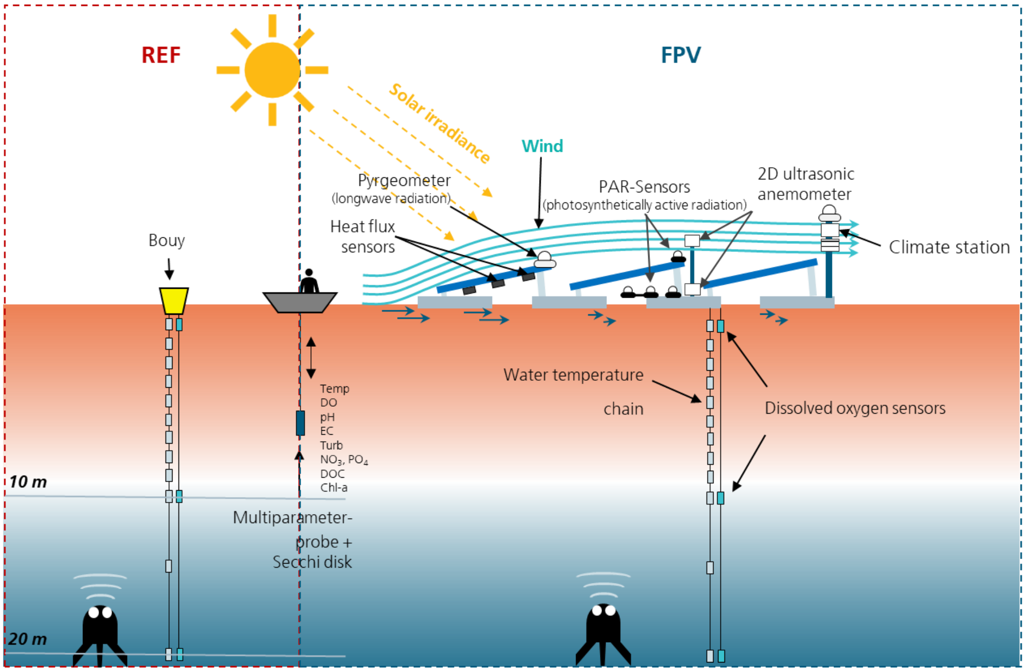


Figure 7. Setup for Advanced tier with high-resolution temperature and oxygen monitoring and extended hydrochemical profiling.

2.6 Lessons learned from environmental Monitoring for Inland FPV

1. **Ensure accessibility**: Design sensor placement so that instruments remain safely accessible for maintenance after installation and during adverse weather conditions, including high water levels, wind, waves, or ice.
2. **Plan for redundancy:** Measure critical parameters such as water temperature, wind, or power supply redundantly wherever possible to avoid data loss.
3. **Implement robust cable management:** Protect cables against abrasion, tensile loads, movement, and UV exposure, and inspect them regularly.
4. **Account for biofouling:** Plan realistic cleaning and maintenance intervals, particularly for sensors prone to fouling (e.g. dissolved oxygen, pH, turbidity).
5. **Ensure time synchronization:** Precisely synchronize all loggers and sensors, especially in distributed multi-sensor configurations.
6. **Design a reliable power supply:** Dimension autonomous power systems, including solar panels and battery storage, to reliably cover prolonged periods of low irradiance or winter conditions, and allow connection to the plant’s AC output when required.
7. **Document metadata comprehensively:** Record sensor depths, heights, positions, calibrations, and any subsequent changes in a consistent and traceable manner.
8. **Establish a clear safety concept:** Conduct all work on floating structures under clearly defined safety and rescue protocols.

9. **Check data quality early:** Systematically verify data quality and plausibility immediately after installation and during the first weeks of operation.
10. **Consider long-term stability:** Select materials, fixations, and sensor positions to withstand multi-year exposure to mechanical stress, UV radiation, and continuous movement.

2.7 Adaptive Management and Response Strategy for adverse ecological effects

To ensure ecological protection while maintaining planning certainty, a staged adaptive management framework is proposed for FPV installations. Responses to detected ecological effects are proportional, transparent, and explicitly linked to monitoring results and site-specific evidence, partial of full system removal is considered only as a last resort or in cases of non-compliance with regulatory requirements.

Monitoring results are evaluated in an integrated, ecosystem-based manner, accounting for both negative and positive FPV-related effects. Assessment is not based on isolated parameter changes, but on the overall ecological status and ecosystem functioning of the lake or reservoir. A deterioration in a single parameter does not automatically trigger mitigation or intervention if it is balanced by improvements in other relevant parameters. Management decisions are guided by the net effect on ecosystem resilience and ecological status.

Exceedance of predefined trigger values does not automatically result in corrective measures. Trigger values initiate a verification and causal analysis, during which observed changes are assessed in relation to natural variability, external pressures, and co-occurring positive effects. Only impacts that are confirmed, persistent, and ecologically relevant at the system level lead to further response stages.

Where impacts are confirmed, operational adjustments represent the next level of response. These may include seasonal operating constraints, modifications to FPV layout or orientation, or adjustments to maintenance practices aimed at reducing ecological stress during sensitive periods. If such measures prove insufficient, technical mitigation options can be implemented. These include structural modifications to improve hydrodynamic exchange, partial reduction or relocation of FPV coverage to ecologically less sensitive zones, or other site-adapted retrofitting measures.

If some residual impacts cannot be fully avoided, targeted ecological compensation or restoration measures can be carried out at the lake or catchment scale. These measures are intended to offset remaining pressures and at the same time support wider restoration objectives.

Partial or full removal of the FPV installation constitutes the final escalation step and is reserved for situations where significant adverse effects persist despite mitigation efforts, or where the operator fails to cooperate with monitoring requirements and corrective actions. By defining this hierarchy of responses in advance, the framework provides clarity for regulators and operators alike, ensures proportionality of interventions, and enables flexible, site-specific FPV integration without compromising ecological safeguards.

2.7.1 Staged Adaptive Response Model for Adverse Ecological Effects

Stage 0 – Reference conditions and trigger values

Before installation, site-specific reference conditions are established and indicators with associated threshold values are defined. These form the basis for impact detection, evaluation, and transparent decision-making throughout the project lifetime.

Stage 1 – Verification and causal analysis

Monitoring is temporarily intensified to confirm observed deviations and to assess their magnitude, duration and spatial extent. The analysis explicitly examines whether deviations can be causally attributed to the FPV installation or are driven by other factors, such as external stressors or natural variability. The analysis explicitly documents both adverse and beneficial ecological changes and evaluates whether observed trade-offs result in a net deterioration or improvement of ecosystem condition.

Stage 2 – Operational adjustments

Operational and maintenance practices that remain flexible after installation are adapted to reduce ecological pressures. This primarily includes adjustments to O&M activities, such as timing and frequency of maintenance operations, temporary access restrictions, or reduced activity during ecologically sensitive periods (e.g. fish spawning or bird breeding seasons). Measures at this stage aim to minimize disturbance and secondary impacts while leaving the system structure and energy output largely unchanged.

Stage 3 – Technical and operational mitigation within system constraints

Proportionate mitigation measures are implemented within the technical and structural constraints of the installed FPV system. These may include minor layout modifications, optimization of hydrodynamic exchange where feasible, or further refinement of operational practices. Where structural interventions are limited or impractical, priority is given to non-invasive measures, potentially complemented by ecological compensation (Stage 4).

Stage 4 – Ecological compensation or restoration

If residual impacts persist despite on-site mitigation, targeted ecological compensation or restoration measures are implemented at the lake or catchment scale. These may range from low-effort interventions (e.g. bird breeding refuges or support of fish spawning habitats) to higher-effort actions such as technical lake maintenance or restoration (e.g. littoral reconfiguration, sediment management, or nutrient load reduction). The level of intervention is selected proportionately, aiming to offset remaining pressures while contributing to long-term ecological improvement. Compensation and restoration measures are designed to address remaining system-level impacts rather than isolated parameter deviations and may explicitly build on positive FPV-related effects to enhance overall ecological performance.

Stage 5 – Partial or full system removal

Partial or full removal of the FPV installation is considered only as an *ultima ratio* under exceptional circumstances. These include cases where monitoring provides robust evidence of persistent and significant ecological impacts that threaten the integrity of valuable or legally protected ecosystems, where there is a high and substantiated risk of system failure or accident leading to severe environmental harm, or where irreversible pollutants or hazardous substances are demonstrably released into the aquatic environment. System removal may also be required in cases of non-compliance with agreed monitoring, mitigation, or safety measures.

2.7.2 Integration of Temporal Monitoring Phases and Adaptive Response Measures

The adaptive response framework is aligned with the monitoring phases (baseline, early operation, late operation), reflecting decreasing flexibility for structural intervention over time.

Baseline phase (pre-installation)
Reference conditions, indicators, and trigger values are defined. Preventive design measures are prioritized, as planning flexibility is highest before installation and strongly determines the scope of later mitigation options.

Early operation phase (0–3 years)
This phase is critical for detecting FPV-related effects. Monitoring is intensified, and exceedance of trigger values initiates verification and causal analysis (Stage 1). If impacts are confirmed, operational adjustments (Stage 2) and technical mitigation measures (Stage 3) can still be implemented with comparatively limited constraints.

Late operation phase (>3 years)
System responses are generally characterized and monitoring may be reduced. Structural modifications are often limited; responses therefore focus on ecological compensation or restoration measures (Stage 4). Partial or full system removal (Stage 5) remains a safeguard for persistent or severe impacts.

Across all phases, monitoring results are interpreted proportionally at the ecosystem level. Opposing trends among individual indicators do not necessarily require intervention if the overall ecological condition remains stable or improves.

3. Monitoring Concept and Parameters for FPV on Nearshore Waters

The deployment of nearshore floating photovoltaics (NFPV) systems in coastal environments entails a distinct set of technical challenges that clearly differentiate them from inland freshwater installations. Operating in marine or brackish conditions, such as at the Port of Brest (France), requires the system to maintain long-term structural and electrical integrity under combined mechanical loading, aggressive corrosion processes, and biological colonization. These site-specific stressors demand a design approach rooted in marine engineering principles rather than conventional inland FPV practice.

From a metocean perspective, wind loading frequently represents the governing design parameter in nearshore environments. In European coastal regions, systems must be designed to withstand extreme gusts of up to 40 m/s for a 50-year return period. Site-specific measurements from a demonstrator in Brest indicate absolute maximum gusts of 43.1 m/s (Fig.8) and maximum sustained wind speeds of 21.74 m/s. Such wind forces generate aerodynamic uplift on PV modules, amplify internal wave formation within harbor basins, and significantly increase mooring line tension. Although port infrastructure provides partial wave attenuation, storm conditions can still produce significant wave heights in the range of 1.0 to 1.5 m. These waves induce platform motions, including heave, pitch, and roll, and contribute to fatigue loading in structural connections and anchoring systems.

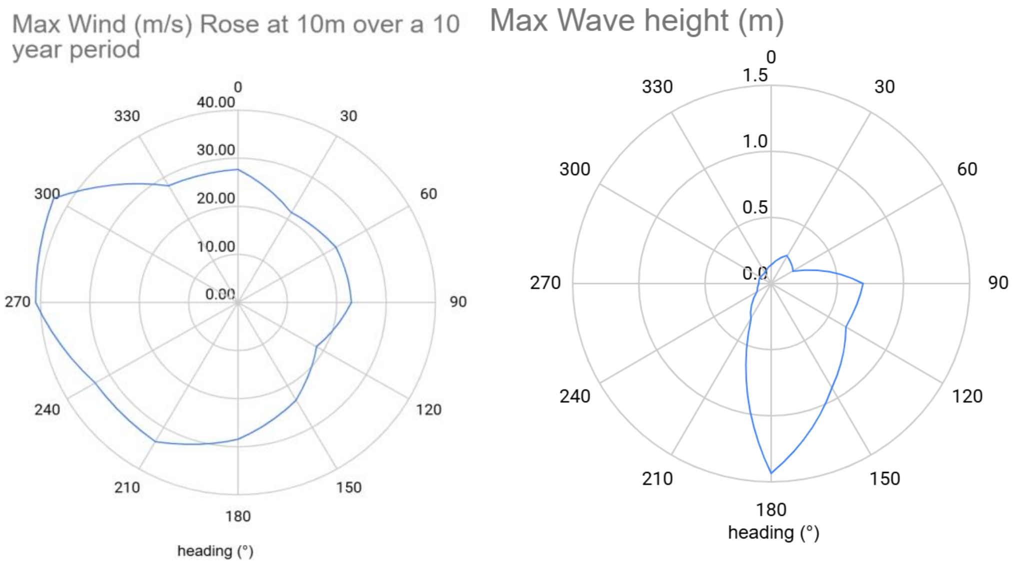


Figure 8. Max. wind speed and wave height in dependence to the wind direction measured at a NFPV demonstrator near Brest (France).

Hydrodynamic influences further complicate system design. In high-tidal regions, vertical water level variations can reach up to 7.5 m, requiring mooring configurations with sufficient slack and adaptability to accommodate large amplitude vertical displacement without inducing excessive tension (Fig. 9). In estuarine contexts, current velocities may approach 1 m/s, affecting anchor stability, increasing drag forces, and potentially enhancing seabed scour processes. Together, wind, waves, tides, and currents define the mechanical boundary conditions for safe long-term operation.

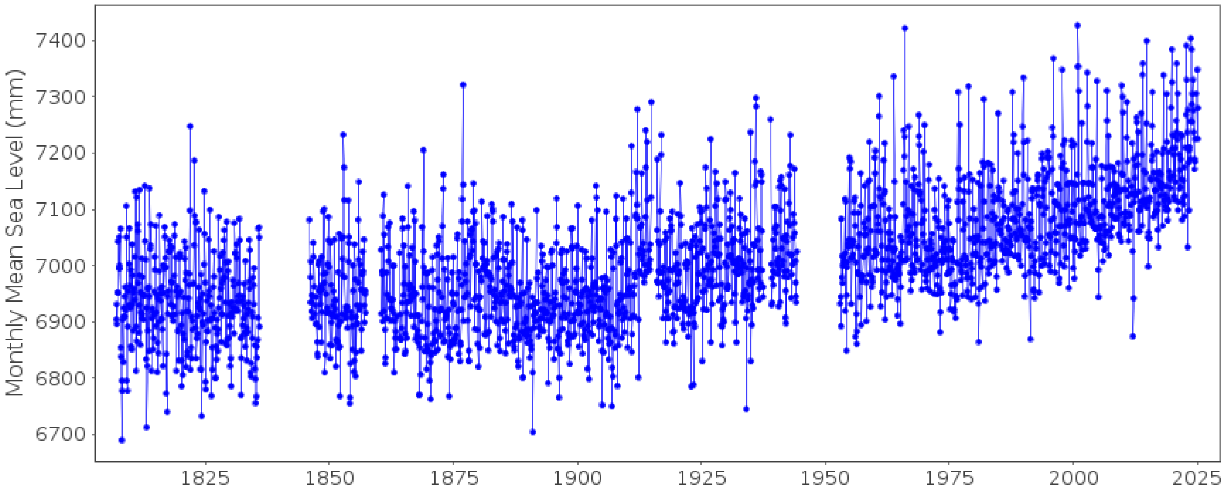


Figure 9. Monthly mean sea level (mm) from the early 19th century to 2025, illustrating long-term rise and variability. In high-tidal coastal and estuarine environments, vertical fluctuations of several meters, combined with wind, waves, and currents, define critical hydrodynamic boundary conditions for mooring stability and structural design of nearshore FPV systems.

Material degradation constitutes an additional critical risk factor in marine deployments. A key issue identified during the pilot phase in Brest was accelerated galvanic corrosion in anchoring assemblies composed of dissimilar metals. In one documented case, a 14 mm galvanized steel chain connected to a stainless-steel shackle exhibited a mass loss of 32.5% within 24 months. This degradation far exceeded conventional safety thresholds of 10 to 12% and was driven by the high electrolyte conductivity of Atlantic seawater combined with galvanic coupling between the more noble stainless-steel cathode and the less noble galvanized steel anode. The resulting electrochemical potential difference effectively created a local galvanic cell, accelerating anodic dissolution.

Electrical components were similarly affected by the harsh marine environment. Standard MC4 connectors, despite IP67 or IP68 ratings, proved insufficient under persistent high salinity exposure. Salt deposition, combined with temperature-driven pressure equalization processes within connectors, facilitated internal moisture ingress. This led to the formation of copper carbonate and copper chloride corrosion products, commonly referred to as “green rot”, and in some cases resulted in electrical arcing. Capillary transport mechanisms and vapor entrapment within protective tapes further intensified internal corrosion processes, highlighting the limitations of standard terrestrial sealing strategies in marine contexts.

Biological processes also exerted significant influence on structural performance. Marine biofouling, particularly mussel accretion on submerged components, substantially increased system mass during the Brest pilot phase. The average mass per floater increased from 30 kg to 43 kg, corresponding to a 43% rise in weight. This additional load reduced effective buoyancy, caused partial submergence of critical connectors, and restricted the movement of articulated mechanical elements such as hinges. Beyond structural implications, biofouling also introduces maintenance challenges and may alter hydrodynamic behavior.

Addressing these interrelated challenges requires a systematic transition toward marine-grade design standards. This includes the use of corrosion-resistant materials such as high-density polyethylene and homogeneous galvanized assemblies to avoid galvanic coupling, structural configurations that position sensitive and mobile components above the waterline, and hermetically sealed electrical systems. For electrical protection, dual-wall adhesive-lined heat-shrink solutions and fully marine-certified connectors provide enhanced resistance to salt ingress and moisture diffusion.

In summary, NFPV in marine environments is technically feasible, but only when site-specific metocean conditions, electrochemical interactions, hydrodynamic loads, and biological growth processes are explicitly integrated into engineering design and long-term operational planning.

3.1 Monitoring Concept Adaptation

Ensuring the long-term sustainability of NFPV and inland FPV systems requires monitoring strategies that reflect the fundamentally different physical and biological dynamics of marine and freshwater environments. Coastal installations, such as the demonstrator at the Port of Brest, are primarily governed by extreme mechanical forcing and aggressive corrosion processes. In contrast, inland systems are more strongly influenced by limnological variability, water quality dynamics, and ecological stability.

In nearshore environments, monitoring concepts must prioritize high-energy interactions between structure and environment. Sensor systems should capture high-resolution wave characteristics, tidal currents, wind speed, and aerodynamic uplift forces. Structural health monitoring plays a central role, with continuous measurement of mooring line tension and platform motions including pitch, roll, and yaw. Accelerometers and inclinometers enable calibration of hydrodynamic models against observed sea states, including storm conditions with significant wave heights approaching 3 m. This data-driven validation is essential for assessing fatigue behavior, anchor performance, and long-term structural reliability under cyclic loading.

Inland FPV installations require a different focus. Here, bio-accretion and ecological processes often dominate operational risk. The accumulation of mussels, algae, or other aquatic organisms can significantly alter buoyancy and load distribution. Monitoring strategies therefore include periodic inspections of submerged components using remotely operated vehicles, combined with quantification of biomass accumulation and its contribution to structural weight. In addition, parameters such as water temperature, dissolved oxygen, nutrient concentrations, and turbidity are relevant to detect eutrophication trends that may affect both system performance and ecosystem integrity.

A unified monitoring framework can be established through a digital twin approach. In this concept, site-specific meteorological and hydrodynamic data such as wind, solar radiation, air temperature, waves, and currents are integrated with in situ biological and structural measurements. The digital twin enables predictive maintenance by linking environmental stress indicators to structural response and degradation pathways. Maintenance activities, including cleaning of biofouling or inspection of electrical connectors, can thus be scheduled based on measured environmental loads rather than fixed time intervals.

By tailoring monitoring protocols to site-specific boundary conditions, operators can address distinct risk profiles. In marine settings, this includes mitigation of corrosion phenomena such as green rot under high salinity exposure, while inland systems must manage risks associated with stagnation and nutrient enrichment. An adaptive, data-driven monitoring strategy therefore constitutes a central component of resilient and environmentally compatible FPV deployment across diverse aquatic environments.

3.2 Lessons learned from Nearshore Floating Photovoltaic Deployment

The Brest-NFPV demonstrator provided critical empirical insights into the structural, electrochemical, and ecological challenges associated with long-term operation in marine environments. The findings demonstrate that NFPV systems cannot be treated as a direct extension of inland FPV technology. Instead, they require dedicated marine-grade design principles. The following lessons synthesize observed failure mechanisms and their implications for future system design and standardization.

1. Electrochemical Compatibility Is a Primary Design Constraint

The most critical structural failure mechanism observed was accelerated galvanic corrosion in the anchoring system. The combination of galvanized steel chains with stainless steel shackles created an electrochemical potential difference in seawater, leading to rapid anodic dissolution of the zinc-coated chain. A diameter reduction of approximately 2.5 mm within 24 months resulted in a 32.5% loss of cross-sectional area, significantly exceeding accepted maritime wear thresholds. This degradation reduced the Minimum Breaking Load to an unacceptable level, posing a structural failure risk under storm conditions.

The corrosion rate was amplified by:

- High electrolyte conductivity due to Atlantic salinity
- Cathode–anode surface area imbalance
- Mechanical abrasion removing protective zinc coating
- Continuous wetting and oxygen availability

Lesson:
Material pairing in marine anchoring systems must follow strict electrochemical compatibility rules.

Mixed-alloy assemblies require electrical isolation or sacrificial anode protection. Inland-derived assumptions regarding corrosion rates are not transferable to marine environments.

Figure 10. Galvanic corrosion in a marine anchoring assembly caused by electrochemical incompatibility between a galvanized steel chain and a stainless-steel shackle, resulting in accelerated material loss and structural degradation.

2. Standard PV Connectors Are Not Marine-Resilient

Despite IP67/IP68 certification, standard MC4 connectors failed under persistent saline exposure. The failure mechanism was not bulk submersion, but salt aerosol ingress combined with daily thermal cycling. Temperature fluctuations caused air exchange within the connector housing, drawing in salt-laden humidity. In the presence of DC voltage, electrolysis accelerated copper dissolution, resulting in:

- Formation of copper chloride/carbonate (“green rot”)
- Increased contact resistance
- Localized overheating
- Electrical arcing
- Ground faults via salt bridges to aluminium frames

Temporary overprotection using self-fusing tape reduced but did not eliminate failure due to capillary ingress and vapor trapping. The implementation of dual-wall adhesive-lined heat shrink tubing represents a transition toward hermetic sealing, eliminating micro-gaps at cable interfaces.

Lesson:
Ingress protection ratings alone are insufficient in marine environments. NFPV systems require

hermetic sealing strategies, physical separation from metallic frames, and marine-certified DC connector solutions.

Figure 11. Corrosion damage to a standard MC4 connector exposed to saline marine conditions, showing copper oxidation ("green rot") and insulation degradation caused by salt aerosol ingress, thermal cycling, and DC-induced electrochemical reactions.

3. Instrumentation Must Preserve Structural Flexibility

The integration of rigid load cells in place of flexible EPDM connectors introduced unintended local stiffness. This altered the natural deformation behavior of the floating structure and created stress concentration points. The resulting localized constraint exceeded design tolerances and led to mechanical failure at the connection interface. The revised configuration integrates load cells within traction lines using flexible websling interconnections, preserving distributed deformation behavior.

Lesson:
Monitoring instrumentation must be mechanically non-invasive. Sensor integration must not modify structural boundary conditions or introduce artificial stiffness discontinuities.

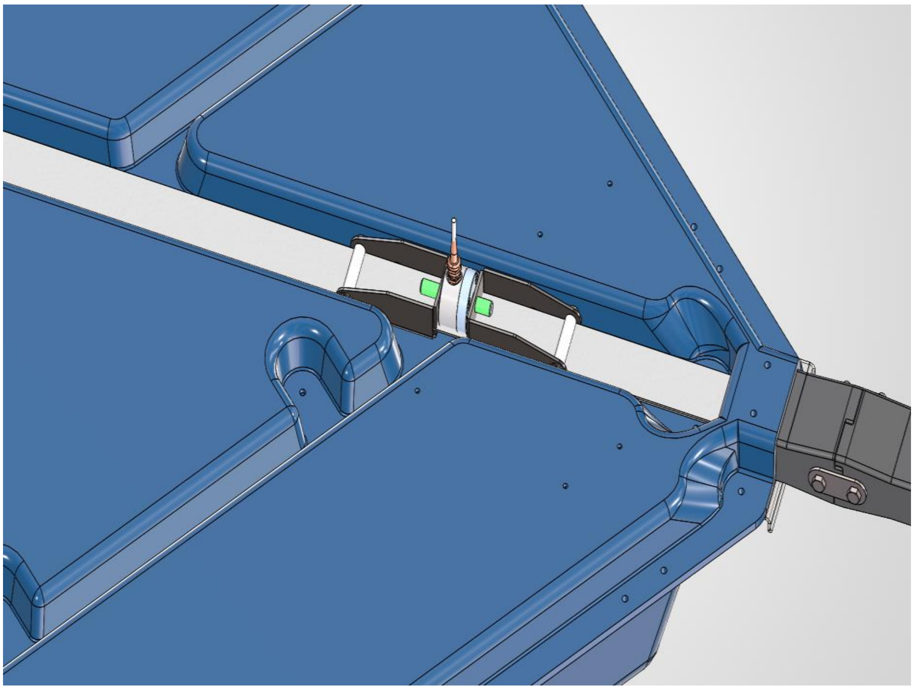


Figure 12. Rigid load cell integration within a floating structure joint, illustrating local stiffness discontinuity and stress concentration at the connection interface due to replacement of flexible EPDM elements.

4. Biofouling Is a Structural Load Case

Marine bio-accretion, primarily mussel colonization, resulted in a 43% mass increase of submerged floaters. The additional weight reduced buoyancy reserve and caused unintended submergence of electrical components.

Biofouling also restricted hinge movement and increased mechanical friction in articulated elements.

This demonstrates that biofouling must be treated not merely as a maintenance issue but as a structural design load case affecting:

- Buoyancy margins
- Fatigue behavior
- Accessibility for O&M
- Electrical safety clearance

Lesson:
Marine growth must be incorporated into structural mass calculations, buoyancy design, and fatigue analysis. Elevated placement of connectors and hinges above the waterline significantly improves resilience.

Figure 13. Biofouling of a submerged floater, showing extensive mussel colonization and marine growth leading to increased structural mass, reduced buoyancy reserve, and restricted movement of articulated components.

5. Elevation and Geometric Separation Increase Robustness

The redesign implemented the following geometric modifications:

- Hinges positioned ≥130 mm above water level
- Lowest panel edge positioned ≥370 mm above water level
- Splash-protected connector cones
- Decoupled connector mounting away from aluminium frames

This passive elevation strategy reduces bio-accretion risk, splash exposure, and salt-bridge formation without relying solely on material solutions.

Lesson:
Geometric separation from direct seawater exposure is an effective and low-complexity resilience strategy in NFPV design.

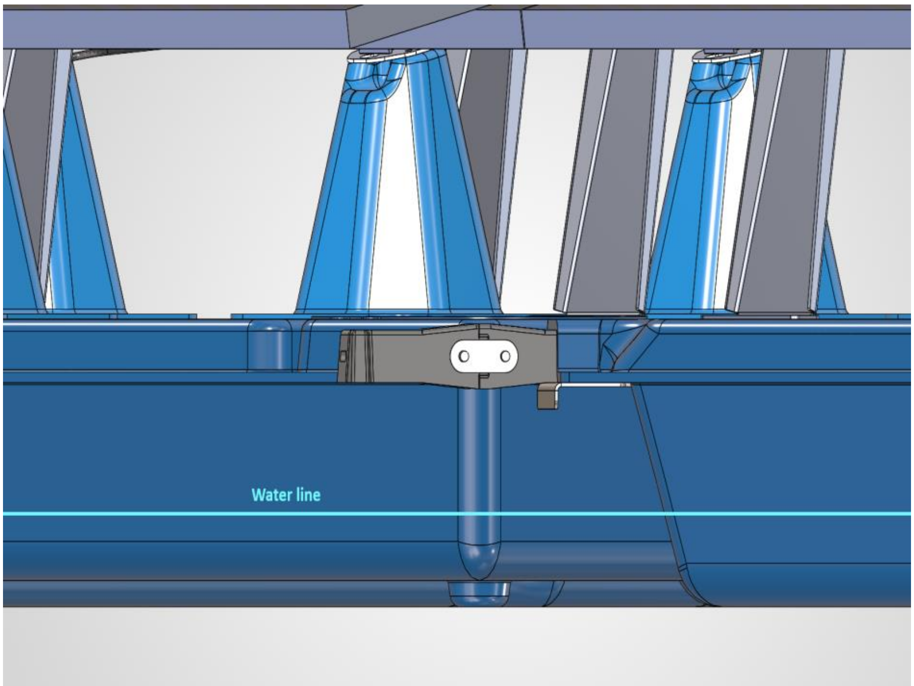


Figure 14. Revised floating PV geometry showing elevated hinges and panel edges above the waterline, illustrating geometric separation as a passive strategy to reduce splash exposure, biofouling, and salt-induced electrical risks.

Structural Implications for Future NFPV Standardization

The demonstrator findings suggest that future NFPV guidelines should formalize:

- Mandatory material compatibility matrices
- Corrosion allowance thresholds
- Hermetic electrical sealing requirements
- Hydrodynamic load integration for fatigue design
- Biofouling mass allowances in buoyancy calculations
- Non-invasive sensor integration protocols

These empirical lessons provide a practical foundation for marine-specific standardization beyond adaptations from inland FPV or offshore energy sectors.

4. Synthesis and Comparative Analysis for Inland FPV and NFPV

4.1 Cross-System Comparison

4.1.1 Differences and Commonalities between Inland and NFPV Systems

FPV systems deployed on inland water bodies and in coastal environments are based on the same core technological concept of modular buoyant PV platforms. However, they differ significantly with respect to hydrodynamic boundary conditions, corrosion exposure, regulatory complexity, and operational requirements (Tab 2.).

Table 2. Comparative overview of inland FPV and Nearshore Floating Photovoltaic (NFPV) systems.

Aspect	Inland FPV (Lakes / Reservoirs)	NFPV (Coastal / Port Waters)	Commonalities
Environment			
Water Type	Freshwater	Brackish or seawater	Floating PV platforms installed on water surface
Salinity Exposure	Low	High; salt spray and marine corrosion	UV radiation and humidity affect materials
Wave Conditions	Typically low (0.1–0.5 m operational)	Moderate; storm-driven waves possible (up to ~3 m in sheltered basins)	Wave-induced motion influences structural fatigue
Wind Loads	Moderate exposure	Higher average and extreme gusts	Wind is a primary structural load driver
Tidal Influence	None or negligible	Possible tidal variation up to several metres	Mooring systems must accommodate movement
Currents	Minimal, except in rivers	Significant in estuaries (1–3 m/s possible)	Hydrodynamic forces influence anchoring design
Engineering			
Structural Requirements	Designed for limited hydrodynamic stress	Designed for marine fatigue, corrosion, and dynamic loading	Modular floating structures supporting PV panels
Mooring & Anchoring	Bank or bottom anchoring; simpler systems	Engineered marine mooring (e.g., catenary or elastic systems)	Anchoring design based on site-specific loads
Corrosion Risk	Low	High due to saltwater and marine atmosphere	Protective coatings and durable materials required
Operation			
Biofouling	Algae and freshwater organisms	Marine growth such as barnacles and mussels	Maintenance required to control biological growth

Aspect	Inland FPV (Lakes / Reservoirs)	NFPV (Coastal / Port Waters)	Commonalities
Soiling & Bird Droppings	Mainly pollen, dust, and bird droppings; manageable through periodic freshwater cleaning	Increased exposure to seabirds and salt spray, potentially enhancing soiling and corrosion interactions	Surface contamination reduces module efficiency and requires periodic cleaning
Installation Complexity	Moderate	Higher due to marine logistics and safety requirements	Modular assembly and floating deployment
Operation & Maintenance	Boat access; freshwater cleaning	Marine access; corrosion management	Regular inspection of electrical and mechanical components
Governance			
Environmental Assessment	Focus on water temperature, oxygen levels, aquatic ecology	Focus on marine habitats, fisheries, and bird interactions	Environmental impact assessments often required
Regulatory Framework	Water management authorities; land-use planning	MSP frameworks; coastal and port authorities	Permitting subject to national and EU environmental law
Spatial Competition	Mainly recreational and ecological uses	Competition with shipping, fisheries, aquaculture	Multi-stakeholder consultation required
Applications			
Grid Connection	Often on-site direct energy consumption or near hydropower dams, connect to high- or medium-voltage grids	Typically close to industrial or port loads	On-site consumption and grid export possible
Typical Applications	man-made water bodies, hydropower hybridization and decarbonizing the quarrying gravel industry	Port decarbonization; industrial self-consumption	Contribution to renewable energy targets
Technology Maturity	Commercially mature; widely deployed	Emerging but growing; fewer installations	Rapidly evolving engineering standards

In summary, inland FPV systems operate in comparatively stable freshwater environments with lower structural and maintenance complexity. NFPV systems, by contrast, must withstand salinity, stronger wind and wave loads, tidal dynamics, and a more complex maritime regulatory environment. Despite these differences, both configurations rely on the same fundamental floating PV principles and contribute to the expansion of renewable energy generation in spatially constrained regions.

4.1.2 Comparative Overview of Environmental Processes, Monitoring Needs, and System Design Requirements

The deployment of FPV systems creates a direct interface between floating structures and aquatic ecosystems. This interaction changes physical boundary conditions at the air–water interface and requires an integrated framework that links environmental assessment, monitoring strategy, and engineering design. A comparison of inland and NFPV installations highlights both shared mechanisms and site-specific sensitivities.

Environmental Processes and Ecosystem Interactions

FPV installations alter incident solar radiation and surface-atmosphere exchange processes. A primary effect is the reduction of photosynthetically active radiation beneath the platform, which directly influences primary production and light-dependent habitats. In inland reservoirs, this may affect phytoplankton dynamics, thermal stratification patterns, and dissolved oxygen distribution. In coastal NFPV systems, shading effects can interact with tidal mixing and salinity gradients, potentially modifying benthic habitats and local productivity.

Wind shielding by floating structures further alters surface heat fluxes and momentum transfer. Reduced wind stress may weaken vertical mixing and stabilize stratification in lakes, while in nearshore environments the effect interacts with wave action and tidal forcing. These coupled processes influence oxygen dynamics, nutrient cycling, and, ultimately, ecological status.

Tiered Environmental Monitoring Framework for Inland FPV/NFPV

To quantify environmental effects and ensure regulatory compliance, a tiered monitoring concept can be implemented, with intensity scaled to site sensitivity and project size:

- **Basic**: The basic level focuses on baseline characterization and long-term trend detection. For inland FPV, this includes continuous measurement of water temperature profiles, dissolved oxygen, pH, conductivity, turbidity, and light penetration to assess stratification dynamics and primary production changes. In NFPV systems, the same core parameters could be monitored, focusing on data such as wind speed and water level to capture tidal influence (Tab 3.).
- **Extended**: The Extended level supports process-oriented assessment at moderately sensitive sites. In inland systems, this involves expanded monitoring of nutrients such as nitrate and phosphate, dissolved organic carbon, and phytoplankton composition to evaluate eutrophication risks and trophic responses. In NFPV environments, the Extended tier may further focus on salinity, sediment characteristics, and biological indicators such as macrozoobenthos or fish presence.
- **Advanced**: The advanced tier is reserved for ecologically sensitive areas, Natura 2000 proximity, or research-driven projects. In inland FPV, this may require high-resolution profiling of stratification, hydrodynamics, detailed benthic and macrophyte surveys, and food web analysis. For NFPV, advanced monitoring may incorporate high-resolution wave dynamics, flow velocity measurements, sediment transport processes, benthic habitat mapping, and assessment of potential contaminants such as microplastics.

Table 3. Monitoring parameter matrix for environmental assessment of FPV and NFPV systems across implementation levels.

Parameter Domain	Representative Parameters	Basic		Extended		Advanced	
		FPV	NFPV	FPV	NFPV	FPV	NFPV
Physical forcing	Light climate, wind, water level	X	X	X	X	X	X
	Heat fluxes / stratification			X	X	X	X
	Wave dynamics / flow velocity				X	X	X
Water quality	Temperature, DO, pH, conductivity, turbidity, chlorophyll-a	X	X	X	X	X	X
	Nutrients, DOC			X	X	X	X
	Pollutants / microplastics					X	X
Substrates & morphology	Shoreline structure, sediments	X (qual.)	X (qual.)	X (detailed)	X (detailed)	X (detailed)	X (detailed)
Primary producers	Macrophytes / phytobenthos	X (presence)		X	X	X	X
	Phytoplankton / benthic diatoms		X	X	X	X	X
Consumers	Zooplankton / macrozoobenthos			X	X	X	X
	Fish				X	X	X
	Birds / mammals		X	X	X	X	X

4.2 Integration and Harmonization

The transition of FPV technology from a niche to utility-scale deployment depends on the systematic integration of interdisciplinary engineering principles and the harmonization of currently fragmented standards. FPV systems operate at the interface of structural, electrical, marine, and environmental engineering, yet the regulatory and technical framework remains largely derived from adjacent sectors.

At present, the industry relies on adapted methodologies from Oil and Gas, offshore wind, and land-based photovoltaic engineering. This sectoral transfer has enabled rapid development but has also resulted in inconsistencies in load assumptions, safety factors, and durability concepts.

Ongoing standardization efforts aim to consolidate these approaches into dedicated FPV guidelines. A prominent example is DNV-RP-0584, which provides a structured framework for the design, assessment, and operation of floating photovoltaic systems, integrating marine engineering practice with photovoltaic performance requirements. A key engineering principle is the harmonized distribution of mechanical loads throughout the floating array and mooring system. Unlike static ground-mounted PV installations, FPV structures are subject to coupled aerodynamic and hydrodynamic forces. Poorly coordinated stiffness and anchoring concepts may lead to progressive load redistribution and localized overstressing. Robust design therefore requires the integration of site-specific data, including wind, waves, currents, and water level variability, with structural safety philosophies based on defined consequence categories and target reliability levels. This approach may ensure mechanical stability, electrical safety, and material durability over a typical operational lifetime of 20 to 25 years.

Digitalization plays a central role in this integration process. Digital Twin concepts create a dynamic link between the physical installation and a continuously updated numerical model. Real-time data from field instrumentation, such as anemometers, wave sensors, and load cells measuring mooring tension, are used to calibrate hydrodynamic and structural simulations. This reduces uncertainty in performance prediction, supports condition-based maintenance, and enhances risk management.

Harmonization also encompasses environmental monitoring. A standardized tiered framework, structured into Basic, Extended, and Advanced levels, enables proportional and site-adapted monitoring intensity across both inland FPV and NFPV systems. Core physical and chemical parameters are assessed consistently to ensure comparability, while additional hydrodynamic or ecological indicators are incorporated depending on site sensitivity. Such structured monitoring facilitates regulatory approval, supports environmental impact assessments, and improves technical optimization through feedback loops between environmental response and structural performance. Beyond technical alignment, harmonization must address the regulatory interface. FPV and NFPV projects must comply with maritime spatial allocation, water protection legislation, and biodiversity conservation frameworks, including Marine Spatial Planning, the Water Framework Directive, and Natura 2000 requirements. Integration into existing maritime uses such as fisheries and aquaculture requires early stakeholder engagement and spatial compatibility assessment.

Finally, technological integration enhances system-level efficiency. Hybridization of FPV with hydropower reservoirs allows shared transmission infrastructure and complementary generation profiles. Coupling FPV with green hydrogen production or industrial self-consumption models can further improve economic viability and contribute to energy autonomy in coastal and inland regions. Overall, the harmonized integration of engineering design, environmental monitoring, digital modeling, and regulatory compliance forms the foundation for resilient, scalable, and environmentally compatible FPV deployment.

4.3 Opportunities for Unified Monitoring Standards across Aquatic FPV Applications

The expansion of FPV across freshwater reservoirs and nearshore marine environments offers a strategic opportunity to establish unified monitoring standards. Although inland FPV and NFPV operate under different hydrological and ecological boundary conditions, they share core structural, electrical, and environmental interfaces. A harmonized monitoring framework can therefore ensure methodological consistency while remaining adaptable to site-specific sensitivities.

Key opportunities for harmonization include:

- **Comparable databases**: Standardized monitoring protocols enable cross-site comparability of energy yield, structural performance, and ecological impacts across FPV and NFPV projects. This supports cumulative evidence generation, cross-border research cooperation, and robust regulatory assessment.
- **Tiered monitoring integration**: A unified Basic, Extended, and Advanced tier structure allows monitoring intensity to scale with ecological sensitivity and project size while maintaining methodological comparability between inland FPV and NFPV.
- **Uniform core variables**: Core parameters such as electrical yield, performance ratios, water temperature, dissolved oxygen, turbidity, and light attenuation can be monitored consistently across all aquatic systems, ensuring comparable environmental and technical datasets.
- **Digital Twin integration:** Linking real-time environmental and structural sensor data with predictive models enables standardized lifecycle management, condition-based maintenance, and risk reduction across diverse FPV applications.
- **Standardized technical robustness**: Defining minimum requirements for monitoring equipment, including IP67 or IP68 protection and corrosion resistance for NFPV systems, enhances durability and data reliability.
- **Regulatory alignment**: Unified monitoring standards reduce uncertainty in environmental impact assessments and facilitate structured dialogue with authorities responsible for Marine Spatial Planning, water protection, and biodiversity conservation.

Through these measures, harmonization improves scientific comparability, regulatory transparency, and long-term operational resilience across both inland FPV and NFPV deployments.

4.4 Recommendations for Adaptive Monitoring Frameworks and Data Interoperability

Large-scale FPV deployment requires a transition from static compliance-based monitoring toward adaptive and interoperable data systems. Monitoring concepts must remain robust over a typical 20 to 25 year design life while enabling cross-project learning.

Monitoring strategies should be aligned with project phases, including baseline assessment, early operation, steady-state operation, and late-life evaluation. Initial deviations from baseline conditions should trigger causal analysis rather than immediate technical intervention. Over time, adaptive flexibility may shift from structural adjustments toward ecological mitigation or compensation measures.

Data interoperability is essential for international comparability. Monitoring programs should follow FAIR principles to ensure datasets are findable, accessible, interoperable, and reusable. Standardized metadata schemes and persistent identifiers enhance transparency and facilitate integration into regional and international repositories. Environmental and technical datasets should be stored in open, machine-readable formats such as CSV, JSON, NetCDF, or HDF5 to enable model integration and long-term archiving. Mapping project-specific data to recognized sensor and energy data structures improves compatibility across research and regulatory systems.

Adaptive monitoring can be strengthened through Digital Twin concepts. Continuous integration of wind, wave, mooring tension, and water column measurements into calibrated multi-physics models supports predictive maintenance, structural risk management, and yield optimization, particularly for NFPV systems exposed to dynamic marine forcing.

Monitoring equipment must ensure long-term stability under freshwater and marine conditions, include redundancy for critical parameters, and maintain synchronized time-stamping across distributed sensor networks. Reliable data continuity is essential for detecting gradual ecological change and structural fatigue.

Standardized monitoring outputs should be archived in trusted repositories to enhance scientific credibility and regulatory transparency. Open data practices reduce uncertainty regarding environmental impacts and support integration into Marine Spatial Planning and broader sustainability assessments.

5. Conclusions and Outlook

The comparative assessment of inland FPV and nearshore FPV (NFPV) systems demonstrates that while both technologies share a common FPV architecture, their monitoring requirements, risk profiles, and environmental interfaces differ fundamentally. These differences are primarily driven by hydrodynamic forcing, salinity exposure, ecological sensitivity, and regulatory complexity.

Inland FPV systems operate in relatively controlled freshwater environments where limnological processes dominate. Monitoring priorities focus on stratification dynamics, nutrient cycling, primary production, and dissolved oxygen stability. The main environmental concern lies in potential alterations of thermal regimes and trophic cascades in semi-enclosed water bodies. Structural loads are comparatively moderate, and corrosion risks are limited, allowing monitoring frameworks to emphasize ecological process understanding and long-term water quality trends. In contrast, NFPV systems are governed by marine boundary conditions. Wind loads, wave action, tidal variability, and saline exposure introduce dynamic mechanical stress and accelerated material degradation. Monitoring must therefore extend beyond ecological parameters to include hydrodynamic forcing, mooring integrity, corrosion development, and biofouling accumulation. Environmental assessment shifts toward marine habitat interaction, benthic communities, fish, and avifauna. Consequently, NFPV monitoring frameworks require stronger integration of structural health monitoring and marine ecosystem observation. Despite these differences, substantial harmonization potential exists. A unified tiered monitoring framework provides methodological consistency while allowing site-specific scaling. Core physical and chemical parameters, including temperature, dissolved oxygen, turbidity, and light attenuation, are relevant across both systems and enable cross-comparison. Digital Twin integration offers a common analytical layer by linking environmental data and structural performance models in both freshwater and marine contexts. Standardized data structures and interoperable formats further support cumulative knowledge generation and regulatory transparency. The key challenge moving forward lies in balancing standardization with adaptability. Overly rigid monitoring prescriptions risk inefficiency in low-sensitivity sites, whereas insufficiently defined protocols reduce comparability and regulatory confidence. Future frameworks must therefore remain modular, allowing inland and nearshore applications to share a common core while incorporating environment-specific extensions.

Looking ahead, three strategic priorities emerge. First, the development of internationally harmonized monitoring standards tailored to floating solar applications will strengthen permitting predictability and investor confidence. Second, long-term datasets from both inland FPV and NFPV installations are essential to quantify ecological thresholds, fatigue behavior, and corrosion progression under real operating conditions. Third, interdisciplinary integration between hydrodynamic modeling, ecological assessment, and structural engineering will be critical for optimizing system resilience and environmental compatibility. In summary, inland FPV and NFPV represent complementary pathways for expanding photovoltaic deployment on water surfaces. Their successful large-scale implementation depends not only on technological robustness but also on the establishment of adaptive, interoperable, and scientifically defensible monitoring systems that reconcile energy production with aquatic ecosystem protection.

6. References

Arora, P., Prasad Patel, B., Ahmad, S., Jain, A.K., Joe Joe, C.S., Aggarwal, P., 2023. CFD-Based Simulation for the Stability of Floating Solar Arrays, in: Volume 8: Ocean Renewable Energy. Presented at the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers, Melbourne, Australia, p. V008T09A017. https://doi.org/10.1115/OMAE2023-108232

Attar, H., Alahmer, A., & Borowski, G. (2025). Comprehensive review of advancements, challenges, design, and environmental impact in floating photovoltaic systems. Ecological Engineering and Environmental Technology. PDF

Barré, K., Baudouin, A., & Froidevaux, J. S. P. (2024). Insectivorous bats alter their flight and feeding behaviour at ground-mounted solar farms. Journal of Applied Ecology, 61(1), 122–134. https://doi.org/10.1111/1365-2664.14555

Bellio, M. G., Kingsford, R. T., & Kotagama, S. W. (2021). Bird responses to wetland modification: implications for FPV planning in biodiverse aquatic systems. Wetlands Ecology and Management, 29(5), 777–791. https://doi.org/10.1007/s11273-021-09800-z

Benjamins, S., Williamson, B., Billing, S.-L., Yuan, Z., Collu, M., Fox, C., Hobbs, L., Masden, E.A., Cottier-Cook, E.J., Wilson, B., 2024. Potential environmental impacts of floating solar photovoltaic systems. Renewable and Sustainable Energy Reviews 199, 114463. https://doi.org/10.1016/j.rser.2024.114463

Brentrup, J.A., 2017. The role of water transparency in regulating carbon dynamics in lakes: Experimental, comparative, and high-frequency approaches (PhD Thesis). Miami University.

Błotnicki, J., Buta, B., Głowski, R., Jarzembowski, P., 2025. Drifting Impact: A Comprehensive Review of Floating Debris.

Bossi, G., Müller, H., & Catalano, F. (2024). Light and primary production under floating photovoltaics: Field evidence of altered phytoplankton dynamics. Aquatic Sciences, 86(1), 21. https://doi.org/10.1007/s00027-024-00914-w

Bossi, S., Blasi, L., Cupertino, G., dell'Erba, R., Cipollini, A., De Vito, S., Santoro, M., Di Francia, G., Tina, G.M., 2024. Floating Photovoltaic Plant Monitoring: A Review of Requirements and Feasible Technologies. Sustainability 16, 8367. https://doi.org/10.3390/su16198367

Cagle, A.E., 2023. Land sparing, environmental, and hydrological impacts of floating solar photovoltaic energy installations (PhD Thesis). University of California, Davis.

Cannon, D.T., Vasel-Be-Hagh, A., 2024. Daytime thermal effects of solar photovoltaic systems: Field measurements. Journal of Renewable and Sustainable Energy 16, 056501. https://doi.org/10.1063/5.0219179

Chen, W., Zhang, Q., & Wang, C. (2021). The response of macroinvertebrate communities to eutrophication and oxygen depletion in subtropical reservoirs. Ecological Indicators, 125, 107480. https://doi.org/10.1016/j.ecolind.2021.107480

Choi, S.M., Park, C.-D., Cho, S.-H., Lim, B.-J., 2023. Effects of various inlet angle of wind and wave loads on floating photovoltaic system considering stress distributions. Journal of Cleaner Production 387, 135876. https://doi.org/10.1016/j.jclepro.2023.135876

Cole, J.J., Caraco, N.F., 1998. Atmospheric exchange of carbon dioxide in a low-wind oligotrophic lake measured by the addition of SF6. Limnology and Oceanography 43, 647–656.

Cory, R., Harrold, K., Neilson, B., Kling, G., 2015. Controls on dissolved organic matter (DOM) degradation in a headwater stream: the influence of photochemical and hydrological conditions in determining light-limitation or substrate-limitation of photo-degradation. Biogeosciences 12, 6669–6685. https://doi.org/10.5194/bg-12-6669-2015

Debnath, K., Hsieh, C.-C., Huang, C.-Y., Barman, J., Kuo, C.-F.J., 2025. Experimental investigation and economic evaluation of wind impacts on the solar panel array of a floating photovoltaic (FPV) system across different turbulence intensities. Energy Nexus 17, 100380. https://doi.org/10.1016/j.nexus.2025.100380

De Carvalho, A.R., Hanozin, E., Jacobs, G., Jordens, J., Voorspoels, S., 2025. Addressing chemical contamination from floating photovoltaic systems: the need for comprehensive analytical monitoring. https://doi.org/10.1051/kmae/2025014

De Jong, M., Montoya, D., Pinho, P., & Jordano, P. (2022). Floating solar panels and birds: A systematic review of potential interactions and knowledge gaps. Renewable and Sustainable Energy Reviews, 161, 112346. https://doi.org/10.1016/j.rser.2022.112346

De Rijk, S., van Eck, L., Graef, A., van Veenendaal, E., Dionisio, M., Wieland, S. 2025a. Sustainable, reliable and efficient floating PV power plants: Monitoring concepts (Deliverable D1.1). SuRE project, (Horizon Europe grant no. 101135567)

De Rijk, S. de, Wieland, S., Ilgen, K., Pires, M.D., Eck, L. van, 2025 b. Chapter nine - Impact of floating photovoltaics on the inland aquatic ecosystem, in: Rosa-Clot, M., Tina, G.M. (Eds.), Progress in Floating Photovoltaic Systems. Elsevier, pp. 195–217. https://doi.org/10.1016/B978-0-443-21972-6.00010-4

Denis, P., Capet, A., Vanaverbeke, J., Kerkhove, T.R.H., Lacroix, G., Legrand, S., 2025. Hydrodynamic alterations induced by floating solar structures co-located with an offshore wind farm. Front. Mar. Sci. 12, 1674859. https://doi.org/10.3389/fmars.2025.1674859

Du, J., Zhang, D., Zhang, Y., Xu, K., Chang, A., Zhao, S., 2024. Design and comparative analysis of alternative mooring systems for offshore floating photovoltaics arrays in ultra-shallow water with significant tidal range. Ocean Engineering 302, 117649. https://doi.org/10.1016/j.oceaneng.2024.117649

Engel, F., Fischer, H., 2017. Effect of thermal stratification on phytoplankton and nutrient dynamics in a regulated river (Saar, Germany). River research and applications 33, 135–146.

European Commission (2025a). REPowerEU: Affordable secure and sustainable energy for Europe. European Commission. https://commission.europa.eu/topics/energy/repowereu_en

European Commission (2025b). Water Framework Directive. European Commission. https://environment.ec.europa.eu/topics/water/water-framework-directive_en

European Commission (2025c). Natura 2000 – Permitting procedure. European Commission. https://environment.ec.europa.eu/topics/nature-and-biodiversity/natura-2000/permitting-procedure_en

European Parliament and the Council (2012). Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32011L0092

Exley, G., Armstrong, A., Page, T., Jones, I.D., 2021. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. Solar Energy 219, 24–33. https://doi.org/10.1016/j.solener.2021.01.076

Exley, G., Page, T., Thackeray, S.J., & Folkard, A.M. (2022). Floating solar panels on reservoirs impact phytoplankton populations: A modelling experiment. Journal of Environmental Management. https://www.sciencedirect.com/science/article/pii/S0301479722019831

Exley, G., 2022. Environmental impacts of floating solar photovoltaics on their host water bodies : Opportunities and risks (phd). Lancaster University.

Falkowski, P. G., & Raven, J. A. (2007). Aquatic Photosynthesis (2nd ed.). Princeton University Press.

Friel, D., 2024. Dynamic responses of floating photovoltaic arrays under wave loads. Queen’s University Belfast.

Goldman, C.R., Elser, J.J., Richards, R.C., Reuters, J.E., Priscu, J.C., Levin, A., 1996. Thermal stratification, nutrient dynamics, and phytoplankton productivity during the onset of spring phytoplankton growth in Lake Baikal, Russia. Hydrobiologia 331, 9–24.

Golubkov, M., Golubkov, S., 2024. Patterns of the relationship between the Secchi disk depth and the optical characteristics of water in the Neva Estuary (Baltic Sea): the influence of environmental variables. Front. Mar. Sci. 11, 1265382. https://doi.org/10.3389/fmars.2024.1265382

Graham, M., Li, J., 2024. Vortex shedding and induced forces in unsteady flow. Aeronaut. j. 128, 2149–2190. https://doi.org/10.1017/aer.2024.82

Gurnell, A., Petts, G., Hannah, D. M., Smith, B. P. G., Edwards, P. J., Kollmann, J., … & Ward, J. V. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms, 26(1), 31–62. https://doi.org/10.1002/1096-9837

Haas, J., Khalighi, J., & De La Fuente, A. (2020). Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. Energy Conversion and Management, 223, 113295. https://doi.org/10.1016/j.enconman.2020.113295

Hanson, P.C., Bade, D.L., Carpenter, S.R., Kratz, T.K., 2003. Lake metabolism: Relationships with dissolved organic carbon and phosphorus. Limnology & Oceanography 48, 1112–1119. https://doi.org/10.4319/lo.2003.48.3.1112

Hernandez, R. R., Forester, E., Cagle, A. E., & Rodriguez, J. T. (2025). Aligning floating photovoltaic solar energy expansion with waterbird conservation. Nature Water, 1, Article 00429. https://www.nature.com/articles/s44221-025-00429-4

Ibrahim, S. A., Yusop, Z. M., Daud, M. Z., & Suyono, H. (2024). Evaluating the Horizon of Renewable Power: A Comprehensive Review of Floating Photovoltaic Systems' Performance and Technologies. ResearchGate. PDF

Idso, S.B., 1973. On the concept of lake stability. Limnology and oceanography 18, 681–683.

Ilgen, K., Schindler, D., Wieland, S., Lange, J., 2023. The impact of floating photovoltaic power plants on lake water temperature and stratification. Sci Rep 13, 7932. https://doi.org/10.1038/s41598-023-34751-2

Ilgen, K., Goulart, C.B., Hilgert, S., Schindler, D., Van De Weyer, K., De Carvalho Bueno, R., Bleninger, T., Lastrico, R., Gfüllner, L., Graef, A., Fuchs, S., Lange, J., 2025. Hydrological and ecological effects of floating photovoltaic systems: a model comparison considering mussel, periphyton, and macrophyte growth. Knowl. Manag. Aquat. Ecosyst. 11. https://doi.org/10.1051/kmae/2025008

Ilgen, K., 2026. Submitted. Enhancing Climate Resilience of Lakes through Yield-Optimised Floating Photovoltaics. Dissertation. University of Freiburg, Freiburg im Breisgau.

Jeppesen, E., Søndergaard, M., Kanstrup, E., & Petersen, B. (1998). The importance of macrophytes for structuring fish and plankton communities in shallow lakes. Hydrobiologia, 408/409, 91–97. https://doi.org/10.1023/A:1017070504516

Jeppesen, E., Meerhoff, M., Davidson, T. A., Trolle, D., Søndergaard, M., Lauridsen, T. L., ... & Nielsen, A. (2014). Climate change impacts on lakes: an integrated ecological perspective based on a multi-faceted approach, with special focus on shallow lakes. Journal of Limnology, 73(s1), 84–107. https://doi.org/10.4081/jlimnol.2014.844

Johnson, J. A., Wallace, M. C., & Abolt, C. J. (2020). Evaluating potential avian impacts from utility-scale solar energy development on waterbodies. Environmental Management, 66(2), 231–243. https://doi.org/10.1007/s00267-020-01308-7

Joo, H.-J., Heo, S.-J., Kim, S.-H., Choi, W., 2023. Wind Load Distribution in Float Photovoltaic System. Applied Sciences 13, 12144. https://doi.org/10.3390/app132212144

Kalff, J., 2002. Limnology: inland water ecosystems. Prentice Hall New Jersey.

Kanotra, R., Shankar, R., 2022. Floating Solar Photovoltaic Mooring System Design and Analysis, in: OCEANS 2022 - Chennai. Presented at the OCEANS 2022 - Chennai, pp. 1–9. https://doi.org/10.1109/OCEANSChennai45887.2022.9775352

Kiesecker, J. M., Evans, J. S., & Fargione, J. (2019). Renewable energy and land use in wildlife conservation: Balancing priorities. Biological Conservation, 232, 230–238. https://doi.org/10.1016/j.biocon.2019.02.002

Knighton, D. (1998). Fluvial Forms and Processes: A New Perspective. Arnold Publishers.

Kennedy, R.H., Walker, W.W., 1990. Reservoir nutrient dynamics. Reservoir limnology: ecological perspectives 109–131.

Kristensen, E., Ahmed, S. I., & Devol, A. H. (2012). Benthic macrofauna effects on organic matter mineralization and nutrient cycling in coastal marine sediments: a review. Geochimica et Cosmochimica Acta, 85, 1–18. https://doi.org/10.1016/j.gca.2012.02.032

Lambert, T. (2022). Introducing the Ecosystem Service Concept to Solar Landscapes. Wageningen University Repository. PDF

Langenheder, S., Lindström, E. S., & Tranvik, L. J. (2017). Structure and function of bacterial communities emerging from different sources under identical conditions. Applied and Environmental Microbiology, 83(7), e00100-17. https://doi.org/10.1128/AEM.00100-17

Li, C., Zhang, P., Zhu, G., Chen, C., Wang, Y., Zhu, M., Xu, H., Jiang, C., Zou, W., Shi, P., others, 2022. Dynamics of nitrogen and phosphorus profile and its driving forces in a subtropical deep reservoir. Environmental Science and Pollution Research 29, 27738–27748.

Lian, Y., Chen, Q., Zheng, J., Zhang, J., Sheng, D., Tao, L., Shu, S., Chen, W., Zhou, M., Yim, S.C., 2025. Effects of water level variation on the response of mooring systems for offshore floating photovoltaic platforms. Ocean Engineering 339, 122088. https://doi.org/10.1016/j.oceaneng.2025.122088

Mancini, M., Colomer, J., Solari, L., Serra, T., others, 2024. Experimental observations on synthetic microfibers re-suspension under silty and sandy soil conditions, in: 26th Annual International Workshop on Physical Processes in Natural Waters-Proceedings. Department of Environmental Physics-University of Girona.

McGowan, S., Maberly, S. C., & Heathcote, A. J. (2023). Sediment diagenesis and benthic–pelagic coupling under changing organic matter inputs in lakes. Biogeochemistry, 162, 211–230.
https://doi.org/10.1007/s10533-023-01034-1

Mehl, D., Mehl, C., Kühl, A.-R., Johnson, D., 2024. Schwimmende PV-Anlagen: Auswirkungen auf Arten, Lebensräume und Landschaftsbild (und Ansätze zur Vermeidung). https://doi.org/10.19217/skr

Merino-Ibarra, M., Ramírez-Zierold, J.A., Valdespino-Castillo, P.M., Castillo-Sandoval, F.S., Guzmán-Arias, A.P., Barjau-Aguilar, M., Monroy-Ríos, E., López-Gómez, L.M., Sacristán-Ramírez, A., Quintanilla-Terminel, J.G., others, 2021. Vertical boundary mixing events during stratification govern heat and nutrient dynamics in a windy tropical reservoir lake with important water-level fluctuations: a long-term (2001–2021) study. Water 13, 3011.

Minor, E.C., Oyler, A.R., 2023. Dissolved organic matter in large lakes: a key but understudied component of the carbon cycle. Biogeochemistry 164, 295–318.

Nair, A., Huang, L., Verdin, P.G., 2025. Computational Fluid Dynamics and Potential Flow Modelling Techniques for Floating Photovoltaic Systems: A Systematic Review. Symmetry 17, 1508. https://doi.org/10.3390/sym17091508

New, T. R. (2020). Insect Conservation and Australia's Inland Waters. Springer.

Nobre, R., Boulêtreau, S., Colas, F., Azemar, F., Tudesque, L., Parthuisot, N., Favriou, P., Cucherousset, J., 2023. Potential ecological impacts of floating photovoltaics on lake biodiversity and ecosystem functioning. Renewable and Sustainable Energy Reviews 188, 113852. https://doi.org/10.1016/j.rser.2023.113852

Nobre, R.L.G., Vagnon, C., Boulêtreau, S., Colas, F., Azémar, F., Tudesque, L., Parthuisot, N., Millet, P., Cucherousset, J., 2025. Floating photovoltaics strongly reduce water temperature: A whole-lake experiment. Journal of Environmental Management 375, 124230. https://doi.org/10.1016/j.jenvman.2025.124230

Nobre, R.L.G., Cucherousset, J., & Boulêtreau, S. (2025). Diatom assemblages colonizing floating photovoltaic floaters are distinct from those in benthic and pelagic compartments of gravel pit lakes. Knowledge and Management of Aquatic Ecosystems, 2025(1). https://www.kmae-journal.org/articles/kmae/abs/2025/01/kmae240124/kmae240124.html

Ogles, D.V.B. (2021). Evaluating the Potential of Using Floating Photovoltaic Technology (FPV) on Bodies of Water in California. ProQuest Dissertations Publishing. https://search.proquest.com/openview/74623af172167c8693c219102b4a47dd

Oliveira, P. M. B., Almeida, R. M., & Cardoso, S. J. (2025). Effects of floating photovoltaics on aquatic organisms: A review. Hydrobiologia. https://doi.org/10.1007/s10750-024-05686-0

Prandini, M.K., Bueno, R. de C., Rigotti, J.A., Bleninger, T., Mannich, M., Novak, L.H., 2025. High frequency monitoring for impact assessment of temperature, oxygen and radiation in floating photovoltaic system. Sci Rep 15, 19719. https://doi.org/10.1038/s41598-025-96257-3

Ray, N.E., Holgerson, M.A., Grodsky, S.M., 2024. Immediate Effect of Floating Solar Energy Deployment on Greenhouse Gas Dynamics in Ponds. Environ. Sci. Technol. 58, 22104–22113. https://doi.org/10.1021/acs.est.4c06363

Read, J.S., Hamilton, D.P., Jones, I.D., Muraoka, K., Winslow, L.A., Kroiss, R., Wu, C.H., Gaiser, E., 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. Environmental Modelling & Software 26, 1325–1336. https://doi.org/10.1016/j.envsoft.2011.05.006

Reynolds, C. S. (2006). The Ecology of Phytoplankton. Ecology, Biodiversity and Conservation. Cambridge University Press.

Rocha, S.M.G., Armstrong, A., Thackeray, S.J., Hernandez, R.R., M Folkard, A., 2024. Environmental impacts of floating solar panels on freshwater systems and their techno-ecological synergies. Environ. Res.: Infrastruct. Sustain. 4, 042002. https://doi.org/10.1088/2634-4505/ad8e81

Round, F. E., Crawford, R. M., & Mann, D. G. (1990). The Diatoms: Biology and Morphology of the Genera. Cambridge University Press.

Rueda, F.J., Ramón, C.L., Schladow, S.G., 2025. The Hydrodynamic, Thermodynamic, and Mixing Impacts of Floating Photovoltaics on the Surface of a Lake. Water Resources Research 61, e2025WR039917. https://doi.org/10.1029/2025WR039917

Sandrini, G., Wagenvoort, A., van Asperen, R., Hofs, B., Mathijssen, D., van der Wal, A., 2025. Illuminating the impact of a floating photovoltaic system on a shallow drinking water reservoir: the emergence of benthic cyanobacteria. Water 17, 1178. https://doi.org/10.3390/w17081178

Selj, J., Wieland, S., Tsanakas, I. (2025). Selj, J., Jahn, U., Maugeri, G. (Eds.), Floating Photovoltaic Power Plants: A Review of Energy Yield, Reliability, and Maintenance (Report No. T13-31:2025). IEA PVPS Task 13. https://iea-pvps.org/key-topics/floating-pv-plants/

Sharip, Z., Yusoff, F.M., Zakaria, S., 2025. Lakes, in: Progress on Ecosystem Restoration of Tropical Inland Waters: On the Path of the UN Decade on Ecosystem Restoration. Springer, pp. 29–65.

SolarPower Europe (2024). Recommendations for onshore Floating PV. SolarPower Europe. https://api.solarpowereurope.org/uploads/Floating_PV_position_paper_bd193aa871.pdf?updated_at=2024-04-16T15:51:53.642Z

Stumm, W., Morgan, J.J., 1996. Aquatic chemistry: chemical Equilibria and rates in natural waters. Environmental Science and Technology. Wiley.

Tanabe, Y., Hori, M., Mizuno, A.N., Osono, T., Uchida, M., Kudoh, S., Yamamuro, M., 2019. Light quality determines primary production in nutrient-poor small lakes. Sci Rep 9, 4639. https://doi.org/10.1038/s41598-019-41003-9

Trapani, K. (2014). Flexible floating thin film photovoltaic (PV) array concept for marine and lacustrine environments. MSc Thesis, Laurentian University. PDF

Verschoor, A.M., Van Dijk, M.A., Huisman, J., Van Donk, E., 2013. Elevated CO_2 concentrations affect the elemental stoichiometry and species composition of an experimental phytoplankton community. Freshwater Biology 58, 597–611. https://doi.org/10.1111/j.1365-2427.2012.02833.x

Vouhe, P., Rodríguez-Pérez, H., Wissel, B., Lengagne, T., Metaireau, A., Colas, F., 2025. Potential impacts of floating photovoltaics on carbon fluxes across aquatic-terrestrial boundaries. Knowledge & Management of Aquatic Ecosystems 13. https://doi.org/10.1051/kmae/2025005

Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems. Gulf Professional Publishing.

Winslow, L.A., Zwart, J.A., Batt, R.D., Dugan, H.A., Woolway, R.I., Corman, J.R., Hanson, P.C., Read, J.S., 2016. LakeMetabolizer: an R package for estimating lake metabolism from free-water oxygen using diverse statistical models. Inland Waters 6, 622–636.

Xu, W., Sun, Y., He, Z., 2024. Hydrodynamic performance study of floating photovoltaic arrays with multiple floating bodies. Applied Ocean Research 153, 104286. https://doi.org/10.1016/j.apor.2024.104286

Zhao, C., Ren, Y., & Liu, B. (2023). Influence of floating photovoltaic systems on lake water quality and clarity: A modeling and monitoring approach. Environmental Pollution, 326, 121368. https://doi.org/10.1016/j.envpol.2023.121368

Zhou, J., Liu, W., Chen, X., & Li, Y. (2023). Effects of floating photovoltaic installations on bird diversity and behavior in reservoir ecosystems. Ecological Indicators, 148, 110094. https://doi.org/10.1016/j.ecolind.2023.110094