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International Energy Agency
Photovoltaic Power Systems Programme

Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

Floating Photovoltaic Power Plants: A Review of Energy Yield, Reliability, and Maintenance

2025

Report IEA-PVPS T13-31:2025

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programmes are made up of 6,000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCPs within the IEA and was established in 1993. The mission of the programme is to “enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.” To achieve this, the Programme’s participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct ‘Tasks,’ that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, the United Kingdom, and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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What is IEA PVPS Task 13?

Within the framework of IEA PVPS, Task 13 aims to provide support to market actors working to improve the operation, the reliability and the quality of PV components and systems. Operational data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarize and report on technical aspects affecting the quality, performance, reliability and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries, we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

Task 13 has so far managed to create the right framework for the calculations of various parameters that can give an indication of the quality of PV components and systems. The framework is now there and can be used by the industry who has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS countries participating in Task 13 are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, Thailand, and the United States of America.

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COVER PICTURE

PV Floating System in Zwolle, Netherlands. Copyright BayWa r.e.

INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS Task 13

Reliability and Performance
of Photovoltaic Systems

Floating Photovoltaic Power Plants: A Review of Energy Yield, Reliability, and Maintenance

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LIST OF ABBREVIATIONS

BOS	Balance of system
CAPEX	Capital Expenditures
CFD	Computational Fluid Dynamics
EU	European Union
EYA	Energy yield assessment
FEM	Finite element method
FMEA	Failure modes and effects analysis
FPV	Floating photovoltaics
FRP	Fiber-reinforced plastic
GPV	Ground-based photovoltaics
HDPE	High-density polyethylene
HJT	Heterojunction
IAV	Inter-annual variability
IEA	International Energy Agency
IEC	International Electrotechnical Commission
I-V	Current-Voltage
LCOE	Levelized cost of electricity
LeTiD	Light and elevated temperature induced degradation
LSLR	Least squares linear regression
MPPT	Maximum power point tracker
NIR	Near infrared
OLS	Ordinary least squares
O&M	Operation and Maintenance
PERC	Passivated emitted and rear contact
PID	Potential induced degradation
PLR	Performance loss rate
POA	Plane-of-Array irradiance
PV	Photovoltaics
RH	Relative humidity
ROV	Remotely operated vehicles
RPN	Risk priority number
SC	Short circuit
SCADA	Supervisory Control and Data Acquisition
SR	Shading ratio
SSC	Sea State Codes
STL	Seasonal and trend decomposition
STC	Standard test conditions
TopCON	Tunnel oxide passivated contact
TRL	Technology readiness level
UAV	Unmanned Aerial Vehicle
UV	Ultraviolet
VIS	Visible

WIL	Wave-induced losses
WIML	Wave-induced mismatch losses
WVTR	Water vapor transmission rate
WS	Wind speed
YoY	Year-on-Year

EXECUTIVE SUMMARY

Photovoltaic (PV) systems are essential for the transition to sustainable energy, reducing fossil fuel dependence and mitigating climate change. Although PV requires minimal land area — PV can meet the European Union's energy needs using only 0.26% of its land — space for deployment is often scarce in densely populated regions. Floating photovoltaics (FPV) offer an effective solution to land-use challenges by installing PV systems on floating structures in water bodies. FPV is a growing niche within PV with a cumulative installed capacity reaching 7.7 GW globally by 2023. Almost 90% of the installed FPV capacity is in Asia, with close to 50% of in China alone, while the Netherlands and France are the largest markets outside Asia [3]. FPV shows strong potential to support climate targets, but still faces challenges like regulatory barriers, cost competitiveness compared to ground-based PV (GPV), and uncertainties about environmental impacts and system reliability. FPV systems are currently installed mainly on sheltered inland waters, such as quarry lakes, irrigation ponds and reservoirs.

FPV technical standards are still being developed. Guidelines have been published by the World Bank, DNV, and Solar Power Europe, and emerging national standards from South Korea, China, and Singapore address design, components, and safety. The International Electrotechnical Commission (IEC) is working on formal standards for floats, mooring systems, and electrical connectors. However, the published best practices lack quantitative guidance for yield modelling and reliability, which this report aims to address. It provides data-driven insights, models, and parameters essential for accurate energy yield, reliability, and maintenance predictions over FPV systems' lifetimes.

Energy Yield Assessment

The report provides guidelines and quantitative recommendations for the accurate energy yield assessment (EYA) of FPV systems, a key factor for determining the levelized cost of electricity and project profitability. Current models for EYA are insufficient, lacking reliable data for critical parameters like module temperature, wave-induced losses, soiling losses, and performance loss rates. Standard modelling tools do not adequately cover FPV-specific needs, and existing meteorological databases often exclude sea and coastal areas, which limits FPV yield estimation. This chapter identifies essential parameters and highlights knowledge gaps in meteorological data, energy production modelling, and uncertainty analysis that distinguish FPV EYA from that of GPV.

1. **Meteorological Data Requirements**: The report highlights the need for improved meteorological data tailored to FPV, as the water-based environment affects variables like irradiance, wind, and temperature. It is uncertain how this affects prediction accuracy for FPV.
2. **Thermal Losses**: Thermal performance depends on the FPV system design. Modelling tools, such as PVsyst and pvlib, need to incorporate these specifics for more accurate yield estimates.
3. **Wave-Induced Losses**: Wave motion affects irradiance by altering module tilt and creating irradiance non-uniformity. No complete model for wave-induced losses currently exists and the report encourages field data collection to improve accuracy in yield modelling.
4. **Soiling Losses**: FPV systems may experience unique soiling challenges, including bird droppings and other debris from surrounding ecosystems.

The report underscores that FPV yield estimation tools and methods are still evolving, and it encourages improved empirical studies and data-sharing to refine modelling approaches and align them with the distinctive characteristics of FPV installations.

RELIABILITY

When assessing the reliability of an FPV system, one faces important knowledge gaps and challenges. First, the stress profiles experienced by components in a FPV installation are neither well understood nor quantified and will vary a lot depending on float technology and water body conditions. Second, open information and systematic studies on observed degradation and field failures remain scarce, as are studies of performance loss rates (PLR). And third, as a result of the first two points, there is no accelerated stress testing protocol developed for component reliability evaluation. In the following, each of these three topics will be further discussed.

The term *degradation* denotes the gradual process of change in characteristics with operational time of a material / component / system triggered by stress impact. Typically, we distinguish between three types of degradation: reversible degradation, irreversible degradation, and failures. For FPV, the balance of system components may be even more critical than the PV modules. Junction boxes, cables, connectors, and related protecting materials may suffer from additional stress compared to GPV systems. The report provides an overview of environmental stressors in the operating environment of FPV systems, and finally discusses three different sources for quantification of degradation effects:

1. **Field data:** collection of long-term field data is indispensable for accurate identification of failure modes and the design of appropriate testing protocols. As the available field data on failures and degradation is very limited, performance stability is measured through long-term trends in historical production data. Three commonly used statistical methods are deployed to calculate the PLR through historical PV performance and climatic data: Ordinary Least Squares (OLS), seasonal and trend decomposition using locally weighted scatterplot smoothing (STL), as well as Year-on-Year (YoY). These methods are based on determining trends in the historical data. The major drawback of statistical methods is that they do not trace the correlation of the evaluated degradation rates with the climatic variables and degradation processes. Despite the significant number of FPV systems that have now been operating for several years, long-term FPV performance studies are rare. A study by SERIS using three years of data from a large FPV test bed found PLRs between -0.7% and -0.5% per year, like those of nearby rooftop PV.
2. **Laboratory:** in the lab environment, accelerated stress tests enable reliability screening of key components in short timeframes, to identify and mitigate quality issues before they manifest as problems in actual installations. A challenge with laboratory testing for FPV is that there are no standards on reliability testing of FPV components, and few field measurements of stressors and field degradation. IEC standards that can be relevant for FPV components are summarized in this section.
3. **Simulation Models:** simulations are one convenient option to overcome the lack of experimental (long-term) data, and to capture the correlations between the degradation rates and the stressors/climatic variables. However, we emphasize the importance of using validated simulation models to obtain reliable results. For FPV, four types of simulations are of particular interest to study the influence of single stressors: a) Wind loads through Computational Fluid Dynamics (CFD) and mechanical simulations, b) Moisture ingress through mass transport simulations, c) Hotspot formation through electrical and thermal simulations, d) Thermally Induced Stress through thermal and mechanical simulations.

Operations & Maintenance

There are currently no standards available that describe the recommended sensors and procedures for monitoring of FPV power plants. Instrumentation requirements for GPV power plants, including requirements with respect to accuracy and number according to the size of the plant, can be found in IEC 61724-1.

The report introduces a preliminary failure mode and effects analysis of technical and operational challenges, and how these impact operation and maintenance (O&M). Available data is limited, and one can only anticipate that the occurrence and degree of severity for the different events may change as more data is collected. A list of key aspects and considerations when budgeting for FPV O&M projects is also provided.

FPV technology faces key R&D challenges, especially as installations scale up and offshore projects expand. Major areas include:

- Monitoring and Remote Sensing: Remote FPV sites, especially offshore, struggle with data transmission reliability and high communication costs. Advanced solutions using drones and satellites can enhance monitoring and reduce O&M costs.
- Expert Dependence: FPV's complexity requires specialized experts (e.g., divers, marine engineers) for maintenance and inspections, increasing costs and time. AI-driven data analytics, Unmanned Aerial Vehicle (UAV) based inspections, and autonomous systems offer potential to reduce human intervention.
- Extreme Weather and Degradation: Marine environments introduce severe stressors like corrosion and UV exposure, accelerating FPV component degradation. R&D in advanced materials, protective designs, and robust emergency-response plans is crucial to improve FPV durability.
- Environmental Impact and Regulations: Concerns on FPV effects on aquatic ecosystems, such as water quality and habitat shading, call for eco-friendly designs and regulatory standards that minimize harm and adapt O&M practices for sustainability.

Conclusions

FPV offers a promising solution for expanding renewable energy without increasing land-use pressures. However, the absence of regulatory frameworks and limited long-term data creates uncertainty for developers, regulators, and investors, slowing FPV adoption. Rapid innovation in the field often prioritizes confidentiality, even though the industry would benefit from open data sharing. This report aims to support FPV development by building a knowledge base on energy yield, reliability, and O&M — areas where FPV diverges from GPV. Key research priorities include understanding FPV-specific stressors, improving predictive models, automating O&M, and assessing environmental impacts. Addressing these gaps can lead to a more mature, sustainable FPV industry, ready for broader deployment.

1 INTRODUCTION

PV is a cornerstone in the transition to sustainable energy, and accelerated deployment is essential to reduce reliance on fossil fuels and mitigate global warming. While PV systems occupy relatively small amounts of land — for instance, meeting the current energy demand of the European Union (EU) with PV would require only 0.26% of its total land area [1] – land availability for solar deployment is often limited in densely populated areas. One solution is to deploy PV systems on water bodies. Floating Photovoltaics refers to mounting solar photovoltaic systems on structures that float on water. It is a relatively novel, but rapidly growing technology, exhibiting promising synergies with other usage of water bodies.

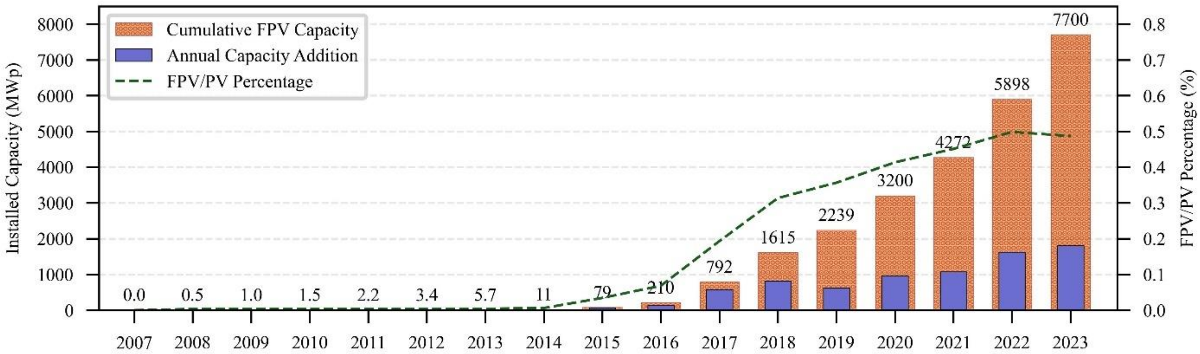

Figure 1. Annual and cumulative growth in deployment of FPV by installed capacity (MW_p) and by percentage of total global PV installations (%).

Figure 1 shows the cumulative and annual installed capacity of FPV since the first deployment in 2007. The deployment has grown from just above 1.6 GW at the end of 2018 to 7.7 GW by the end of 2023 [2]. Almost 90% of the installed FPV capacity is in Asia, with close to 50% of in China alone [3], followed by Taiwan, India, Israel, Japan and South Korea. However, FPV also holds potential to support the EU's climate neutrality goals, with the Netherlands and France currently hosting the 7th and 10th largest FPV capacities [3]. As the technology matures,

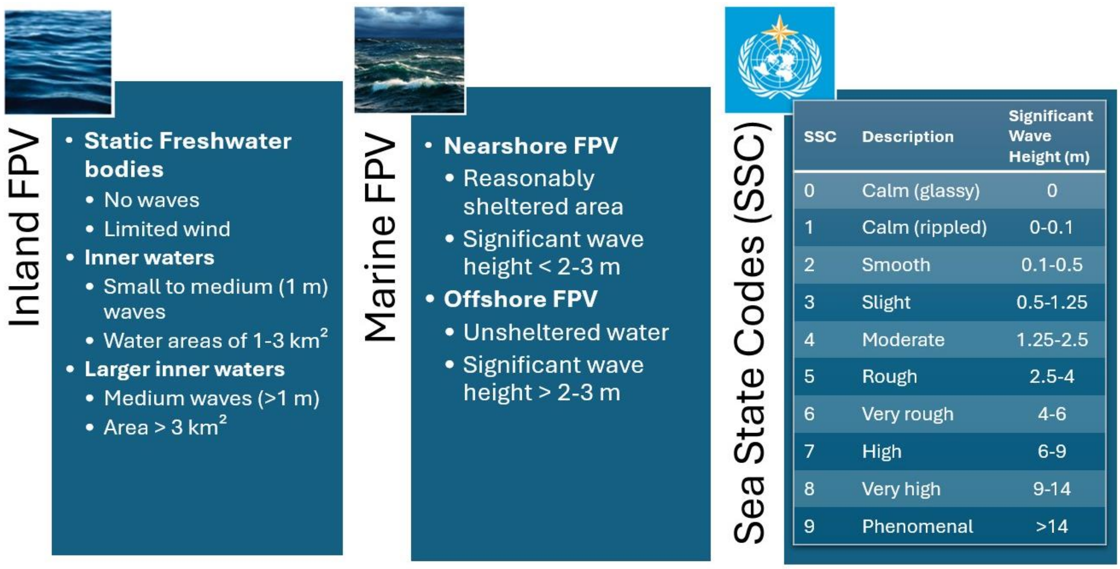

Figure 2. Categorization of FPV as suggested by Solar Power Europe [1] and the WMO sea state codes [4].

FPV deployment is expected to accelerate further, but several barriers persist. Legislative hurdles, cost competitiveness relative to ground-based PV, and uncertainties surrounding environmental impact and reliability could impede global adoption.

The commercial deployment of FPV systems today is on sheltered waters. However, there is currently no consensus regarding how deployment on different types of water bodies should be classified. Solar Power Europe [1] suggests a division between onshore (or inland) FPV and marine FPV, where onshore is further separated into static freshwater bodies, inner waters, and larger inner waters, while marine FPV is separated into nearshore FPV and offshore FPV, as shown in Figure 2. Another option is to use the Sea State Codes (SSC) of the World Meteorological Organization (WMO). This scale spans from no waves (SSC 0) to wave height > 14 m (SSC 9). The two may also be used in combination, although the suggested wave height in [1] must be modified to fit with established WMO SSC codes. In this report, we use the term *inland FPV* for deployment of FPV on freshwater bodies, while the term *nearshore FPV* is used for deployment of FPV at sea, but close to the coastline.

Figure 3. Installation of FPV on quarry lake, sandpit, and hydropower dam in Europe.

This report is limited to address inland and nearshore FPV, as some technologies may be suited for both applications. The report does not cover offshore FPV applications, as both the challenges it faces, and the FPV technologies under development for these conditions differ significantly from inland and nearshore FPV. The majority of current FPV installations in Europe are deployed on quarry lakes, sandpit lakes, irrigation ponds and other man-made water bodies. Figure 3 shows installations on a) a mining and quarry lake, b) a sandpit lake and c) a hydropower dam.

The installation and operational costs will depend significantly on the category of application, but focusing on sheltered waters (corresponding to FPV deployed at Static Freshwater bodies and Inner waters), a cost premium of 20-25% in Europe and USA respectively is estimated compared to GPV [4], [5]. The CAPEX is highly affected by float costs, which are influenced by wind and snow loads, as well as the efficiency of the PV modules. The CAPEX estimates are also in line with a median CAPEX cost of 1.18 USD/W (2022), recently reported by SERIS based on their comprehensive FPV database [3]. Of all projects installed in 2022 or earlier, 30 projects have reported CAPEX lower than 1 USD/W and the lowest CAPEX reported for any FPV project is 0.41 USD/W for 36 MW FPV in India [6].

The development of technical standards for (any type of) FPV systems is currently limited but actively pursued by various national and international organisations. These efforts aim to address the unique challenges associated with deploying solar PV systems on water bodies. The first comprehensive guideline was the ‘Floating Solar Handbook for Practitioners’ published in 2019 [7]. The technical considerations covered by the handbook include site selection and assessment, FPV system design and components, electrical safety measures, as well as operation and maintenance procedures. Also published in 2019 were national standards for PV modules in FPV applications by South Korea [8] and for the high-density polyethylene (HDPE) floats and structures by China [9], [10], [11], [12].

While the ‘Floating Solar Handbook for Practitioners’ is targeted towards a more general audience and includes non-technical aspects, more normative standards are provided by the DNVGL-RP-0584 Recommended Practice [13] and the Singapore Technical Reference TR 100:2022 [14]. DNVGL-RP-0584 was developed in a joint industry project with FPV developers, investors, installers, and equipment suppliers. Meanwhile, Singapore's TR 100:2022 modified the GPV standard IEC TS 62738:2018 [15] for FPV contexts by addressing the specific nature of FPV systems over water; also referencing other existing standards from adjacent technologies such as the marine industry.

Efforts are ongoing in the IEC Technical Committee 82, Working Group 3 (TC82 WG3) to formalise an international standard for FPV systems. This standard will also have links to two other Recommended Practices by DNV, which are currently underway to develop better guidance on the floats (various types) and the anchoring & mooring systems. Similarly, IEC TC82 WG2 plans to develop a standard for PV modules when deployed in FPV applications.

Generally, the key focus areas addressed in the technical standards include proper design, component selection and implementation of FPV systems to ensure long-term durability and reliability, including (but not limited to) cables, floats, anchors, and mooring systems, taking into account the exposure of components to high humidity, their possible submergence into the water and the dynamic environmental conditions (combined wind, wave, and possibly tidal forces). Ultimately, clear and comprehensive guidelines will boost FPV system design and installation quality, as well as investor’s confidence and bankability.

While the published best practice reports from DNV [13], the World Bank [7], and Solar Power Europe [1] provide valuable contributions to different areas within FPV, they fall short of offering quantitative recommendations for energy yield modelling or addressing reliability and field failures. The aim of this report is to address these gaps by focusing on topics at the forefront of FPV research. Specifically, we provide observations, models, and quantitative parameters to support the efficient and economically viable deployment of FPV systems. The report examines factors influencing the energy yield over the lifetime of FPV plants, along with the associated O&M requirements, incorporating quantitative values where available.

Sustainability of FPV power plants represents a very wide and multifaceted topic, encompassing everything from environmental impacts, carbon footprints, and recycling, to socio-economic and socio-cultural impacts.

With respect to environmental impacts, a wide range of both potential benefits and potential adverse impacts have been discussed in the scientific literature. Case studies detailing the impact of FPV power plants at specified sites are starting to appear [16], [17], [18] as are guidelines for monitoring [19] and impact assessment [20]. However, the impact depends on the sensitivity of the water body itself, local climate, and FPV design and coverage, making it is difficult to generalize the findings. Overall, the knowledge base on the environmental impact of FPV power plants remains limited, and more research is needed.

IEA PVPS Task 12 published a report on Carbon Footprint Analysis of FPV in 2024 [21], concluding that the two studied FPV technologies had a slightly greater carbon footprint than the GPV references, but seven times lower than that of the grid mix in the countries where they were installed (Germany and the Netherlands). The largest contribution to the carbon footprints is from the manufacturing of the PV module (60% to 70%, depending on the system).

The scientific literature provides very little information on social impacts, and acceptance, of FPV. Most large waterbodies provide extensive ecosystem services to local communities including fishery, irrigation water, recreation, tourism and transportation. While it is often claimed that installing FPV instead of GPV will reduce the level of conflict for space, there are few studies that can support these arguments [22].

A detailed discusson on sustainability of FPV is comprehensive and beyond the scope of this report. We recommend that these aspects are dealt with in a separate report.

2 FPV ENERGY YIELD

The purpose of this chapter is to provide concrete guidelines and quantitative recommendations for a selection of parameters essential for accurate energy yield assessment (EYA) of various FPV technologies. EYA, or modelling of the average yearly expected energy production, is crucial for determining the levelized cost of electricity (LCOE) and, consequently, the profitability of a project. The absence of published and validated values for parameters used in EYA for FPV can hinder the development and investment in new FPV projects.

The toolbox for EYA of FPV is currently inadequate. Models that accurately estimate module temperature and wave-induced losses (WIL) are not available in standard modelling software. Soiling losses and performance loss rates (PLR) should ideally be based on published and validated empirical values, but such values are currently unavailable. The validation of models and empirical values is challenging due to the scarcity of high-quality data series that include both production and weather data. Additionally, while meteorological data suitable for energy production estimates for PV is readily available, coverage of sea and coastal areas is missing from many databases and PV modelling tools. An important effort in this report is hence to provide an overview of both what is known and current gaps in knowledge needed for accurate EYA of FPV.

EYA can be divided into three components: meteorological input data, energy production estimates, and uncertainty analysis. As good procedures for EYA exists for GPV, the focus in this chapter is on the topics that separate EYA for FPV from GPV.

Section 2.1 provides a brief overview of current knowledge and knowledge gaps related to meteorological data sets above water bodies.

Sections 2.2, 2.3, and 2.4 are concerned with energy production estimates. A challenge for energy production estimates for FPV is the diversity of FPV technology. In Section 2.2, we give a brief introduction to FPV technologies and classification schemes for the different technologies. The quantitative losses and the models to describe them will depend on both FPV technology and site/sea state, inferring that a broad set of data series spanning different type of technologies and sites will be necessary to gain a good understanding and validate models and values in different conditions. We also address the impact of technology design choices on various losses. In Section 2.3, we describe three loss mechanisms that are important input to energy production estimates, and which differ from their GPV counterparts in terms of value and/or origin: Thermal losses, WIL, and soiling losses. The impact of these losses on different types of FPV technologies is, to the extent possible, quantified. The PLR is also an important input to energy production estimates. However, as it represents a sum of various degradation mechanisms, it is covered in Chapter 3 on Reliability. Section 2.4 provides an overview of modelling options for FPV in the industry standard modelling software, PVsyst, and in pvlib, commonly used in research and development.

The third part of an EYA is uncertainty analysis. To date, no published efforts are known for quantifying uncertainties in crucial FPV modelling steps such as soiling or WIL. Section 2.5 summarizes the main methods to model uncertainty and provides advice on how to deal with uncertainty analysis for EYA of FPV.

2.1 Meteorological input data for FPV

The long-term and short-term solar resource variability represents the single greatest uncertainty in a solar power plant's predicted performance. Satellite-derived, and high-quality historical solar radiation data sets covering at least 10 years are usually considered necessary for the site selection of large solar energy systems [23].

Solar resource data above water bodies has not been of interest to the providers of meteorological data for solar power plants until recently.

There are currently no dedicated measures undertaken to ensure that the meteorological parameters used in PV yield assessments are accurate above inland water bodies. For nearshore- and offshore locations, the meteorological parameters are lacking in several of the databases commonly used for solar power plants, including SARAH2-PVGIS, ERA5-PVGIS, and Meteonorm (8) for PVsyst. In the new release of PVGIS, the databases will be updated to cover nearshore – 25 km towards the sea - to enable assessment of FPV close to the coastlines. The spatial resolution for the coastal areas will be the same as for inland areas, SARAH3's native resolution at 0.05° x 0.05°, and ERA5 interpolated to the resolution of ERA5-Land at 0.1° x 0.1° (A. Martinez, personal communication, May 17, 2024).

Historical data based on satellite imagery of meteorological data above sea can be obtained from the NASA POWER service [24]. Comparing the irradiance on land with irradiance ~57 km offshore, Golroodbari et al. [25] finds that in 70% of the locations, the average value for irradiation at the offshore site is higher than at the land-based site.

For inland water bodies, it will also be of interest to evaluate, and likely improve, the accuracy of temperature and wind data, as this will be affected by the water body. It is also worth noting that easier access to data assessing the sea states of water bodies would facilitate planning and implementation of FPV.

2.2 FPV technology overview

The term FPV encompasses a wide range of technologies, with a broad range of different FPV floating system manufacturers currently in operation. Figure 4 provides an overview of the major FPV technology manufacturers and their market share measured by installed capacity. Each manufacturer naturally aims to differentiate their products with unique characteristics, making any categorization scheme prone to inaccuracies and oversimplifications. This diversity poses a challenge when modelling EYA for FPV. Early reviews and reports often overlooked this critical information, leading to confusion about the expected performance of various FPV technologies.However, to address the different types of FPV technologies

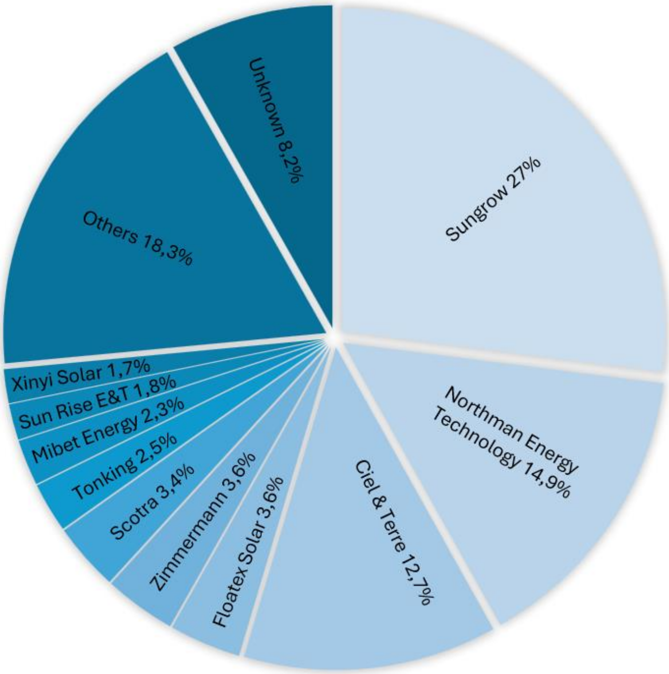

Figure 4. Market share of FPV technologies by installed capacity. Data based on [3].

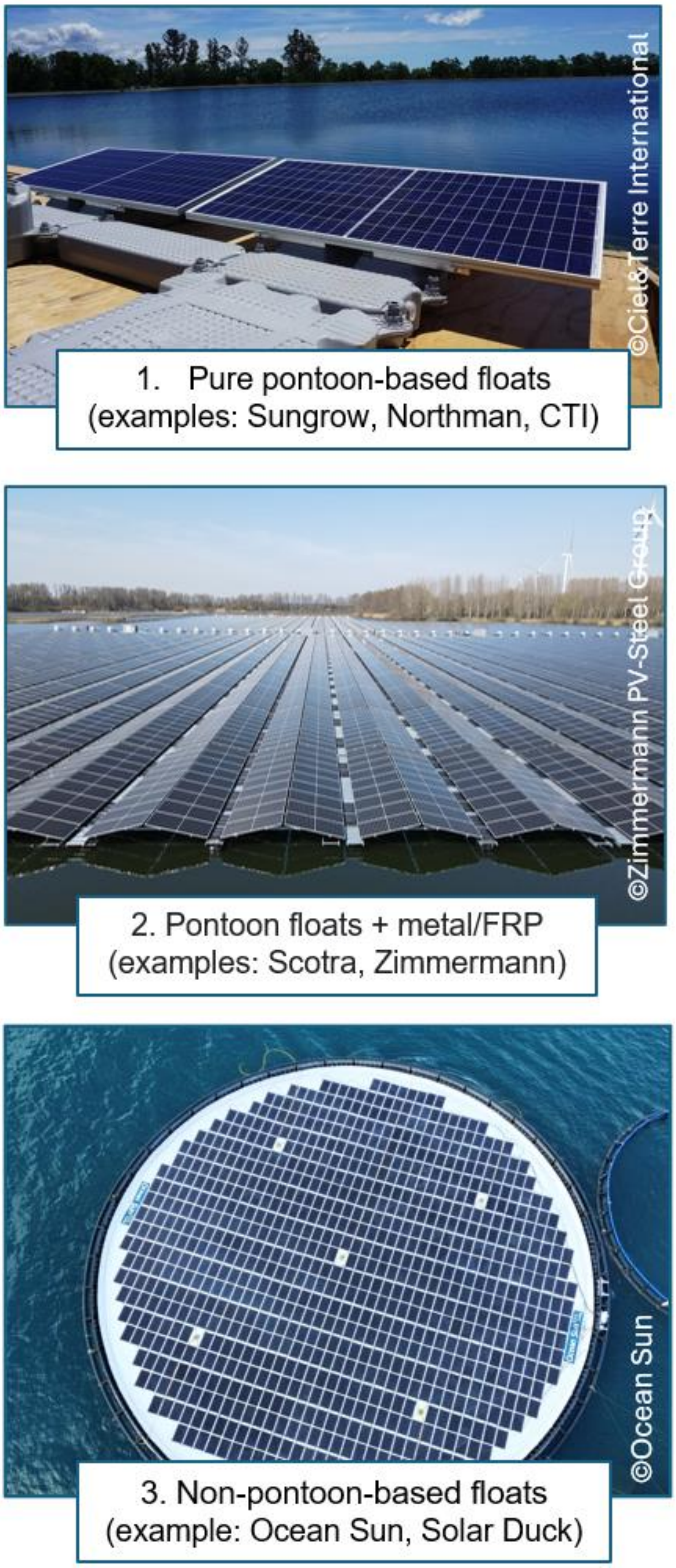

Figure 5. Categorization of FPV system based on float type. Illustration based on [3], [8], [121].

efficiently without delving into specifics, we find it beneficial to use the categorization shown in Figure 5.

Category 1 is pure-floats, which, as the name indicates, are solutions fully composed of floats, typically made of high-density polyethylene (HDPE). *Category 2* combines metal or fiber-reinforced plastic (FRP) with floats or pipes, with ZIM Float being a well-known European example. *Category 3* encompass other types of FPV technologies such as platforms, ferro-cement structures, and membrane technology. The latter is patented by the company Ocean Sun. Technologies submerged in water and FPV systems that utilize active water cooling (water is pumped and sprayed onto the modules) are not specifically addressed in this report.

2.2.1 Pure pontoon-based float technology (pure-floats)

Pure-float FPV technology was the first to gain commercial traction, and the three dominating FPV technologies world-wide, developed by Sungrow, Ciel & Terre, and Northman Energy Technologies are all pure-floats. According to SERIES FPV database, these technology providers have a market share of more than 50% (27%, 12,7% and 14,9% respectively) [3]. The category also encompasses many other, smaller technology providers, covering a range of different float designs. The development of the float technologies over time can also be substantial, as an example, Figure 6 shows the iterative development of Ciel & Terre's Hydrelio® technology. Naturally, the properties of the floats will change with the design, but also with choices made with respect to tilt angle and electrical configuration.

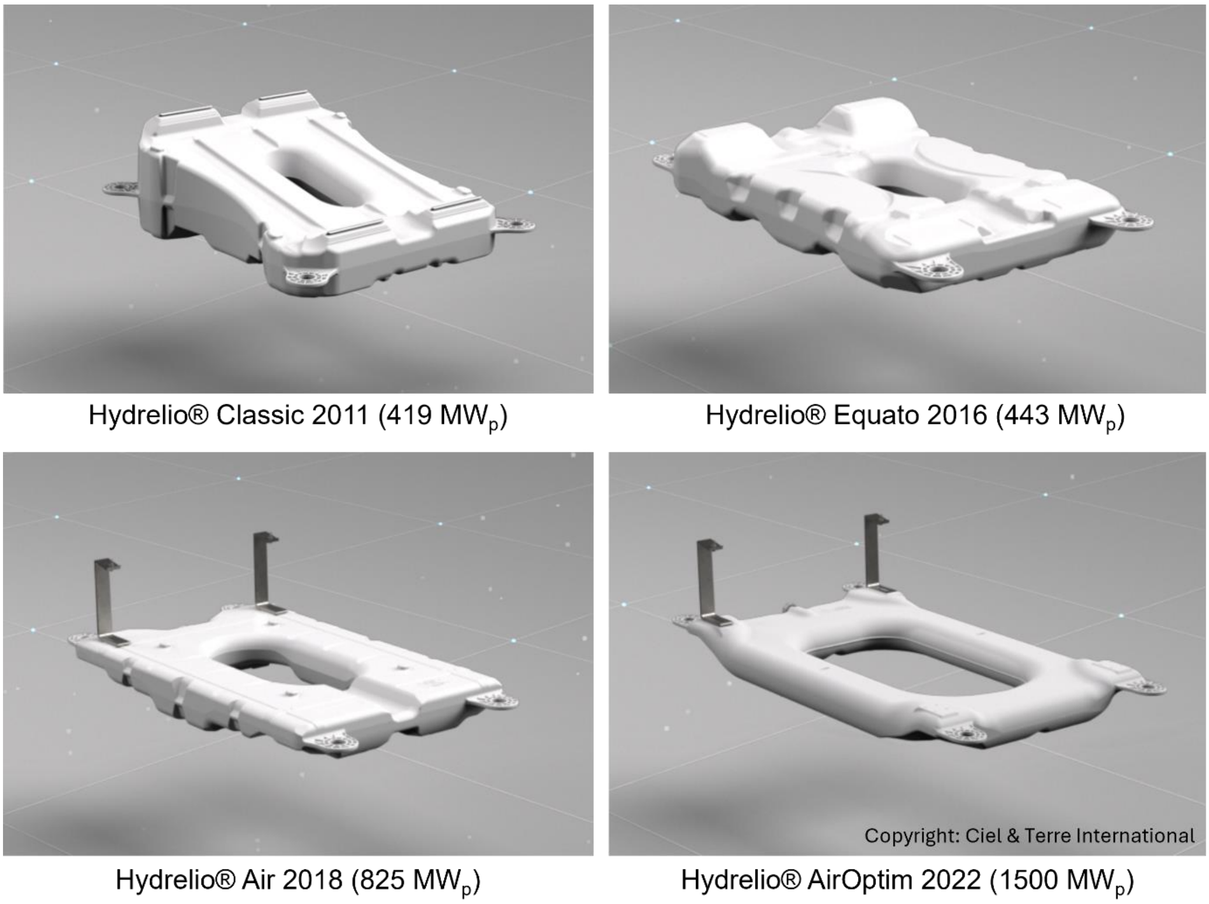

Figure 6. Development of Ciel & Terre Hydrelio® technology. The numbers refer to accumulated installed capacity for Ciel & Terre up until the given year. Copyright: Ciel & Terre International.

2.2.2 Pontoon floats + metal or FRP structures

Another type of structure that is utilized as mounting for FPV is based on a combination of floats (or pipes) and metal or FRP structures. Here, the floats do not support the individual PV modules directly, as with the pure-float technology, but instead support the metal or FRP structure that the PV modules are in turn mounted on to. Examples of this type of FPV technology include the European ZIM Float by Zimmermann PV-Steel Group and the Korean Scotra. The ZIM Float technology is currently the most widely deployed FPV technology in Europe with more than 250 MW installed predominantly in Germany and the Netherlands. There are currently two versions of the ZIM Float technology, ZIM Float1 and the second-generation ZIM Float2. The South-Korean company Scotra has developed FPV systems for more than a decade and installed their first commercial FPV plant (500 kW) in 2012. There exist many generations of the float with quite substantial developments over the years. ZIM Float and Scotra have world-wide market shares (by the end of 2022) of 3.6% and 3.4% respectively [3]. An FPV power plant with ZIM Float technology is depicted in Figure 7.

Figure 7. FPV power plant with ZIM Float technology installed in 2021 with a capacity of 13.7 MW at Lippe Gabrielsplas in the Netherlands.

2.2.3 Non-pontoon-based floats

One alternative technology involves deploying PV modules on a thin membrane that floats directly on the water's surface. This solution patented by the company Ocean Sun [26], [27], uses a ring of HDPE material to provide buoyancy, with the PV panels fastened using keders welded onto the membrane. PV modules deployed with this technology experience different environmental impacts compared to pure-floats. Irradiance conditions and wave movement effects vary, the dominant heat dissipation mechanism is different, and soiling and cleaning will be influenced by the horizontal mounting solution. Consequently, the models and parameters used to describe the yield must also be adapted.

2.3 Energy production estimates for FPV

Estimating the energy production of FPV systems introduces additional challenges and complexities compared to GPV. This section delves into three loss mechanisms that differ significantly from their GPV counterparts. For a comprehensive overview of PV yield and associated losses, refer to the IEA-PVPS Task 13 Report “Performance Modelling Methods and Practices” [28].

Section 2.3.1 introduces the most relevant parameters for describing the heat exchange between an FPV system and its environment. Section 2.3.2 examines the effects of irradiance non-uniformity caused by wave-induced dynamic tilt variations. Section 2.3.3 explores the issue of soiling in FPV systems. In each section the loss mechanism is described in general, before quantitative values for different FPV technologies are discussed. The maturity and understanding of these topics vary significantly, which is also reflected in the text.

2.3.1 Thermal losses

Temperature impacts both the instantaneous and long-term performance of PV modules. As cell temperature increases, PV efficiency decreases. Additionally, high temperatures and frequent temperature cycles can accelerate various degradation mechanisms. Therefore, minimizing operating temperature and thermal cycling can enhance power generation and potentially extend the lifetime of a PV system [29].

The operating temperature of PV modules mounted in various FPV systems has been widely discussed. Several studies indicate that FPV systems often operate at lower temperatures compared to co-located GPV installations [30], [31]. However, other studies report similar or even higher operating temperatures for FPV compared to GPV [32]. Thus, improved thermal performance is not an inherent advantage of all FPV installations; it depends critically on system design and local climate conditions.

The temperature of a PV module in the field depends on numerous factors, including irradiance, ambient and sky temperature, circulation and humidity of the surrounding medium, mounting structure, and materials. To (try to) differentiate the impact of all these local climatic conditions from the impact of the technical installation itself, it is convenient to use so-called heat loss coefficients, or U-values. These coefficients measure a system's capacity to exchange heat with the environment. Higher U-values indicate better heat exchange and thus leading to cooling and, therefore, lower operating temperatures.

Forced convection increases heat transfer between the module and ambient medium compared to free convection, both because a greater temperature difference is maintained and because the heat transfer coefficient increase with turbulence. Hence, wind will have a significant effect on the cooling and therefore an explicit dependence on wind is often introduced by splitting the U-value into a constant term U_c and a windspeed (WS) dependent term U_v: $U = U_c + U_v WS$. In a meteorological context, and hence in most databases that include wind measurements, wind velocity is provided at 10 m above land, in a free environment. These will not be representative values for the wind experienced by a PV system, and it is therefore common to neglect wind effects in EYA of PV. U-values reported as a single constant is also default in PVsyst. However, reporting a single U-value inhibits the possibility of finding the explicit dependency of wind. Single U-values are therefore less useful to describe the thermal properties of a specific design than U-values with an explicit term for the wind dependency.

Although U-values are convenient, both when modelling energy yield and comparing the thermal properties of different technologies and PV mounting solutions, they also introduce a wide range of potential pitfalls. The most serious pitfall, perhaps, is that while U-values are often perceived to describe a property of the (F)PV system, there is still a significant dependency on several environmental parameters that are not accounted for in the equations.

In addition, a U-value is not uniquely defined. To understand why one U-value may not be directly comparable to another, and why the equations describing module temperature as a function of U-values take different forms, it is illustrative to look at how the most common models are derived.

The U-value – how it is derived and why it is not uniquely defined

The commonly used models to estimate PV module temperatures are based on a steady-state thermal balance:

$$q_{sun} - q_{elec} - q_{rad} - q_{conv} - q_{cond} = 0 \quad (1)$$

where q_{sun} is the energy flux from the sun, q_{elec} is the energy flux extracted as electrical power, and the remaining three terms are the heat losses by radiation, convection and conduction (all in W/m^2). Often, both the radiative and conductive heat loss are assumed to be negligible, and the convective heat loss is a function of the difference in temperature (*T*) between the module (m) and its surroundings (a, ambient), hence

$$q_{sun} - q_{elec} - U_{conv}(T_m - T_a) = 0 \quad (2)$$

Rearranging to calculate the module temperature T_m Eq. (2) becomes

$$T_m = T_a + \frac{q_{sun} - q_{elec}}{U_{conv}} \quad (3)$$

The U-values in the literature referenced in this section are derived with models based on Eq. (3). Another simplification that is often implemented, is that the electrical output power scales with the energy flux from the sun. The simplest way to express the scaling would be

$$q_{elec} = q_{sun}\,\eta, \quad (4)$$

where η is the module efficiency. Note that inaccuracies are introduced with this scaling, because the module efficiency is temperature dependent and because q_{sun} is defined as the energy flux *entering* the module, while the module efficiency is normally defined as a fraction of the *incoming* irradiance, including light reflected from the surface of the module.

It is convenient to use variables that are commonly measured in the field or that are known from module data sheets. In PVsyst, q_{sun} is expressed as $G_{POA}\alpha$, i.e. the incoming radiation G_{POA}, multiplied by the absorption coefficient, α (defined as $1 - r$, where r is reflection). q_{elec} can then be expressed as

$$q_{elec} = q_{sun}\,\eta = G_{POA}\alpha\eta \quad (5)$$

Inserting this expression for q_{elec} and q_{sun} in Eq. (3) we get

$$T_m = T_a + \frac{G_{POA}\alpha(1 - \eta)}{U_{conv}} \quad (6)$$

This equation, with the choice of using either a single U value or the $U_c + U_v WS$ term, is used in PVsyst. Note that in the PVsyst manual the cell temperature, T_c, is used in this equation, while in the Faiman model [33], and in IEC 61853-2 [34], module temperature T_m is used.

An alternative to expressing q_{elec} as a function of q_{sun} is to express both q_{sun} and q_{elec} as functions of G_{POA}

$$q_{sun} = G_{POA}\,\alpha \quad (7)$$
$$q_{elec} = G_{POA}\,\eta \quad (8)$$

Inserted in Eq. (3) this gives

$$T_m = T_a + \frac{G_{POA}\alpha - G_{POA}\eta}{U_{conv}} = T_a + \frac{G_{POA}(\alpha - \eta)}{U_{conv}} \quad (9)$$

In this version of the equation the use of the module efficiency is in accordance with the standards for measuring module efficiencies (i.e. reflection is included).

There are also other ways of expressing q_{sun} and q_{elec} which lead to small variations in the equations used (such as in Liu et al. [35], where q_{sun} is expressed as $q_{sun} = \alpha\tau G_{POA}$, where τ is the transmittance of the glass and α is the absorption of the PV layer). These nuances in the equations will generally lead to negligible differences in the resulting temperature or U-values. However, it must be noted that U-values derived using Faiman or IEC 61853-2 will not be directly comparable to U-values derived using Eq. (6) and Eq. (9). In Faiman/IEC 61853-2 nomenclature,

$$T_m = T_a + \frac{G_{POA}}{\frac{U_0}{\eta_O - \eta_e} + \frac{U_1}{\eta_O - \eta_e} WS} = T_a + \frac{G_{POA}}{U'_0 + U'_1 WS} \qquad (10)$$

the optical losses and electrical efficiency of the module are integrated in the U-values. This is easily overlooked. None of the U-values cited in Table 1 have the module efficiency term included in the U-values.

Finally, there are also models that include the radiative term in Eq. (1). This could be of relevance to improving the accuracy of the temperature models in general, and of particular relevance if night-time temperature effects are of interest, e.g. for degradation models. Driesse et al. [36] have suggested how the equations above can be altered to include a radiative term.

Eq. 6, 9, or 10 can be used to derive U-values based on field measurements and module parameters.

Air-cooled FPV systems

Most FPV systems installed so far can be called Air-cooled FPV systems, meaning designs where the modules are not in direct contact with water and their only ambient medium is air. In this configuration the thermal behaviour of the FPV system is influenced by the same parameters as a GPV system: irradiance, air temperature, wind speed, humidity, and mounting design. Such FPV systems are predominantly cooled by air. The water temperature does not have a direct effect on the operating temperature of the module, but can influence the ambient air temperature, and hence indirectly the operating temperature of the module. The mounting structure and the local wind conditions are therefore the most critical parameters to determine the cooling efficiency of air-cooled FPV systems.

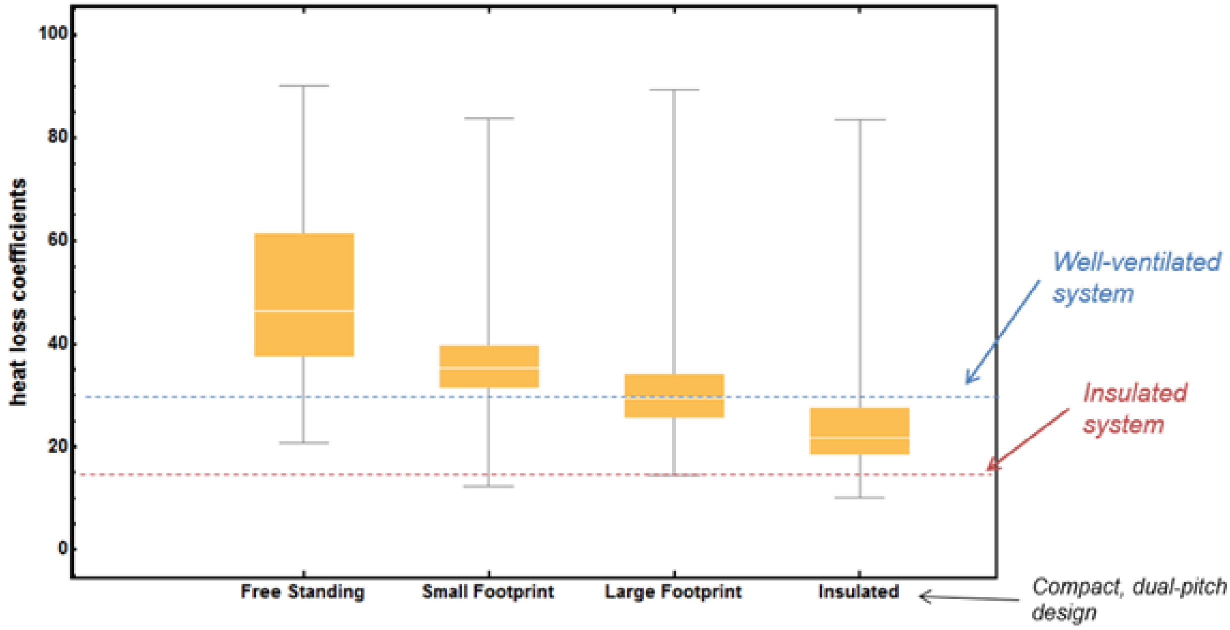

Figure 8. Heat loss coefficients (U-values) based on the different PV structures. Source: Liu et al. 2018 [35]

As illustrated in Figure 8, mounting structures that obstruct the rear surface of the modules (i.e. they have a “large footprint” on the water surface) will also usually lead to less efficient cooling by the wind and greater operating temperatures than mounting structures that are more open (i.e. they have a “small footprint” on the water surface). In large footprint configurations, the operating temperatures of FPV may exceed those of well-ventilated GPV installations [29], [32], [37]. Liu et al. published one of the first papers quantifying U-values for systems categorized as free-standing, small-footprint, and large-footprint [37].

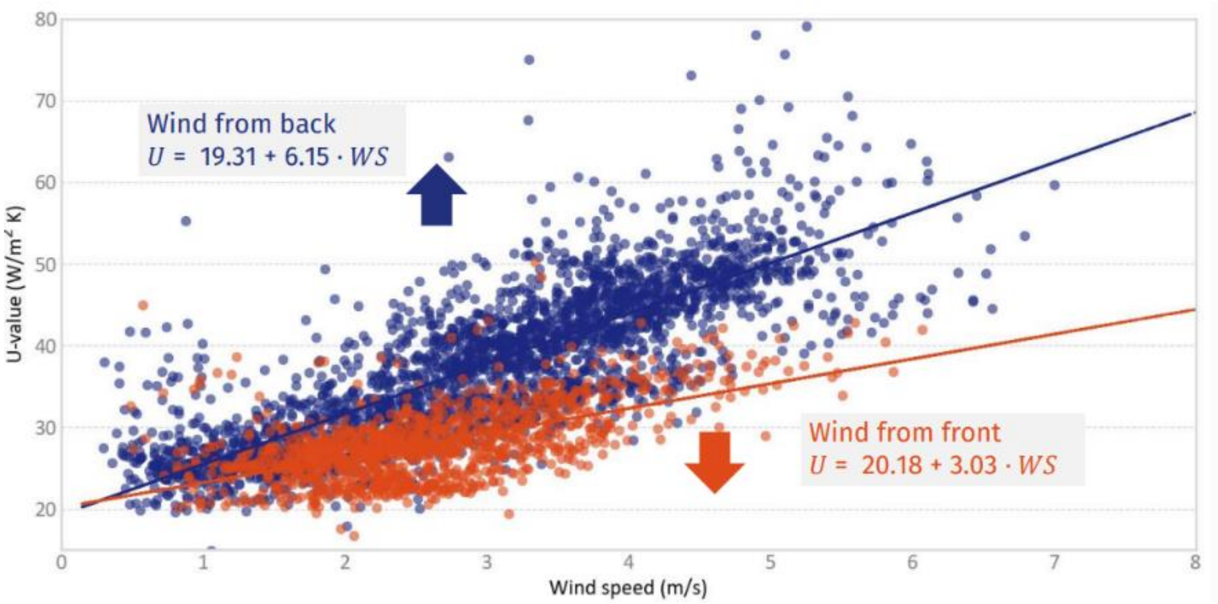

Figure 9. The wind direction impacts the best fit U-value. The graph is based on measurements performed on a Ciel & Terre FPV system in Marlenique, South Africa [38]. Given the same wind velocity, it is evident that the FPV modules are more efficiently cooled by wind coming from the rear than from the front.

Local wind conditions are affected by topography, vegetation, and infrastructure. Generally, the wind speed will increase over open areas, such as water bodies. The size of the water body, vegetation/buildings on the shore, and the placement of the FPV system on the water body, will influence the wind conditions experienced by the system. The wind direction may also be of importance for the operating temperature of the PV modules. Figure 9 illustrates how wind direction impacts the U-value (and hence operating temperature) of a Ciel & Terre system deployed in Marlenique, South Africa. In this system, the wind cools the modules more efficiently when coming in from the rear side of the modules (which are all oriented in the same direction) [38].

Water-cooled FPV systems

FPV designs where the modules can be mounted horizontally, directly in contact with the water surface, also exists. We will denote these systems as water-cooled. In this configuration, the modules can benefit from the higher heat transfer coefficient of water compared to air and of the more limited thermal cycles water basins experience. In this configuration, the water temperature becomes the dominant parameter affecting the cell temperature. Water-cooled FPV systems are likely to achieve lower operating temperatures, compared to air-cooled installations. The circulation of the ambient water significantly influences the operating temperature of such FPV systems, with increasing water velocities leading to more efficient heat transport, equivalent to the effect of wind velocity.

Pure-floats

An FPV module mounted on a pure-float structure will be cooled by the ambient air and wind, fundamentally like a module mounted on a GPV system. The most important feature of the pure-float with respect to thermal losses, is therefore to what extent it exposes the PV module to wind. Even within the individual categories introduced by SERIS, there will be substantial differences in the thermal properties of the individual floating structures.

Even though FPV systems consisting of a version of pure-float technology is dominating on the world market, remarkably, only a few publications with quantitative assessment of U-values from such systems exist. In the categorization by Liu et al. the pure-float belongs to the large footprint tag and has a reported U-value of around 30 W/m^{2}K [37], similar to a well-ventilated rooftop system. The pure-float systems in reference [37] is the Hydrelio® Classic FPV technology from Ciel & Terre. Another analysis performed on unspecified large footprint systems in the Netherlands and in Singapore reports median U-values of 37 W/m^{2}K and 36 W/m^{2}K respectively [29]. The wind-dependent U-values of the same systems are $U = 24.4 + 6.5WS$ and $U = 34.8 + 0.8\ WS$. From a Ciel & Terre pure-float system in Marlenique in South Africa, U-values of $U = 19.3 + 6.2\ WS$ and $U = 20.2 + 3.0\ WS$ are reported [38], depending on the prevailing wind direction.

Note that the floats in the pure-float category have been continuously developed. The footprint of the floats has decreased and the accessibility of wind underneath the mounted module has increased with development of the pontoons, as exemplified in Figure 6. No absolute criterions for the footprint classification have been published, but it may well be that the most recent pure-float models no longer fit in the large footprint classification. In much of the scientific literature available today, only the type/category the FPV system belongs to is provided, while the specific technology and producer is not detailed. With respect to accessibility and transparency of information it would be beneficial to report the specific FPV technologies tested, rather than only the type/classification.

Metal or FRP structures + floats/pipes

As with the pure-floats, the metal/FRP structure mounted on floats or pipes will be cooled by the ambient air and wind. This type of structure will usually allow more air to flow beneath the PV modules and will often be categorized as a medium footprint structure. In [29] data from this type of structure is fitted to provide a median (single) U-value of 41 W/m^{2}K, or, with the wind term included, $\mathrm{U} = 18.9 + 8.9\ WS$. The single U-value is 5 W/m^{2}K greater than the median U-value of the large footprint system in the same study (see Table 1). However, comparing the U-values with explicit wind terms, the wind dependent term is significantly greater for the Metal/FRP structure, implying that a greater differences in the operating temperature of these two technologies will be expected at windy sites.

ZIM Float, the FPV technology with the highest installed capacity in Europe, is Category 2, but there are also several other technologies in this category. There is ongoing work to publish performance analysis of FPV power plants with ZIM Float technology, but the only work currently published with a confirmed Category 2 FPV technology is [29] (O. Gandhi, SERIS, personal communication, August 6, 2024).

Membrane FPV technology

When PV modules are installed on a thin membrane directly floating on the water surface, it alters the dominating heat dissipation mechanism. While PV modules mounted on pontoons will be predominantly cooled by air convection, PV modules mounted in thermal contact with a thin membrane will predominantly release heat through the membrane. The membrane in turn is cooled by water convection. The circulation of water underneath the membrane is therefore important for efficient cooling of the membrane and modules.

For water bodies with significant circulation, a simplified Computational Fluid Dynamics (CFD) calculation suggests that almost all heat absorbed by the PV module is conducted down into the water [39]. Measurements performed at a pilot site in Skaftå, Norway, show that U-values are in the range of 70-80 W/m^{2}K for this technology [31]. The modules in this technology effectively have air as ambient medium on their front side and water as ambient medium on their rear side (assuming that the membrane is thin). Hence, the model for heat dissipation should not use only air as ambient. Currently, only air is available as ambient medium in the commercial modelling tools. It is recommended to include water temperature data to accurately calculate module operating temperatures or U-values for FPV technologies where the PV modules are in contact with water. Figure 10 shows an installation with Ocean Sun technology at the Magat dam in the Philippines.

Figure 10. Ocean Sun FPV system in Magat in the Philippines. Copyright: Ocean Sun

Table 1: Summary of U-values reported in literature.

Cooling mechanism	Configuration	Location	U W/m²K	$U_c + U_v WS$ W/m²K	Ref
Air-cooled	Free standing GPV array	Default, PVsyst	29	29.0 + 0 WS	[40]
Air-cooled	Free standing GPV array	PVUSA		25.0 + 1.2 WS	[40]
Air-cooled	Hydrelio Classic, Ciel & Terre	Tengeh Reservoir, in Singapore, near the sea	~ 30	NA	[37]
Air-cooled	Tracked, small footprint and open structure	Inland lake (NL), near the sea	57	24.4 + 6.5 WS	[29]
Air-cooled	17◦-tilted, East-West oriented, large footprint and closed structure	Inland lake (NL), near the sea	37	25.2 + 3.7 WS	[29]
Air-cooled	7◦-tilted east, Large footprint and close structure, SG	Tengeh Reservoir, in Singapore, near the sea	36	34.8 + 0.8 WS	[29]
Air-cooled	12◦-tilted east, medium footprint and close structure, SG	Tengeh Reservoir, in Singapore, near the sea	41	18.9 + 8.9 WS	[29]
Air-cooled	10◦-tilted east, free standing and open structure, SG	Tengeh Reservoir, in Singapore, near the sea	55	35.3 + 8.9 WS	[29]
Air-cooled	Horizontal module, 3.2-cm off a floating membrane	Fjord's Inner branch on (NO) west coast	46	NA	[31]
Air-cooled	SolarisFloat azimuthal tracking FPV system	Lake Oostvoorne (NL)	39.5	24.7 + 3.9 WS	[30]
Air-cooled	Current Solar 15°-tilted modules mounted on high-density PE pipes	Small pond, Kilinochchi, Sri Lanka	33.2	25.7 + 2.8 WS	[30]
Air-cooled	15°-tilted modules mounted with Ciel & Terre FPV system	Small pond, Marlenique (SA)	NA	20.2 + 3.0 WS	[38]
Air-cooled	15°-tilted modules mounted with Ciel & Terre FPV system	Small pond, Marlenique (SA)	NA	19.3 + 6.2 WS	[38]
Water-cooled	Horizontal module on a floating membrane	Fjord's Inner branch on Norwegian west coast	71[1]	NA	[31]

[1] As the cooling mechanism infers, this U-value has been calculated using water temperature, and not air temperature, as ambient medium temperature.

2.3.2 Wave-induced losses

FPV systems are floating structures that move with wind and waves, causing fluctuations in the effective tilt angle and orientation of the PV modules. This movement affects the incident irradiance on the modules and gives rise to wave-induced losses (WIL). The WIL of an FPV system encompass an irradiance loss (or gain) due to a difference in average tilt of all the modules compared to a static system with the same tilt, and a mismatch loss due to different irradiance conditions on the individual modules.

Currently, only a limited number of studies have been published on this topic, and terminology is still evolving. Dörenkämper et al. introduced the term "wave-induced mismatch loss" (WIML), defining it as the difference in power output between a system with fixed tilt and one with tilt that varies due to wave motions [41]. In this definition, WIML consists of two components: one due to different irradiance conditions on the individual modules (mismatch loss), and one due to a difference in average tilt of all the modules (irradiance loss or gain). Chen et al. [42] use the terms mismatch induced loss and insolation induced loss to address the two components separately.

For practical purposes, modelling software like PVsyst may treat WIL as a combined "effective" mismatch value. However, to fully understand WIL, it is helpful to address the mismatch and irradiance components separately and use the term "wave-induced losses" (WIL) to encompass both.

All PV systems are affected by mismatch losses. Mismatch losses within a string of series connected PV modules are caused either by differences in the experienced conditions or in the rated power of the individual modules. The output of the string will be limited by the module with the lowest current. A wave-induced mismatch loss will come in addition to the mismatch loss induced by differences in rated power (or degradation).

The WIL depends significantly on a large set of parameters, including both environmental parameters and the FPV structure itself. Currently, measured values for WIL are not accessible. Modelling of WIL requires three basic modelling steps: 1) modelling of the interaction between the FPV structure and waves, 2) modelling of the irradiance on the array, and 3) modelling the electrical response to the irradiance. Results from modelling approaches are scarce and only validated to a limited extent, and complete validation requires high resolution measurements of (at least) sea state/waves, module/float movement, design plane-of-array (POA), and irradiance at module-level. There are, however, modelling efforts published that provide insight to the sensitivity of WIL to different parameters.

In DNVs recommended practice [13] the current recommendation is to use one of three methods to estimate WIL: wave tank measurements, numerical analysis or engineering judgement. It may not be feasible to model WIL in detail for each new FPV project, but with increasing number of publications and experience, the engineering judgements will become more precise. Providing generic values for WIL is not possible due to the significant technology dependence. However, a table with WIL values for the most established FPV technologies for different sea states would be useful, but this information is not currently available.

Impact of FPV technology on WIL

Different aspects of FPV technology will be decisive for various loss mechanisms.

- *Number of modules per float*. Intuitively, the number of modules per float impacts WIL significantly. When all modules that are connected to the same maximum power point tracker (MPPT) are situated on the same rigid float, they all have the same orientation and do not experience wave-induced *mismatch* losses. Note that the system can still experience changes in the effective tilt, and hence irradiance and production, due to waves. Systems with one or a few modules per float experience different orientations due to wave motion, leading to increased mismatch losses (if connected to the same MPPT).

- *The extent to which floats follow wave movement* also affects WIL. Designs like membrane-based systems, which move freely with waves, are expected to experience higher mismatch losses. Pure-float systems are somewhat more resistant to wave influence (depending on how they are connected), while semi-closed structures or systems using rigid materials (metal or FRP with floats/pipes) show lower mismatch due to a more rigid structure.
- *The electrical configuration and the length of the PV string* has also been shown to affect the mismatch loss. For commercial size FPV systems with more than 20 PV modules in a string, the mismatch loss will saturate [41], [43]. It can be understood by looking at the probability of (at least) one module positioned in the "worst" possible angle towards the sun.

Impact of environmental parameters on WIL

The severity of WIL also depends heavily on environmental parameters such as the sea state and the irradiance angle of incidence [13], [41]. There is currently no published literature with measured values for WIL. A few papers publish modeled values of WIL [41], [42], [43] that explore the effects of the sea state (wave period, wave height, wave direction), latitude and time of year on the resulting WIL.

The impact of the sea state and latitude is summarized below.

- *Sea state.* The combination of wave height and wave period is important for the magnitude of the WIL [41], [42], [43]. *Steep waves* will induce larger differences in tilt between the modules and hence larger mismatch losses. The shorter the wave period for a specific wave height, the higher the power loss of the system influenced by waves compared with the static system. In addition, increasing *wave height* will also lead to greater WIL. An important conclusion from this is that the effect of WIL on FPV systems deployed at lakes, dams and reservoirs with calm water is small or moderate even for the most affected, one-module-per-float or membrane systems.
- *Latitude and seasonal dependence*. Reflection increases nonlinearly with angle of incidence. Therefore, larger angles of incidence infer both a greater irradiance loss *and* greater differences between the irradiance absorbed by modules (at a given absolute difference in tilt). FPV designs with non-optimal tilt for a given latitude will therefore experience higher WIL (everything else being equal). For the typical, relatively horizontal FPV system, this implies that WIL is greater at higher latitudes, and that it has a seasonal dependence, with the highest relative yield losses when the tilt angle is least optimal (i.e. winter for Europe) [41], [43].

The simplest approach to model the sensitivity of different parameters (environmental and technology specific) on WIL is to assume that the floats are "slave-to-the-waves", i.e. that the floats do not dampen the waves, and that each individual float is not constrained in its movements. In Figure 11 and Figure 12, this approach has been taken to model the sensitivity of a one-module-per-float technology, based on Nysted et al. [43].

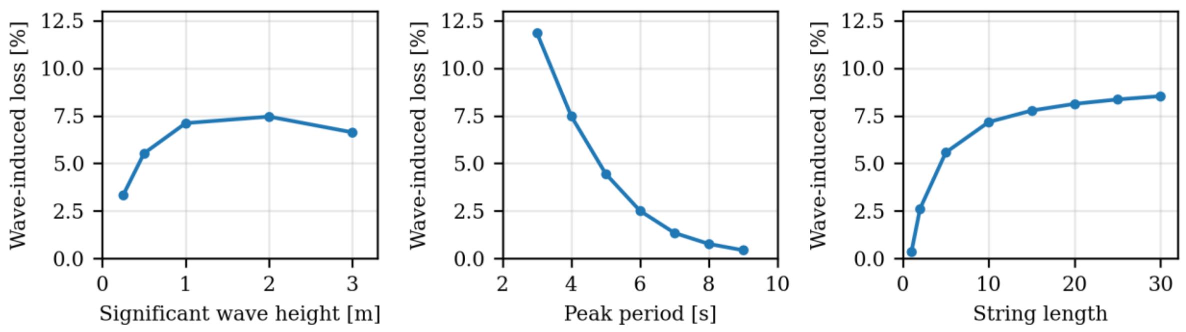

Figure 11. Modelling of the sensitivity of WIL for a) significant wave height, b) peak period and c) string length for a one-module-per-float type technology, based on **[43]**.

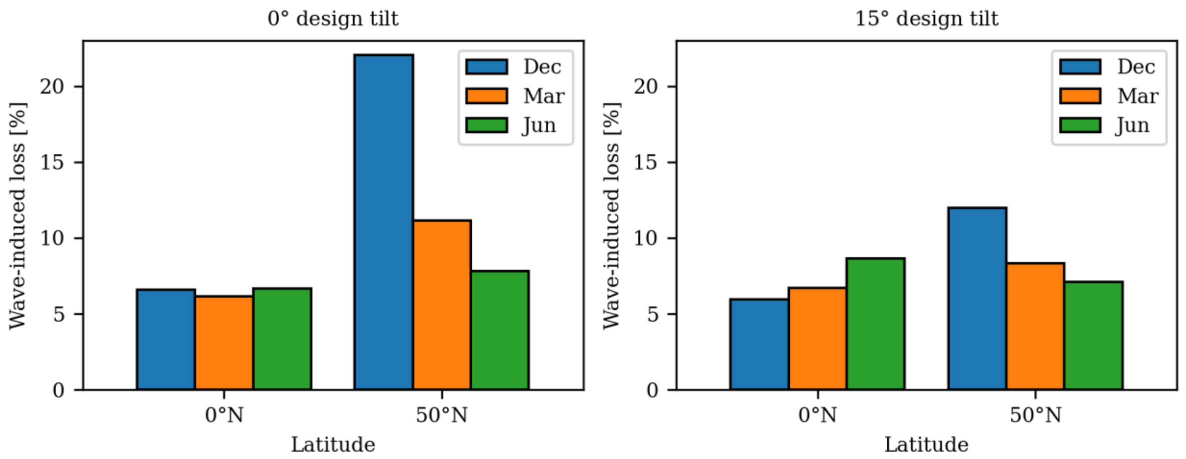

Figure 12. Modelling of WIL for different times of year for two latitudes, 0°N and 50° N for a system with a design tilt of a) 0° and b) 15°, based on the modelling method in **[43]**.

Pure-floats

With respect to WIL, the most important adaptation to account for different FPV technologies will be in the wave-float interaction. The mismatch model published by Dörenkämper et al. [41] represents a floating structure that resembles the pure-floats. The tilt angle is 12°, and the float is according to the paper "in-line with commercial products of single floats on the market today". Two different movement models were used, the first assumes that the PV modules perfectly follow the waves and that the floats do not dampen the waves. These are the same basic assumptions as in the paper by Nysted et al. [43]. The other movement model is a mechanical simulation of movements of interconnected floats on the water surface. The model accounts for gravity, buoyancy, wave forces, interconnection forces and inertia. A comparison of both models confirms the expectation that with the mechanical simulation, the movements are dampened compared to the wave-following model, and therefore the calculated wave-induced losses are lower.

Metal or FRP structures + floats/pipes

There is currently no published literature reporting on modeled or measured WIL for a metal/FRP type of structure. For this type of structure, the PV modules mounted on the same rigid float will have the same orientation, reducing or eliminating *mismatch* losses between the modules on the same float. The changes in irradiance compared to a fixed-tilt system will also likely be reduced (which may be a loss or a gain). In sum, it is expected that FPV systems with rigid materials (metal or FRP with floats/pipes) will be less affected by WIL than pure-floats given the same sea state.

Membrane FPV technology

As previously mentioned, in the membrane FPV technology the PV modules are expected to follow the local wave motion, with only limited damping. Therefore, although the impact of the membrane size and the fasting mechanism of the modules are not known, it can be argued that the slave-to-the-waves approach is a good starting point to model WIL for this FPV Category. Nysted et al. [43] use linear irregular waves and a response model where the PV modules are assumed to follow the local wave motions exactly and not dampen the energy of the incoming waves. Using these assumptions, in addition to the more general modelling steps for mismatch described in section 2.3.2, the dependency of WIL on a combination of significant wave height and peak period is shown in Figure 11.

In this section, Figure 11 is used to illustrate general trends for the sensitivity of WIL to different parameters. The values can also be interpreted as a worst-case scenario for WIL for membrane FPV technology, and one-module-per-float technologies.

2.3.3 Soiling losses

Although FPV has the potential to provide numerous advantages, it can also lead to new challenges, such as potentially more severe soiling losses. These losses are produced by particles or objects that accumulate on top of the solar panel, which block the irradiance reaching the solar cells, and thus reducing their power output. Furthermore, if the soiling is concentrated in a particular area of the solar panel, e.g. soiling due to bird droppings, this can produce hotspots, as seen in Figure 13, which can accelerate the panel degradation and result in higher O&M costs. Pre-construction bird surveys may help to identify such possible issue during the project development phase.

To reduce the soiling losses, studies have shown that a higher panel tilt is advantageous [44]. FPV systems, however, are typically kept with a tilt below 20°, regardless of the geographical location. This typically low tilt is a trade-off between optimizing POA irradiance and keeping capital expenditure (CAPEX) low and power density high. CAPEX will increase with increasing tilt due to increased requirements for the float, mooring and anchoring system, while the power density will reduce due to interrow shading. In addition, numerous FPV systems are installed at locations surrounded by diverse fauna and as a result, bird droppings can become a challenge due to local (nesting) and migratory birds. Potential solutions to tackle this challenge are bird deterrents such as shiny reflective surfaces, ultrasound devices, lasers and scare techniques like water sprayers, scarecrows and fake falcons. However, the use of bird deterrents should be evaluated with respect to sustainability, and the use of such systems may be regulated.

On the other hand, as these systems are not installed on land, they are expected to experience lower soiling from dust in comparison to GPV systems. Moreover, the water required to clean them is directly available (although it needs to be assured that clean fresh water is used). In addition, there may be more water reaching the solar panel’s surface, e.g. via waves and wind influence, thus potentially reducing soiling losses.

If the soiling effect is considerable for a particular project, manual or automatic cleaning using robots might have to be done periodically. Nevertheless, as these systems are surrounded by water, cleaning can be challenging and thus, the FPV system needs to be properly designed to allow for these O&M tasks to take place in an adequate way.

Too little open information is currently available to establish a span of expected soiling rates for various FPV technologies in different climates. Expected FPV soiling losses of 1-3% has been reported by [7], while it is also noted that this depend on the site and cleaning schedule. Scientific reports on soiling rates for FPV systems would be of importance to improve accuracy of EYAs.

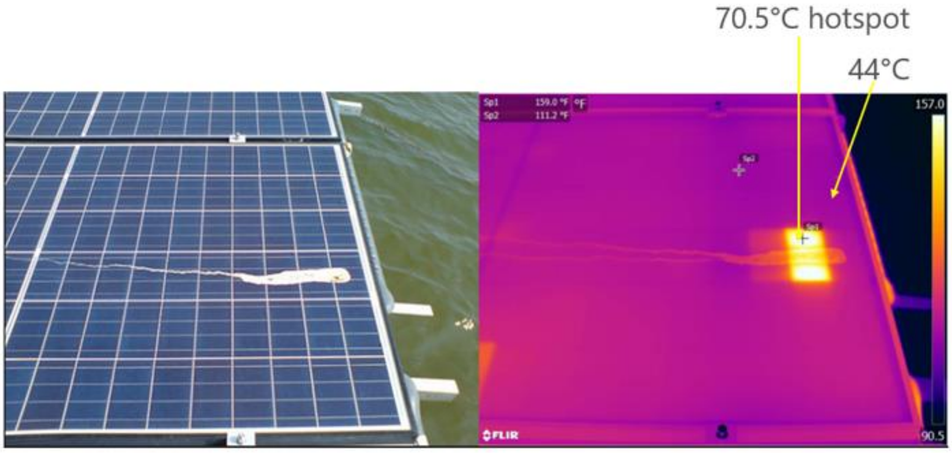

Figure 13: Higher local temperature due to hotspot induced by bird dropping.

2.4 Modelling yield for FPV systems

There is a range of tools capable of modelling, with different degrees of accuracy, the energy yield for GPV. The list includes, but is not limited to, PVsyst, SAM, PV*Sol, Homer, PVGIS, PVWatts, PVCase, and pvlib. To our knowledge, none of these modelling tools have implemented features to deal specifically with the loss factors of FPV. One could also imagine that other FPV related features such as modelling of evaporation or irradiance reaching the water surface could be included in the same modelling tool. This, however, is not within the scope of this report to discuss. In the following section, we will focus on the modelling capabilities and shortcomings of two important modelling tools, pvlib and PVsyst, with respect to FPV losses and yield. pvlib and PVsyst are chosen because they are widely used for research and development of PV projects.

Modelling the performance of any PV system follows certain predefined steps regardless of what software is used. These steps include calculation of: POA irradiance, effective irradiance, module (and cell) temperature, array IV curve (or P_{mp}), and inverter efficiency. For an FPV system, some of these steps need to be adjusted to account for system and site-specific conditions. For example, FPV arrays are not fixed and can move as waves pass through the array, therefore, calculation of POA irradiance needs to account for a moving array and may require wave conditions as input. Another example is module and cell temperature modelling. As discussed in Section 2.3.1, FPV systems are affected by irradiance, air temperature and wind speed, as are terrestrial systems. However, the effects of water temperature, relative humidity and direct splashing of water onto the modules may also need to be considered.Furthermore, FPV systems where the modules are mounted on a membrane that floats directly on the water will have a much different thermal signature than modules suspended over the water surface.

2.4.1 FPV modelling in PVsyst

The solar industry's most widely used software simulation tool for assessment of a PV system's bankability is PVsyst. This is in part due to the actual modelling capabilities, interface and databases of PVsyst, and in part due to the relatively long trustworthy history of the software.

Temperature modelling in PVsyst

Numerous models have been proposed for simulation of the module temperature. In PVsyst, module temperature is estimated using the Faiman model (Eq. (11)) [33].

$$T_c = T_a + \frac{G_{POA} \cdot \alpha \cdot (1-\eta)}{U_c + U_v \cdot ws} \tag{11}$$

where T_a is the ambient temperature, G_{POA} is the plane-of-array irradiance, α is the absorption coefficient, η is the electrical efficiency of the module and WS is the wind speed. U_c and U_v are the constant and convective heat transfer components, with unit W/(m^{2}K) and W/(m^{2}Km/s), respectively. Often, a simplified version of the equation with a lumped heat loss factor, $U,$ is used: $U = U_c + U_v ws$. Note that IEC 61853-2 [34] also recommends the Faiman model for yield assessment.

PVsyst recommends U-values of $U_c = 29$ W/(m^{2}K), $U_v = 0$ W/(m^{2}Km/s) for free standing (open-rack) systems. For modules with a fully insulated back side, PVsyst recommends a value of $U_c = 15$ W/(m^{2}K), $U_v = 0$ W/(m^{2}Km/s) with the argument that only the front side contributes to the convective heat exchange. The default value proposed by PVsyst for new projects lies between these two, $U_c = 20$ W/(m^{2}K), $U_v = 0$ W/(m^{2}Km/s), which is considered representative for typical rooftop systems. For utility scale PV plants, single U-values are also commonly used as input, and wind data is not taken into account.

Fundamentally, the Faiman equation will be adequate to model temperatures of FPV systems when the main heat exchange mechanism is convective heat transfer to the ambient air, as it is for GPV. For membrane floats (Category 3 in Figure 5) given that they are in thermal contact with the membrane (negligible air gaps), and other FPV technologies where the PV panels are in contact with water, the modelling of heat transfer should consider that the ambient on the rear side of the module effectively is water. This results in a new expression for the heat balance, and hence an altered equation to calculate cell temperature [31], [39]. PVsyst does not provide the possibility to change the model for the cell temperature calculations, and hence cannot accurately model the temperature of this type of FPV technology. If PVsyst, or similar, is used for EYA of this type of FPV, it is shown that using water temperature as the ambient temperature will improve the module temperature model [31].

Mismatch modelling in PVsyst

In PVsyst, mismatch is treated as a constant loss factor, valid for the whole simulation. Hence, it is not a detailed model of the mismatch under the simulated conditions, simply an estimate of the total effect of non-identical module and string parameters. The value will usually be dominated by the dispersion of the module efficiencies (power class for new modules, power class + degradation for older modules). According to PVsyst, the mismatch value for GPV systems is usually set to 2%. The origin of the mismatch for FPV is discussed in Section 2.3.2. As there is no actual modelling of mismatch performed in PVsyst, such modelling must be performed outside of PVsyst, and the aggregated result must subsequently be input to the PVsyst model.

2.4.2 FPV modelling in pvlib

pvlib python is a community-developed open source toolbox for simulating the performance of PV systems [45]. The python library contains more than 100 PV performance modelling functions, which aligns with the core mission of providing open, reliable, and reference implementations of PV system models. The functions cover all the modelling steps for estimating energy yield. The current version of pvlib (v0.11.2) does not feature major FPV-specific capabilities, however, due to pvlib's flexible design, it is possible to account for many of the modelling aspects specific to FPV.

Temperature modelling in pvlib

pvlib python supports several PV temperature models developed for GPV, including Fuentes, SAPM, NOCT SAM, Faiman, PVsyst, Ross, and a generic linear heat loss factor model. As reported in Section 2.3.1, most FPV systems are predominantly air-cooled with a thermal behaviour similar to GPV systems. For such systems, the existing models in pvlib are straightforward to use for modelling PV module and cell temperature. Similar to PVsyst, it is possible to use water temperature instead of air temperature as the heat sink temperature used by the aforementioned temperature models. In any case, appropriate heat loss coefficients should be used, as discussed in Section 2.3.1. The pvlib documentation contains an example of how to calculate FPV module temperature.

Mismatch modelling in pvlib

Although constant loss factors are easily applied in pvlib as well, pvlib also offers functionality needed for modelling electrical mismatch in full fidelity. This is made possible by two main capabilities: no limitation on the maximum number of module orientations, and no fixed or minimum simulation time interval. This is particularly beneficial for FPV systems, as variation in module orientation caused by waves occurs on a short time scale on the order of seconds [43]. Given module orientation values from an external wave model, pvlib can simulate the incident irradiance and temperature of each module individually. These module-specific operating conditions can then be passed into pvlib's electrical functions (e.g. the CEC and PVsyst single-diode models) to simulate I-V curves for each module.

The user can then process these I-V curves using general-purpose numerical python packages to combine the module-level I-V curves into string- and array-level curves, allowing calculation of the wave-induced electrical mismatch loss. Alternatively, streamlined simulation of array-level I-V curves is possible using SunPower's Python package PVMismatch [46]. The string- or array-level curves can then be passed into any of pvlib's existing inverter models. Note that some of pvlib's inverter models are capable of accounting for multiple maximum power point tracking (MPPT) inputs, a required consideration when simulating multi-MPPT inverters connected to mismatched strings.

Possibilities and shortcomings

As with existing commercial PV simulation software, pvlib lacks dedicated capabilities for modelling FPV systems. To achieve more accurate yield simulations, FPV-specific temperature models should be added, particularly temperature models which are capable of accounting for heat transfer to both air and water. Auxiliary functions for determining the inputs to these FPV models, such as module orientation variation due to wave action and wind speed adjustments, may also be added. Information on water albedo was added in the latest release of the software.

In terms of mismatch modelling, it should be noted that PVMismatch is not actively developed/maintained. Additionally, its simulation functionality relies on a particular electrical model for which PV module parameters are not readily available. For these reasons, it is desirable that pvlib's own electrical simulation capabilities be extended to facilitate the process of combining mismatched I-V curves.

2.5 Uncertainty analysis

Uncertainty in annual EYA arises from two main categories of uncertainty: random (aleatory) uncertainty and lack of knowledge (epistemic) uncertainty. On the one hand, random uncertainty is inherent in annual energy estimates, with the inter-annual variability of the solar resource being one of the largest sources of uncertainty in annual energy modelling [47]. The latter is for example quantified in [47] as the coefficient of variation of the annual GHI, and given a range of 2% to 6%. On the other hand, epistemic uncertainty includes uncertainty in all data measurements, modelling parameters, and models that are imperfect representations of the physical system. In theory, this uncertainty, could be reduced through improved data measurement and accurate performance models [48].

Literature mainly considers uncertainty propagation in models of *generic* PV systems [48], [49], [50], [51]. This usually entails identifying the main loss factors in the PV model chain, together with their underlying uncertainty - either through measurement or educated guesses. The first steps are often to distinguish the involved type(s) of uncertainty, the affected model input (parameter or variable) and settle on an uncertainty measure, such as standard deviation. With that at hand, mainly three approaches are commonly pursued, and combined if needed:

i) *Independent input variables*. For simple models, such as linear combinations of input variables or products of *independent* input variables, uncertainty propagation from input to output can be done analytically by calculating variances. Even though there are interdependencies in the PV modelling process, standard literature [48], [50] often represent the annual PV yield as a product of independent loss factors to be able to utilize this relatively simple, analytical model to calculate the output averages and variances [48]. However, it shifts the challenge towards interpreting and determining the uncertainties of the loss factors.

ii) *Small and uncorrelated input uncertainties*. The so-called Gaussian law of error propagation relates the variances of a model's input and output when the model can be represented by an analytical equation. It simplifies uncertainty propagation by assuming small and uncorrelated input uncertainties[2]. Additionally, this approach provides a more accurate calculation of average output values for nonlinear models, where the average output generally differs from the result obtained by merely averaging the inputs.

iii) *Correlated input variables.* One can use Monte-Carlo simulations that stochastically sample input uncertainty to calculate uncertainty in important output variables such as the annual yield. The advantage of this strategy is that it can trace uncertainty propagation along the full PV simulation chain, and in doing so can also account for correlated input variables. This, however, comes at a cost, most notably the need for a lot of sampling of input statistics to obtain reliable output statistics. Also, it is difficult to draw analytic conclusions from computed output statistics.

To address the uncertainty with respect to the selection of competing *component models* in the PV chain (accounting for the variability in predictions of, e.g., the Faiman and Sandia

[2] However, input covariances can easily be incorporated. Note also that, despite the name, Gaussianity of input probability distributions is no prerequisite.

module temperature model), an ensemble of model chains can be utilized, with each ensemble member being a sequence of different component models. This so called “poor man’s ensemble” approach can also mimic epistemic uncertainties by assigning respective standard values to the parameters of each considered component model.

To date, no published efforts are known for quantifying uncertainties in crucial FPV modelling steps such as soiling, fluctuating POA irradiance or mismatch losses. For best results, modelers are advised to combine educated guesses with a critical reading of existing literature on uncertainty propagation.

3 RELIABILITY OF FLOATING PV

The economic viability of PV power plants is fundamentally linked to their lifetime energy yield. Factors such as degradation effects and the overall lifespan of the power plant directly impact electricity production and the levelized cost of energy (LCOE), consequently influencing profitability [45, p. 11]. In Section 3.1, we begin by defining degradation and exploring methods to quantify it.

Conducting an effective reliability analysis is essential for minimizing failures and ensuring a stable power supply [52]. However, while evaluating the reliability of an FPV system, several significant knowledge gaps and challenges arise, which will be addressed in this chapter.

Firstly, climatic and environmental factors play a major role in degradation and are by nature location specific. The stress profiles experienced by components in an FPV installation are neither well understood nor quantified and will vary a lot depending on float technology and water body conditions. An overview of what is currently known regarding climatic stressors for FPV is provided in Section 3.2. The second knowledge gap relates to the scarcity of information on and systematic studies of observed field failures as well as of degradation/performance loss rates and is addressed in Section 3.3.1. And third, as a result of the first two points, there is no accelerated stress testing protocol developed for component reliability evaluation, complicating the process of gaining relevant insight from indoor testing. Existing knowledge and current efforts are summarized in Section 3.3.2. A final source of insight into FPV degradation effects is simulations, which will be discussed in Section 3.3.4. The correlations between the main topics of the Chapter are illustrated in Figure 14.

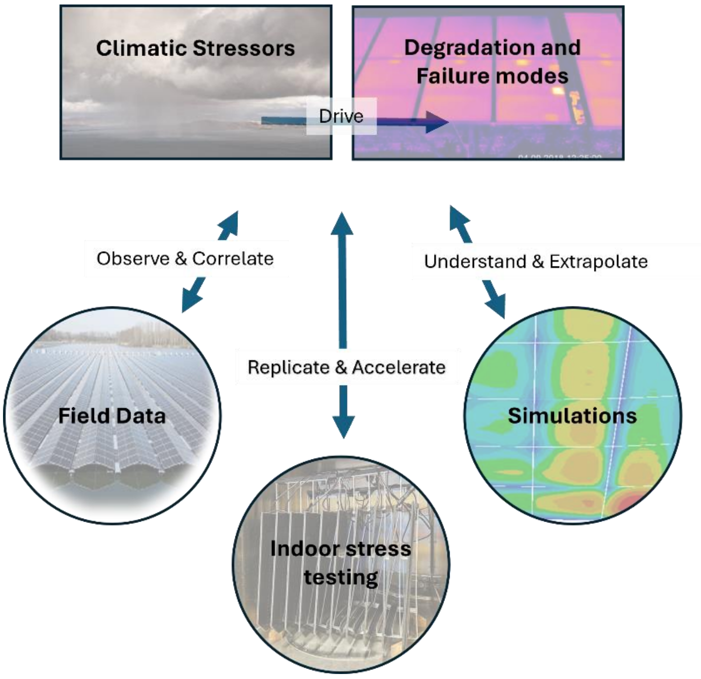

Figure 14. Figure adapted and reprinted under under a CC BY 4.0 license from [53].

3.1 Defining degradation

3.1.1 Definitions

The term *degradation* denotes the gradual process of change in characteristics with operational time of a material, component, and/or system triggered by stress impact. Typically for PV, this aging process causes a decrease in performance, and hence a power loss [54, p. 15]. Degradation is caused by stressors, such as physical, chemical, or mechanical stress acting on a material, component or system. Examples include temperature, irradiation [ultraviolet (UV), visible (VIS), near infrared (NIR)], water/moisture, electrical potential as well as mechanical stresses such as compressive or tensile impact. The sum of the local stressors that a PV module experiences during operation is specific to its design and exact location and surrounding, e.g., stress induced from mounting or variations in temperature and shading. The microclimate can be inhomogeneous even within a PV module (different humidity or cell temperature) [54, pp. 16, 17].

Typically, three different kinds of degradation are distinguished: reversible degradation, irreversible degradation, and failures.

Reversible degradation is either related to accumulated soiling, including the growth of algae and loot, which will not be removed by natural rainfall, but may be removed with dedicated cleaning actions. Other effects of reversible degradation include electric phenomena like polarization (potential induced degradation, PID) or light and elevated temperature induced degradation (LeTiD), from which PV modules may (partly) recover naturally, e.g. during nighttime, or driven by specific electrical devices during nighttime.

Irreversible degradation is mostly related to material ageing both within the solar cell and with the embedding materials. Solar cells may degrade by a variety of diffusion and corrosion processes, which again may be related to changing properties of the embedding materials. Moisture ingress through the back sheet or the edge seal may increase with time, and embedding polymers may change their transparency with time. Mechanical stress may lead to an increasing number of micro-cracks in solar cells which can lead to a reduced power output.

Based on IEC 60050-191 [55], the definition of failure is *the termination of the ability of an item to perform a required function*. For a PV module, this means that the module needs to be replaced. While that is relatively clear from a safety perspective, it is less so from a performance perspective. However, a performance of 80% of the initial value is often used as a threshold for failure. Failures are commonly subdivided into *early life* (1-2 years) failures, often related to poor design or manufacturing errors, failures during the *steady-state life*, often either random or the result of technology limitations, and *wear-out* failures, caused by mechanisms that degrade the performance gradually until the device does not function anymore. Ideally, wear-out failure only occurs after the warranty period expires [56].

Regarding FPV, the balance of system (BOS) components may be even more critical than the PV modules. Junction boxes, cables, connectors, and related protecting materials may suffer from additional stress compared to GPV systems, while additionally, there are FPV-specific BOS components like anchors and floats whose reliability also needs to be considered.

3.1.2 Quantification of degradation

PV module and system degradation may be detected in several ways. Some of them are preventive and should be part of standard O&M procedures (see Chapter 4), others are retrospective and related to the fulfilment of contractual obligations. Standard evaluations rely on yield data and meteorological data only. More advanced assessments look for specific data signatures and are combined with onsite visual and infrared inspections and sometimes even with lab testing of selected components.

As a typical degradation measure, the performance loss rate (PLR) is often used. It is stated in percentage per year and quantifies the temporal decline of a PV system's power output in relation to its irradiation input. Accurate long-term PLR information is vital for predicting electricity output, improving system reliability and anticipating maintenance requirements. On the economic side, PLR has been shown to be one of the most influential factors of LCOE.

Beyond the irreversible physical degradation of PV modules, the PLR also captures performance-reducing events, which may be reversible or even preventable through good operations and maintenance (O&M) practices [57], [58], [59], [60].

3.1.3 Distinction of degradation effects

As mentioned above, observed degradation effects may be divided into component failures, reversible degradation, and irreversible degradation. To evaluate irreversible degradation in a correct manner, most or all reversible effects must be known (and ideally repaired or removed). In the process, also shading losses must be accounted for, which may increase with time when caused by vegetation, decreasing the overall system yield.

As degradation assessments typically deal with long-term observations, i.e. large sets of operational data, methods of automated failure detection may play an important role. These algorithms, often run concurrently, are generally grounded in expert knowledge, assisted by statistical and machine learning methods, validated with field data, and designed to be flexible and adaptable to the characteristics of PV systems and O&M service providers. They can include communication faults, inverter outage and inverter late wake up, check on open-circuit conditions, several relative comparisons between individual strings and inverters, and all kinds of sudden changes in performance indicators [61].

Beside the distinction of "real" degradation from failures or reversible effects, further (algorithm-driven) differentiation between degradation mechanisms is desirable. This, however, needs further research, as "real" degradation is often related with very small changes of performance with time, and as new cell and module technologies may even show - previously unknown degradation modes.

3.2 Driving degradation – describing FPV specific stressors

A PV system will experience a combined effect of multiple stressors over its lifetime in the outdoor environment. Knowledge about these stressors is a precondition for the creation of meaningful predictions of degradation and service life. The stressors include temperature, humidity, UV radiation, wave and wind loads, tidal variations, temperature fluctuations [62], [63], high voltages, corrosive compounds, soiling, abrasive loads, shading, and flora & fauna. The stressors are design- and water body-dependent and, when co-occurring, can attenuate or have amplified effects.

When comparing FPV to conventional GPV, one might intuitively expect some of these stressors (e.g., humidity and mechanical loads) to have more significant differences in stress profiles than others (e.g., UV radiation). For example, the design and placement of a mooring system for FPV platforms must account for water-level variations, soil conditions, bathymetry, and location. In deep water, the construction of a mooring system can consequently present significant challenges and incur substantial costs [64], [65]. For components common to both

GPV and FPV systems, there is however little openly available quantitative information on FPV specific stress profiles. If available, such stress profiles could be compared with available stress profiles from GPV environments, to assess to which extent, e.g., qualification testing and module design considerations originating from the conventional GPV industry are applicable or in need of modification.

Biofouling and soiling

Biofouling is an often discussed problem for FPV installations [66] and can act as a stressor by affecting corrosion processes or inducing weight and stability issues for the floating structure. Biofouling removal will lead to increased O&M costs but can also in itself act as a stressor by increasing wear on various components.

Soiling can block incoming light and thus decrease the performance of PV modules [67]. FPV installations have been seen to attract birdlife [37], and bird droppings impact the short-term performance of FPV systems more than for GPV [68] and lead to hotspots.

Bird droppings is an example of FPV stress profiles having a major dependence on both float technology (e.g., plastic pontoon versus membrane versus metal platforms, see Figure 5) and water body (e.g., of different Sea State Codes as discussed in the Introduction). Different float technologies will also yield significant differences in, e.g., wave-induced mechanical loads or the exposure to water for various components. While stress profiles on calm inland water bodies will likely not be too different from a conventional GPV system, the differences are expected to increase when going to larger water bodies and eventually to near-shore or offshore conditions. In case of high winds and wave forces, the floating structure may experience drifting or deformation, and materials may leach into the water because of damage [69]. Waves can also affect the electrical components of FPV systems, leading to disconnections or damage, which impacts the system’s electrical integrity and performance.

Humidity

A few reports have compared humidity measurements from meteorological stations at FPV systems on inland and nearshore water bodies and found modest differences in average relative humidity; on the order of 0-10 percentage points higher relative humidity for average daily values [37], [70], [71]. However, these results are hard to generalize. Further, relative humidity values aggregated to a daily timescale carry limited relevant information in this context, as the coupling of humidity and temperature is of central importance for moisture ingress and related degradation phenomena. In addition to the sources of mechanical loads present for GPV, FPV has waves as an additional factor, including potential wave-slamming and -breaking. An FPV system typically involves more complex and dynamic structures than a GPV system to provide mechanical support for electrical components, making it essential to assess factors such as fatigue. Some reports exist in the literature examining FPV specific mechanical loads, so far mostly focused on the mechanical integrity of the float system [72], and less on the PV module and other electrical components. Lower module operating temperatures for FPV have been widely discussed in the context of increased module efficiency (Section 2.3.1), but also has the potential to significantly influence reliability. Most degradation processes are thermally activated; thus, a lower operating temperature will dampen the effect of other stressors such as UV and humidity. How significant such an effect might be has so far not been properly studied.

Salt

When deployed in nearshore or offshore waters, the presence of salt will present a significant reliability concern. The level of salt exposure will far exceed levels in most GPV systems, again depending strongly on float design and water body characteristics. This will potentially drive corrosion on various components and pose risks to supporting devices [73]. It can also pose significant stress and enhance problems with PID [74] (see Figure 13).

3.3 Understanding and quantifying degradation – sources of information

Ensuring FPV reliability alongside the rapid growth of cumulative installed capacity and fast technology development and diversification is a major challenge. However, it is a challenge that needs to be resolved to take down real and perceived reliability risks and ensure the bankability of FPV technology. To meet the challenge, it will be of central importance that field failure observations and quantified stress profiles be collected to develop accelerated stress test regimes.

3.3.1 Field data on degradation and failures – overview of observed and potential failures

Learning from observed field degradation and failures has been an indispensable part of reliability development for conventional GPV [75]. For FPV, projects are still relatively young, and public literature on degradation and failure modes specific for an FPV environment is very limited. This holds true both for the structural (floats, connectors, anchors, mooring) and electrical (PV modules, cables, inverters etc.) parts of the system.

Collection of long-term field data is indispensable for accurate identification of failure modes and the design of appropriate testing protocols.

Table 2: Overview of potential failures of FPV systems. compiles a non-comprehensive list of potential failures of the FPV system and single mechanical and/or electronic components that might be caused by (a) the altered stress profiles experienced in FPV compared to GPV and (b) the fact that FPV introduces new components compared to GPV (e.g., anchoring, hinging between floats) resulting in new reliability challenges. Examples of early reliability concerns or failures that have been observed in pilot and/or commercial FPV projects are shown in Figure 15.

Table 2: Overview of potential failures of FPV systems.

Environmental stressors specific, more pronounced, or with more severe impact for FPV	System or component	Potential events and failures
Mechanical movements due to wave and wind actions, ice, water currents and/or water level variations	Mooring, anchoring, float and mechanical support system	Failures in the mechanical integrity of the system and/or the mooring of the system
	Mechanical interconnectors between subsystems	Accelerated materials fatigue, breakage of connectors
	Plastic parts in the system	Rubbing damage
	PV modules	Glass cracking or deformation by wave slamming
		PV cell cracking Interconnect breakage Frame deformation or breakage
	BOS components (inverters, cables, connectors)	Internal electrical disconnect (“electrical open”) induced by continuous movements
		Accelerated wear of cable mantles induced by continuous movements leading to shunts, arcs
Humid and corrosive environment	Steel and aluminium parts in mechanical connectors and mounting systems	Accelerated corrosion
	PV modules	(1) Corrosion of cell metal contacts, (2) delamination, (3) accelerated PID, (4) frame and glass corrosion, (5) Junction box failure
	BOS components (inverters, cables, connectors)	Degradation of insulation material, cable and connector corrosion leading to increased leakage currents, inverter shutdown
Specific forms of pollution and fouling (bird droppings, biofouling, salt and limescale deposition)	Floats, submerged components	Can add extra weight and drag, potentially altering the buoyancy and balance of the system
	PV modules	Hotspot-induced failures (diode failures, local melting, microcracks)
		Increased soiling losses due to organic or inorganic fouling
Exposure to UV radiation	Plastic parts (floats, float connectors, cables)	Embrittlement and cracking, reducing the structural integrity of the plastic parts

a) Rubbing damage on an HDPE part

b) Rubbing and stress damage on an HDPE part

c) Torsion damage on an aluminium part

d) Loss of mechanical integrity due to wave forces

e) Damage on PV modules due to wave slamming

f) Biofouling of underwater component **[76]**

g) Corroded junction box

h) Partly delaminated edge seal **[77]**

Figure 15. Examples of early failures or reliability concerns observed in pilot and commercial FPV systems. For 15a, b, c, d, e, and g, the source of the images is TNO.

3.3.2 Degradation measured through performance loss rates

Data on the accumulated long-term effects of various degradation mechanisms on performance stability is quantified through the PLR, as illustrated in Figure 16

Figure 16. Figure adapted and reprinted under under a CC BY 4.0 license from [53].

Three commonly used statistical methods are deployed to calculate the PLR through historical PV performance and climatic data: Ordinary Least Squares (OLS), seasonal and trend decomposition using locally weighted scatterplot smoothing (STL), as well as Year-on-Year (YoY).

Least squares linear regression (LSLR) is the most popular type of linear regression, and it is based on the minimization of the squared error of residuals. The idea behind Seasonal and Trend Decomposition Procedure Based on Locally Weighted Regression (Loess), commonly referred to as STL, is to decompose the PR or predicted power time-series into a seasonal part, a remainder and a trend using locally weighted, non-parametric regression. The YoY is a method for PLR assessment which, instead of calculating one value for the loss rate, provides a distribution of rates of which the median represents the overall long-term PLR [78]. The distribution is obtained by calculating the loss in performance between all pairs of datapoints that are exactly one year apart.

Based on the current practices, the statistical PLR calculation pipeline can be divided into the following steps: (a) initial data quality assessment, (b) data filtering, (c) performance metric calculation and data aggregation, (d) possible performance time-series feature corrections, and (e) the calculation of the actual PLR using a statistical model. Although the general pipeline from step (a) to (e) is well established [79], the PLR estimation is nontrivial because the selection of each individual step as well as the interplay between these steps determines the final value. Numerous studies [78], [79], [80], [81], [82] have been conducted to find the optimal pathway for calculating PLR, especially focusing on (b), (c) and (e).

The various methods to quantify PLR differ in their accuracy but are all based on similar principles; to determine the trends in the historical data. The major drawback of these statistical methods is that they do not trace the correlation of the evaluated degradation rates with the climatic variables and degradation processes. To capture these correlations, physical models can be utilized, and different physical models have been proposed for different degradation mechanisms [54, p. 14].

Despite the significant number of FPV systems that have now been operating for several years, long-term FPV performance studies are rare. Some of the comparative PLR calculation studies, such as [58], [60], [79], [83], [84], compare methods by using data from different FPV sites in temperate climate. SERIS has published two studies in tropical climates [37], [70], with one and three years of field data.

Data on the performance stability of FPV systems is still sparse. A systematic and detailed analysis of the performance stability of FPV systems was published by SERIS [70]. Using three years of data from a FPV test bed, PLRs were calculated for eight FPV strings. Three different statistical methods (OLS, STL and YoY) were used to calculate PLRs, yielding values between -0.7 and -0.5%/year, similar to PLR values of a nearby PV-rooftop system. It was however highlighted that some failure modes specific for FPV could manifest at a later stage.

3.3.3 Indoor stress testing

Lab testing is used to study, in a controlled environment, the impact of stressors on various PV components. In the lab environment, accelerated stress tests enable reliability screening of key components in short timeframes to identify and mitigate quality issues before they manifest as problems in actual installations. The IEC certification sets respective test standards for GPV systems. The certificates generally do not certify different quality and performance levels, but rather the required basic functionality and safety. The certification thus guarantees the essential operating requirements. The use of accelerated stress to qualify PV modules are covered in IEC 61215 [85] including stressors such as temperature, humidity, snow, wind and hail. The IEC 61730 [86] standard deals with the certification for mechanically and electrically safe operation of PV modules over the expected service life of PV modules.

In FPV systems, it is important to test the mechanical strength of the modules under real installation situations. As dynamic loads through wave and wind are to be expected, it is recommended to request a Dynamic Mechanical Load Test in accordance with IEC TS 62782 [87]. Furthermore, if the system is designed for environments close to the sea, a Salt Mist Corrosion Test following IEC 61701 [88] is applicable to all critical components.

In the FPV context, pre-normative work on accelerated stress testing will lay the foundation for qualification standards for critical components such as floats, connectors, anchoring system, PV modules and cabling. It is important that the developed stress testing regimes are founded as much as possible in existing standards for GPV and other relevant industries, to ensure efficient and rapid implementation. At the same time, FPV-specific stressors as laid out in Table 2 shall be accounted for. It will thus take time to depart from the current situation without FPV-specific standards towards a situation with an established certification framework leading to a safer and more mature industry. Each step taken in this process increases confidence and reduces risk perception for bankers/investors. Due to some reported issues with insulation resistance in FPV systems and the general risk of long-term exposure of electrical components to water, sealing and galvanic corrosion and increased water ingress protection beyond the IEC 62852 [89] standards are necessary. While DC cables for GPV installations are typically qualified according to IEC 62930 [90], and EN 50618 [91] respectively, cables for FPV applications are not designed for longer-term submersion in water and may hence have issues in permanently moist environments. Combiner boxes and inverters are typically designed as fixed/non-moving parts and if installed on the floating bodies certainly also need to be tested such that they withstand the potentially higher humidity and dynamic load associated with FPV projects.

DNV is currently working together with the FPV community by creating recommended practice documents as a technical reference for inland FPV in all its aspects covering the floats, anchoring & mooring, design, energy yield analysis and electrical components. As an early result, the world's first recommended practice on the design, development, and operation of FPV systems (DNV-RP-0584) was successfully introduced in 2021 [13]. Next steps are currently taken to expand this reference into design standards for floats, anchoring and mooring.

For the electrical aspects of FPV, modification of current IEC standards is under discussion in the IEC TC82 working groups [92]. These standardization activities are so far focusing on inland water FPV where the technology readiness level (TRL) is larger than 8. Offshore FPV is still in an experimental stage with only a few pilot and demo projects with TRL levels between 3 and 5. A lot of data collection and learnings from pilots, demos and scientific research is required to progress towards full maturity and design guidelines for large scale, low cost, and reliable offshore FPV farms. The goal is that technical standards adequately capture, among others, mechanical stress at the joints of rigid structures and testing of marine conditions like corrosive environment, tides, waves, biofouling of floats and parts in contact with water.

3.3.4 Simulations

Simulations are one convenient option to overcome the lack of experimental (long term) data. The advantage of simulations is that virtually every operating condition can be simulated and long-term behavior investigated. Also, simulations enable an in-depth analysis of phenomena of interest, unhindered by measuring devices of limited precision. The drawback is that each simulation is only a model of reality using certain simplifications and assumptions, which must be drawn wisely. Therefore, it is important to use validated simulation models to obtain reliable data. Typically, a combination of experiments and simulations yields the most accurate results, and experiments can often be performed on scaled or simplified samples.

Stressors may be amplified or altered in FPV applications, and simulations are of particular interest to study the influence of:

1. Wind loads through Computational Fluid Dynamics (CFD) and mechanical simulations
2. Moisture ingress through mass transport simulations
3. Hotspot formation through electrical and thermal simulations
4. Thermally induced stress through thermal and mechanical simulations

To all, the finite element method (FEM) can be applied, which is a method to model complex geometries in detail by splitting it into smaller fragments. But also, other appropriate methods can be used. In the following, a fitting simulation method is briefly introduced for each of the four stressors. To study superposition of the stressors, the models could be combined.

Simulation Models: mechanical loads

For GPV systems, the primary environmental sources of mechanical loading are snow and wind, in addition to impacts from hail. These systems are typically mounted on rigid, ground-fixed structures, where the modules and electrical components are either static or moved in a controlled manner by motorized mechanics, usually along one axis to track the sun. In comparison, FPV systems face a more complex set of environmental conditions. In addition to wind, snow, and hail, FPV systems must also withstand waves, currents, and water level variations. To manage these forces, FPV support structures are generally more dynamic. At larger scales, the entire system may have freedom of movement depending on the anchoring and mooring design. At smaller scales, different subparts of the system, such as individual floats, can move relative to each other, although restricted by hinges or other mechanical connectors. Modelling these dynamics accurately is a challenging task. The modelling approach depends heavily on the specific problem and may require multi-scale modelling techniques and the integration of various modelling tools

If looking at the PV module specifically, it was not until recently that CFD was coupled to FEM simulations for GPV to translate CFD-computed wind pressure distributions on the module exterior computed into FEM-computed detailed stress levels in the module interior [93]. To do a similar exercise for a FPV structure would additionally require coupling to modelling tools capable of handling both the hydrodynamics of the system and the flexibility of its components, such as 3DFloat [94] or Orcaflex [95]. The complexity of the hydrodynamic situation requires additional input from potential flow multi-body solvers (e.g., WAMIT [96]), input from similar mid-fidelity fluid simulation software or the development of new engineering models. This holds especially for large arrays of connected units where interaction and damping effects become important. Another challenge is being able to use the high-level structural loads as computed by these modelling tools to obtain the previously discussed detailed stress distributions interior to the modules, which would be required to fully understand the implications of the floating environment on the structural performance of these units. Modelling the wind loads could also be a challenge for some systems as the local flow field becomes complex close to the water surface and when there are many units close together. The motion of the floating units due to the waves also means that dynamic coupled simulations of this issue is necessary, i.e., CFD simulations with the PV units standing still will not be sufficient. Wind loads are likely significant when a large number of tilted panels are exposed to the wind, the total load being potentially design-driving for, e.g., the mooring system. Simpler approaches within only one modelling tool might be sufficient to address more narrowly defined problems; an example is the effect of O&M personnel walking on modules in a membrane FPV concept [97]. The sheer variety of studied FPV concepts makes developing relevant modelling tools challenging. This is further exacerbated by the fact that most concepts have significant differences compared to more established floating technologies, such as, e.g., floating offshore wind [98], for which current modelling tools and mechanical design guidelines for floating structures were developed.

Simulation Models: moisture ingress

Moisture ingress in PV modules is the origin of a range of degradation effects, including metallization corrosion, discoloration of polymers and PID. This is detailed and illustrated in [99]. Thus, simulating moisture ingress in PV modules using FEM is critical to gauge the performance of a PV module design and its constituents during long-term outdoor exposure.

Moisture ingress modelling for FPV is critical since the modules can be exposed to higher relative humidity due to proximity to water, as mentioned in Section 3.3.1. PV modules are generally exposed to moisture in the form of water vapor. The water molecules are adsorbed onto the surface of diffusing elements (backsheet, encapsulant and/or edge sealant, depending on the module design) and then diffuse into the bulk material.

The commercially available finite element simulation package, COMSOL Multiphysics is generally used for simulating moisture ingress in the PV industry. The diffusion is modeled by using the Transport of Diluted Species (TDS) physics interface in COMSOL.

To model the moisture ingress in PV modules exposed outdoors, the diffusion coefficient is modeled as a function of temperature using the Arrhenius equation, while the saturation concentation is computed for varying temperature and relative humidity using the Arden Buck equation [100] as reported in [101].

In some cases, Fickian diffusion cannot accurately describe measured moisture ingress or egress. The Fickian model assumes that water molecules diffuse evenly though the material. However, there can be states where the water molecules bond at certain sorption sites while diffusing [102]. Therefore, other non-Fickian models, such as Langmuir and dual-diffusion models, are used to model the diffusion behavior of water inside PV constituents [103], [104].

Simulation Models: hotspot formation

Hotspots may occur in any type of PV system. Although there is little published material quantifying the losses due to bird droppings (and other soiling) on FPV systems, images and anecdotal evidence strongly suggest that FPV systems are particularly exposed to this type of soiling. Bird droppings can significantly reduce the irradiance reaching the cells in a PV system, but also constitute hard shade, known to induce high temperatures in the cell. The dissipated heat of a partially shaded solar cell in reverse bias can lead to high temperatures that can degrade the encapsulation and backsheet materials but also the solar cells in the module, especially for heterojunction (HJT) solar cells which are known to be more sensitive to temperature than *Passivated Emitted and Rear Contact* (PERC) or Tunnel Oxide Passivated Contact (TOPCon) solar cells. Numerical tools such as SPICE [105] are used to compute the dissipated heat.

Simulation Models: outlook

There are other FPV-relevant phenomena worth exploring numerically, such as thermally induced stresses, which occur whenever there are high temperature gradients. For brittle materials, such as glass or silicon solar cells, high tensile stresses can lead to fracture. In FPV applications, wave slamming can exert both mechanical and thermal stress simultaneously. Beinert *et al.* [106] developed a coupled thermal and mechanical FEM model, which takes real weather data into account to simulate the PV module temperature and from this the stress and fracture probability of mainly the PV module glass. This method could be extended to take the cooling by water and waves into account.

Even with all sub models of relevant FPV degradation processes in place, the actual challenge consists of coupling them to account for *co-occuring* stressors on *interacting* FPV components, also comprising feedback loops that are hard to capture through modelling single processes. Some of the underlying interdependencies between mechanical loads are briefly laid out in the respective section on simulation models but have not yet been captured in their entirety. Moreover, relevant interdependencies stretch to other stressor domains, e.g., moisture ingress and corrosion also depend on the position of affected components above water, which in turn is affected by mechanical loads on and within the FPV system. To identify, prioritize and subsequently model these interdependencies is essential for obtaining a proper multiphysics model of FPV degradation.

4 OPERATION AND MAINTENANCE OF FLOATING PV

This chapter highlights new monitoring equipment and O&M actions that must be performed for FPV systems compared to the existing, well-established standards and best practices for GPV. The chapter details observed challenges within O&M of FPV power plants and discusses FPV specific cost of O&M. Finally, we provide our prespective on areas where new O&M technology and solutions can be of significant value for FPV.

4.1 Instrumentation

There are currently no standards available that describe the recommended sensors and procedures for monitoring of FPV power plants. Instrumentation requirements for GPV power plants, including requirements with respect to accuracy can be found in IEC 61724-1 [107]. Requirements related to the number of sensors, also according to IEC 61724, is included in Table 3. For recommendations regarding FPV systems, DNVs recommended practice published in 2021 [13] can provide guidance until a standard is published.

The purpose of the monitoring is essential to establish which parameters should be monitored, and with what accuracy. IEC 61724-1 defines two classes of monitoring systems, Class A, intended for large PV systems (large commercial or utility) and Class B, for smaller systems (rooftop to medium commercial). Table 4 provides an overview of parameters needed for monitoring of FPV systems (Class A in IEC 61724-1). The overview is compiled based on IEC 61724-1 and DNVs recommended practice.

Table 3. Multiplier table for sensors according to 61724-1 [107]. Referenced in Table 4.

System Size (AC) MW	Multiplier
< 40	2
≥ 40 < 100	3
≥ 100 to < 300	4
≥ 300 to < 500	5
≥ 500 to < 700	6
≥ 700	7, plus 1 for each additional 200 MW

Table 4. Compressed overview of parameters needed for monitoring of FPV systems (Compiled based on Class A systems in IEC 61724-1 [107] and DNV's recommended practice [13]. Electrical parameters are not included).

Parameter	Class A	Number of sensors	Sensor requirements	Reference
In-plane irradiance	X	1 x Table 3	Pyranometer: Class A per ISO 9060:2018. PV reference devices: conform to IEC 60904-2	IEC 61724-1
Global Horizontal Irradiance	X	1 x Table 3		IEC 61724-1
PV module temperature	X	3 x Table 3	Resolution ≤ 0.1 °C Uncertainty ≤ 1 ºC	IEC 61724-1

Ambient air temperature	X	1 x Table 3	Resolution ≤ 0.1°C, Uncertainty ≤ 1°C	IEC 61724-1
Rainfall/precipitation	X	1 x Table 3	Resolution 0.3 mm Uncertainty < 5%	DNV RP/ IEC 61724-1
Wind speed	X	1 x Table 3	Resolution: 0.1 m/s Uncertainty ≤ 3%	DNV RP/ IEC 61724-1
Wind direction	X	1 x Table 3	Uncertainty ≤ 3%	DNV RP/ IEC 61724-1
Relative humidity	NA	Not included in IEC 61724-1	Uncertainty ≤ 3%	DNV RP
Soiling ratio	X	1 x Table 3	Local measurements of soiling may not be representative.	IEC 61724-1
Water temperature	NA	Not included in IEC 61724-1	Uncertainty ≤ 0.15˚C	DNV RP
Waves	NA	Not included in IEC 61724-1		DNV RP
Water current	NA	Not included in IEC 61724-1	Recommended methods: Velocity-area and Acoustic Doppler Current Profiler	DNV RP

The light green marked rows in Table 4 indicate the minimum requirement of a meteorological monitoring station for yield assessment of FPV according to DNV RP. The only additional parameter in the minimum requirement compared to IEC 61724-1 is relative humidity. For ambient- and module temperature, wind speed and wind direction, DNV RP recommends higher quality measurements than IEC 61724-1. For wind parameters, the recommendations from DNV RP are used as these parameters may be more critical for an FPV system than a GPV system, which the IEC 61724-1 is designed for. For ambient and module temperature, Table 4 refers to the values in IEC 61724-1. The importance of the different environmental parameters, such as water temperature, current and waves will vary with FPV technology, while the impact of humidity on yield is not determined. The term accuracy, used in DNV RP, is here replace by the term uncertainty. More details can be found in the references.

4.2 Main O&M actions, importance and best practices

O&M for FPV systems encompasses a combination of routine (preventive and corrective) maintenance tasks, continuous monitoring & predictive maintenance tasks, as illustrated in Figure 17, in addition to risk preparedness (or emergency-response) plans**.** Streamlined O&M practices are indispensable to ensure the long-term performance, reliability, safety, and environmental sustainability of these systems, through a twofold mission: i) efficient mitigation of potential technical risks (hence, downtime), ii) maximized long-term PV energy yield, with a direct positive impact on LCOE and the payback time.

Figure 17. O&M approach for PV systems [7].

The main O&M challenges for FPV systems can be summarized as follows:

1. To address additional risks associated with the water-based working environment.
2. To ensure accessibility and reachability for all maintenance activities across all components.
3. To provide safe and cost-effective access to the floating platform, which is inherently more complex, risky, and time-consuming than accessing ground-mounted plants.
4. To establish clear requirements for cleaning and maintenance, as poor accessibility can lead to a high number of person-hours for O&M activities, potentially resulting in longer downtime.

The inclusion of the water/marine dimension in O&M, for the case of FPV systems, implies additional considerations and requirements necessary for ensuring minimal impact from and to the environment, as well as efficient mitigation of FPV-specific safety and technical risks. This can be related to key new (as compared to conventional PV) components such as floats, anchors and mooring systems, as well as electrical components.

Table 5 summarizes the main O&M actions and their rationale, importance, and best practices. The table includes information from the Best Practice Guidelines from Solar Power Europe [1], Recommended Practice from DNV GL [13], results from the TRUSTPV and SerendiPV projects [108], [109], [110] and the IEC standard for operations and maintenance of GPV systems [111].

Table 5: Main actions, their rationale, importance and best practices specific to FPV O&M.

Action	Rationale/Importance and overview of best practices
Anchoring/ mooring systems inspection	Anchoring and mooring systems are critical to maintain the stability of the FPV installation and limit mechanical stresses (e.g. due to strong winds, wave forces, etc.). Therefore, it is imperative for FPV asset managers to establish a comprehensive O&M plan dedicated to anchoring and mooring, covering inspections, maintenance, and spare components scheduling and budgeting. Although, normally, FPV-site specific risk assessments dictate the frequency and level of detail of anchoring/mooring inspections, increased attention is given to critical parts (e.g. those receiving relatively higher stresses or having sustained previous failures) and in special cases e.g. following extreme weather events. Regular (typically visual) inspections facilitated by trained specialized personnel (divers) or remotely operated vehicles (ROVs) are imperative to assess issues related to wear, fatigue, corrosion, chafing, marine growth, bio-fouling including vegetation/algae growth and other forms of degradation or damage in the anchoring and mooring systems. Key areas targeted for mooring inspections are the mooring lines (continuous integrity checks and tension measurements). On the other hand, anchor inspections focus – at minimum – on identifying physical degradation of the anchor or its pad eye [13].
Floats inspection	Buoyancy inspections are crucial in the FPV O&M agenda, aiming at identifying any leaks, wear, fatigue or failure in the floating platforms. As in the case of anchoring/mooring systems, more rigorous inspections of the floats are focused on critical parts and in cases following extreme weather events. Potential damages detectable from such inspections may include leaks due to punctures and cracks, loss of buoyancy/stability, loosening of connection pins and corrosion of metallic components [13].
FPV arrays inspection	FPV arrays inspections are essential part of the FPV O&M and, as in the case of GPV systems, are carried out according to the guidelines and requirements in IEC 62446-1 [112], IEC 62446-2 (maintenance procedures) [111] and IEC TS 62446-3 (infrared imaging) [113]. Such inspections, apart from detecting/diagnosing common PV failures, are crucial for FPV systems to reveal and track degradation mechanisms prominent in such marine environments, such as corrosion, moisture ingress and UV degradation. Besides, due to the typically limited accessibility of FPV arrays, inspections by means of airborne equipment (e.g. drones) and remote sensing technologies are favoured.

Action	Rationale/Importance and overview of best practices
Soiling (and snow) mitigation	Soiling mitigation plans in FPV O&M should ideally consider FPV-specific factors such as the combined impact of humidity, water/salt spray, organic matter and seasonal effects such as pollen and airborne sand. In practice, the severity of soiling is difficult to predict, and it is normally determined either by measurements on site or prior experience from the same area. In areas where resident or migratory birds are present, significant soiling levels may be encountered in the form of bird droppings. In such cases, monitoring of bird population and historical records of bird presence and migrations can be employed to identify the “high soiling risk” periods, in order to schedule (or intensify) cleaning interventions, whereas measures to repel birds may be also taken into account [1], [13]. Besides, aerial imagery (IR and RGB) inspections can help detect and quantify soiling on FPV arrays caused by bird droppings [110], which can be used to frame the frequency of the cleaning schedule. For FPV projects in tropical areas or waters with high nutrients, such as irrigation ponds, runoff from farmland, or areas with surrounding forests, biofouling is a potential concern, as it can contribute to soiling losses or near-shading losses when plants grow on the FPV arrays. Cleaning interventions may also be important in the case of FPV installations in snow-prone regions, where snowfalls and snow built-up on the FPV arrays can result in significant losses, as well as excessive mechanical loads on key components such as the floats and the FPV arrays. The cleaning schedule of FPV systems can usually be tuned after sufficient operational experience from a specific site.
Corrosion and moisture ingress	FPV installations are characteristically prone to moisture ingress and corrosion effects. Protecting metal components from corrosion is vital for the longevity of the FPV system. On-site measures for corrosion protection, such as the application of retrofit coatings, help maintain the structural integrity of the different FPV components. Attention is also given at monitoring (and mitigating, where applicable) moisture ingress and humidity levels inside enclosures, whereas diligent measures are necessary for certain FPV components exposed to UV, due to the adverse effects of combined UV and humidity/corrosion stresses, that accelerate physical, electrical and chemical degradation.
Circuitry and cabling checks	The electrical circuitry equipment of FPV, including primarily cables and connectors, requires periodic inspections and maintenance, in compliance with IEC 60364, IEC 62446-2 and OEM manuals [111], [114]. Inspections are further scrutinized for specific cases in FPV systems such as cables and connectors inadvertently in contact with water, areas with potential insulation faults and submerged cables which are often subject to marine organisms and buildup of organic matter. Finally, an additional point of inspection for cables in FPV installations is on cable runs to ensure that the appropriate amount of slackness is present to prevent stress.

Action	Rationale/Importance and overview of best practices
Earthing, equipotential bonding and lightning protection system	Earthing is the main factor which needs regular inspection to ensure the safety of O&M personnel. Earthing standards vary from country to country. It is necessary to make sure the earthing resistance requirements as per the designed standard are not compromised. Regular checking of earthing resistance value should be inspected. If the system has been earthed to water, then periodic checks of the conductor (rod/tape) ensures that it has not been etched or corroded. Verification is required to ensure that the cabling for equipotential bonding is still in good condition.
Inverters maintenance	Inverters' maintenance procedures follow the technical specifications and guidelines of the OEM manuals. Inverter inspections are triggered when deviations in FPV performance are identified through the SCADA or monitoring systems, as well as in follow-up of extreme weather events.
Monitoring & Upkeep of instrumentation	Monitoring should be implemented according to IEC 61724-1 [107] and best practices commonly applied to GPV systems, providing real-time data analytics and feedback for early detection of underperformance and potential faults; thus allowing for prompt corrective action, minimizing downtime and optimizing energy production. Yet, specifically for FPV applications, string level monitoring sensors are considered indispensable. This requirement allows FPV O&M teams to identify underperforming strings with sufficient spatiotemporal granularity (time-series data at string/combiner box level), thus minimizing the need for on-site interventions which are particularly costly and complex in the case of FPV, due to their limited accessibility (need for access by boat, special equipment for marine environments, etc.). In this sense, it would be advisable to invest upfront and install equipment to monitor V and I at each string level.
Water quality control	Maintaining water quality, including control of contaminants and algae propagation are all crucial measures in the FPV O&M plan to prevent fouling and degradation of the water environment, which in turn may have negative impact on both the FPV performance and the local ecosystem.
Safety inspections and training	Safety inspections are an indispensable part of FPV O&M, aiming at protecting the personnel working on or around (and under) the floating platform. Ongoing training for O&M personnel, specific to FPV conditions and risks, ensures that they are well equipped to handle routine maintenance and respond effectively to any issues. The water, the waves and the wind comprise the three main (environmental) risk factors for worker safety in FPV installations.

4.3 Failure modes and effects analysis in O&M: example for FPV

Considering the relative infancy of FPV technology and, therefore, the limited experience from in-field reliability of FPV installations throughout their operational lifecycle, there have been limited data and rather fragmented understanding of FPV-specific failures and degradation mechanisms. What is currently known has been summarized in detail in Chapter 3. In this section, we take a broader view, looking at both technical and operational challenges and how this impacts O&M using a failure modes and effects analysis (FMEA) approach. In Table 6, on the basis of literature, public reports, research programs and lessons learnt from demonstrations in operational FPV installations, we provide a first FMEA for FPV systems [1], [13], [64], [69], [108], [110], [115], [116]. Through this matrix, we identify potential flaws and risks of failure/degradation in key FPV system components and assess their (indicative) severity and risk priority number (RPN), to eventually (propose to) prioritize inspection and mitigation actions at the design and O&M stages of FPV projects.

Table 6: Example Failure Modes and Effects Analysis (FMEA) matrix for FPV systems.

Failure mode	Indicative Occurrence (1-4)	Indicative severity (1-5)	Indicative RPN (1-10)	Mitigation measure
Early / mid-life failures at FPV module or array level (e.g. cell cracks, delamination, PID, hotspots, bypass diode failures). Power output loss and risk of follow-up failures (e.g. fire).	2	3	8	Scheduled and/or data-driven inspections (primarily visual, I-V tracing, IR and EL images). Repairs or replacement of failed parts or PV module(s), where applicable.
Soiling/debris build-up. Soiling losses and potential hotspots.	2	2	5	Cleaning interventions at site-specific intervals, through manual or robotic solutions. Deployment of anti-soiling retrofits (e.g. coatings).
Buoyancy / float systems failures. Loss of stability and safety of the FPV arrays; risk of follow-up failures e.g. submerging or high mechanical stresses on the FPV arrays.	2	4	9	Scheduled and/or data-driven inspections. Targeted complementary inspections in response to extreme weather events or historical data indications.
Anchor system failures; Dislocation, loss of stability and increased mechanical stresses for the overall FPV platform; risk of follow-up failures e.g. on the FPV arrays or the floats.	2	4	8	Scheduled and/or data-driven inspections by specialized personnel (divers) or remotely operated vehicles (ROVs). Targeted complementary inspections in response to extreme weather events or historical data indications.
Failed or malfunctioning electrical component, including erroneous cabling; circuitry cuts or shunts; risk of follow-up failures (electrical arcs, severe hotspots, fire).	3	4	9	Visual and electrical inspections aided by SCADA/monitoring system alarms. Targeted inspections of potential insulation faults and cables that are fully

				submerged or in potential contact with water.
Inverter failure; Power losses at PV string(s) level.	2	2-3	5	Scheduled O&M-manual based inspections of inverters; repairs or replacement where applicable.
Water quality compromised; Risk of follow-up fouling and degradation of the local ecosystem.	2	2	5	Implement water quality management practices; use of components/materials resistant to water contamination.
Non-compliance to regulatory framework updates	2	3	7	Establish regular audits and follow-up of regulatory framework at local, national and international level.
Poorly established or managed inventory of spare parts	3	1-2	4	Use of return-of-experience/historical data; real-time tracking and update of spare parts inventory.
Unexpected wide-scale failures, including extreme weather events; Extensive failures and losses, potentially at multiple components (e.g. FPV arrays, anchors/mooring, floats, inverters).	1	5	10	Deployment of emergency response plans; Design of FPV O&M plans for weather resilience and preparedness, including improved local weather forecasts.
Monitoring system deficiency; Misconfiguration; hardware or software malfunction; data quality compromised, data gaps; Misdetection or delayed detection of underperformance issues; suboptimal performance	3	1-2	5	Rigorous initial installation, instrumentation, and configuration, complying with best practices and IEC specifications. Benchmarking with peer/similar or nearby PV plants, to potentially uncover undetected suboptimal performance, due to deficient monitoring.

Legend:

Occurrence	1 = Rare	2 = Occasional	3 = Likely	4 = Frequent	
Severity	1-2 = Minor	2-3 = Minor Moderate	3 = Moderate	4 = Severe	5 = Highly severe
RPN	<4 = Low priority	4-6 = Medium priority	7-9 = High priority	10 = Emergency	

This FMEA matrix is aimed to be further and regularly updated and complemented in the future, with future research outputs and new insights from broader return-of-experience in O&M of real-scale FPV projects.

4.4 O&M budgeting – Cost aspects

O&M costs for FPV systems can be highly variable, based on multiple interrelated factors. In general, when budgeting for the O&M of FPV systems, it is essential to conduct a thorough survey including i) procurement and due diligence plans, ii) site and location (inshore, near-shore, offshore, etc.) assessment, iii) consider the specific characteristics of the FPV technology to be used (i.e. including its floats and anchoring/mooring technology), and iv) account for the monitoring/inspection and maintenance needs in terms of hardware, software and manpower, in order to ensure optimal performance and reliability throughout the whole lifecycle of the FPV installation. An important aspect that is often overlooked in O&M budgeting is the importance of staying updated on industry best practices, lessons learnt, innovations and trends, the right tracking of which can help in identifying potential cost-saving measures and streamline O&M schedules (switching from "per-schedule" and preventive, to data-driven and predictive).

A representative list of key aspects and considerations when budgeting for FPV O&M projects is given below [5], [110], [117].

- **Site characteristics**: accounting for factors such as the location (e.g., inland, nearshore, offshore), water quality, microclimatic conditions and stressors, soiling, far shadings, etc.
- **Technology and Design**: as function of the chosen FPV technology and design, including anchoring/mooring and buoyancy mechanisms and materials, which in turn can influence e.g. the frequency or the complexity (and, thus, costs) of certain inspections.
- **Accessibility and Logistics**: for instance, remote or challenging-to-reach locations may require specialized personnel and equipment which should increase O&M costs.
- **Cleaning / Soiling mitigation needs**: the choice of the soiling mitigation strategy in terms of frequency and cleaning approach (manual or automated, waterless or water-based), takes into consideration multiple factors, such as accessibility, FPV configuration and site characteristics and has a direct impact on the overall O&M budget.
- **Inspection of electrical components/BOS**: accounting for factors such as the electrical architecture, the type and size of inverters, the overall length of cabling, etc.
- **Monitoring System / SCADA**: accounting for costs of instrumentation, installation, configuration and upkeeping of software and hardware components, as well as level of automation. On the other hand, performance tracking and early detection of issues through monitoring systems can contribute to streamlined cost-efficient O&M, counterbalancing the above costs.
- **Labor Costs and Training**: accounting for all manned O&M activities, such as routine inspections, cleaning and repairs interventions, upkeep of software and hardware, etc. The chosen (or required) level of skillsets, availability and anticipated training of labor in the project location has a direct impact on the global labor cost.
- **Soft costs**: accounting for insurance, regulatory compliance and warranty considerations.
- **Spare parts and reserve for contingency**: accounting for spare parts inventory management and logistics, as well as for contingency funds (for instance, to address unforeseen circumstances, prolonged downtime or emergency repairs, in the context of emergency response plans e.g. following extreme weather events.

Figure 18 illustrates the breakdown of such FPV O&M costs into five main budgeting streams: costs associated with the monitoring and inspections of all remote monitoring systems and instrumentation (sensors, communication, etc.), inspection tools (drones, underwater vehicles and ROVs), data analytics software and their upkeep. The key components and equipment inspections budget encompasses all costs for inspection, repair/retrofitting, or replacement of structural systems (mounting arrays, floating platforms, anchoring/mooring), PV modules, inverters, combiner boxes, cables, etc. Site management and control budgeting refers primarily to environmental monitoring (water quality monitoring, monitoring, and assessment of impact on aquatic life, compliance with environmental standards) and cleaning and biofouling control plans (soiling mitigation through manual or automated systems, antifouling coatings, biofouling monitoring). Labor costs include O&M payroll, training, and certification programs, as well as external contractor costs for specialized tasks such as underwater interventions. Finally, soft costs encompass regulatory compliance, safety, insurance, and financial reserves.

Figure 18. FPV O&M costs breakdown.

Yet, specific and detailed real-case figures for FPV O&M budgeting and breakdown are not readily available, so far. NREL recently conducted a bottom-up analysis [5] of the installed costs for FPV systems deployed on artificial water bodies under average site conditions (wind load of about 40 m/s, snow load of 20 psf (about 980 Pa), water depth of 50 m, water level variation of 10 m, and swell height of 1 m); which may be a guide as well for assessing the additional (“premium”) associated O&M costs as well, compared to standard PV. The study estimated an installed system cost premium of \$0.26/W_{DC} (25%) for 10-MW_{DC} fixed-tilt FPV systems, compared with fixed-tilt GPV, indicating that higher structural costs related to the floats and anchoring system are the largest contributors to this premium [5].

4.5 Outlook: O&M challenges and opportunities

As utility scale FPV is still in an early phase, especially in terms of upscaling and O&M experience, there are several ongoing and emerging R&D challenges (and therefore opportunities) in the framework of FPV O&M, in the following areas:

- ***Monitoring and remote sensing:*** there is a major need for addressing consistent challenges associated with the remote (or semi-remote) nature of FPV installations, especially offshore ones: i) the lack of reliable data transmission on one hand; ii) on the other hand, the complexity and high costs of distant wide-area communication and monitoring/sensing systems. Leveraging unmanned aerial vehicles (notably hovering drones) and satellite technology, cloud storage and Internet of Things solutions, along with robust remote communication protocols, will be a differentiator for future O&M services tailored to FPV installations.

- ***Expert dependence:*** in addition to the FPV remoteness and monitoring challenges, the complex and multidisciplinary nature of FPV installations, involving several different, distant and interdependent systems (FPV arrays, electrical systems, anchoring/mooring, floats, etc.) significantly increases the expert dependence in O&M, compared to GPV O&M. For instance, corrective maintenance interventions in FPV platforms often require specialized personnel (e.g. divers, marine engineers and technicians, etc.), while FPV inspections and analysis of FPV operational data are far more time-consuming tasks (compared to standard PV), involving a number of different experts and equipment operators. Emerging R&D and innovation opportunities here lie upon the development and deployment of advanced FPV data analytics, artificial intelligence (AI) and UAV-based inspections and autonomous interventions (e.g. drone-based imagery, drone-based robotic cleaning), for data-driven predictive and unmanned O&M in FPV.
- ***Extreme weather stressors and FPV-specific degradation:*** marine environments and associated microclimatic stressors are typically more aggressive and complex to assess in FPV installations, compared to standard PV ones. Further R&D is required towards improving the longevity of key FPV components, i.e. PV modules, anchor/mooring and floating structures, and submerged cables at both design (novel materials and coatings, passive protection configurations) and post-commissioning level (retrofitting solutions), notably against corrosion, UV exposure, and mechanical stresses. Besides, improved weather preparedness and emergency-response plans based on data-driven approaches are becoming indispensable for FPV installations, which are often more prone to large-scale degradation and failures following extreme weather events, such as hurricanes, severe storms or floods
- ***Environmental impact – Regulatory framework:*** impending concerns regarding the impact of FPV installations and O&M on the local marine and near/inshore ecosystems (e.g. How is the water quality and/or the aquatic flora/fauna affected under FPV arrays shading? Which O&M tasks, such as detergent-based cleaning, should be excluded or adapted to protect the aquatic ecosystem?) should be better investigated, assessed and addressed, through further research and innovative alternatives. Such innovations are focused on passive environmental- and habitat-friendly designs of FPV platforms, along with evolving regulatory frameworks and standards for FPV O&M practices.

5 CONCLUSION

FPV presents a significant opportunity to accelerate and facilitate the adoption of renewable energy while mitigating the increasing pressure on land areas.

However, the present lack of established regulatory frameworks and limited long-term experience with FPV systems creates uncertainty for developers, regulatory bodies, and investors alike, posing significant challenges to accelerating FPV deployment. The industry is characterized by rapid developments and high innovation rates, accompanied by a focus on confidentiality and company-internal development which can hinder collaboration and data sharing – crucial elements for research and development. However, the potential for deployment of FPV far surpasses the current market [7], giving compelling reason to believe that the entire industry could benefit if developers, regulatory bodies and investors could lean on more openly available data and knowledge.

This report aims to contribute to build a robust knowledge base that supports the development of new standards, regulations, and technologies by gathering the data that is available and illuminating gaps in current knowledge. The report summarizes the available knowledge from scientific literature, reports and the experience of the authors, in three important aspects of FPV power plants: energy yield, reliability, and operation and maintenance. Within each of these fields, the focus is on addressing the areas where FPV differs from traditional ground-based photovoltaic systems. Other important topics within FPV, such as environmental impacts, offshore applications, recycling, calculations of deployment potentials and cost curves are excluded from the report to limit scope and enhance readability. We recommend that these aspects will be handled in separate reports. Targeted research efforts and access to data are critical to close the identified knowledge gaps and this research should include, but not be limited to:

- understanding and quantifying the unique operational conditions and stressors FPV systems face, including wave action, wind loads, temperature, and biological fouling.
- developing and verifying models and methodologies to accurately predict how these stressors impact FPV system performance over their lifetime and under different operating conditions.
- develop methodologies and equipment to automate monitoring and maintenance operations for FPV power plants
- understanding and quantifying environmental impacts of FPV systems: evaluating the potential effects of FPV on water quality, aquatic ecosystems, and surrounding habitats.

By addressing these research priorities, the industry can move towards a more mature and sustainable deployment of FPV, ultimately paving the way for its widespread adoption.

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