Where Sun Meets Water

FLOATING SOLAR HANDBOOK FOR PRACTITIONERS

WORLD BANK GROUP
THE WORLD BANK IBRD · IDA
IFC International Finance Corporation

ESMAP
Energy Sector Management Assistance Program

SERIS
Solar Energy Research Institute of Singapore

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Energy Sector Management Assistance Program (ESMAP)

The Energy Sector Management Assistance Program (ESMAP) is a global knowledge and technical assistance program administered by the World Bank. ESMAP assists low- and middle-income countries to increase their know-how and institutional capacity to achieve environmentally sustainable energy solutions for poverty reduction and economic growth. ESMAP is funded by Australia, Austria, Canada, Denmark, the European Commission, Finland, France, Germany, Iceland, Italy, Japan, Lithuania, Luxemburg, the Netherlands, Norway, the Rockefeller Foundation, Sweden, Switzerland, the United Kingdom, and the World Bank.

Solar Energy Research Institute of Singapore (SERIS)

The Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore, founded in 2008, is Singapore's national institute for applied solar energy research. SERIS is supported by the National University of Singapore, National Research Foundation (NRF) and the Singapore Economic Development Board. It has the stature of an NUS University-level Research Institute and is endowed with considerable autonomy and flexibility, including an industry friendly intellectual property policy.

SERIS' multi-disciplinary research team includes more than 160 scientists, engineers, technicians and PhD students working in R&D clusters including (i) solar cells development and simulation; (ii) PV modules development, testing, certification, characterization and simulation; (iii) PV systems, system technologies, including floating PV, and PV grid integration. SERIS is ISO 9001 & ISO 17025 certified.

SERIS has extensive rich knowledge and experience with floating PV systems, including having designed and operating the world's largest floating PV testbed in Tengeh Reservoir, Singapore, which was commissioned by PUB, Singapore's National Water Agency, and the Economic Development Board. Launched in October 2016, this testbed compares side by side various leading floating PV solutions from around the world. Through detailed monitoring and in-depth analysis of performance of all the systems, SERIS accumulated deep insight into floating solar and SERIS' objective is to disseminate the best practices in installation and operation of floating solar pants as well as help to formulate standards for floating PV.

CONTENTS

ACRONYMS AND ABBREVIATIONS

AC	alternating current
ADB	Asian Development Bank
CFD	computational fluid dynamics
DC	direct current
E&S	environmental and social
EHS	environmental, health, and safety
EIA	environmental impact assessment
EPC	engineering, procurement, and construction
ERA	ecological risk assessment
ESA	environmental site assessment
ESMAP	Energy Sector Management Assistance Program
ESMP	Environmental and Social Management Plan
FAA	Federal Aviation Administration
FPV	floating solar photovoltaic
GWp	gigawatt-peak
HDPE	high-density polyethylene
Hz	hertz
IFC	International Finance Corporation
IPP	independent power producer
IT	isolated-earth
kWh	kilowatt hour
kWp	kilowatt-peak
LPS	lightning protection system
LV	low voltage
m2	square meter
MPPT	maximum power point tracking
MSDS	materials specification data sheet
MV	medium voltage
MW	megawatt
MWp	megawatt-peak
O&M	operations and maintenance
PID	potential induced degradation
PIM	permanent insulation monitor
POE	polyolefin
PPA	power purchase agreement
PV	photovoltaic
RTI	relative temperature index
SCADA	supervisory control and data acquisition
SERIS	Solar Energy Research Institute of Singapore
SGHAT	Solar Glare Hazard Analysis Tool
TPO	thermoplastic polyolefin
Wp	watt-peak

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EXECUTIVE SUMMARY
FLOATING SOLAR HANDBOOK FOR PRACTITIONERS

Why is this handbook needed?

Floating solar photovoltaic (FPV) installations reached 1.3 gigawatt-peak (GWp) of total installed global capacity at the end of 2018, and deployment appears likely to accelerate as the technologies mature, opening up a new frontier in the global expansion of renewable energy. When combined with other demonstrated benefits—such as higher energy yield, reduced evaporation, and in certain cases improved water quality—FPV is likely to be an attractive option for many countries. Several countries with high population density are looking at large-scale floating solar deployment in order to avoid using their scarce land resources for solar power generation.

With a global potential of 400 GWp under conservative assumptions, FPV could become a significant market segment for solar photovoltaic (PV) deployment, without the challenges of acquiring the land required for ground-mounted installations. At some large hydropower plants, covering just 3–4 percent of the reservoir area with FPV could double the estimated installed capacity, potentially allowing water resources to be more strategically managed by utilizing the solar output during the day. In addition, combining the dispatch of solar and hydropower could smooth the variability of the solar output while making better use of existing transmission assets—a benefit that could be particularly valuable in countries where grids are weak.

Although FPV technology is considered commercially viable, given the number of large-scale projects that have been implemented, challenges to its deployment remain. They include the lack of a robust track record; uncertainty about costs; uncertainty about the environmental impact; and the technical complexity of designing, building, and operating on and in water (especially electrical safety, anchoring and mooring issues, and operations and maintenance [O&M]). An active dialogue among all stakeholders, public and private, is required to further the global understanding of FPV technologies and the development of well-designed projects while minimizing possible negative environmental and social impacts. Through this handbook, the World Bank Group, the Energy Sector Management Assistance Program (ESMAP), and the Solar Energy Research Institute of Singapore (SERIS) hope to contribute to this goal and to disseminate lessons learned from early projects.

Phases of development

As in a conventional, ground-mounted PV project, the development of an FPV project can be divided into several major phases: site identification/concept stage, prefeasibility study, feasibility study, financing/contracts, detailed design; environmental and social considerations; procurement and construction; testing and commissioning; and O&M.

Site identification

Proper site selection for an FPV plant is a prerequisite for successful project development. The site must be identified during early-stage concept development, before feasibility studies are conducted. Early data collection allows project developers to make informed assessments of a project's viability. The aim at this stage is to choose the best possible site for the project or to shortlist the most promising sites.

The main considerations for assessing site suitability for FPV installations include:

- Solar resource
- Local climate conditions
- Available water surface area and shape
- Bathymetry
- Water level, wave amplitudes, and wind speeds
- Subsurface soil conditions
- Shading, soiling, and other site conditions
- Environmental considerations
- Grid access, substation location, and power availability
- Access rights, permits, and regulations.

Table E.1 summarizes the key elements to consider when selecting a water body for an FPV system. It is unlikely that a site possesses all the desirable features. Cost-benefit analysis will help developers ensure that benefits outweigh possible costs.

TABLE E.1 Decisive factors in selecting a water body for a floating solar photovoltaic plant

Factor	High preference	Low preference
Location	• Near load centers and populated regions • Easily accessible by road • Secured/fenced • Close to manufacturing facilities or ports for simplified logistics	• Remote places with high transportation cost[a]
Weather and climate	• High solar irradiation • Little wind or storms • Calm water • Dry region where water conservation is important	• Cold regions with freezing water • High winds and risk of natural disasters such as typhoons and tsunamis • Seasonal flooding • Drought events that lead to exposure of water bed
Type of water body	• Manmade reservoirs • Hydropower dams • Industrial water bodies, such as cooling ponds and wastewater treatment facilities[b] • Mine subsidence areas • Irrigation ponds	• Natural lakes • Tourist or recreational sites
Water body characteristics	• Regular shape • Wide opening toward south (for northern hemisphere) or north (for southern hemisphere)	• Narrow strip between mountains (gorges) • Presence of islands/obstacles in the middle
Water body ownership	• Single owner • Legal-entity owner	• Multiple owners • Individual private owners
Underwater terrain and soil conditions	• Shallow depth • Even terrain • Hard ground for anchoring • Water bottom clear of any cables, pipelines, or other obstructions	• Soft mud ground for anchoring
Water conditions	• Freshwater with low hardness and salinity	• Salty water • Dirty/corrosive water • Water prone to biofouling
Other site conditions	• Existing electrical infrastructure, transmission lines • Easy water access • Sufficient land area for deploying and placing electrical equipment • Self-consumption loads, such as wastewater treatment and irrigation pump facilities	• No existing electrical infrastructure[c] • Complicated banks, presence of bund walls • Extensive horizon shading from nearby mountains • Nearby pollution sources (for example, chimneys, burning crops, quarries)
Ecology	• Simple and robust ecology	• Natural habitat of preserved species • Frequent bird activity • Water species that are sensitive to water temperature, dissolved oxygen, and sunlight

Source: Authors' compilation.

a. In some cases, FPV can be highly valuable to remote regions.

b. This is relevant only if water quality remains suitable for FPV.

c. This may not be a concern, depending on the circumstances of the FPV project.

Energy yield analysis

During the feasibility study, the developer needs to estimate a project's likely energy yield. FPV installations can differ from ground-mounted ones. For example, module cooling is better on water; on water, the range of tilt angles will depend on the float design; FPV installations may suffer from above-average bird droppings (a major source of soiling); and degradation rates for electrical components placed near bodies of water may differ from rates seen with land-based systems. All these parameters need to be taken into account in the expected energy yield analysis.

Engineering design

The engineering design of above-water FPV plants resembles that of ground-mounted plants in many respects (the floating structures and anchoring and mooring systems are, of course, different). To design the floating system, one has to account for relevant site conditions, required functionality, O&M, and environmental impact. It is particularly important to look at aspects of the quality of the floating structures and the mooring and anchoring systems. Modules of FPV systems need to withstand constant movement, high humidity, and the potentially higher stresses of corrosion. Cable routing and management are more critical than they are for ground-mounted systems. The water environment imposes more stringent requirements with regard to electrical safety. In some cases, hybrid operation with a hydropower plant may be a viable option, in which case the system is designed to exploit the synergies.

Financial and legal considerations

As with ground-mounted PV projects, FPV systems can be owned by independent power producers or by utilities, depending on the country and the regulatory framework in place.

Regarding bankability and risk assessment, the due diligence process for utility-scale FPV projects resembles the process for ground-mounted PV projects. Because the FPV industry is still nascent, however, few companies are able to provide integrated solutions; FPV projects may require many contractors throughout the project life cycle. This fact increases the integration risk and complexity of building and operating such plants. Given the lack of experience that banks, insurers, and regulatory bodies have with FPV, permitting and financial closing are likely to take longer than for ground-mounted PV projects.

As for any project finance transaction, thorough due diligence must take place. Lenders and insurers will evaluate the following risks for each project (the list is not exhaustive):

- Country risk
- Sponsor/owner risk
- Resource risk
- Technology risk
- Regulatory/compliance risk
- Construction risk
- Offtake risk
- Operations and maintenance risks
- Decommissioning risk.

It is essential to carry out a detailed risk analysis and, where possible, to quantitatively evaluate factors that could affect FPV system performance during the system's lifetime of 20 years or more.

Obtaining the licenses, permits, and authorizations to install an FPV system can be challenging, especially in countries with complex regulations or lack of experience with FPV. The permitting/authorization phase can take from a few months to several years in some extreme cases. A clear framework of FPV regulations and policies would reduce development costs and encourage investment.

Environmental and social considerations

The environmental and social (E&S) impacts of FPV projects depend on project size, the technology employed, site characteristics, and other local conditions. Project planners must take all possible impacts into account as they follow international good practices, domestic regulations, and, where applicable, financing institutions' expectations and requirements. Qualified and experienced professionals should determine the applicability of specific technical recommendations. Where domestic regulations differ from the recommendations presented in this document, it is suggested that projects follow the more stringent of the two.

During the initiation phase of the project, project developers must assess all relevant direct, indirect, and cumulative E&S risks and impacts of a project throughout its entire life cycle. The E&S assessment should be based on up-to-date information, including an accurate description of the project and associated elements and E&S baseline data at a level of detail sufficient to inform the characterization and identification of risks and impacts and mitigation measures. The assessment should also examine project alternatives and identify ways of improving project selection, siting, planning, design, and implementation, in order to apply the mitigation hierarchy for adverse E&S impacts.

The entire "area of influence" of an FPV project must be assessed. It includes the project's immediate footprint; associated facilities (such as the electrical infrastructure, including substations, electrical transmission lines and towers, dams, and other infrastructure); the water body where FPV components would be installed; and, depending on the circumstances, upstream and downstream waters and their associated uses/users.

Assessing potential environmental risks and impacts as early as possible in the project life cycle maximizes the range of options available to anticipate and avoid them. Where avoidance is not possible, careful plans must be made to minimize potential negative impacts—and, where residual impacts remain, to compensate or offset them. Baseline assessments should include seasonally representative information (on hydrologic regimes, aquatic or terrestrial ecology, and similar issues), following internationally accepted practices.

FPV projects may affect water quality and aquatic-supported biodiversity. The degree of the impact varies dramatically depending on the type of reservoir (natural, manmade, onstream, off-stream) and its uses (hydropower, recreation, conservation, water supply, and so forth). Multiple factors—including location, seasonality, the size of the water body, the percentage of the water body covered by the FPV system, incoming water sources, and the materials used as part of the FPV installation, to name a few—determine the effect of an FPV system on water quality and aquatic-supported biodiversity.

Most occupational health and safety issues during the construction, operation, maintenance, and decommissioning of FPV projects are common to large industrial facilities. They include, among others, exposure to physical hazards from the use of heavy equipment, cranes, hazardous materials, dust and noise, and falling objects; trip and fall hazards; and electrical hazards (from the use of tools and machinery). Occupational health and safety hazards specific to FPV projects primarily include the risks associated with live power lines, electric and magnetic fields, and working over and under water. Primary community health and safety hazards specific to FPV facilities include water navigation and safety, aviation, and public access.

Because FPV is a relatively new industry, additional studies, adaptive management, and long-term monitoring will be required to assess and understand the effects on water quality and aquatic flora and fauna. Knowledge gained from early projects will be instrumental in informing the industry as it grows and in developing best practices related to manufacturing project components as well as construction, operation, maintenance, and decommissioning.

Procurement and construction

Selecting a contractor for EPC (engineering, procurement, and construction) is typically done through a tendering process that considers the candidates' experience, record of engineering accomplishments, knowledge of the relevant country, and financial strength. The EPC contractor assumes responsibility for all design, engineering, procurement, construction, commissioning, and testing. High-quality EPC contractors have connections with top-tier suppliers of FPV components such as float structures, modules, and inverters. These contacts enable cost-effective and timely procurement of materials.

Procurement must be carried out before construction begins; materials need to be on site on time and per the specifications in the contracts. Procurement involves planning to determine what to procure and when and how to do it; awarding contracts to selected qualified suppliers; controlling contract performance; and closing each contract, including resolving issues pertaining to warranty clauses.

A number of stakeholders are involved during the construction phase. To ensure smooth implementation of all construction activities, the site construction head must manage all the contractors, subcontractors, suppliers, machinery operators, and the owner. Managing stakeholder interface is critical. It keeps momentum going and ensures on-time delivery of the project. Proper installation and good workmanship are important at every step. EPC contractors should provide daily, weekly, and monthly progress reports to the owner. They should plan and implement in-process quality checks, which facilitate the early identification of issues that can arise during construction and help avoid redoing the work or repairs. The owner and the lender (possibly assisted by the owner's engineer or the lender's engineer) are advised to regularly monitor construction progress and the quality of implementation. For FPV systems, key focus areas during the deployment include preparation of the site, delivery of materials (floats), assembly of the floating structure, deployment of the mooring and anchoring system, routing of cable, installation of electrical equipment, and connection to the grid.

Testing and commissioning

Once the project is mechanically complete and connected to the grid, qualified electrical inspectors, such as licensed electrical workers or certified professional engineers, test and commission the system. Among other things, they must endorse the design calculations and drawings for the floating structure and for the mooring and anchoring system. For a system to feed electricity into the grid, certain documents must be submitted, as specified by law or regulation in the country where the system is located. Local standards for the manufacturing and field-testing of floats must be respected, since international standards are not yet established.

System verification involves a thorough visual inspection, followed by a verification of electrical measurements to ensure their compliance with the requirements of the EPC contract. Well-documented testing and commissioning reports serve as a baseline reference to ensure that all the components are functioning in accordance with design calculations and specifications.

Operations and maintenance

After attaining commercial operation, an FPV project moves into the O&M phase. With few moving parts, solar PV plants generally have minimal maintenance and servicing requirements; they are designed for an expected lifetime of 20–25 years. The aim of O&M of any type of PV system is to maximize the electricity generation yield through the system's efficient operation while minimizing the costs through careful system maintenance that ensures the longevity of its components. Maintenance also ensures a safe working environment for O&M personnel.

FPV systems are relatively new, with most systems having been in operation for only a few years. The maintenance of FPV systems requires new skillsets, techniques, and procedures.

The principal contractor responsible for monitoring the system usually performs three types of maintenance: preventive, corrective, and predictive. Preventive maintenance involves the routine inspection and servicing at predetermined intervals planned, with the goal of preventing the occurrence of damage and breakdown. Corrective maintenance occurs on an as-needed basis when components break down. Predictive maintenance is the real-time, data-based monitoring of the power plant, with the goal of predicting possible failure modes.

Conclusions and next steps

Most activities necessary for development of FPV projects are similar to those for ground-mounted PV projects, but important differences remain (table E.2)

The World Bank Group is committed to supporting the development of FPV by financing public and private investments and by generating and disseminating knowledge. The priority over the next few years should be to strategically deploy FPV at sites where it is already economic while applying the "precautionary principle" when it comes to possible environmental or social impacts. Applying this principle may involve setting initial limits on the portion of the water surface that is covered and avoiding installations in the littoral zone near shore, where plant and animal life may be more abundant. The development of the constituent technologies and knowledge of positive and negative impacts will be greatly enhanced if early installations are diligently monitored, which will entail some public expenditure. The need for monitoring, added to the possible additional capital costs of FPV over ground-mounted systems, makes early

TABLE E.2 Comparison of development of floating and land-based photovoltaic projects

Item	Floating PV	Land-based PV
Site identification		
Land/water surface use	• Does not compete for land with agricultural, industrial, or residential projects • Often easier to find sites near densely populated areas • Potential integration with aquaculture	• Suitable/affordable land may be far away from load centers, requiring costly transmission infrastructure • Requires change in land use, which can be time consuming • Competes for land with city dwellings, industrial development, and agriculture, though in certain cases integration is possible
Power system benefits	• Synergy with existing electrical infrastructure (such as hydropower plants) • Possible hybrid operation with hydropower	• Costs of grid interconnection are often borne by project developer and can be prohibitively high
Energy yield analysis		
Operating environment	• Open and flat surface • Low reflected diffuse light from water surface • General presence of evaporative cooling and higher wind speed • Presence of dynamic movement	• Terrain type may vary • Albedo depends on ground type • No movement
Losses	• Lower module temperatures (effect is dependent on climate) • Nearly no shading from nearby objects • Less soiling from dust, but potentially more from bird droppings • Potential mismatch loss from temperature inhomogeneity and misalignment in module facing	• More temperature losses in hot and arid climates • More sources of shading and string mismatch
Performance	• Overall higher initial performance ratio (5–10 percent, climate specific) • Long-term degradation (such as potential induced degradation) still uncertain	• Can benefit from tracking, bifacial modules, and optimum tilt angle/row spacing • Yield prediction is better established

TABLE E.2 continued

Item	Floating PV	Land-based PV
Engineering design		
Array configuration	• Modular design on “flat” water surface • Limited tilt (because of wind load considerations) implies lower energy yield in high-latitude regions • Row spacing determined by floating structure • Consists of floating islands	• Design must accommodate terrain constraints or requires leveling • Flexible row spacing • May consist of large tables of PV panels
Mounting and support structures	• Floating platform structure • Anchoring and mooring system is essential • Need to provide maintenance walkway • Floating platform experiences forces from winds, snow, waves, and water currents	• Piles and racks structure • Mounting structure experience forces from winds and snow only • Easier to implement tracking • Potentially more susceptible to resonance effects
Electrical equipment and cables	• Electrical equipment may be placed on floats or on shore • Cables mainly routed on floats • Potential need for higher protection standards and test certifications • Many floating platform designs require equipotential bonding wires	• String inverters and electrical boxes may be placed under PV modules • Cables are placed in conduits above ground or buried underground
Safety	• Platform design needs to consider additional risks for personnel performing O&M • High humidity environment leads to lower insulation resistance and increased risks of electrical leakage • Proper cable management is important to accommodate constant movement that may otherwise lead to cable damage and fire risks	• Safety relatively well established
Financial and legal considerations		
Investment	• Slightly higher costs on average because of floats, anchoring, mooring, and plant design • Cost of floats expected to drop as scale of deployment increases • Higher perceived risk because of lower level of maturity • Expected lower site rental/leasing cost • Additional benefits on energy yield from cooling effect of water and possible reduction in water evaporation losses, depending on system design	• Huge installed capacity and hence very established investment and financing sector • Costs continue to drop • Land acquisition or rental can be difficult and costly in certain regions
Regulation and permits	• Permitting generally more difficult for natural lakes and easier for artificial ponds • Water surface ownership often unclear • Lack of specific regulations	• More established permitting process • Clearer regulations
Experience/level of maturity	• Cumulative capacity as of end of 2018 exceeded 1.3 GWp • More than 350 projects built • Four years of experience with large-scale projects (maximum size project to date 150 MWp)	• Cumulative capacity as of end of 2018 exceeded 500 GWp • Thousands of projects built • 10–30 years of experience
Environmental and social considerations		
Environmental	• Long-term effects on water quality not well-established • Potential impact on biodiversity, including aquatic ecosystems • Potential to reduce algae growth • Potential to reduce water evaporation	• Some adverse impacts during construction • Potential habitat loss or fragmentation
Safety	• Risk of personnel falling into water	• Generally safe

TABLE E.2 continued

Item	Floating PV	Land-based PV
Procurement and construction		
Installation and deployment	• Assembly generally easy, but highly variable, depending on location and workforce availability • Transportation of bulky floats to site is difficult; favors local production • Needs suitable launching area • May need specialized equipment or divers to install anchoring system	• Efficiency of assembly varies depending on location and workforce availability • Needs heavy equipment and land preparation • Complexity and costs depend on soil quality
Testing and commissioning		
Testing	• No international standards exist for verifying floats	• Testing and commissioning procedures are well-established
Grounding	• Grounding module frame or mounting structure may be challenging if constant motion causes bonding conductor to loosen or snap	• Grounding module frame or mounting structure is well-established
Operations and maintenance		
Technical	• Harder to access and replace parts • Wave action increases mechanical wear and tear • Biofouling likely • High-humidity environment may accelerate corrosion/oxidation of metal parts • More maintenance for structural elements • Easier access to water for cleaning • Lower risk of theft/vandalism	• Generally easy to access and replace parts • More vegetation • Easier to deploy automated cleaning routines • Less maintenance for civil work and ground foundations
Safety	• Constant movement of floats poses walking hazards • Risk of personnel falling into water	• Generally safe, with stable ground for walking

Source: Authors' compilation.

installations in developing countries a strong candidate for concessional climate financing.

ESMAP continues to support floating solar community by generating and disseminating knowledge on FPV. As part of the *Where Sun Meets Water* series, earlier in 2019 the World Bank Group, ESMAP, and SERIS published the "Floating Solar Market Report." This "Floating Solar Handbook for Practitioners" is the second publication in the series. It will be followed by a report on technical designs and project structuring for hydro-connected solar. The series will be accompanied by an online geospatial mapping tool showcasing the global potential of FPV.

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World Bank Group, ESMAP (Energy Sector Management Assistance Program), and SERIS (Solar Energy Research Institute of Singapore). 2019. “Where Sun Meets Water: Floating Solar Market Report.” Washington DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/31880/Floating-Solar-Market-Report.pdf?sequence=1&isAllowed=y.

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1 INTRODUCTION

1.1 Why is this handbook needed?

Floating solar photovoltaic (FPV) technology is considered commercially viable, given the number of large-scale projects that have been implemented. Challenges to its deployment remain, however, including the lack of a robust track record; uncertainty about costs; uncertainty about the environmental impact; and the technical complexity of designing, building, and operating on and in water (especially electrical safety, anchoring and mooring issues, and operation and maintenance).

This handbook provides developers, utilities, contractors, investors, regulators, and decision-makers with practical guidelines on FPV projects. Most of the handbook focuses on technical aspects relating to developing and operating FPV projects; some sections focus on commercial and legal aspects. Most of the observations are made for inland water bodies or near-shore coastal FPV installations. Many observations incorporate learning and opinions from the industry, but they are also based on the experience from the 1 megawatt-peak (MWp) floating solar testbed in the Tengeh Reservoir in Singapore. The testbed has a comprehensive monitoring system that tracks more than 500 parameters in real time, ranging from electrical to meteorological and module-related factors.

Given the early stage development of the technology, this handbook cannot answer all questions about FPV. Further studies and field data analysis are needed to better understand some of the risks of FPV systems, especially their environmental impact and long-term performance. All recommendations provided in this report are based on past and current experiences, which are limited to several years of operating data for most projects. A longer operating lifetime of FPV installations will lead to new and improved recommendations and best practices; new developments in technology, testing, certification, and equipment/materials deployed are likely to evolve as the industry grows and diversifies.

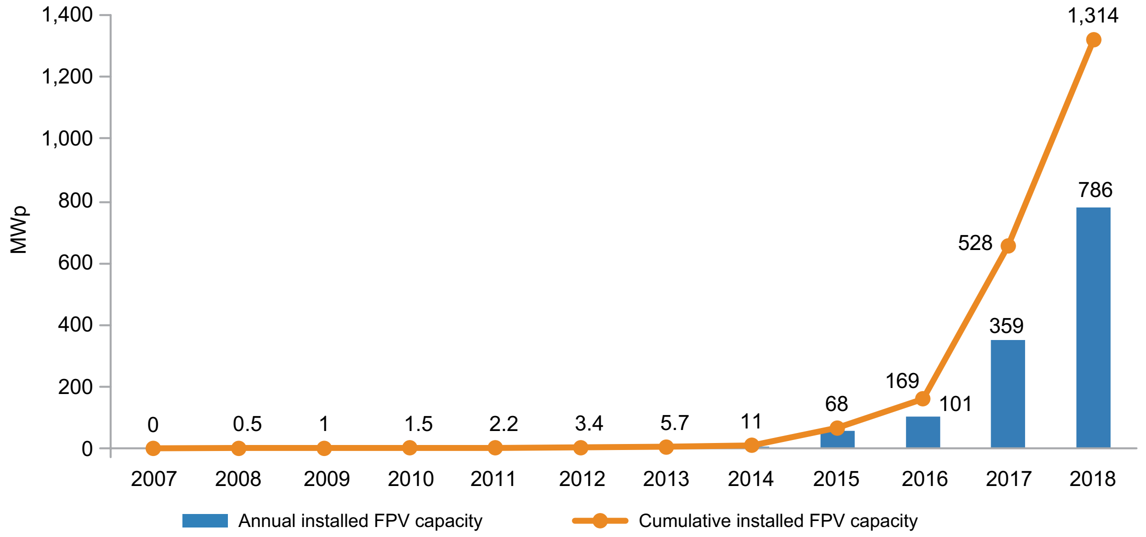
An active dialogue among all stakeholders, public and private, is required to further the global understanding of FPV technologies and the development of well-designed projects while minimizing possible negative environmental and social impacts. Through this handbook, the World Bank Group, the Energy Sector Management Assistance Program (ESMAP), and the Solar Energy Research Institute of Singapore (SERIS) hope to contribute to this goal and to disseminate lessons learned from early projects.

1.2 Market trends for floating solar

FPV installations reached 1.3 gigawatt-peak (GWp) of total installed global capacity at the end of 2018 (figure 1.1), and deployment appears likely to accelerate as the technologies mature, opening up a new frontier in the global expansion of renewable energy (World Bank Group, ESMAP, and SERIS 2019). When combined with other demonstrated benefits—such as higher energy yield, reduced evaporation, and in certain cases improved water quality—FPV is likely to be an attractive option for many countries. Several countries with high population density are looking at large-scale floating solar deployment in order to avoid using their scarce land resources for solar power generation.

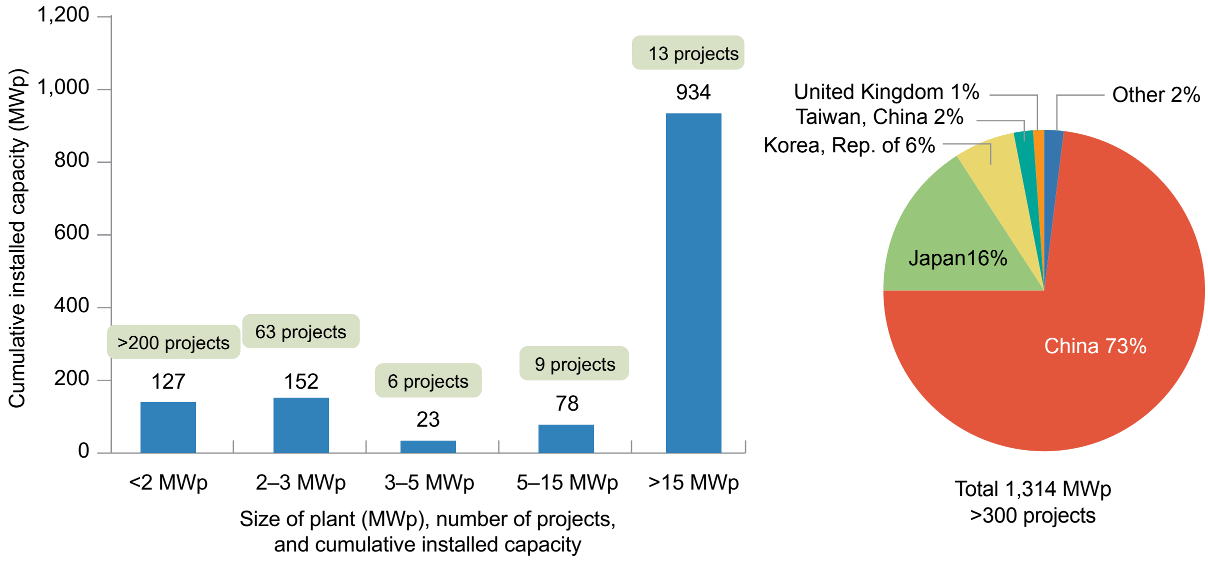
With its installation of a few large FPV systems since 2017, China has become the market leader, with installed capacity of more than 950 megawatt-peak (MWp) in 2018, representing about 73 percent of the world's total (figure 1.2). As of the end of 2018, the remainder of the installed capacity was spread mainly among Japan, the Republic of Korea, Taiwan,

FIGURE 1.1 Global installed FPV capacity and annual additions



Source: World Bank Group, ESMAP, and SERIS 2019.

FIGURE 1.2. Distribution of FPV plants according to their size, as of December 2018

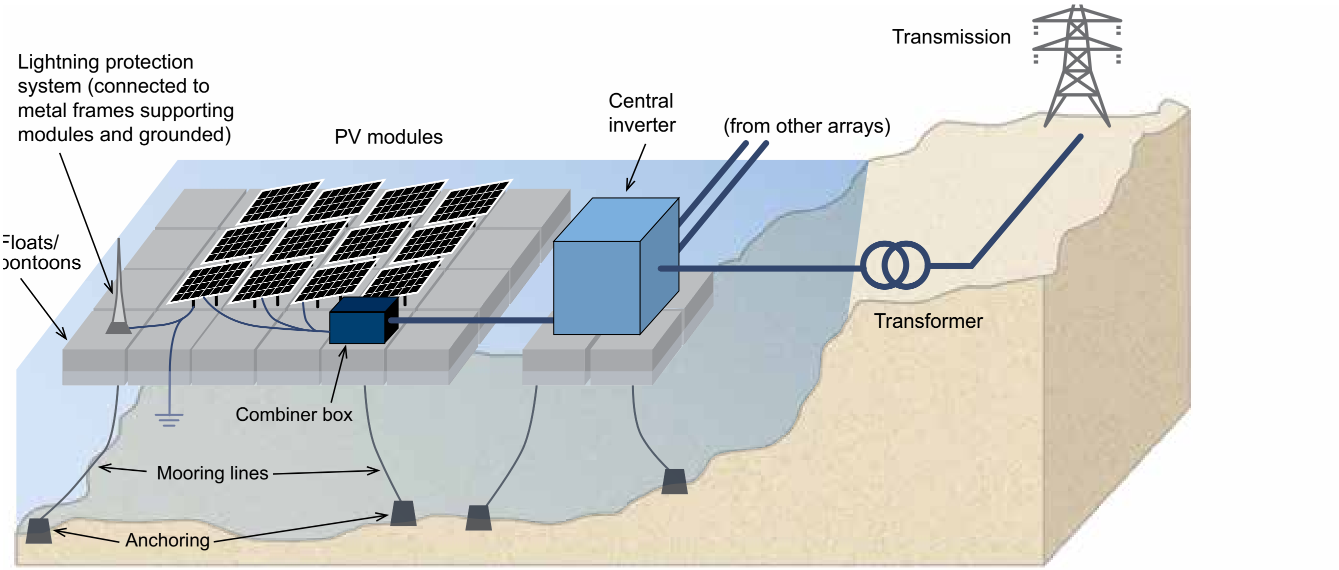


Source: World Bank Group, ESMAP, and SERIS 2019.
Note: MWp = megawatt-peak. Some projects may have been omitted, despite efforts to compile exhaustive list.

China, and the United Kingdom; the rest of the world accounted for only 2 percent. However, FPV projects were under development in more than 30 countries (World Bank Group, ESMAP, and SERIS 2019).

With a global potential of 400 GWp under conservative assumptions, FPV could become a significant market segment for solar photovoltaic (PV) deployment, without the challenges of acquiring the land required for ground-mounted installations (World Bank Group, ESMAP, and SERIS 2019). At some large hydropower plants, covering just 3–4 percent of the reservoir area with FPV could double the estimated installed capacity, potentially allowing water resources to be more strategically managed by utilizing the solar output during the day. In addition, combining the dispatch of solar and hydropower could smooth the variability of the solar output while making better use of existing transmission

FIGURE 1.3 **Schematic representation of a typical large-scale FPV system with its key components**



Source: SERIS.

assets—a benefit that could be particularly valuable in countries where grids are weak.

The general layout of an FPV system is similar to that of a land-based PV system, except the PV arrays and often the inverters are mounted on a floating platform. The floating platform is held in place by an anchoring and mooring system, the design of which depends on factors such as wind load, float type, water depth, and variability in the water level (figure 1.3).

Floating PV is benefiting from the rich experience of the land-based PV industry, significantly reducing the risks associated with the electrical aspects of the systems. Enough large-scale (megawatt-scale) projects have been implemented for FPV technology to be considered commercially viable, but technical challenges linked to the aquatic environment remain. The experiences of other technologies operating in aquatic environments, including near-shore environments, offer good lessons to incorporate in FPV designs.

In addition to technical aspects, challenges relate to the permitting and commercial aspects of development. They include a lack of clarity on licensing/permitting (especially concerning water rights and environmental impact assessment); difficulties in selecting qualified suppliers and contractors, as a result of a general lack of experience in this relatively immature market segment; difficulties in designing insurance policies that include liabilities for potential damage of hydropower plants; and uncertainties about the adequacy of warranties on the performance or reliability of critical components, such as the floating structure and the anchoring and mooring system. In most countries, the policy and regulatory framework needs to be adjusted to provide more clarity on some of these areas.

General information on the FPV market, technologies, policies, and costs can be found in the first report from the Where Sun Meets Water series: Floating Solar Market Report (World Bank Group, ESMAP, and SERIS 2019).

1.3 Key phases of a floating solar project

As in a conventional, ground-mounted PV project, the development of an FPV project can be divided into several stages, from inception of the idea to the start of commercial operations, as described in "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015). Similar to ground-mounted PV projects, developing an FPV project involves many stages and requires a multidisciplinary team of experts to perform all the required tasks. Projects typically start with concept development and site identification, followed by prefeasibility and feasibility studies, permitting, financing, engineering, construction, and commercial operation.

Each of these stages consists of a distinct set of activities, some of which may be conducted in parallel. The stages are often sequenced according to milestones along a project timeline.

As preconstruction activities are crucial, adequate time and resources must be spent on them. Certain activities, such as the environmental and social impact assessment, need to start from project inception and be repeated as project development proceeds, with ever-increasing level of detail, until financial closure.

Table 1.1 shows a project development overview of a typical utility-scale PV project. It is also applicable to FPV projects. The timing and sequence of activities in prefeasibility, feasibility and financing/contract stages can vary significantly by project.

During the concept stage, a project investment opportunity is identified and the developer looks for a site on which to build the project. A preliminary or conceptual design is developed to help estimate installed capacity, the budget, energy yield, and the expected tariff and associate revenues (implying that the developer must have a good understanding of the regulatory framework and any financial support mechanisms). Offtaker creditworthiness and a financing strategy will also be looked at. This stage aims to understand the main risks, costs, and revenues associated with the project, in order to evaluate whether it is worth pursuing.

A prefeasibility study follows. The developer fine-tunes its assessment of the plant design and the investment requirements from the concept stage to further assess the financial viability of the project. The advantages and disadvantages of different technical options are considered in terms of efficiency and costs. Further market assessment and permitting needs are researched, to improve costs and revenue estimates, and potential legal risk is identified.

The feasibility study can be similar to the prefeasibility study. The main difference is that the feasibility study

TABLE 1.1 Stages of development and main activities for a utility-scale PV or FPV project

Stage of project development	Main activities
Site identification/concept	• Identification of potential site(s) • Funding of project development • Development of rough technical concept
Prefeasibility study	• Assessment of technical options • Estimate of costs/benefits • Assessment of permitting needs • Market assessment
Feasibility study	• Technical and financial evaluation of preferred option • Assessment of financing options • Initiation of permitting process • Development of fine-tuned technical concept
Financing/contracts	• Permitting • Development of contracting strategy • Selection of suppliers and negotiation of contracts • Financing of project
Detailed design	• Preparation of detailed design for all relevant lots • Preparation of project implementation schedule • Finalization of permitting process
Construction	• Supervision of construction
Commissioning	• Performance testing • Preparation of as-built design (if required)

Source: Adapted from IFC 2015.

uses site-specific data and fine-tuned assumptions, in order to identify the best viable option (for example, the preferred site, if multiple are considered, preferred technical design, or financing option). The permitting process can also be initiated at this stage, together with a detailed review of environmental and social considerations and the identification of potential grid-connection issues.

The financing/contract stage typically includes obtaining permits, securing funding, preparing a detailed and bankable financial model, and beginning pre-implementation activities, such as the set-up of commercial contracts for the owner's engineer; engineering, procurement, and construction (EPC); the power purchase agreement (PPA); and operations and maintenance (O&M). A detailed environmental and social impact assessment may be required during this stage. Obtaining permits may require amending plant design. In certain locations, for example, anchoring on the reservoir bed is not allowed (only bank anchoring is possible). These constraints should be identified early on, as they might affect the overall design as well as the financial viability of the plants.

Detailed engineering/plant design and procurement of equipment are typically coordinated by an EPC contractor based on specifications agreed upon with the developer/owner. Construction activities are implemented during this stage. At the end of construction activities, acceptance tests are performed. If the results are positive, the plant is transferred to the owner/operator. Commercial operation, including the performance and reliability tests specified in the EPC contract, starts after commissioning.

During project development, the developer gathers sufficient data and information to estimate the risks involved and make an informed decision about whether or not to proceed further. The time to completion of a typical FPV project (from the initiation phase) varies, depending on local administrative requirements, the degree to which tasks are spaced out, the amount of resources involved, and the types of contracts issued to subcontractors, among other factors. In general, megawatt-scale projects take one to three years to develop from project initiation until the plant becomes fully operational. Compared with ground-mounted PV, the initiation phase of an FPV project may take longer, which can be attributed to the relative immaturity of this market segment and FPV-specific technical considerations, such as site identification, engineering designs, and the absence of applicable regulations. In contrast, the regulatory and administrative process can be relatively simple on sites where installation is planned on a water body owned by a single entity, such as a private industrial site, and construction of FPV projects typically takes less time than construction of ground-mounted PV projects, as less site preparation is needed.

Most activities necessary for development of FPV projects are similar to those for ground-mounted PV projects. "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015) provides detailed information on aspects that are pertinent to both FPV and land-based PV projects. This report focuses on aspects of the development process that are unique or particularly important to FPV projects, such as site identification, energy yield assessment, engineering design, permitting, environmental and social impact, procurement and construction, testing, commissioning, and O&M.

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2 SITE IDENTIFICATION

2.1 Introduction

Proper site selection for floating photovoltaic (FPV) is a prerequisite for successful project development. The site must be identified during early-stage concept development and before feasibility studies are done. Early data collection allows project developers to make informed assessments of projects' viability. The aim at this stage is to choose the best possible site for the project or to shortlist the most promising sites. In general, the selection methodology is similar to that used for ground-mounted PV projects, as described in the report "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015). The ideal site should have adequate solar irradiance, a favorable local climate, shallow reservoir depths, a water surface not used for competing purposes, an accessible grid-connection point, and a stable legal and regulatory framework for FPV development.

The regional or climatic location of the water body also plays a role, especially when it comes to mechanical and thermomechanical stresses. For example, wind and wave events caused by typhoons have necessitated changes in design in some cases (Sahu, Yadav, and Sudhakar 2016). Similarly, alpine lakes or certain water bodies located in the northern hemisphere undergo seasonal freezing, which can create problems for FPV. And offshore installations will be subject to mechanical stresses far greater than those experienced by plants based on land or in fresh-water environments.

The main considerations for assessing site suitability for FPV installations include:

- Solar resource
- Local climate conditions
- Available water surface area and shape
- Bathymetry
- Water level, wave amplitudes, and wind speeds
- Subsurface soil conditions
- Shading, soiling, and other site conditions
- Environmental considerations
- Grid access, substation location, and power availability
- Access rights, permits, and regulations

Site selection considerations for floating PV compared with land-based PV systems is shown in table 2.1.

TABLE 2.1 Floating and land-based photovoltaic systems: A comparison of site identification aspects

	Floating PV	Land-based PV
Land/water surface use	• Does not compete for land with agricultural, industrial, or residential projects • Often easier to find sites near densely populated areas • Potential integration with aquaculture	• Suitable/affordable land may be far away from load centers, thus requiring costly transmission infrastructure • Requires change in land use, which can be time consuming • Competes for land with city dwellings, industrial development, and agriculture though in certain cases integration is possible
Power system benefits	• Synergy with existing electrical infrastructure (e.g. hydropower plants) • Possible hybrid operation with hydropower	• Costs of grid interconnection are often borne by project developer and can be prohibitively high

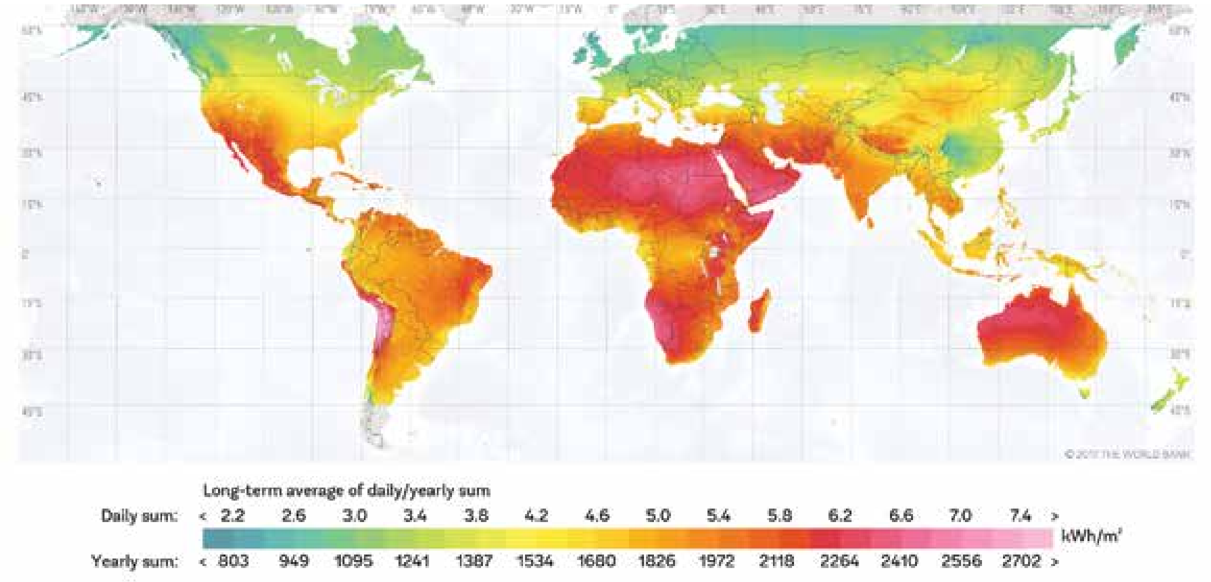
Source: Authors' compilation.

2.2 Solar irradiance and climate conditions

As with other PV projects, data on solar irradiance at the proposed water surface is of primary importance. Because solar irradiance determines the energy yield and project economics, it should therefore be assessed at the site-identification stage. Such information can be readily retrieved from various resources such as the Global Solar Atlas (figure 2.1).

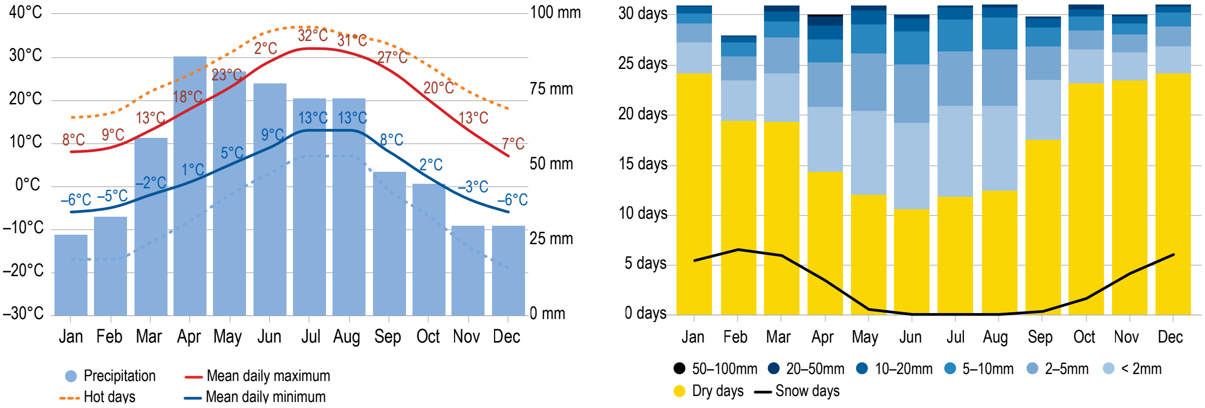
Climatic conditions also have significant implications for construction, foundations, system design and layout, as well as system reliability. Seasonal variations in weather—such as temperature range, precipitation, wind speed, wind direction, humidity, pollution index, lightning occurrence, and storm statistics (examples shown in figures 2.2–2.4)—are key factors that require close study. Usually, only generic data with low spatial resolution is available, but efforts should be made to obtain the most refined and accurate meteorological

FIGURE 2.1. Solar irradiance map from Global Solar Atlas



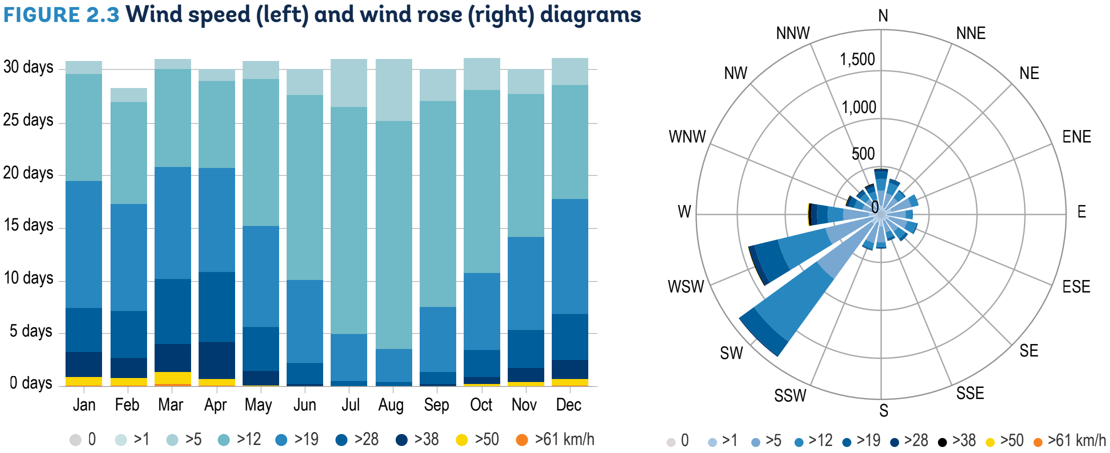
Source: Global Solar Atlas (https://globalsolaratlas.info), © World Bank Group (2019).
Note: kWh/m² = kilowatt-hour per square meter.

FIGURE 2.2 Example of seasonal weather variation: temperature (left) and rainfall (right)



Source: Meteoblue (https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/denver_united-states-of-america_5419384).

FIGURE 2.3 **Wind speed (left) and wind rose (right) diagrams**



Source: Meteoblue (https://www.meteoblue.com/en/weather/archive/windrose/singapore_singapore_1880252).

readings on local water bodies, as their microclimate (for example, humidity) may differ slightly from surrounding land areas.

Wind is an important consideration. The prevailing direction should be determined for both extreme gusts and average speeds. This is especially so for typhoon- and hurricane-prone regions. Figure 2.4 shows tropical storm paths recorded from 1968 to 2018. Because natural catastrophes like typhoons or hurricanes are becoming more frequent and extreme, their likelihood should be considered early in the site identification phase. Strategies for mitigating the effects of extreme storm events are discussed in more detail in chapter 4, which addresses mechanical stability and the mooring and anchoring of floating PV systems. Subsequently, waves need to be studied by considering water currents, the fetch lengths of the water surface, or tides if applicable. All this information together provides the initial considerations required to design a floating structure and anchoring system. For dams and reservoirs, comprehensive studies on wind and expected wave characteristics often already exist. It might be useful to seek this information from the relevant parties to save time and effort.

2.3 Bathymetry and water body characteristics

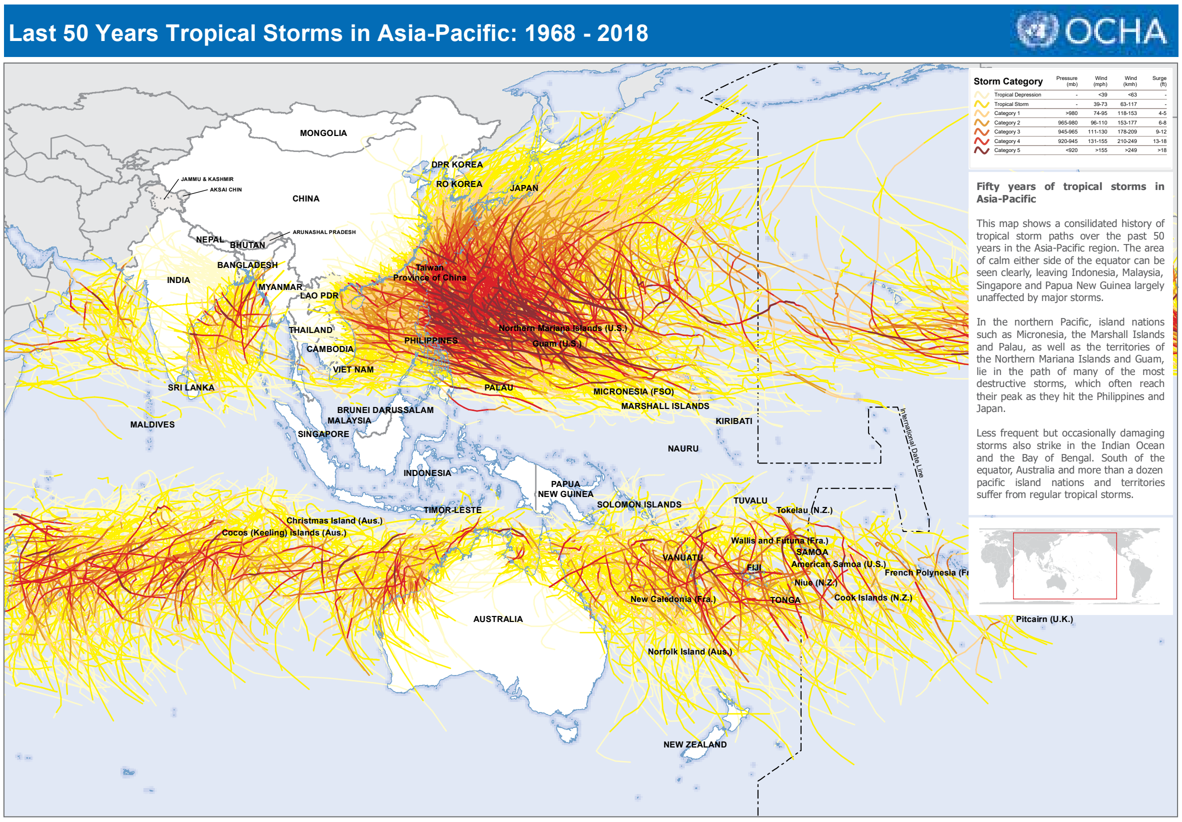
The essential information to collect regarding a water body is summarized in figure 2.5, which include:

- Shape of the boundaries
- Average depth and depth distribution
- Structure of the water bed, including properties of subsoil at different strata
- Sedimentation and sedimentation load rate (in case of dams)
- Structure of the water body banks
- Hydrology and water level variations

In particular, bathymetry is important for choosing a position for the floating island and designing the mooring and anchoring systems. Bathymetry is the mapping of the water body bed, with depth contours providing the size, shape, and distribution of underwater features. A bathymetry report (figure 2.6) should include the topographic map, boring logs, and detailed relief of the water bed (Jaiswal and others 2016). The common grid size for bathymetry survey ranges from 100m x 100m to 2m x 2m. To make it cost-effective, bathymetry could be conducted with a large grid size while identifying a suitable area within the water body. Once a suitable area is identified, then a study with a smaller grid size is conducted. A 5m x 5m grid size is a reasonable choice, but suitability ultimately depends on the type and condition of the water body.

A rectangular or square body of water would help to maximize area utilization. Irregular-shaped water bodies generally have smaller percentage of area available for deployment. Any obstacles in/on the

FIGURE 2.4 Historical records (paths and categories) of tropical storms in the Asia-Pacific over the past 50 years (1968–2018)



Last 50 Years Tropical Storms in Asia-Pacific: 1968 - 2018

Storm Category	Pressure (mb)	Wind (mph)	Wind (kmh)	Surge (ft)
Tropical Depression	-	<39	<63	-
Tropical Storm	-	39-73	63-117	-
Category 1	>980	74-95	118-153	4-5
Category 2	965-980	96-110	153-177	6-8
Category 3	945-965	111-130	178-209	9-12
Category 4	920-945	131-155	210-249	13-18
Category 5	<920	>155	>249	>18

Fifty years of tropical storms in Asia-Pacific

This map shows a consilidated history of tropical storm paths over the past 50 years in the Asia-Pacific region. The area of calm either side of the equator can be seen clearly, leaving Indonesia, Malaysia, Singapore and Papua New Guinea largely unaffected by major storms.

In the northern Pacific, island nations such as Micronesia, the Marshall Islands and Palau, as well as the territories of the Northern Mariana Islands and Guam, lie in the path of many of the most destructive storms, which often reach their peak as they hit the Philippines and Japan.

Less frequent but occasionally damaging storms also strike in the Indian Ocean and the Bay of Bengal. South of the equator, Australia and more than a dozen pacific island nations and territories suffer from regular tropical storms.

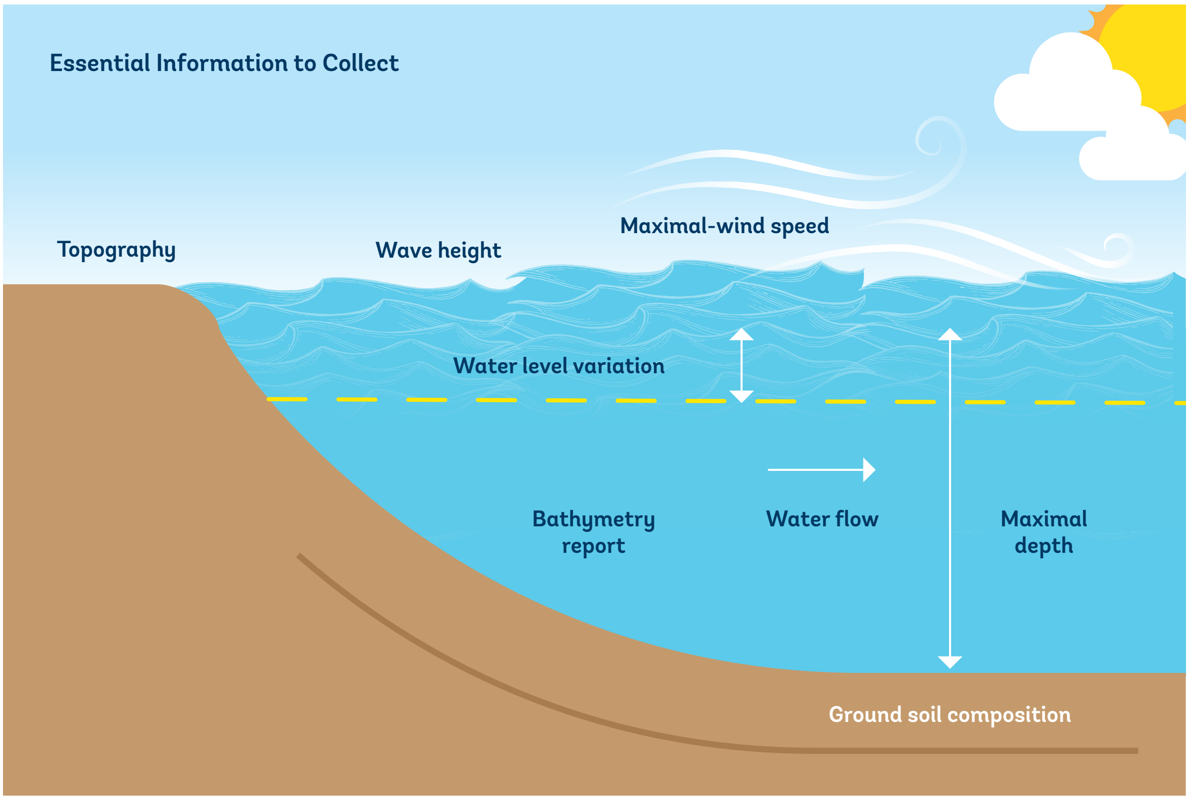
Source: UN Office for the Coordination of Humanitarian Affairs (OHCA) (https://reliefweb.int/map/world/last-50-years-tropical-storms-asia-pacific-1968-2018).

water (for example, a bridge, small islands, pipelines, cables, and so on) would also affect the available area for deployment. In general, for FPV deployment, one MWp requires roughly 1 hectare for the floating island and 1.7 hectares of water area, after taking into account anchoring.

Water level is another crucial piece of information to gather, and this includes the depth at different points as well as the water-level changes over different seasons. Water-level variation due to reservoir operation, serving purposes like hydropower generation or irrigation, should also be taken into consideration. In general, FPV is best deployed at sites where water levels are 15 meters deep or less, with minimum variation. For sites with considerable water-level variation, the system will have to be designed for extreme water-level variations as well as short-term variations due to waves or tides. In the event where water completely dries out and the bottom exposed, it is important to ensure that the bottom terrain and obstacles such as rocks and tree branches will not damage the floating structures. It should be noted that not all floats are designed to handle such events, which might void their warranties in this scenario. Therefore prior agreement should be made with the float manufacturers. Greater depths and water-level variations will require more complex and costly anchoring and mooring solutions.

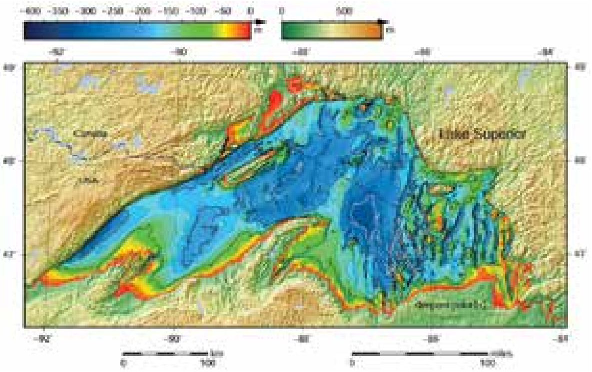
A project developer will also want to consider the type of banks a water body has. An ideal FPV site would be a body of water with a natural bund, with compact soil and gentle slopes—ideal for the construction of launching ramps. The FPV islands can be assembled on land and then progressively pushed into the water body. Water bodies with a bund wall will require lifting equipment or a temporary launching structure, which adds to costs.

FIGURE 2.5 **Water body characteristics**



Source: Authors' compilation based on Ciel & Terre International.
Note: Water quality and other weather conditions such as the possibility of frost, snow, and hail should also be collected, where relevant.

FIGURE 2.6 **Sample bathymetry report**



Source: National Geophysical Data Center 1999.

2.4 Soil investigations and water analysis

Solar PV construction projects often involve earthwork, foundations for substations, and other general construction works. Designs of foundations and excavations require accurate soil analysis and data on soil-structure interactions. In the case of FPV, a water body's subsurface soil conditions influence the anchoring methods and location (on the bottom or attached to the banks).

Typically, this work is done by geotechnical, civil, and structural experts during the site assessment. Analyses of soil and groundwater tests should be performed to identify soil composition, strength, and chemical properties (such as pH, sulphate, chloride, magnesium, and salinity). Sample sinkers are also dropped into the water body and monitored over an adequate period of time (figure 2.7).

Exploratory boreholes (that is, drilling for disturbed and undisturbed soil samples at different depths for the Standard Penetration Test) are drilled, and laboratory testing of the collected soil samples are performed. Results are typically presented as logs or borehole models showing the soil composition and its properties at each depth.

FIGURE 2.7 Concrete sinker test, Singapore Tengeh Reservoir testbed

Source: © SERIS.

Testing the water quality and performing an elemental compositional analysis of the water are also important. The amount of minerals and salinity will determine the materials used when components are selected for the project. Extremely briny water will require the use of anticorrosive materials.

2.5 Shading, soiling, and environmental considerations

FPV projects generally benefit from openness and flat water bodies that have minimal shade; attention needs to be paid to central inverters at the center of FPV arrays. These may cast shadows if the entire design does not leave enough spacing. In addition, some water bodies may be located in mountainous areas where horizontal shading from afar may become a concern. FPV systems also tend to suffer less soiling from dust than installations on land; biosoiling (particularly from bird droppings) can adversely impact performance. This may lead to hotspots and accelerated degradation and higher O&M costs (Ghazi and Ip 2014). Project developers should therefore conduct a preliminary survey of bird species and their numbers at the site. This survey can be part of environmental impact studies that help developers assess the effect of an FPV system on a site's fauna and flora, especially marine life, water quality, and algae growth. Environmental impacts and social considerations are explained in more detail in chapter 6.

2.6 Accessibility, grid infrastructure, and power availability

Proximity to a main road is beneficial as transportation costs of all required materials affect the overall cost of FPV projects. For a utility-scale project, the amount of materials requiring transport from storage to the construction site is substantial. The site should be served by roads (ideally, gravel-chip finish or better) that allow truck access. The closer the site is to a main access road, the lower the cost of additional infrastructure and safe transportation of solar panels.

One large cost element of PV projects can be the capital required to connect to the grid. New grid infrastructure is costly, so system integrators are often advised to site their projects near existing grid connections (that is, within 1–3 kilometers). Careful study will ascertain the ability of existing power grids to manage the generation capacity of large-scale FPV plants. Auxiliary grid power is recommended during the construction phase of the project. Running construction machinery on diesel generators adds to the cost of the project.

2.7 Other site conditions

From a reliability and safety perspective, the importance of operational environment (temperature, humidity) and structural loads (wind) (Camus and others 2017) is similar to a ground-based system. But water environment may imply greater relative humidity and more wave- or weather-induced static and dynamic loads on the solar modules and electrical connections. The following factors need to be carefully assessed to maximize the benefits and minimize risks of a water environment:

- Temperature
  - Take advantage of convective cooling by providing good airflow around the panels.
  - Evaluate the area for potential soiling (precipitates from the water) or biofouling that can lead to hotspots.
- Humidity/water
  - Saltwater or briny coastal systems create a more corrosive environment for metals, including structural elements, grounding, and electrical connectors and wiring.
  - Potential induced degradation (PID) is accelerated by voltage levels and moisture. Dew points should be considered from prevailing humidity and air temperature levels. Discussions on how these affect module selection can be found in chapter 4 (section 4.4) and Annex A.
  - Consider the possibilities for mounting panels above the water; the larger clearances achieved with pontoons/stilts may reduce the impact of humidity on the panels.
- Mechanical loads
  - Identify risks for catastrophic wind events (typhoon, hurricane).
  - Roughly evaluate mechanical stress of mounted structures with respect to dynamic and static loads.
  - Expect greater challenges for coastal/offshore sites due to larger waves and platform movement.
- Animal activities
  - Other than birds, animals in natural habitats at the site (otters, crocodiles, water rats, snakes, and fish) may have certain implications on the system performance, O&M, and personnel safety.

2.8 Summary for selecting a water body

Table 2.2 provides a summary of key elements to consider when selecting a water body for an FPV system. It is unlikely that a site possesses all the desirable features. In these cases, a cost-benefit analysis will help developers ensure that benefits outweigh possible costs.

TABLE 2.2 Decisive factors in selecting a water body for a floating solar photovoltaic plant

Factor	High preference	Low preference
Location	• Near load centers and populated regions • Easily accessible by road • Secured/fenced • Close to manufacturing facilities or ports for simplified logistics	• Remote places with high transportation cost[a]
Weather and climate	• High solar irradiation • Little wind or storms • Calm water • Dry region where water conservation is important	• Cold regions with freezing water • High winds and risk of natural disasters such as typhoons and tsunamis • Seasonal flooding • Drought events that lead to exposure of water bed
Type of water body	• Manmade reservoirs • Hydropower dams • Industrial water bodies such as cooling ponds and wastewater treatment facilities[b] • Mine subsidence areas • Irrigation ponds	• Natural lakes • Tourist or recreational sites
Water body characteristics	• Regular shape • Wide opening toward south (for northern hemisphere) or north (for southern hemisphere)	• Narrow strip between mountains (gorges) • Presence of islands/obstacles in the middle
Water body ownership	• Single owner • Legal-entity owner	• Multiple owners • Individual private owners
Underwater terrain and soil conditions	• Shallow depth • Even terrain • Hard ground for anchoring • Water bottom clear of any cables, pipelines or other obstructions	• Soft mud ground for anchoring
Water conditions	• Freshwater with low hardness and salinity	• Salty water • Dirty/corrosive water • Water prone to biofouling
Other site conditions	• Existing electrical infrastructure, transmission lines • Easy water access • Sufficient land area for deploying and placing electrical equipment • Self-consumption loads such as wastewater treatment and irrigation pump facilities	• No existing electrical infrastructure[c] • Complicated banks, presence of bund walls • Extensive horizon shading from nearby mountains • Nearby pollution sources (for example, chimneys, burning crops, quarries)
Ecology	• Simple and robust ecology	• Natural habitat of preserved species • Frequent bird activity • Water species that are sensitive to water temperature, dissolved oxygen, and sunlight

Source: Authors' compilation.

a. In some cases FPV can be highly valuable to remote regions.

b. This is relevant only if water quality remains suitable for FPV.

c. This may not be a concern, depending on the circumstances of the FPV project.

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3 ENERGY YIELD ANALYSIS

3.1 Introduction

During the feasibility study, the developer needs to estimate a project's likely energy yield. The efficiency of PV systems under time-varying operating conditions depends not only on system design and components but also on various environmental factors. Mechanisms contributing to energy losses should be broken down in a loss diagram (see an example in figure 3.1).

A good energy-yield analysis uses irradiance data from various sources to predict how much electricity a PV system might generate. Poor-quality solar irradiance data will yield inaccurate results even if good simulation programs are used. The irradiance data is fed into simulation software that estimates the energy production expected from a system at the chosen site. Different programs such as PVsyst, PVSol by Valentine Software, HelioScope, and SAM provided by National Renewable Energy Laboratory (NREL) are available on the market. These types of software are also suitable for FPV systems, but certain parameters and assumptions need to be adjusted to reflect the difference from typical ground-mounted systems. For example, one parameter to note in particular for FPV is the thermal-loss factor, which is used to model the module temperature. Its value could be higher than for ground-mounted and rooftop PV systems due to better module cooling on water.

Energy yield prediction is well known to most project engineers. The overall framework is the same as for ground-mounted PV projects. Readers are encouraged to refer to "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015) for further details. It should be noted, however, that bodies of water create microclimates, so the environment at the project site may differ from what weather stations predict for the region. The mechanisms leading to various losses are generally not identical to conventional ground-mounted or rooftop projects either. The following sections discuss key considerations for simulating the energy yields of FPV systems by highlighting some elements that may be different.

A general (simplified) comparison on energy yield between floating and land-based PV systems is shown in table 3.1.

3.2 Solar resource and irradiance in the plane of solar modules

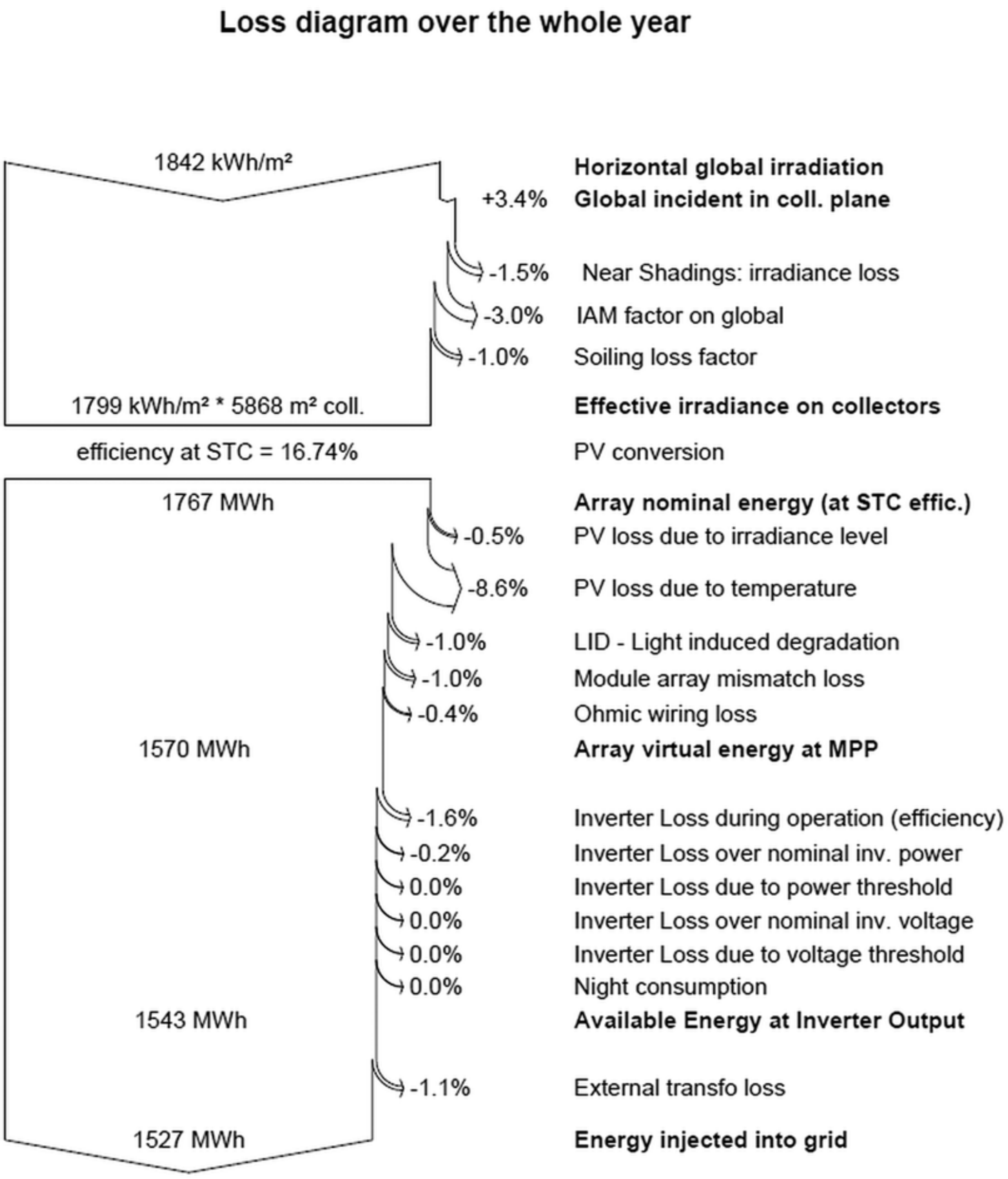
Adequate prediction of system generation requires input of accurate solar irradiation with its subcomponents:

- Direct normal irradiation (DNI)
- Diffuse horizontal irradiation (DHI)
- Global horizontal irradiation (GHI)

Ideally, weather and solar irradiation measurements from ground weather stations at or near the site location, or at least site-adapted satellite-derived data, should be used for project planning or design. Numerous databases exist for estimating solar resource. Solargis, 3Tier and Meteonorm are examples of solar irradiance data with wide geographical coverage.

The ideal tilt angle varies according to site latitude. As a rule of thumb, solar modules should be tilted at angles close to the latitude of the location for capturing maximum direct sunlight. Module tilts toward true south for the northern hemisphere and true north for the southern hemisphere; they can be optimized using simulations, similar to the analysis for ground-mounted PV plants. For FPV, however, the tilt angle may be limited by float design and wind load. Most FPV plants use

FIGURE 3.1 A loss diagram from typical report of PVSyst



Source: SERIS (adapted from PVSyst).

tilt angles not greater than 15 degrees; tilts at these angles allow for the so-called self-cleaning effect—where rainfall is frequent enough to wash off substantial accumulations of dirt and dust on the PV module surfaces. Some commercially available floats allow for tilt angles to be adjusted from 5 to 20 degrees. The simulation software automatically calculates the amount of irradiance received in the module plane.

3.3 Shading losses

An advantage of FPV systems over ground-mounted systems is that water surfaces are both flat and distant from structures like trees or buildings that cast shade on ground-mounted or rooftop systems. In addition, the low tilt angle of modules means minimal inter-row shading. Nevertheless, shading from far horizons or adjacent to the banks may occur, especially in mountainous regions, so a shading analysis should still be

TABLE 3.1 Floating and land-based photovoltaic systems: A comparison of energy yield aspects

	Floating PV	Land-based PV
Operating environment	• Open and flat surface • Low reflected diffuse light from water surface • General presence of evaporative cooling and higher wind speed • Presence of dynamic movement	• Terrain type may vary • Albedo depends on ground type • No movement
Losses	• Lower module temperatures (effect is dependent on climate) • Nearly no shading from nearby objects • Less soiling from dust, but potentially more from bird droppings • Potential mismatch loss from temperature inhomogeneity and misalignment in module facing	• More temperature losses in hot and arid climates • More sources of shading and string mismatch
Performance	• Overall higher initial performance ratio (5–10 percent, climate specific) • Long-term degradation (e.g., potential induced degradation) is still uncertain	• Can benefit from tracking, bifacial modules, and optimum tilt angle / row spacing • Yield prediction is better established

Source: Authors' compilation.

conducted. Note that shading may even change diurnally or seasonally when there are significant water level variations. Central inverters in the middle of floating arrays can also cast shadows if the design does not leave sufficient spacing. Dedicated instruments (such as SunEye® from Solmetric) are sometimes needed to conduct shading assessments.

3.4 Soiling

In real-world installations, PV modules are often covered with substances (for example, dust, dirt, biomass particles, leaves, bird droppings, salt and scale deposits) that can obscure the light path. Losses due to soiling are location-dependent. They are usually 1-3 percent without considering unusual sources of soiling, depending on site conditions and cleaning schedules. To minimize soiling losses, tilt angles of at least 10 degrees are recommended; this allows for better self-cleaning through natural rainfall than lower angles.

Bird droppings are sources of soiling. Nesting birds prefer sheltered areas and minimal disturbance from humans. As it happens, solar panels and the floats between rows of panels provide such retreats, allowing birds to rest without disturbance. Heavy soiling can be the result, however, which then by far exceeds the 3 percent soiling usually assumed (figure 3.2).

3.5 Temperature-dependent losses

For an irradiance of 1,000 W/m^2, the temperature coefficient of the selected module determines the deviation of the power at non-standard test conditions—that is, when the module operates at temperatures other than the 25°C prescribed in the standard test condition.

Efficiency losses caused by the higher operating temperatures of PV panels constitute a major loss factor for energy generation in hot locations, where a large share of the market potential for FPV lies. Careful assessment of potential cooling effects (for example, from wind or the surrounding water) and the calculation of operating temperatures are therefore important for an accurate yield analysis. The ambient air temperature on water tends to be lower than on the ground. Wind speed also tends to be higher, improving ventilation of PV modules on water. As a result, cooling is typically more effective for floating than for ground- or rooftop-based PV systems.

Standard meteorological databases and simulation software tools do not automatically reflect those favorable ambient conditions. Manual adjustments may therefore be required after the site survey to accurately reflect the operating conditions. During simulations, the module temperature is simulated with analytic models and empirically parameterized coefficients. A common and simple model relates module temperature to incident irradiance and air temperature, whereby the

FIGURE 3.2 **Severe bird droppings on an FPV project in the United Kingdom**

Source: © Lightsource BP Floating Solar Array, London.

cooling effect is reflected as U-values, or heat-loss coefficients (see box 3.1). A case study from Singapore Tengeh Reservoir testbed shows actual results about this cooling effect (see box 3.2).

3.6 Water surface albedo

For FPV, backside irradiance is generally smaller than ground-mounted or rooftop installations due to low water-surface reflection (albedo). Therefore, bifacial modules deployed in FPV will likely not enjoy power generation gains. Real-world measurements from the Singapore testbed showed that water surface reflectivity is low (average 6 percent) at typical daytime incidence angles—lower than those of a concrete rooftop (figure 3.5) (Liu and others 2018)—and the reflection is mainly specular but not diffuse. This implies that reflection from water surface will not play a large role during the majority of a day when sun position is high. In addition, most large-scale FPV installations have low tilt angles, which further reduce possible gains from harnessing backside diffuse irradiation for bifacial modules.

3.7 Mismatch losses

Mismatch losses are introduced both within a string of PV modules or between different strings of the same maximum power point tracking (MPPT). These might come from differences among modules, as well as inhomogeneity in the incoming irradiance and temperature distribution at different locations of a system. In general, mismatch losses on the order of 1 percent are considered standard values for ground-mounted installations, and can be adopted for FPV. For floating platforms, however, with large relative movement between modules as a result of waves, misaligned orientations of individual PV modules may introduce additional mismatch losses. The exact loss depends on the complex interplay among factors like module tilt and sun position (which are generally related to latitude), relative share of direct and diffuse light, and wave characteristics. It is

BOX 3.1

Module temperature simulation

Module operating temperature T_m depends on both ambient air temperature T_a and irradiance level G. It is usually modelled according to Eq. 1 below:

$$T_m = T_a + G \cdot \left(\frac{\tau \cdot \alpha}{u_L}\right) \cdot \left(1 - \frac{\eta(T)}{\tau \cdot \alpha}\right) \qquad \text{(Eq. 1)}$$

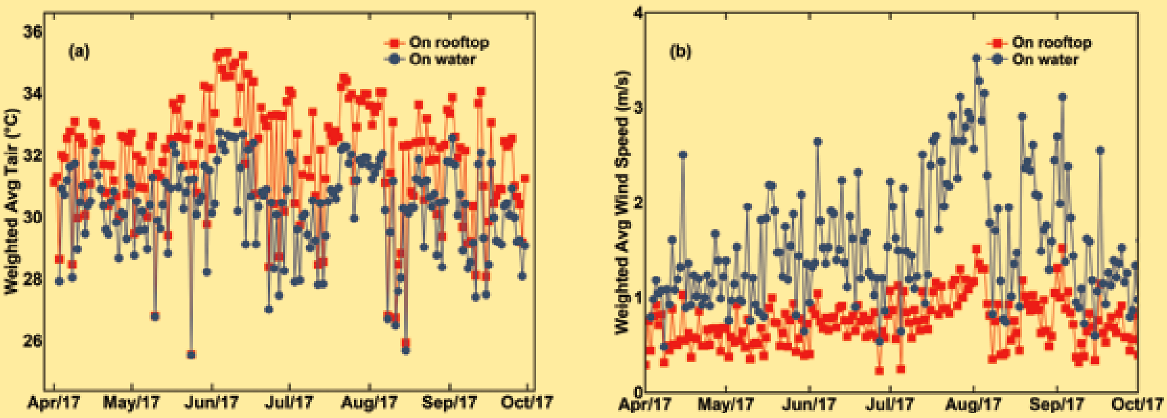
where τ is the transmittance of glazing, α is the fraction of the solar spectrum absorbed, u_L the heat loss coefficient (or U-value, which has a unit of W/m^{2}K), $\eta(T)$ is the efficiency of the module, which is itself also dependent on temperature. This equation essentially describes an energy balance between incoming radiation flux, energy extracted as electrical energy by solar cells, and waste heat that is dissipated to the surrounding. More simply, the module temperature is roughly linearly dependent on irradiance level: $T_m = T_a + kG$. Here k is known as the Ross coefficient. U-value measures how effective waste heat is dissipated to the surrounding. The higher the U-value, the lower operating temperature would be.

BOX 3.2

Case study from Singapore’s testbed

A study from Singapore’s FPV testbed revealed that the ambient above-water air temperature is lower by around 1–3°C, compared with an adjacent rooftop installation; wind speeds are also consistently higher (Liu and others 2018) (figure 3.3).

FIGURE 3.3 (a) Average daily ambient air temperature and (b) daily average wind speed for on-water (offshore) and on-rooftop (onshore) environments

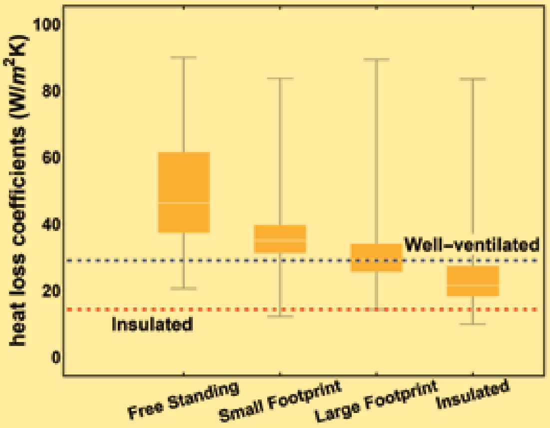


Source: Liu and others 2018.

More in-depth analysis indicates that the cooling effect depends on the type of floating platform and the array configuration (figure 3.4). The cooling is best for a free-standing floating design, followed by floating structures with a small footprint (smaller water coverage and more open space at PV modules’ back for ventilation), and is least effective for platforms with a large water footprint and less ventilation. In addition to floating platform configurations, water temperature and other local climate conditions also affect cooling rates. In Singapore’s context, with its annual insolation around 1,600 kWh/m^2, increasing U-value from 30 to 35 W/m^{2}K leads to approximately 2–3°C drop in module temperature and thus a 1 percent increase in energy yield (or 16 kWh/kWp).

As a conservative estimate, for normal FPV arrays (meaning not thermally insulated dual-orientation compact design on floats with poor ventilation), the U-value assumed should be at least as good as well-ventilated ground-mounted or rooftop systems. Consequently, the simulated temperature loss should be similar to or less (in cases when ambient temperature on water is lower) than standard ground-mounted PV plants.

FIGURE 3.4 Extracted heat-loss coefficients (U-values) for different types of floating structures



Source: Liu and others 2018.

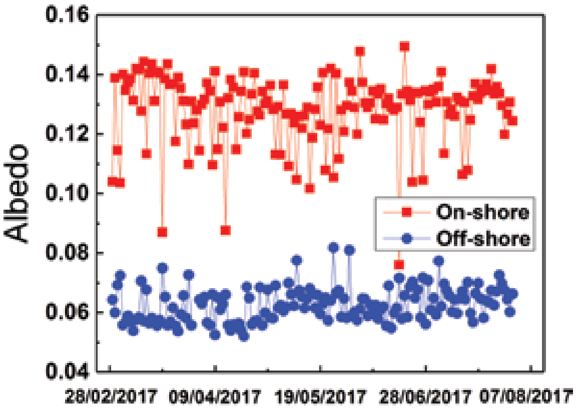
Note: Higher values correspond to better cooling. The floating structures are roughly categorized based on ventilation and water-surface coverage (footprint on the water). The graph also depicts the U-values for a well-ventilated (blue dashed line) and an insulated ground-based or rooftop system (red dashed line). The formula follows the PVSyst simulation tool.

hard to quantify at the moment, and active research is still going on. A simulation study from the Solar Energy Application Centre, part of TNO institute in the Netherlands (TNO-SEAC), estimates a loss of up to 3 percent based on wave properties observed in their testbed (Dörenkämper 2019).

3.8 Cabling losses

Accurate cable-loss estimates must consider the length of individual cables along with the cable materials and cross-sections. The choice of cables is typically made to hold losses at 0.5 percent to 2 percent. For FPV, it is important to consider island dimensions, cable-routing schemes, distance to shore, and whether inverters/transformers will be placed on a floating platform or on land. The electrical cabling losses should then be calculated accordingly. The exact loss depends on details of system design, but in principle should not be much different from ground-mounted installations.

FIGURE 3.5 Daily average albedo (weighted against irradiance) of water vs. concrete rooftop surfaces over a period of four months from a testbed in Singapore



Source: SERIS.

Note: Measurements are from Singapore's FPV testbed using an albedo meter placed 2 meters above the water's surface.

3.9 Efficiency losses of the inverter

Efficiency values for inverters are estimated with reference to the manufacturer's data sheets under the assumption of static MPPT and that the inverters operate within the specified temperature range. The dynamic MPPT efficiency, however, may be lower in reality due to highly variable conditions. Other than cloud movement, platform movement in FPV systems may also lead to rapid shifting of maximum power point that is not adequately followed by inverters.

3.10 Long-term degradation rates

The degradation rates for electrical components placed near bodies of water may differ from rates seen with land-based systems. For instance, potential induced degradation (PID) for PV modules can be an issue in high-humidity aquatic settings. Degradation rates will need to be adjusted to obtain a more realistic value of long-term energy yield and LCOE. The FPV projects are still relatively new, and systematic investigation of the actual degradation of modules and other electrical components are still being carried out.

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4 ENGINEERING DESIGN

This chapter elaborates on the engineering design and electrical safety peculiarities specific to FPV installations.

4.1 Introduction

Large-scale FPV installations to-date have almost exclusively employed pontoon-mounted crystalline silicon wafer-based modules with associated inverters and wiring. But installations of flexible membranes or self-buoyant PV modules have also been demonstrated or proposed (Bjorneklett 2017; Schmaelzle and Julian 2017); also conceptualized are modules that float above the water or that are attached to existing floating structures such as reservoir covers (Haarburger 2017). Several research groups are now also proposing FPV designs for offshore environments.

Floating PV systems can in fact have different applications with unique qualities:

- Above water (mounted on pontoons or stilts)—moderate humidity, some cooling benefit from evaporation
- On water (for example, using membranes)—high humidity, increased cooling benefit from rear-side cooling, depending on design
- Submerged—saturated humidity, potentially high convective cooling from front and rear of panel; potential for self-cleaning but also for marine-habitat formation

The "above water" application is, however, the most common, and therefore is the focus of this chapter.

The engineering design of "above water" FPV plants resembles that of ground-mounted in many respects; of course, the floating structures and the anchoring and mooring systems are different. To design the floating system, one has to account for relevant site conditions, required functionality, O&M, and environmental impact. It is particularly important to look at quality aspects of the floating structures and the mooring and anchoring systems. In addition, even though standard PV modules may be used in most FPV systems, care should be taken because modules of FPV systems need to withstand constant movement, high humidity, and the potentially higher stresses of corrosion. Cable routing and management are comparatively more critical than for ground-mounted systems. The water environment imposes more stringent requirements with regard to electrical safety. In some cases, hybrid operation with a hydropower plant may be a viable option, in which case the system is designed to harvest the synergies.

It is important to look into these specific details during the planning and design stage of an FPV project. Subsequent sections of this chapter provide details on quality and design details specific to FPV projects. For more general aspects of PV plant design, the readers may refer to "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015).

A general (simplified) comparison of plant designs for floating and land-based PV systems is shown in table 4.1.

4.2 Floating structures and platforms

4.2.1 Overview

The floating platform comprises structures with enough buoyancy to support PV modules, electrical equipment on water, as well as personnel during construction and O&M. The design of the floating system

TABLE 4.1 Floating and land-based photovoltaic systems: A comparison of plant design aspects

	Floating PV	Land-based PV
Array configuration	• Modular design on "flat" water surface • Limited tilt due to wind load considerations imply a lower energy yield in high-latitude regions • Row spacing determined by floating structure • Consists of floating islands	• Design must accommodate terrain constraints or requires leveling • Flexible row spacing • May consist of large tables of PV panels
Mounting and support structures	• Floating platform structure • Anchoring and mooring system is essential • Need to provide maintenance walkway • Floating platform experiences forces from winds, snow, waves, and water currents	• Piles and racks structure • Mounting structure experience forces from winds and snow only • Easier to implement tracking • Potentially more susceptible to resonance effects
Electrical equipment and cables	• Electrical equipment may be placed on floats or on shore • Cables mainly routed on floats • Potential need for higher protection standards and test certifications • Many floating platform designs require equipotential bonding wires	• String inverters and electrical boxes may be placed under PV modules • Cables are placed in conduits above ground or buried underground
Safety	• Platform design needs to consider more risks for personnel performing O&M • High humidity environment leads to lower insulation resistance and increased risks of electrical leakage • Proper cable management is important to accommodate constant movement that may otherwise lead to cable damage and fire risks	• Safety relatively well established

Source: Authors' compilation.

is project specific and subject to a number of considerations, some of them listed below:

- Scale of the project, including maximum possible coverage of the water body and distribution of the FPV sections (that is, grouped together or in small groups placed around the water body, for example, to reduce environmental impacts); this will affect the sizes of the individual subsections of the FPV system and determine water-evaporation reduction.
- Suitability of the water body's bed or banks to properly hold the derived subsections in place.
- Cable routing to protect cables and connectors against the high-moisture environment.
- Functions to be achieved: (i) maximize evaporative-cooling effect of the PV modules for lower operating temperatures and hence higher yield, or (ii) minimize evaporation to conserve reservoir water.
- Compatibility of the structure with preferred PV module types or key electrical components (for example, string or central inverters).
- Accessibility or configuration of maintenance corridors to carry out O&M.
- Ease and speed of deployment given the site conditions and access to the water.
- Layout configurations and impact on costs and O&M activities (Sahu, Yadav, and Sudhakar 2016).

An FPV subsection, or island, is commonly a rectangular or square platform. For large central-inverter configurations, the inverters sit on floating platforms at the center of the plant to minimize cable runs and electrical losses (figure 4.1). For string-inverter configurations, they are usually placed alongside each platform (figure 4.2) on secondary or multifunction floats designed to hold electrical equipment or serve as maintenance walkways. For small systems near the bank, inverters can be placed onshore; these better-protected and less humid settings also provide easier access for maintenance crews. But for larger systems, onshore solutions are not always possible because of the long runs of DC cable. Remote strings experience greater voltage and ohmic losses

FIGURE 4.1 Central-inverter configuration for FPV systems, China

Source: © Sungrow.

FIGURE 4.2 Layout of FPV systems with string inverter placed on floats, Singapore Tengeh Reservoir testbed

Source: © SERIS.

and increase design complexity because the various strings can be mismatched by the time they reach the inverter. But on-water inverters require higher safety measures to prevent loss of buoyancy and toppling—this last possibility poses a risk to personnel safety.

The maximum size of an island depends on the floats' capability to withstand the stress induced by various forces, including wind load; these stresses are typically evaluated using finite element analysis (FEA) and computational fluid dynamics (CFD). Access routes and corridors (or at least space) are desirable, as they allow maintenance crews to move around the platforms. Some platform designs have no permanent walkways but are designed so temporary bridges or planks can be laid down to ease ad hoc access.

4.2.2 Quality and reliability aspects

Floats are generally made of high-density polyethylene (HDPE); different additives provide for UV resistance and other physical properties. HDPE floats are used with metal frames or other mounting structures that can fix the PV modules at different tilt angles. Other materials used in floats include an expanding polystyrene foam filling to avoid loss of buoyancy due to perforation.

Many of these composites aim to be recyclable, hard-wearing, UV-stable, and rot- and fire-resistant. They are often derived from materials recycled from decking material and can be further modified for greater manufacturability, stiffness, load-bearing capacity, or durability.

Key performance indicators for materials used in FPV installation include stability, strength, and long-term reliability. It is important to check a materials specification data sheet (MSDS) for the desired properties of the floats and their intended use, including any potential contaminants for floats deployed on drinking-water reservoirs. For example, the floats should not contain any toxic metals (arsenic, chromium) or excessive chlorine.

Typically, PV modules are tested to last 20 to 25 years. Similarly, float structures should also be resilient for the lifetime of a PV plant, otherwise maintenance and replacement costs would jeopardize the project economics. Floats (together with other supporting structures and components) need to withstand the stress from various sources, such as internal stress and strain developed from wind and wave movements. For durability, it is important to check the following site conditions:

- Maximum wind speed
- Snow load
- Minimum/maximum temperatures
- Maximum water current velocity
- Maximum wave-height and frequency
- Water-quality and composition (to assess corrosion risk)

In some designs, module mounting structures made of aluminium or stainless steel are used along with the pontoon. These structures are usually galvanized for corrosion resistance. Anticorrosion tests may be performed. This is especially important if the water analysis indicates high salinity.

International standardized testing has yet to be developed for floats, although some countries have developed their own certification programs. For example, floats' tensile strength and maximum elongation have been tested in Japan in accordance with JIS K 6922-2. Many manufacturers conduct such tests independently during the design of their product and can provide the relevant test results. Some relevant tests are shown in table 4.2.

In addition, the floats should comply with environmental requirements. When FPV systems are deployed in drinking-water reservoirs, they must be tested for drinking-water compliance, as shown in table 4.2. Another useful and more general standard for testing environmental compliance is IEC 62321. Some normally tested properties include:

- Turbidity
- Chromaticity
- Taste
- Odor
- Total dissolved oxygen (TDO)
- Total organic carbon (TOC)
- Residual chlorine
- Other hazardous substances

To ensure long-term reliability, a project's developer is advised to thoroughly check the suppliers' test reports on float materials and structures. Quality control during the manufacturing process is also essential. Most plastic floats are made using blow-molding

TABLE 4.2 Examples of relevant tests for floats

Test Item	Comments
Wind-tunnel test	Tests platforms in fully assembled condition with winds from various directions at different speeds
Tensile strength test	Tests floaters Examples include ISO 527-2/3 and Chinese standard GB/T1040.2
Bending fatigue test	Simulates platform under waves
Material composition test	Tests material composition of floaters
Temperature- and UV-accelerated aging test	Demonstrates no plastic degradation throughout the design lifetime of 25 years
Polymeric material properties	Evaluates for (a) flammability, (b) mechanical stress, (c) thermal stress, (d) resistance to weathering, and (e) electrical resistance
Fire resistance tests	For example, Chinese standard GB/T 2408
Drinking-water compatibility test	For example, Japanese standard JWWA Z 108: 2012 and British standard BS 6920:2000
Corrosion-resistivity test	Tests all structural elements made of metal
Buoyancy / puncture test	Tests floatability
Data from real-world FPV outdoor test sites	For example, high-wind areas

Source: Authors' compilation.

processes. Process-parameter settings can establish an even thickness, consistent mechanical properties, and other aspects of the floats. These may eventually impact their field performance. It is recommended to source floats from reputable float suppliers with stringent quality control in order to minimize risks, especially for large installations with huge capital investment. A quality-control program including factory acceptance tests may also be needed.

Resistance to wind is another key feature to explore, especially in regions prone to strong winds. Box 4.1 shows examples of incidents which happened in Japan and the Netherlands; box 4.2 presents some simple first-hand solutions. Learning from these incidents is key to improve designs for the future.

4.3 Anchoring and mooring systems

4.3.1 Overview

The anchoring and mooring system holds the floating platform in place and provides the mechanical stability that it requires throughout the lifetime of its operation. Anchors and mooring lines are the key components of the system. The structures can range from simple shore anchoring, typical in smaller water bodies or very deep ones, to highly complex anchors suitable for reservoirs with great variations in water level, as can be the case in some hydropower reservoirs. The exact design will be site specific and depend on the use of the water body, soil properties of the reservoir bed, wind loads, and other environmental constraints. There are significant implications for the project costs.

BOX 4.1

Wind resistance incidents

Many FPV platforms are designed to withstand high wind loads; several cases show that they survive major storms. But some early projects experienced setbacks. Two large-scale Japanese FPV systems were damaged by strong winds and high waves brought by a typhoon in 2016 and, more recently, in 2019. The 2019 event in Japan led to a fire, the exact causes of which are still being investigated. Another incident occurred in the Netherlands in 2019 when a localized tornado flipped a few arrays of floats and PV modules onto each other.

One common cause of damage is the flipping over of periphery rows. Possible causes for this include:

- Anchor points were not stationed at the perimeter floats, but a few rows inside the floating island.
- Perimeter floats were installed with PV modules, thereby capturing uplift forces.
- The water level was low so loose mooring cable cannot effectively absorb the wind load.
- The wave height was larger than anticipated.
- Mooring attachment points were damaged due to peak forces created when slack mooring lines suddenly become tense.

Under extremely heavy wind loads, the internal stress developed within the platform may break the connection points or rupture the weaker parts of the floats. This in turn may lead to cascades of failures, because the remaining floats and mooring points may need to bear even larger stress as parts of force bearing structures are detached from the main island. Floating islands may collide into each other or onto the bank, causing modules to pile up and cables to snap. Under bright sunlight, this messy state can easily develop into short-circuiting, DC arcs, or overheated modules, eventually leading to fire.

Engineering solutions, including stronger float connection pins, proper design for the mooring system and island size/configuration, can prevent such incidents. Testing for wind resistance should account for the worst-case scenario, especially in regions prone to climate change and natural disasters. Also, assets should be properly insured as it is hard to foresee extreme instances.

BOX 4.2

Designs for better wind resistance

To prevent the platforms from flipping over, designs reducing the uplift forces produced by PV modules can be considered. For example:

- Dual-orientation configuration, as illustrated in figure 4.3, can be applied in low-latitude tropical regions to mitigate the effects of strong winds.
- Platform configuration with one row of empty floats at the perimeter is a commonly used technique too. Alternatively, weighted perimeter floats, as designed by Ibiden Engineering (Kato 2017), may be useful. In this design, the floating components along the outermost edges contain water and are used as weights (with floats semisubmerged), as shown in figure 4.4. They serve as ballast and prevent floats from flipping in strong winds.
- Windshields can be installed behind the perimeter panels to prevent strong winds blowing into the back of the panels (figure 4.5). This is similar to what is used for some ground-mounted or rooftop PV systems.

FIGURE 4.3 Dual-pitch configuration reduces wind load on FPV modules/systems

Source: © SERIS.

FIGURE 4.4 FPV system with semisubmerged edges used as weights

Source: © Ibiden Engineering.

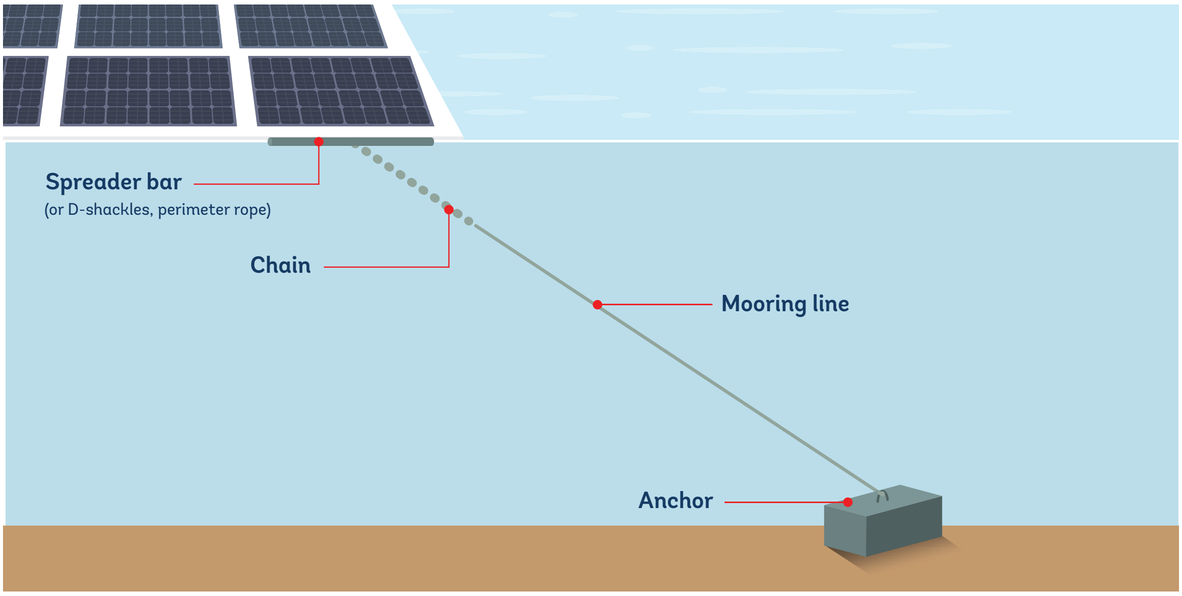
FIGURE 4.5 Windshields on the perimeter row of floats

Source: © SERIS.

Some of the designs of anchoring and mooring can be borrowed from offshore and marine engineering, but FPV platforms have somewhat different requirements from these other floating solutions. Software tools commonly used for simulations are NEMOH and Orcaflex (Arias, Ruiz, and Alonso 2016). The mooring system should be robust enough to resist environmental loading and impacts, as well as loads associated with O&M work. In many cases, the float supplier also designs or suggests the anchoring and mooring, as these components are linked and share several design constraints. If this is not the case, the developer should consult a qualified and experienced marine professional to approve the anchoring solution.

As mentioned above, FPV platforms can be anchored either to the bottom of the water body or to the bank of the shore, as shown in figure 4.6. Common types of anchors used in bottom anchoring are dead weights such as concrete blocks and helical anchors (figure 4.7) that are screwed and piled to the ground. Specialized barges or even divers are usually needed to deploy them. For bank anchoring, civil work is needed to pile the anchors firmly to the ground.

FIGURE 4.6 **Schematic anchoring to reservoir bottom (top), and anchoring on a reservoir's bank (bottom)**



Source: Adapted from Ciel & Terre International.

Source: © ISIGENERE.

FIGURE 4.7 **Concrete sinkers (left), and helical anchors (right)**

Source: © SERIS.

Source: © Ciel & Terre International.

Mooring lines are usually made of wire rope, galvanized steel wires, chains, synthetic-fiber rope (polyester, aramid, or Dyneema®), elastic rubber hawsers, or combinations thereof. Many possible combinations of line type, size, and configuration can be used to achieve the required mooring performance. Conceptually, buoys or even auxiliary weights can be added to the mooring system (figure 4.8). This helps to keep the mooring lines taut to avoid jerks and accommodate water-level changes. Additional weights, however, may cause additional loading and localized wear.

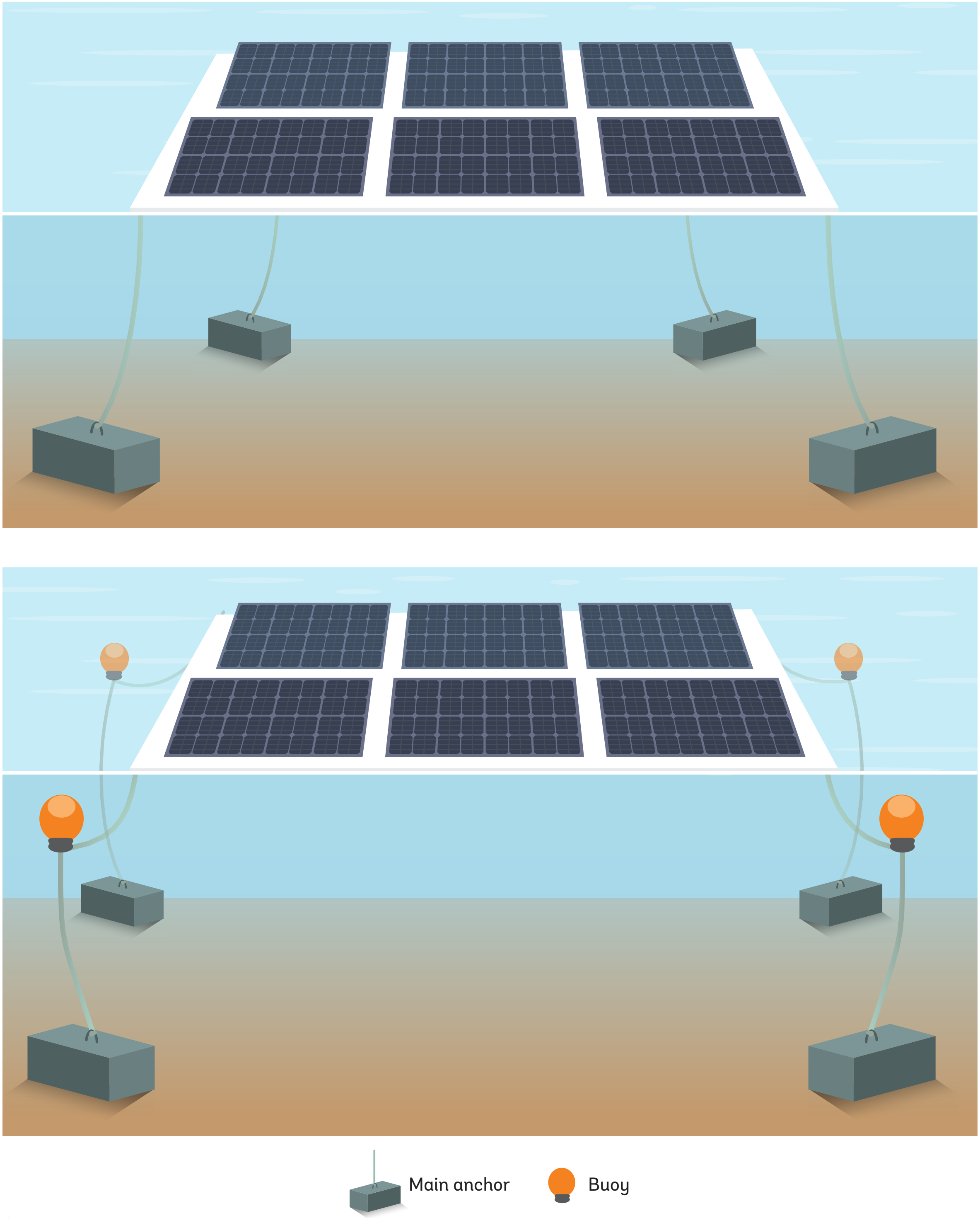
Overall, the system's layout design needs to feature a holistic consideration of all components and their interaction with the floating platform. Wind loads and water movements (currents) are particularly important parameters to consider in order to ensure the integrity of the entire floating platform and its anchors. Failure of the anchoring or mooring system could have severe impacts on the project as rectification might be difficult. Wind and current might damage anchoring or mooring points, or cause the platform to drift and even collide with each other. Wind could flip and dislodge the periphery rows if there is failure of the mooring points. These events may lead to catastrophic results, such as damage to the entire plant, or in some cases, fire. The anchoring system should therefore incorporate redundancy so that failure of a single mooring line does not cause cascading failures of the remaining lines.

Wind-load endurance of anchoring is normally evaluated and specified by the float supplier working with project designers and engineers to calculate the drag forces developed by the floating structures. After consulting with the float supplier on a suitable platform design and the strength required of structural components, developers can decide if additional tests are required (for example, for typhoon-prone areas). Wind speed and direction data are usually available from local weather stations (often visualized with wind rose diagrams). Besides average wind speed, the speed of wind gusts is critical to consider as it determines the maximum forces on the island. As the mooring lines are mainly used to constrain lateral movements, they should be as horizontal as possible to avoid excessive tensile stress under wind load (figure 4.9).

4.3.2 Standards and quality assurance

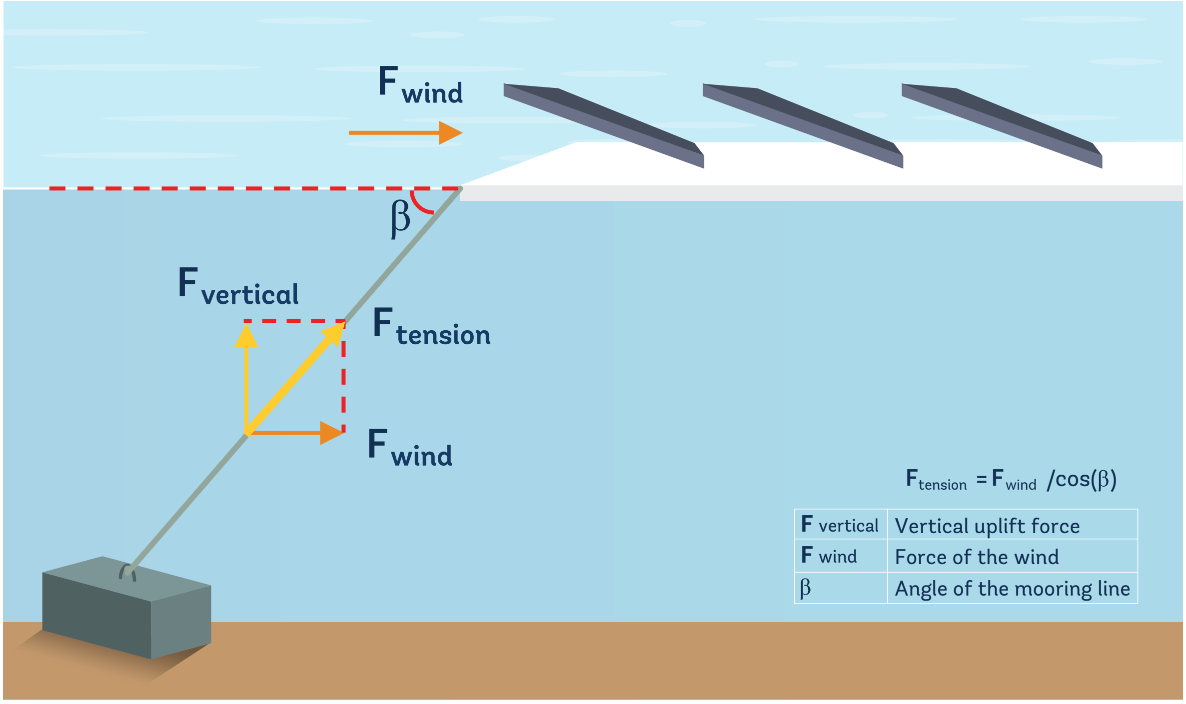
International Electrotechnical Commission (IEC) standards for the design requirements of anchoring and mooring systems are yet to take shape, but the industry practice presently engages qualified professional engineers to certify the load calculations provided by system designers. It is good practice to obtain design drawings from a professional before beginning the construction phase. Design standards from other industries, such as the "DNVGL-OS-E301 Position mooring," can be useful as a reference tool. Wind can cause an entire platform to drift and exert large forces on anchoring structures. Hence, wind load calculations are mandatory for the anchoring and mooring systems. For example, the European code EN 1991-1-4 (wind actions on structures) serves as a guide for such evaluations.

FIGURE 4.8 Example of simple anchoring and mooring (top), and mooring with buoys (bottom)



Source: Authors' compilation.

FIGURE 4.9 Force diagram showing the relationship between the angle of a mooring line and the resulting tension in the line due to force exerted by wind on the floating platform



Source: Adapted from SERIS.
Note: Larger tilt angles (β) will lead to higher tension for the same amount of wind load.

4.3.2.1 Long-term durability

The anchoring system should feature durable and reliable components expected to last over the FPV system lifetime and allow additional margins for wear and tear, corrosion, shock loading, or other compounding factors. Requirements for periodic testing and inspection as well as preventive maintenance must be specified. Other guidelines include:

- Anchor types and their suitability for different types of reservoir beds
- Choice of mooring material—wire, rope, chain, or elastic hawsers
- Compliance with local standards and recommended practices
- Corrosion and fraying of the anchoring components
- Algae and marine growth (biofouling)
- Environmental impact on neighboring fauna and flora, as well as water quality

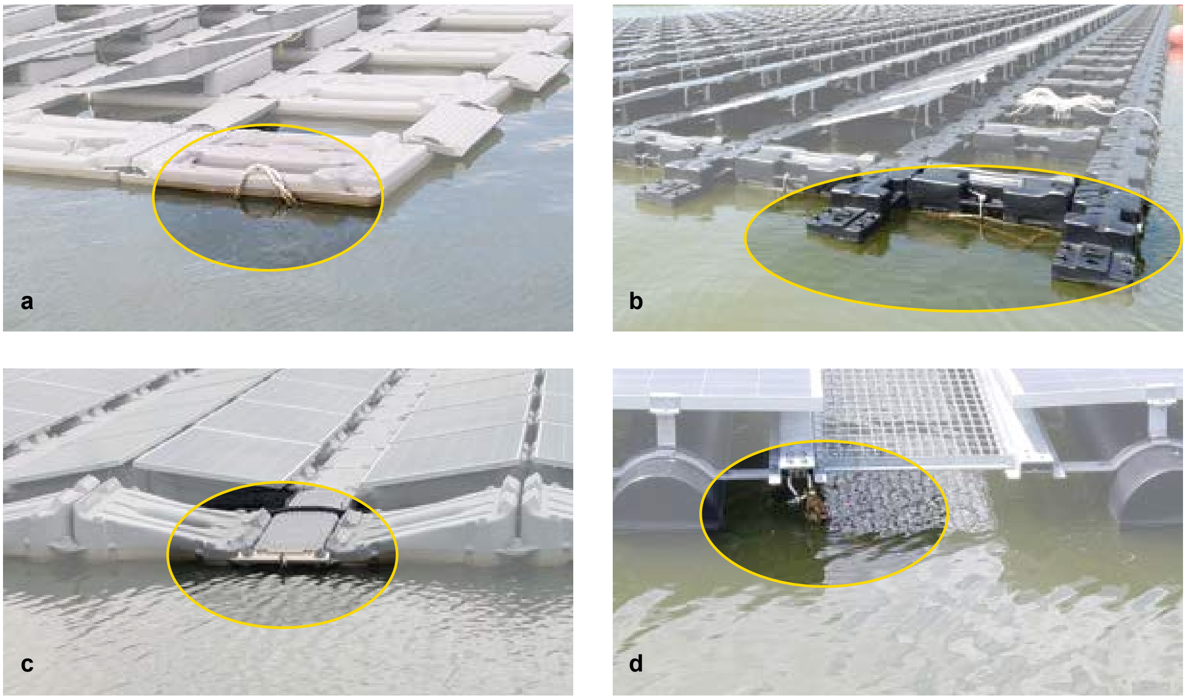
In particular, corrosion and fraying of the components should be avoided in order not to compromise mooring performance. The material of construction should be chosen with care, depending on the water-analysis report. The system should also anticipate and accommodate the impact of biofouling, such as added weights and potential degradation of the materials.

4.3.2.2 Quality aspects of mooring

Stress tends to concentrate at connection points between mooring lines and the floating platform. It is therefore important to ensure that the stress developed at the load-transfer point does not damage the floats or the connection points. Some mooring configurations are shown in figure 4.10. Figure 4.10-a shows a rope with a knot tied directly to the floats—the simplest way of mooring a small platform. An alternative way is to spread out the load by tying the mooring ropes to the entire periphery of the floating platform (figure 4.10-b). When the mooring point is directly on plastic floats, use spreader bars to spread the stress (figure 4.10-c). Figure 4.10-d shows a D shackle secured with a rope tied with a knot.

Typically, redundancy is designed into the systems, which need sufficient lengths of chains or wire ropes.

FIGURE 4.10 **Examples of various mooring methods, Singapore Tengeh Reservoir testbed**



Source: © SERIS.

Note: (a) rope with a knot tied directly to the floats; (b) rope tied to the entire periphery of the floating platform; (c) spreader bar attached to the float and anchored using chain; and (d) D shackle tied with a knot to a rope.

Requirements for periodic testing and inspection as well as preventive maintenance must be planned at the O&M phase.

Every component of the anchoring and mooring system (chain, shackle, and anchor) should be checked and verified for corrosion, tension, and slackness. Certified divers should carry out periodic inspection during the O&M phase.

4.3.2.3 Accommodation of water level variations

Additional care should be given to designing anchoring and mooring at sites with large variations in water level. Mooring lines should be long enough to accommodate water-level changes while still constraining lateral movement. Another challenge is the sudden jerks produced by abrupt lateral movements of the platform, when inelastic mooring lines shift from slack to taut and cause damage to the mooring points. Simpler ways to handle this include auxiliary buoys or weights, as explained earlier in this chapter. More advanced systems use elastic mooring lines with adjustable lengths. For example, the Swedish company Seaflex provides a rubber-based elastic mooring system that elongates and retracts in a slow and smooth movement (figure 4.11). The mooring lines are kept taut in order to resist drag forces and can self-regulate with natural or artificial water-level variations and wind forces ranging from calm winds to hurricane/typhoon strength. Seaflex also helps to avoid sudden peak forces on the float's attachment points.

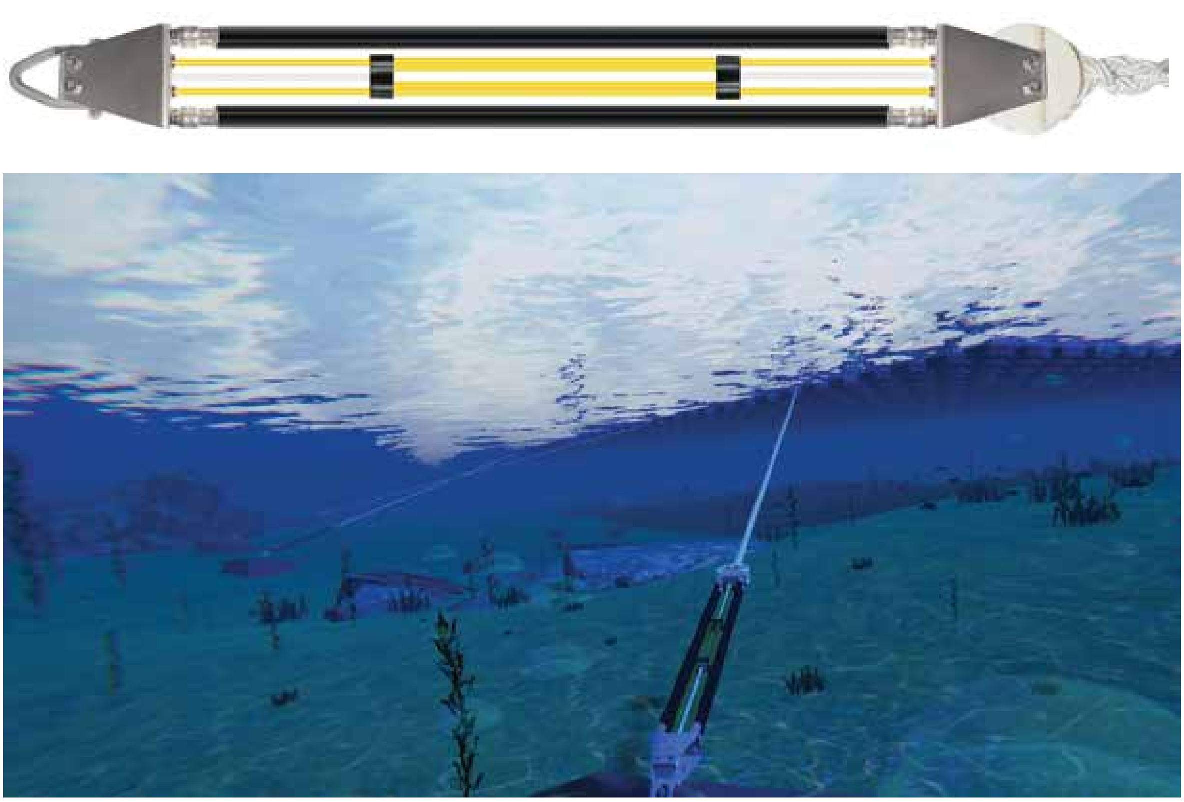
The Seaflex system has shown its advantage in certain extreme environments, including a project with 7-meter tidal fluctuations as well as 30-meter artificial variation and some projects hit by a typhoon and hurricane.

4.4 PV modules

4.4.1 Reliability challenges

PV modules are often exposed to various and extreme environmental conditions, including heat, cold, humidity, snow, and so forth. These stress factors influence the performance of the solar modules, even causing product failure and safety hazards. With respect to both performance and reliability, the FPV market presents a unique environment for modules when com-

FIGURE 4.11 **Seaflex elastic mooring component (top), and schematic drawing of mooring system (bottom)**



Source: © Seaflex.

pared with land-based PV installations. Considerable data exist on degradation rates and mechanisms for these technologies in varied physical environments, including temperature, humidity, and mechanical loading. Failure modes are accelerated by temperature and humidity (for example, backsheet hydrolysis, corrosion, and ribbon fatigue). The evaporative cooling present in floating installations means lower temperatures for modules and increased longevity for the panels. But given the proximity to water, humidity levels will be higher than they are for equivalent land-based systems. In this respect, the design of reliable FPV systems must consider the role of accelerators on the failure rate and the impact of the environment on the solar panels. Understanding these two factors—accelerators and environment—allows system reliability to be determined and module technology to be adapted if necessary.

Over the past three decades, the land-based solar industry has generated a great deal of data on modules through field performance and reliability testing (Jordan and others 2016; Pozza and Sample 2016; Han and others 2018). Nevertheless, failure modes have been identified in the field that were not captured during testing. These modes include potential induced degradation (PID) (Hacke 2015), backsheet degradation (Hu and others 2018), and increased cell cracking and hotspots. Given the rapid pace of FPV installations, significant capacity could be deployed before floating-specific issues are uncovered. It is therefore important to identify and mitigate modes that could lead to significant field failures. Degradation rates could be such that repair or replacement of the panels might become challenging or financially prohibitive.

4.4.1.1 Comparison of floating solar environment with other solar installation environments

As a starting point on reliability, it is helpful to compare PV systems in various operating environments such as a tropical or desert climates. Table 4.3 illustrates the impact of environmental stresses (such as moisture, mechanical stresses, hot-spot, etc.), also

TABLE 4.3 **Impact of environmental stresses on module degradation in various operating environments**

Environmental stresses	Impact of operating environment on the module degradation				
	Lower impact	→	→	→	Higher impact
Moisture	◆		●	▼	▨
Mechanical stresses		◆	●	▼	▨
Hot-spot/shading			●	▨ ▼	◆
UV			▨ ●	▼	◆
High temperature		▨	●	▼	◆
Low temperature	▼	▨	●		◆
Temperature cycling	▼	▨	●		◆

● Temperate environment ◆ Desert environment ▼ Tropical environment ▨ Floating PV systems

Source: Adapted from Harwood 2018.

called "accelerating factors", on module degradation in various operating environments: temperate, tropical, desert and floating. Note that this single icon representation might oversimplify the reality in certain instances.

Moisture is a primary accelerator of degradation for FPV. The FPV testbed in Tengeh Reservoir in Singapore has shown average relative humidity at the module surface to be slightly higher than reference modules on nearby rooftop systems (Liu and others 2018). Convective cooling of the panels will tend to reduce the amplitude of the diurnal cycles, which is beneficial for most thermal-cycle failure modes (Bosco and others 2016). Mechanical stresses on FPV panels stem from design features and location. Ground-mounted PV has issues with cell cracking and interconnect failures; these may be even worse than for FPV due to movements. Biofouling causes hotspot and shading issues, which can be an issue for FPV as bird activities are observed at many FPV projects. Module selection may also take into account the acidity of bird droppings (dependent on birds' diet), which may have implications on glass coating and module warranty.

These environmental stresses represent acceleration factors for module degradation. Based on experience and research, the leading acceleration factors for the degradation of ground-mounted PV systems include humidity, temperature, and temperature cycling. The environment can accelerate mechanical flexing and microcracks; transport and mounting can also accelerate degradation.

4.4.2 Testing standards for floating PV modules

Given the potentially more demanding floating application of solar modules, it is good to follow some minimum requirements of certification for module safety and module design. An additional recommendation is to test for salt-mist corrosion, particularly for coastal and offshore applications. Connectors and junction boxes should be of assured quality too. Some relevant testing standards are:

- IEC 61215 (module design)
- IEC 61730 (module safety)
- IEC 62790 (junction box safety)
- IEC 62852 (connector safety)
- IEC 61701 (salt-mist corrosion)
- IEC 62804 (potential induced degradation)

When FPV systems are deployed on inland drinking-water reservoirs, lead-free modules may be desirable. For more discussions on the failure modes and recommendations on accelerated testing procedures, please refer to Annex A.

4.4.3 Floating PV module options

In general, the standard photovoltaic module has performed well under a variety of conditions and represents much of the installed base worldwide. This standard design features a 60 or 72 multi- or mono-cell glass front. For standard PV module selection criteria, readers may refer to "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015) for more information.

Given the robustness of existing module designs, modules suitable for tropical environments on a pontoon-based installation may be suitable for FPV applications with minimal or no modification. In those cases where an additional margin of security is needed, several options are available for improved reliability, as shown in table 4.4. Developers may check with module manufacturers about their available product features and associated costs in order to weigh the benefits of using specialized modules.

For increased moisture hardening, improved encapsulants and backsheets are on the market. The industry has found ways to increase PID resistance at the cell level; PID can also be mitigated at the system level through grounding strategies.

Mechanical stresses tend to be site and design specific, and ground-mounted PV data will flag areas for caution. Dramatic improvements can be realized by increasing panel stiffness or by mounting and placing strings and cells on the neutral axis. To address fatigue, the industry is adopting half-cut cells to reduce the strain on ribbons (in addition to the electrical benefits, such as lower resistance). Lowering the elastic modulus of encapsulants lessens the transmission of module strain to the cells and limits breakage rate and the formation of cracks. Where cells do crack, multi-busbar connectors and wire/grid technologies can continue collecting current from broken sections of cells (Gabor and others 2015).

For hotspots, reducing the number of cells on a diode can lower the temperature, and using materials with higher ratings will improve heat resistance. In addition, several companies are developing antifouling, antireflective (AR) coatings and cleaning technologies for modules, which may help with the formation of shading in the first place (Fleming and others 2015).

Dual-glass modules have desirable features for FPV application. Inorganic glass surfaces provide the best

TABLE 4.4 Potentially accelerated FPV module failure modes and mitigation strategies

Environmental stresses	Failure mode	Mitigation strategies
Moisture	• Corrosion • Hydrolysis • PID	• Moisture hardened materials • Encapsulants: TPO, POE, ionomer • Backsheets: glass, aluminized PID resistant cells • System level PID compensation
Mechanical stresses	• Interconnect fatigue • Cell cracking	• Increase module stiffness • Cells and string on neutral axis • Cut cells (for fatigue) • Lower modulus encapsulants • Multi-busbar/wire interconnects
Hot-spot/shading	• Arcing • Melting/cracking • Diode failure	• Less cells per bypass diode • Higher RTI materials • Anti-soiling coatings

Source: Adapted from Harwood 2018.
Note: PID = potential induced degradation; TPO = thermoplastic polyolefin; POE = polyolefin; RTI = relative temperature index.

moisture protection. Together with butyl sealant for edges, they can produce a hermetic-like environment for electrical components (Kempe and others 2017). The symmetrical construction places the cells at the neutral axis of the construction, minimizing mechanical stresses on the cells and ribbons. Frameless rail-mounted designs eliminate edge lips that collect debris and soil. Nonconductive rail mounting can eliminate the need for grounding and associated risks of PID. Where soiling does occur, glass-glass construction using a higher relative temperature index (RTI) polyolefin encapsulant can tolerate hotter local temperatures without failure. But there are also potential downsides. Ineffective edge seals permit moisture to accumulate inside the panel, where it cannot be "baked out" during the day as is the case for backsheet. Glass-glass modules are also heavier, which places higher demands both on buoyancy and mechanical mounting. Modules with frameless designs provide less stiffness, which may result in bowing or sagging and may be more vulnerable to extensive bending or vibration under dynamic loads. The overall benefits of glass-glass modules in FPV plants will still need to be evaluated after more years in the field.

4.4.4 Durability and safety

For conventional ground-mounted systems, PV module degradation is typically 0.5 percent per year or less with a linear power warranty of 80 percent performance over 25 years (TamizhMani and Kuitche 2013). Data collected from some of the first systems installed in Europe are consistent with the 0.5 percent per year. But more recent data from hotter climates suggests higher numbers are being observed.

The price of entry for solar modules involves panels certified for IEC 61215 (long-term performance) and IEC 61730 (safety), and the same should be considered for FPV modules. Matching or exceeding the durability of land-based systems and predicting the degradation rate of modules require quantitative performance data through testing for accelerated ageing and the application of those reliability models to in-use conditions. The bankability of solar farms to date has been supported by evidence and data from installations with decades of outdoor operation. For FPV, such large datasets do not currently exist. But early performance trends and fault metrics will form a foundation for the process and, more important in the short term, identify emerging quality issues that can be addressed as the industry grows. For example, issues with PID or hotspots would be expected within the first few years of operation, but cell corrosion, micro-cracking or solder-joint fatigue may take decades before their impact is observed. At this stage, some general guidelines are offered here:

Durability

- Use moisture-hardened designs and materials with extended-reliability test data
- Choose designs with the highest ratings for PID resistance (for example, polyolefin rather than EVA-based encapsulants)
- Evaluate dynamic mechanical loading of mounted modules based on the expected use environment

Safety

- Design junction boxes, wiring, and connectors for above-water use and avoid submersion
- Specify junction boxes rated to a minimum of IP67
- Use backsheets (or rear glass) and encapsulants with higher temperature ratings and low water vapor transmission rates
- Ground and bond as appropriate for corrosive environments

4.5 Cable management on water

The management of cable runs in FPV installations requires careful planning during initiation and implementation phases. Cable lengths and cable routes need to be planned and calculated with care. Slack must accommodate both the movement of the floating islands and the variations in water levels. Otherwise, tension in the cables will cause them to snap and rupture. Taking into account the differences in PV module and float dimensions, as well as orientation of the modules (portrait/landscape), the default cable length from the junction box of the module provided by module manufacturers may or may not be enough.

FIGURE 4.12 Cables routed to land from floating islands in MWp-scale FPV plants in Hyogo Prefecture, Japan (left), and in Anhui Province, China (right)

Source: © Ciel & Terre International.

Source: © Sungrow.

Note: Floating cables are protected with watertight conduits that have enough slack to prevent excessive tension.

On the one hand, modifications of string cable length may be needed when planning for and procuring PV modules. On the other hand, cables need to be properly tied with UV-resistant cable ties or stainless-steel clamps, routed, and protected so excess slack keeps the cables from touching water. In this regard, plans must incorporate these considerations into cable routing and platform designs.

Most large-scale projects will have the inverter, and possibly even the transformer, floating on the PV islands, with the cables routed to the onshore substation. The cables can float on water (figure 4.12) or be submarine cables—although the cost of the latter option will be much higher. Again, designers should plan for sufficient slack (note the S-shaped curves in figure 4.12). In addition, floating cables could obstruct boats, so careful planning is required at the project initiation stage. More information about cable routing can be found in chapter 7.

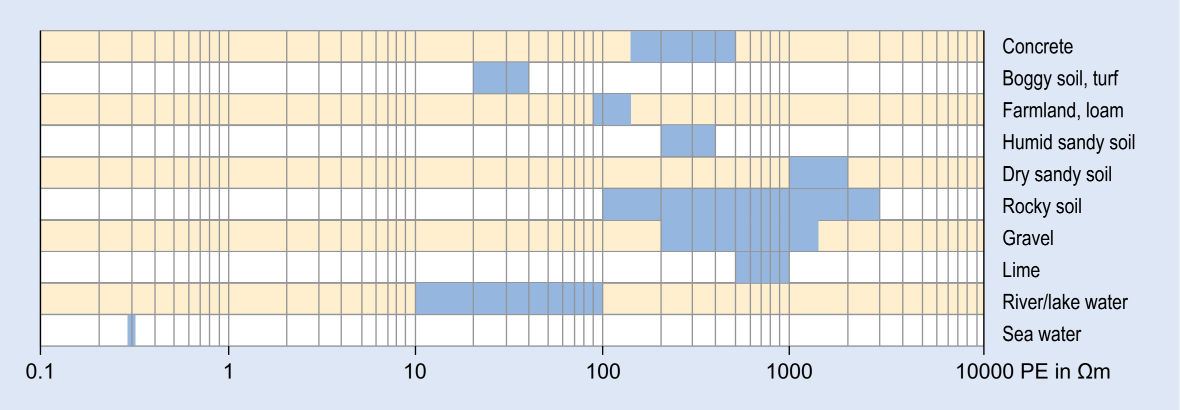
4.6 Electrical safety

Project developers follow electrical safety regulations for equipment and personnel, referring to both international and country-specific standards. For solar installations deployed on land, established and effective electrical safety regulations are in place for DC and AC electrical subsystems and for switchroom and LV/MV/HV transmission systems. Three topics that are particularly relevant for FPV will be discussed in this section. First, for grounding, the earth cables are usually routed to and buried in the earth pit. In the case of FPV, grounding can take slightly different forms. Second, lightning protection systems (LPSs) are typically air terminal rods built around solar farms and grounded to earth. For FPV, developers should explore external LPS options too. Finally, most projects will need to eliminate or mitigate the risk of short-circuiting with the water body. Please note that this section addresses only indicative guidelines and principles. In the future, the industry will need to build up and establish electrical safety standards for FPV applications.

4.6.1 Grounding

For FPV installations, non-current-carrying exposed conductive parts of a PV installation (such as module frames) must be properly grounded. Depending on the required cable length, equipotential bonding is achieved with copper (Cu) cables of at least 6 mm^2 to 16 mm^2. Earth cables can be routed to shore from floating islands and grounded to an earth pit. Acceptable earth resistance at the main earth busbar typically ranges from 0.5 to 1 Ohm (Ω), or as specified in the standards. A natural earth electrode is a metal part in contact with earth or with water either directly or through an earth pit. Resistivity is affected by soil moisture and retention quality, and the size and uniformity of the grains of soil.

FIGURE 4.13 **Resistivity levels of various types of soil**



Source: Adapted from DEHN 2014, p. 121.

As shown in figure 4.13, rivers and lakes have water resistivity ranges from 10 to 100 Ωm, which is lower than the resistivity of most types of soil. River and lake water therefore offers a grounding alternative. Earth cables can be grounded to the reservoir bed (using earth rods buried in the bottom of the reservoir) or to sufficient depth into the water body. Grounding to water or water bed is widely practiced in many large projects.

4.6.2 Lightning protection system

The purpose of a lightning protection system (LPS) is to protect PV installations from direct strikes and possible fires caused by lightning-induced currents. In general, LPSs should be implemented at FPV sites. This includes the onshore substation room built for off-taking FPV power, which should be protected with an LPS as per building regulations. An LPS III according to IEC 62305-3 (EN 62305-3) is recommended. In principle, developers should also perform a risk analysis; this is described in the IEC 62305-2 (EN 62305-2) standard. Developers need to refer to local meteorological service records to determine the frequency of lightning strikes and deploy appropriate LPS. Note, however, that personnel are usually not protected by these measures, so safety protocols should prohibit working on the FPV system when there is inclement weather or the high probability of a lightning strike.

4.6.2.1 External lightning protection system

The external LPS intercepts the direct lightning strike and discharges the lightning current from the point of strike to the ground. It is also used to distribute the lightning current in the ground without causing thermal or mechanical damage or dangerous sparking, which may lead to fire or explosion.

An external LPS (DEHN 2014) consists of the following components:

- Air-termination system
- Down-conductor system
- Earth-termination system
- Lightning equipotential bonding

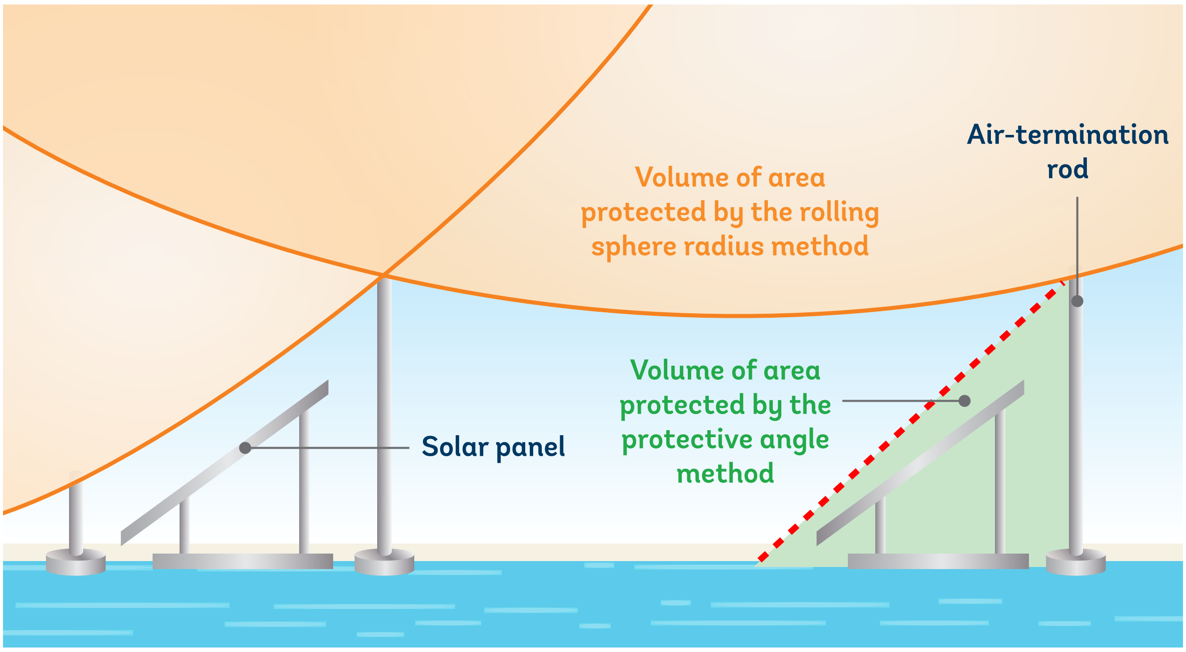
External LPSs are common in ground-mounted or rooftop solar PV plants. The so-called rolling sphere and protective-angle methods are applied to determine the protected volume (figure 4.14). The LPS must maintain a certain distance from its PV system; this separation helps to avoid uncontrolled flashovers to adjacent metal parts in an event of a lightning strike. Figure 4.15 shows an example of external LPS installed on a floating island in Singapore's FPV testbed.

4.6.2.2 Internal lightning protection system

To protect equipment from lightning strikes, surge-protection devices and equipotential bonding for metallic parts and frames, in combination with smart cabling design, would be sufficient. Type II surge-protection devices are recommended for these projects. Both DC and AC sides of the electrical subsystems should be protected with appropriate DC and AC surge-protection devices (figure 4.16).

The DC cables from the solar module to the inverter, and the AC cables from the inverter to the grid connec-

FIGURE 4.14 **Rolling sphere radius and protective angle methods for solar lightning protection systems**



Source: Authors' compilation, adapted from DEHN 2014.

FIGURE 4.15 **Air terminal rods installed on an FPV island, Singapore Tengeh Reservoir testbed**

Source: © SERIS.

FIGURE 4.16 **AC surge arresters installed on the AC electrical subsystem, Singapore Tengeh Reservoir testbed**

Source: © SERIS.

tion point, usually extend long distances over water to the shore. Lightning in the vicinity can induce large currents in the circuit. This effect is more severe for long cables with large conductor loops. It is therefore essential to keep wiring loops as small as possible.

Equipotential bonding is also an integral part of the LPS (figure 4.17). These bonding elements (tap or wires) must be capable of carrying lightning currents to the functional earth termination point. Typically, the bonding cables are routed close to the DC and AC cables. Special attention should be paid to flexibility and the attachment point to manage risk of conductor and connection damage, including from pull-out or concentrated fatigue caused by float movement.

4.6.3 Short circuit risk

In the case of FPV, solar modules are installed near the water surface; they are always energized whenever there is sufficient sunlight. To mitigate the risk of short circuiting in an FPV installation, the AC and DC cables need to be routed from the floating solar modules to onshore electrical distribution systems above the water surface (unless submersible-grade cables

FIGURE 4.17 Equipotential bonding, Singapore Tengeh Reservoir testbed

Source: © SERIS.

are used). Even when cables are deployed on floating platforms or pontoons, there is still significant risk for them to come into contact with water or even get submerged. As water is known to be a good conductor, it is important to take additional precautions to prevent short circuiting with water, as electric-shock drowning is one known cause of death. In general, a small amount of AC current (50/60 Hz) running through a human body can cause paralysis or heart failure, possibly leading to drowning. A proper ground-fault interrupt system is essential.

In the event an electrical fault does occur, where any of the three energized current-carrying conductors (phases 1, 2, or 3) forms a conduction path with water, a so-called isolated-earth (IT) configuration is comparably safer than other configurations. In an IT configuration, the neutral point of the supply source (present in cables, inverters, and transformers) is isolated (unearthed) or impedance-earthed (exposed and extraneous-conductive-parts of equipment are still connected to an earth electrode), whereas in other configurations, the neutral point is connected directly to earth. As electric current needs a closed loop to flow, an electrically floating (isolated) neutral point offers a lower risk of short-circuiting with water. For equipment with other earthing schemes, a permanent insulation monitor (PIM) device (Bender n.d.) could be installed to monitor the changes to R_{iso} (insulation resistance) on the L1, L2, and L3 conductors. This monitor helps to detect insulation drops before they become serious short-circuit faults. The IT configuration can also be combined with this PIM device to further mitigate risks.

4.7 Checklists for plant design

This chapter covers the essential aspects of the engineering design for FPV plants, namely floating platforms, anchoring and mooring systems, and the selection of PV modules; it also highlights the electrical safety issues of particular importance to FPV systems. Detailed in table 4.5 are checklists that touch on the particular requirements and design considerations. More information about other components such as inverters, switchgear, transformers, site facilities, and other general aspects that are similar to ground-mounted PV systems can be found in the report “Utility-Scale Solar Photovoltaic Power Plants: A Project Developer’s Guide” (IFC 2015).

TABLE 4.5 **Checklists for plant design**

Floating and mounting structure checklist
• Suitability for project site, size, and objectives
• Suitability for local site condition with relevant factors properly surveyed
• Supplier track record, bankability and financial strength
• Proper scheme and method for deployment
• Ease of O&M
• Detailed part replacement procedure
• Part warranty and durability
• Designed against extreme weather conditions
• Additional designs to improve wind and wave resistance if necessary
• Relevant test results and certifications

Anchoring and mooring systems checklist
• Proper method for anchoring selected based on water and soil condition together with cost considerations
• Compatibility with floating platform (expected drag forces, proper mooring points, etc.)
• Suitable for local water depth and water level variations
• Long term reliability and durability
• Designed against extreme events
• Deployment method suitable for project site
• Inspection and maintenance schedule, method, and associated cost

Key component selection checklist (including PV modules, inverters, transformers, connectors)
• Suppliers' track record and experience in FPV
• Customized design or advanced technology options if necessary
• Compatibility with floating structures (weight, dimension, mounting method, string cable length for connecting PV modules, etc.)
• Product and power warranty for FPV application scenario
• Additional test results or certifications if required
• Proper IP protection for on water environment
• Avoid mixing of brands and models for PV connectors
• Enhanced safety features if required
• Compatible with environmental requirements

General engineering design checklist
• Proper tilt, orientation, and inter-row spacing in line with floating platform design and location
• Proper energy yield assessment taking into account local site conditions
• Study of potential shading from far horizon and soiling from bird activities
• Connection points need to be properly designed and be of good quality to survive constant movement
• Proper cable selection and cable management to avoid mechanical stress and water/moisture exposure
• Inverter properly sized to accommodate potential increase of string power from enhanced cooling (slightly lower DC/AC ratio)
• Proper location to place inverters and transformers (on float or land)
• System design and construction plans compatible with environmental requirements

Source: Authors' compilation.

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5 FINANCIAL AND LEGAL CONSIDERATIONS

5.1 Overview

Floating solar photovoltaic (FPV) systems do not yet enjoy the same level of maturity as ground-mounted and rooftop photovoltaic (PV) systems. Even though these systems share some components, other components are new and must benefit from larger economies of scale and standardization.

This chapter discusses some of the financial and legal aspects specific to FPV systems. More general information on permits, licensing, policies, power purchase agreements (PPAs) and financial analysis, which are common with ground-mounted solar PV projects, can be found in the report "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015). Information on business models for FPV and project structuring can be found in the previous report from this series "Where Sun Meets Water: Floating Solar Market Report" (World Bank Group, ESMAP, and SERIS 2019).

The financial and legal aspects regarding floating and land-based PV systems are compared below, in table 5.1.

5.2 Risk analysis

As with ground-mounted PV projects, FPV systems can be owned by independent power producers (IPPs) or by utilities, depending on the location and the regulatory framework in place.

Regarding bankability and risk assessment, the due diligence process for utility-scale FPV projects resembles the process for ground-mounted PV projects.

TABLE 5.1 Floating and land-based photovoltaic systems: A comparison of financial and legal aspects

	Floating PV	Land-based PV
Investment	• Slightly higher costs on average due to floats, anchoring, mooring, and plant design • Cost of floats expected to drop as scale of deployment increases • Higher perceived risk because of lower level of maturity • Expected lower site rental/leasing cost • Additional benefits on energy yield from cooling effect of water and possible reduction in water evaporation losses, depending on system design	• Huge installed capacity and hence very established investment and financing sector • Costs continue to drop • Land acquisition or rental can be difficult and costly in certain regions
Regulation and permits	• Permitting generally more difficult for natural lakes and easier for artificial ponds • Water surface ownership often unclear • Lack of specific regulations	• More established permitting process • Clearer regulations
Experience/level of maturity	• Cumulative capacity as of end of 2018: exceeded 1.3 GWp • More than 350 projects built • Four years of experience with large-scale projects (maximum size project to date 150 MWp)	• Cumulative capacity as of end of 2018: exceeded 500 GWp • Thousands of projects built • 10–30 years of experience

Source: Authors' compilation.

Because the FPV industry is still nascent, few companies are able to provide integrated solutions and FPV projects may require many contractors throughout the project life cycle. This fact increases integration risk and complexity to the construction and operation of such plants. Given the lack of experience that banks, insurers, and regulatory bodies have with FPV, permitting and financial closing are likely to take longer than for ground-mounted PV projects.

As for any project finance transaction, thorough due diligence must take place. Lenders and insurers will evaluate the following risks for each project. (The list below is not exhaustive.)

- **Country risk:** Overall political and legal environment, changes in law, political and economic stability, political and financial support for emerging renewable technologies such as FPV, renewable energy targets, including FPV.
- **Sponsor/owner risk:** Financial and technical experience, ability to top-up equity in case of cost overruns.
- **Resource risk:** Independent assessment of the irradiance resource, projected energy yield, including productivity gain from the cooling effect, verified by on-site data measurements as much as possible; impact of climate change risk; soiling risk.
- **Technology risk:** Proven versus unproven floating technologies (track record); climate change risk (for example, frequency of natural disasters); going-concern status of technology provider and ability to provide after-sale services; product warranty; reliability and safety of components (modules, inverters, floating structures and small parts, anchoring and mooring); testing and certification of main components with adequate counterparties (for example, corrosion and fatigue test, wind and wave resistance levels); site assessment (for example, water-quality tests, hydrogeological and geotechnical studies, erosion and flooding risk, water level variation and change over time).
- **Regulatory/compliance risk:** Legal and regulatory environment, licensing and permits, land use and water rights, local public consultations, visual impact, environmental and social impact assessment.
- **Construction risk:** Track record of EPC (engineering, procurement, construction) contractors (turnkey versus separate contracts), liquidated damages, service warranty, structural design and procurement, anchoring and mooring, experience of floating solution providers and support throughout construction, quality inspections, testing and commissioning, insurability, contingency costs.
- **Offtake risk:** Offtaker and curtailment risks.
- **Operations and maintenance (O&M) risks:** Availability of spare parts (including floats and connection points), track record of contractor, audited maintenance plan, length of the O&M contract, service warranty, performance guarantee, level of support from floating solution providers, accessibility of the FPV system, insurability.
- **Decommissioning risk:** Regulations, lack of clarity on roles and responsibilities, recyclability and residual value, environmental impact and waste management, product return and disposal guarantee.

As FPV is a new technology, the analysis should thoroughly examine technology, construction, and O&M risks and the track records of all contractors and component manufacturers.

Based on the risk assessment and the risk appetite of the system owner, the owner—together with the lenders, if applicable—needs to decide which risks can be accepted, which risks need a mitigation strategy (avoidance, reduction, or transfer), and how much each strategy will cost.

In practice, risks are identified, assessed, and managed through key legal, financial, and technical review points. Nonetheless, when assessing the investment-worthiness of an FPV project, various stakeholders such as investors, insurers, and regulatory bodies will evaluate the impact and probability of investment risks differently, depending on their goals. As there is a demand from all sides to understand what key risks are unpredictable, due diligence processes are needed to:

- Safeguard a project's financial structure prior to funding decision, during construction and operation phases, ensuring compliance with project requirements and expected payback levels.
- Quantify and manage the technical risks for current and new FPV solutions.
- Create, maintain, and enrich a professional strategy for managing technical risks (from identification to assessment to management) that would reduce the risks associated with investments in FPV projects.

Table 5.2 summarizes the challenges and risks for FPV projects. Note the list is not exhaustive and that developers/utilities will need to examine each project according to local conditions.

For managing some of the technical risks, four key factors must be considered to ensure sufficient control over the value chain to ensure the performance, reliability, efficiency, and quality of the floating structure solution:

- Estimation of yield in the planning phase
- Responsibility of EPC and O&M contractors versus floating solution providers
- Manufacture and transport of floats
- Standardization

Note that these key factors, discussed in detail in this chapter, are not the sole ones to consider; as several other risks need to be tackled depending on each site and each country's regulatory environment, as shown in table 5.2.

5.2.1 Estimation of yield in the planning phase

Energy yield from an FPV system is not calculated the same way as the yield from a ground-mounted PV system, as explained in chapter 3. Project design, climate, and site conditions will all affect the performance of the system; appropriate technical assumptions must be adopted so the energy yield can be evaluated. These careful steps will have a direct impact on the project's cash flow: correct assump-

TABLE 5.2 Additional risk factors for FPV project, by type, compared to any PV project

	Country	Enabling Environment	Site	Technology	Economics	E&S
FPV	• Political support and adequate regulations for FPV	• Longer processing time due to lack of experience • Water rights • Installation permits	• Water level fluctuation • Design for ice or drought conditions	• Lack of standardization, design specifications • Limited track record of contractors • Suitability of anchoring and mooring systems for the particular project design and local site conditions • Limited number of operating years for large-scale FPV projects	• Tariff setting for FPV installations • Cost reduction of floating systems • Logistics and O&M costs • Potential higher insurance premiums • Warranties for FPV components • Expectation of a higher energy yield	• Environmental impact on aquatic flora and fauna • Water quality requirements • Resistance of floats and other structural and electrical components to water environment • Safety standards for work above and under water (e.g., for divers and O&M workers) • Social impact (e.g., fishing communities)
All PV (land-based and FPV)	• Rule of law • Political risk • Currency risk	• Access to existing transmission infrastructure	• Site assessment • Resource availability • Construction	• Variable output	• Off-taker risk • Bankability of PPA	• Decommissioning and disposal • Social impact (visual aesthetics)

Source: Authors' compilation.

tions mitigate the risks involved in the energy production assessment.

5.2.2 Responsibility of EPC and O&M contractors versus floating solution providers

Regarding procurement, construction, and O&M contracts, developers must have a strategy to ascertain and minimize technological, construction, and performance risks, while meeting minimum investment returns. Two contract models are available to developers of ground-mounted PV projects: (1) multiple contracts or (2) a single turnkey EPC contract. In the first model, the owner engages multiple contractors to deliver/construct different parts of the plant, with one company retaining the responsibility for integrating all components and services under the various contracts (typically the owner/developer or the Owner's Engineer). In case an EPC contract is chosen, a single company is responsible for the entire project.

Most FPV projects are built by EPC contractors, with varying levels of supervision from floating structure solution providers (in some cases, the floating solution provider is also the EPC and/or the O&M contractor). Because many local EPC contractors still lack experience with FPV projects, floating solution suppliers need to provide adequate training so EPC contractors can avoid assembly faults and install systems according to guidelines. The floating solution providers should conduct quality inspections at the start of construction, during construction, and most important, at the end of the construction, to ensure the proper installation of the floating structure.

Because floating solar is still a nascent technology, projects are best served by limiting the number of contractors involved. For example, contractors doing both EPC and O&M will benefit from experience gained during construction and operations, improving their work on subsequent projects. The learning curve is greater, and expertise and knowledge are shared, not isolated, along the separate links of the supply chain. Companies that can offer integrated solutions may gain a competitive advantage over time.

When using an EPC contractor, operators will need to establish an exhaustive matrix of responsibility for each party. The floating solution provider, if different from the EPC and O&M contractors, should provide sufficient support during construction and to some extent during the operation phase. Same holds for anchoring and mooring system provider, if not the same as floating solution provider.

Another key challenge relates to the contractors' status as a going concern and their long-term financial sustainability, particularly the floating solution provider. FPV projects are meant to last at least 20 years, so it is important to select technologies that have been developed by financially sound companies able to meet warranty and provide the required spare parts for the life of the project.

5.2.3 Manufacture and transport of floats

Floats are bulky and therefore expensive to transport over long distances. For a floating structure supplier, low transport costs are key to remaining competitive.

Safeguarding the manufacturing quality of the floats is also paramount. FPV market size and potential in each country are therefore key. If floating structure suppliers believe the market potential is sizable enough, they may want to find local partners to manufacture the floats, catering to a particular local market and easing costs. It is important to find local subcontractors who can ensure quality. If the market potential is sizable, some floating structure suppliers may even decide to set up their own local manufacturing facilities in order to preserve their intellectual property.

It is important to impose quality control at every step of the value chain. Lack of control, supervision, and testing of products at the factory gate can lead to suboptimal floats. The quality of the materials used in the floats should be carefully evaluated; no compromises should be made with respect to the environment impacts (for example, leaching of chemicals) and/or higher operating expenses at a later stage in case replacement is required before the end of the expected lifetime of the floating structure.

5.2.4 Standardization

Testing standards that indicate long-term reliability or performance are voluntary and their role is to reduce transaction costs. Some standards, in particular those ensuring safety or environmental compliance can be compulsory. Standards specific to floating PV structures have not yet been developed.

Blow molding of floats, used in mainstream floating solutions, is a low-tech and relatively easy manufacturing process. It is critical, however, to ensure that sufficient safeguards (such as appropriate testing) are put in place to ensure that the durability and reliability of the floats are not comprised during manufacture, especially in an environment marked by growing cost pressure and competition and where multiple third-party manufacturers are used as subcontractors. The long-term durability of the floating structure must be verified through accelerated testing (appropriate indoor testing equivalents).

Standards are efficient tools to ensure and safeguard the quality and reliability of assets that must have an operating life of at least 20 years. Work on FPV standards is underway in China (quality standards for plastic floats) and internationally (IEC TC 82/WG 3 on installation aspects of FPV systems).

Third-party testing and certification of floats is important. The extent and type depend on various parameters. Introducing new standards on these tests might be an efficient way to improve quality and reliability. Standardization of the scope of the independent engineer (IE) review could also help increase the reliability of FPV systems.

Quality control and inspections over the entire supply chain—from the manufacturing of equipment to the transport and installation of FPV systems—should be clearly defined and implemented by the owner's engineer and lenders' technical advisors during the due diligence and construction phases.

5.3 Economic and financial analysis

Early on, at the beginning of the development phase, owners should undertake cost-benefit and financial analyses. Does the FPV project meet certain minimum investment criteria (for example, economic and financial rate of return, return on equity, payback period, and so forth)? These analyses must be progressively fine-tuned as more precise and site-specific assumptions are made at various development stages.

During the first stages (that is, during concept development and site identification), this assessment will remain relatively high level, sufficient to consider if the project is worth pursuing. In this initial stage, ascertain any support mechanisms, such as fiscal and financial incentives—like tax exemptions, reduced or waived import duties, feed-in tariffs, monetizable environmental attributes—either specific to FPV systems or for PV systems in general. Such support mechanisms may vary by country and project size. Approximate costs for site rental/acquisition, equipment, delivery, construction, and operation must be identified along with predicted revenue sources.

As discussed in section 5.2.3, to anticipate the costs of the floating structure, it is important to understand an ideal design and to know where its main structural components would come from. It will be crucial to estimate the logistical costs related to floats. To date, most large-scale FPV projects are using high density polyethylene (HDPE) floats; these are bulky and therefore costly to transport and store. It may be worthwhile to evaluate different possible manufacturing sources; floats transported over long distances will increase costs.

As discussed in chapter 4, the anchoring and mooring system will depend on site-specific conditions such as underwater soil conditions, water depth, water level variation, wave height, water flow, maximal wind speed, among others. Costs will vary depending on site conditions and on the project's scale.

As part of the feasibility study, the cost-benefit analysis may include externalities such as the environmental benefit of reduced carbon emissions because of the green electricity generated, potential environmental impact (positive or negative) on the ecosystem, impact on activities involving neighboring communities (such as fishermen or recreation offered on the water body), reduced evaporation, co-locating an FPV system with a hydropower plant. It will want to mention any constraints imposed by dam operations. Where appropriate, these contextual elements must be added to the analysis so people understand the intrinsic added value of an FPV project.

As the project moves into the development phase, the developer will supply a thorough financial model, complete with a detailed funding strategy. Estimated capex and operating expenditures are fine-tuned based on quotes obtained from contractors and equipment manufacturers. An example of cost parameters based on 2018 parameters from the industry is provided in Annex B.

Details about costs of FPV projects and a comparison with ground-mounted PV projects can be found in chapter 5 of the first report from the *Where Sun Meets Water* series, "Floating Solar Market Report" (World Bank Group, ESMAP and SERIS 2019). The same report also contains information about business models and project structuring for FPV, provided in chapter 4.

5.4 Licenses, permits, and authorizations

Regulators and policy-makers will need, first, to ensure that floating solar is covered by regulations for solar PV plants; in some cases, the existing regulations might require amendment.

Obtaining the licenses, permits, and authorizations to install an FPV system can be challenging, especially in countries with complex regulations such as the United States (refer to section 5.5.5 for more details) or where experience with FPV is still nascent. The permitting/authorization phase can take from a few months to several years in some extreme cases.

Few countries have taken steps to facilitate the permitting of FPV systems. Action may be taken in the future, if FPV projects start to multiply. A clear framework of FPV regulations and policies would reduce development costs and encourage investment.

Jurisdictions have their own requirements for licenses, permits, and authorizations. Some examples are listed below (many are similar to ground-mounted PV projects):

- Access to the water: site control and water use requests/permits (for example, for restricted areas in the public water domain, establishment of a dam protection zone, and environmental protection regulations)
- Site lease agreement for the water body and land usage nearby (for example, for substations)
- Compliance with water code, fishing, or agricultural laws and regulations
- Planning/land use consents (for example, an FPV project might require a potential land use change application)
- Environmental clearance certificate
- Clearance from forest/national parks department/aviation bodies/etc.
- Industrial clearance and site temporary occupation certificate
- Local community consent (that is, cultural heritage/archaeological sites, stakeholder consultations, impact on fishing communities and potential compensation)
- Grid connection application
- Electricity generation license
- Cable-laying authorization
- Building/construction permit
- Special regulations for hybrid plants (hydropower combined with FPV)

Table 5.3 summarizes some best practices in providing permits for FPV projects.

With regard to permitting and access, the following key elements need to be considered when selecting a site for an FPV system:

TABLE 5.3 Best practices for permitting of FPV projects

	Practice
Site ownership	• Selected site and water body should preferably be owned by a single entity, as seeking permissions from multiple owners can be cumbersome.
Land and water use	• Current permissible land and water use is identified; it may not allow electricity generation and hence require a (typically time-consuming) change of land/site title and purpose. This issue may be salient for first FPV projects in certain jurisdictions, as it is often not clear who owns the water surface of a reservoir and which authorities grant permission to use it for FPV installations.
Evacuation lines	• Overhead lines are run along public roads, as the process of obtaining rights to cross other land plots for the electric evacuation lines to the closest grid-connection point can be complex, especially when taking into account the operational lifetime of FPV systems (20–25 years).
Security	• For security reasons, the plot that houses the land-based equipment and the water-based installation are fenced. If it is not possible to fence the water-based installation, road access to the water body should be restricted.
Local developer or EPC contractor	• The local developer or EPC contractor has experience in installing FPV systems; if not it must have at least experience in installing ground-mounted or large rooftop PV systems. Good relationships with government agencies, regulatory bodies, and the grid operator are an important advantage, especially at the local level, as obtaining permits and regulatory clearance can be a lengthy process.
Local community	• As with other types of renewable energy projects, if the FPV system is to be located near a populated area where people have access to the reservoir, obtaining buy-in from affected communities at an early development stage is key to ensuring the viability of the project. Ownership of the project or a revenue-sharing mechanism can be considered when projects will significantly affect nearby residents in terms of landscape/visual impact or water body usage.

Source: Authors' compilation based on industry experience.

- Ownership of the water body
- Ownership of nearby land
- Current usage and role of the water body (for example, primary purposes of the reservoir and likely impact on water levels)
- Synergy with existing transmission infrastructure for power evacuation
- Interconnection level (high, medium, or low voltage and related regulations)
- Engagement of local stakeholders
- Risk-mitigation measures required for bankability and/or credit enhancement

It can take three months to several years to move from the initiation phase to the "shovel ready" milestone. This period should shorten as agencies in more and more regions gain experience with FPV projects. The time required to put all authorizations in place will vary widely and depend partly on whether the systems are to be built on a privately-owned water body for self-consumption or on a water body owned by a third party, such as a public agency. Three types of ownership are possible:

Private site: An FPV system owned by a private owner (such as an irrigation pond on private agricultural land) is generally used for self-consumption, with excess power potentially exported to the grid. The FPV system can have a private owner (for example, the 60 kilowatt peak [kWp] project in South Africa on the Boplaas fruit farm reservoir) or by the developer with an on-site PPA (for example, the 2.8 MWp projected owned by Cleantech Solar at the CMIC cement pond in Cambodia).

Utility: In an FPV system owned by the developer or the utility, electricity can be sold to the grid or self-consumed by the utility. In the 6.3 MWp Queen Elizabeth II FPV system owned by Lightsource BP, for example, electricity is sold to Thames Water for its wastewater treatment facility.

Hydropower dam (private or public): An FPV system can be owned by the existing hydropower plant owner, by the developer, or jointly. If the owner of the hydropower plant lacks solar PV experience, a third party might own and operate the FPV system; however, this will also depend on whether the FPV and hydropower assets are managed independently or jointly. In the latter case, a joint operation agreement (JOA) will need to be concluded.

Different business models and locations will trigger different licensing, permitting, and authorization schemes, a process to be carefully identified early on by (local) developers and/or utilities before the feasibility stage. Providing access to the water surface to install an FPV system by a third party offers a new source of local green electricity, but it can also become a new source of rental/leasing revenues for the water body owner, similar to land/rooftop lease/rental costs.

5.5 Country case studies

5.5.1 Japan

FPV projects in Japan require two authorizations, first, from the Ministry of Economy, Trade, and Industry (METI), which generates an identification number (under the Electricity Business Act) and, second, from the local power utility, which authorizes a grid connection by contract after approval by the utility's engineering department.

At the national government level, FPV projects built on agricultural land must also comply with the Basic Law on Food, Agriculture, and Rural Areas. This requires that the law be modified, as electricity generation is typically not referenced under the law as an acceptable function of the requested land/water. FPV projects must also ensure that they cause no pollution. But environmental impact assessments (EIAs) are not required at the national level for solar PV projects (including FPV). The Ministry of Environment requires EIAs on solar PV projects (including FPVs) larger than 40 megawatts (MW) beginning in April 2020 (under the Environment Impact Assessment Act). The EIA will need to include evaluations of the atmosphere, water, soil, reflected light, ecosystem, scenery, and waste. Items relevant for FPV projects include the following:

- Noise from PV inverters
- Herbicides and wastewater produced during the cleaning of solar panels
- Impacts of reflected light (glare) on local residents
- Impacts on aqueous ecosystem surrounding floating solar power plants
- Impacts on vistas and scenic points[1]

At the local government (prefecture or city) level, FPV projects must generally comply with local ordinances and voluntary guidelines on the following:

- PV site construction regulations: Need to receive approval for project plan
- Site view regulations
- Environmental regulations: Need to confirm that project will cause no harm to the environment. Some regional governments have already made (F)PV projects the targets of EIA ordinances or will request a report of no violation of relevant regulations[2]

FPV projects in Japan are built on three kinds of water bodies: water bodies owned by (i) cities/towns/villages, (ii) farmers associations, and (iii) local homeowners associations. FPV developers have to seek the approval of the relevant entity, which then rents the water bodies to the developers. To date, these entities have not taken ownership in the projects, but this might change in the future. Projects to be built on water reservoirs that are privately owned by companies (mainly for self-consumption) represent an untapped market.

Most FPV projects in Japan export electricity to the grid at a set price, determined either through the applicable FiT or by auction. The main issue pertains to the grid connection, which can be difficult to obtain in certain areas because of insufficient transmission grid capacity.

FPV projects are not typically built on water bodies located in national parks (which are protected by the Natural Parks Act) or on water bodies where fishing is permitted (fishing rights are very complicated). Most FPV systems have been built on agricultural irrigation ponds.

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1. https://tech.nikkeibp.co.jp/dm/atclen/news_en/15mk/102602447/?ST=msbe?ST=msbe&P=2
2. https://www.pv-magazine.com/2018/09/04/japan-to-subject-large-scale-pv-to-tougher-environmental-regulation/ and https://tech.nikkeibp.co.jp/dm/atclen/news_en/15mk/102602447/?ST=msbe?ST=msbe&P=1

5.5.2 Singapore

This case study describes the experience of Sunseap, a Singapore-based clean energy solutions provider, in developing the world's first large-scale (5 MWp) near-shore FPV project. The project will be located in the Straits of Johor separating Singapore from peninsular Malaysia.

Obtaining clearance and permits can be cumbersome in countries where the shoreline is densely populated and home to strategic industries (for example, utilities, semiconductor factories, gas pipelines, water drainage facilities), as is the case in Singapore. Identifying the location and obtaining the required clearances took Sunseap about 2.5 years; 13 public agencies were involved in the process. One agency, the Economic Development Board (EDB), which supported the project, played a lead role in getting clearances from the other agencies. The fact that this type of project had never been done before protracted the process, because of agencies' lack of experience and uncertainty as to how this project could affect nearby activities.

Based on interviews with Sunseap, the following agencies had to be consulted during the project development phase:

1. Building and Construction Authority: shoreline work, stonewall integrity
2. Singapore Police Force: cross-border security, illegal immigration zone
3. Maritime and Port Authority: works on seawater, navigation channel, marine operations
4. Singapore Land Authority: rental of land, including land under the sea
5. SP Group (the power utility and grid operator): permission to connect to the grid
6. SP Gas: possible impact on existing subsea gas pipeline between Malaysia and Singapore, located underneath the FPV system
7. Urban Redevelopment Authority: Singapore overall master plan
8. Water utility (PUB): drains and pipes
9. National Environment Agency and National Parks Board (NParks): EIA and adherence to NParks's terms and conditions.

The Civil Aviation Authority of Singapore, the Land Transport Authority, and the Singapore Civil Defence Force were also involved.

This case represents an extreme case, because no similar project had been done before and pressure on shoreline usage is great in Singapore. The process is likely to be simpler for inland FPV projects, especially when initiated by public agencies.

The involvement of local developers who have experience with the relevant public agencies was critical. Also important was having at least one public agency promote the project.

5.5.3 Taiwan, China

In Taiwan, China, the central government has played a key role in supporting the development of FPV as a contributor to the ambitious target of installing 20 gigawatts (GW) of solar power by 2025. Given land scarcity and the initial failure of scaling rooftop PV country-wide (mainly because of the multiple competing usages of roofs), FPV is a natural candidate for driving the growth of solar in Taiwan, China.

In the past two years, the central government has made significant efforts to push local public authorities to endorse FPV through capacity tenders under the FiT regime in place. Water agencies are working closely with local and central energy authorities to organize FPV tenders. Certain FPV projects are also being built on privately owned land and water bodies, such as former fishing ponds or the Taiwan Sugar Corporation water retention basins. FPV projects on fishing ponds rather than other types of reservoirs encounter two additional constraints:

- Surface coverage of the FPV system cannot exceed 50 percent of the fishing pond surface area.[3]
- Installation of the FPV system should not reduce fish production by more than 30 percent.

In certain cases where basins from former fishing ponds are no longer used for fish production, devel-

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[3] There is no official limit on surface coverage for water bodies not used for fish production, but FPV projects tend not to exceed 60 percent.

opers can apply for a modification of the basin and land function. Depending on the region, this process can take three months to a year. Where both fishing activities and solar PV production are combined, innovative solutions are also being developed to allow for a better combination of fish and electricity production.

Tariffs are determined by the FiT regime, which is updated annually by the Bureau of Energy, in the Ministry of Economic Affairs.[4] The capacity and rental cost for water-surface usage are typically tendered.

Permitting of FPV systems is similar to permitting for ground-mounted PV systems. It depends on the classification of renewable energy projects:

- **Type 1:** Systems requiring an electrical license
- **Type 2:** Systems used for self-consumption
- **Type 3:** Systems below 2 MW.

EIA requirements and approval depend on the location and type of water body.

5.5.4 The Netherlands

The national Zon op Water (sun on water) consortium[5] commissioned studies to understand the licensing and permitting process applicable for FPV systems in the Netherlands.

These studies concluded that, despite not being defined as such by law, FPV systems should be considered building structures: installed for a long period of time, they are connected to the ground via cables (for power supply and anchoring). In this sense, they could be compared to houseboats, common in the Netherlands, which require environmental permits. If the developer takes the risk of categorizing its FPV system as a boat rather than a building structure or a houseboat, then it runs the risk of facing an objection from a third party (based on case law), which could lead to the cancelation of its permits and the need to remove the system.

According to Deltares (2018), when evaluating the FPV permitting process, developers must first evaluate who controls the water body:

- National: Are works to be undertaken in or close to a water body under the jurisdiction of the Ministry of Infrastructure and Water Management (Rijkswaterstaat) or on a national dam (typically large rivers, lakes and canals)?
- Regional: Are works to be undertaken in regional waters (under the jurisdiction of a water utility) or on provincial waterways, which are smaller water bodies?
- Private: If the water body is owned by an individual or private company, private law applies.

A different set of rules applies for each of these scenarios. The following regulatory aspects need to be evaluated for each scenario (the first two are general regulations; the rest depend on the location):

- Building and spatial (land- and water-use) rules
- Discharge and leaching regulations (from the Water Act)
- Protected areas and species (Nature Protection Act)
- Cabling works on public land
- Archeology
- Groundwater protection and quiet areas (provincial environmental rules and regulations)
- Works in contaminated soil (Soil Protection Act)
- Cabling works on or near infrastructure such as national roads and railways
- Area protected by the Environment and Planning Act
- Environment law and regulations (national, provincial, water board, and city levels)
- Private law (when working on privately owned land).

In most cases, FPV projects receive notices of exemption from the required regulatory framework.

The flowchart shown in figure 5.1 explains the Dutch regulatory framework for FPV systems.

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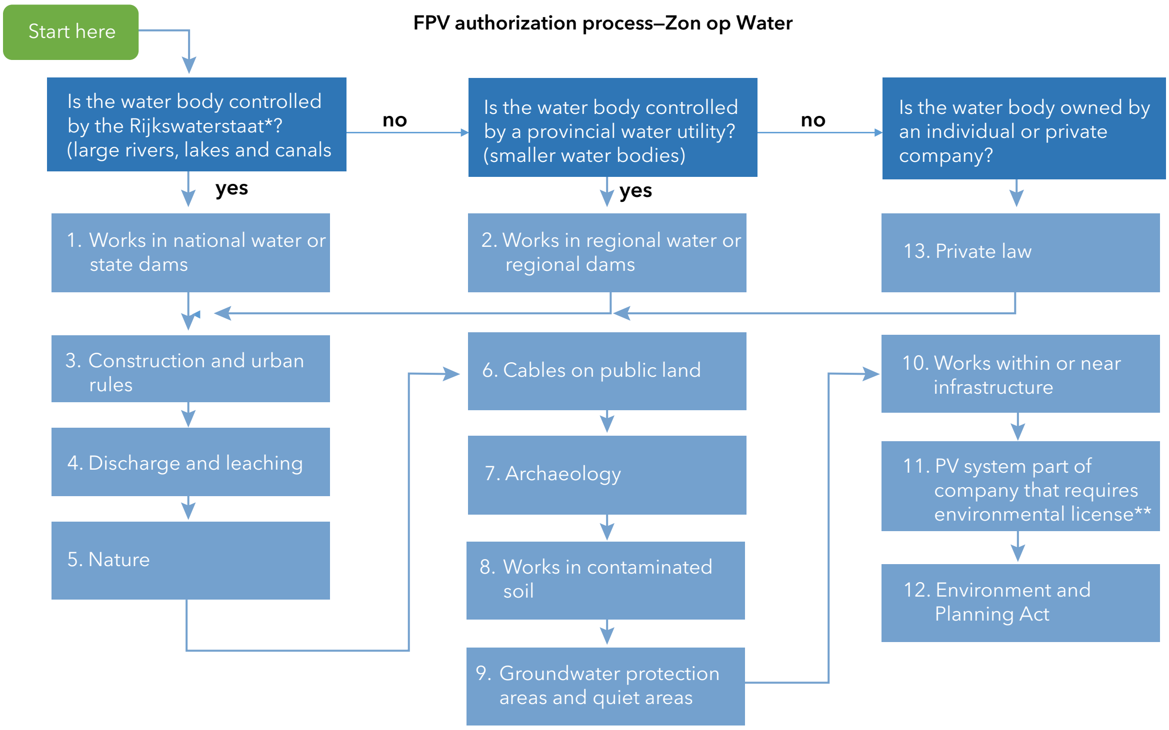
[4] https://www.moea.gov.tw/MNS/english/news/News.aspx?kind=6&menu_id=176&news_id=83360

[5] https://www.zonopwater.nl/

FIGURE 5.1 Flowchart of regulatory framework for FPV systems in the Netherlands



Source: Translated by the authors from Deltares 2018.

Notes: * Rijkswaterstaat is the Dutch Ministry of Infrastructure and Water Management. ** More information can be find at: https://www.infomil.nl/onderwerpen/integrale/activiteitenbesluit/begrip-inrichting/.

5.5.5 United States

No specific regulations or guidelines have been developed for FPV applications in the United States. Developers have followed state-specific solar ordinances as well as other relevant acts and regulations pertaining to environmental quality, land use, and water rights. Each state has its own set of regulations, which can be interpreted in different ways at the county level. Developers thus need to understand and conform to each county's interpretation of state regulations.

A leading FPV supplier believes the permitting process for FPV projects in nonsensitive zones (such as agricultural and industrial ponds) should be simpler than for ground-mounted PV projects, where additional permits/authorizations are required because of heavy civil works (land excavation, tree removal, ground leveling, and so forth) involved. Natural lakes should be avoided in favor of more appropriate places like man-made reservoirs.

As with ground-mounted PV projects, FPV project developers first need to secure a site-control agreement (such as a lease agreement). Next is a Generator Interconnection Agreement (GIA) with the utility to be connected to the grid. Additional agreements may be required if the generator wishes to participate in the wholesale electricity markets.

After that is an enhanced study of possible infringements of land-use law and water rights. As required for ground-mounted PV projects, a Phase I environmental site assessment (ESA) is then conducted to identify potential or existing environmental contamination liabilities. A Phase II ESA is undertaken if issues arise in the first-phase analysis.

States and counties often include model solar ordinances on their websites.[6] An important law in California is the California Environmental Quality Act (CEQA), which requires in-depth EIA studies. FPV project developers can request a notice of exemption (NOE) when the potential environmental impact of the project is zero or minimal (especially for reservoirs or projects with a surface-coverage ratio of less than 50 percent; see figure 5.2). The NOE is filed with the county and opened for public consultation for 30 days. If no complaints are filed, the NOE is approved.

The process is different in Massachusetts, where the Department of Environmental Protection (MassDEP) undertakes an EIA for each project requiring its approval. The state Conservation Commission issues a determination based on the EIA.

Building strong relationships with water utilities and providing them with adequate proactive and anticipatory studies from reputable environmental consulting firms, such as ecological risk assessment (ERAs),[7] are key to facilitating the permitting process. For example, water utilities in California are suffering from evaporation and algae growth. FPV systems can help them solve both issues, facilitating the authorization process. Elsewhere, water bodies may be more affected by mosquitoes, suggesting that FPV developers should collaborate with vector control[8] companies.

These steps, in addition to stakeholder engagement, should be taken early in the development of FPV projects to ensure the site is not considered sensitive and to determine what agencies are involved. For instance, local wetlands and other types of endangered habitats might be protected by specific laws and regulations, which must be considered when installing FPV systems in specific areas.

For safety purposes, FPV systems on large hydropower dams in all states fall under state jurisdiction. These projects are usually subject to a more intense level of scrutiny due to the level of liabilities for the dam owner to ensure the structural integrity of the facilities. Permits are therefore more difficult to obtain, and additional feasibility studies are required.

The number and types of required permits depend on state and county laws and regulation as well as on the environment where the project is located. All projects will require electrical permits (inverters, transformers, interconnection); an encroachment permit for anchoring at the bottom of the reservoir; and various environmental authorizations or exemptions from specific laws or regulations where applicable.

In New Jersey most reservoir beds are considered protected wetlands. FPV systems in New Jersey must therefore be fixed by bank anchoring only. “It took three years of problem solving to build an FPV array for the Sayreville, New Jersey, water utility’s water treatment plant. Every step required consensus building. Environmental permitting took 18 months, because the state had to decide whether the energy or water department was responsible. But in the last six months, utilities seem ready to embrace floating solar,” noted one energy expert.[9]

Most market potential in the United States is expected to be for 1–5 MW FPV projects, mainly water utilities and commercial and industrial customers installing FPV systems for on-site consumption (behind-the-meter projects).

5.6 Conclusion

The few country case studies from the previous sections illustrate how differently (floating) solar regulations may be tackled in each country. The legal frameworks of each country are different, of course, and developers often have to deal with a set of preexisting rules not specifically designed for floating solar applications. Finding a common set of rules applicable across countries would simplify the development of FPV projects across borders; even though this

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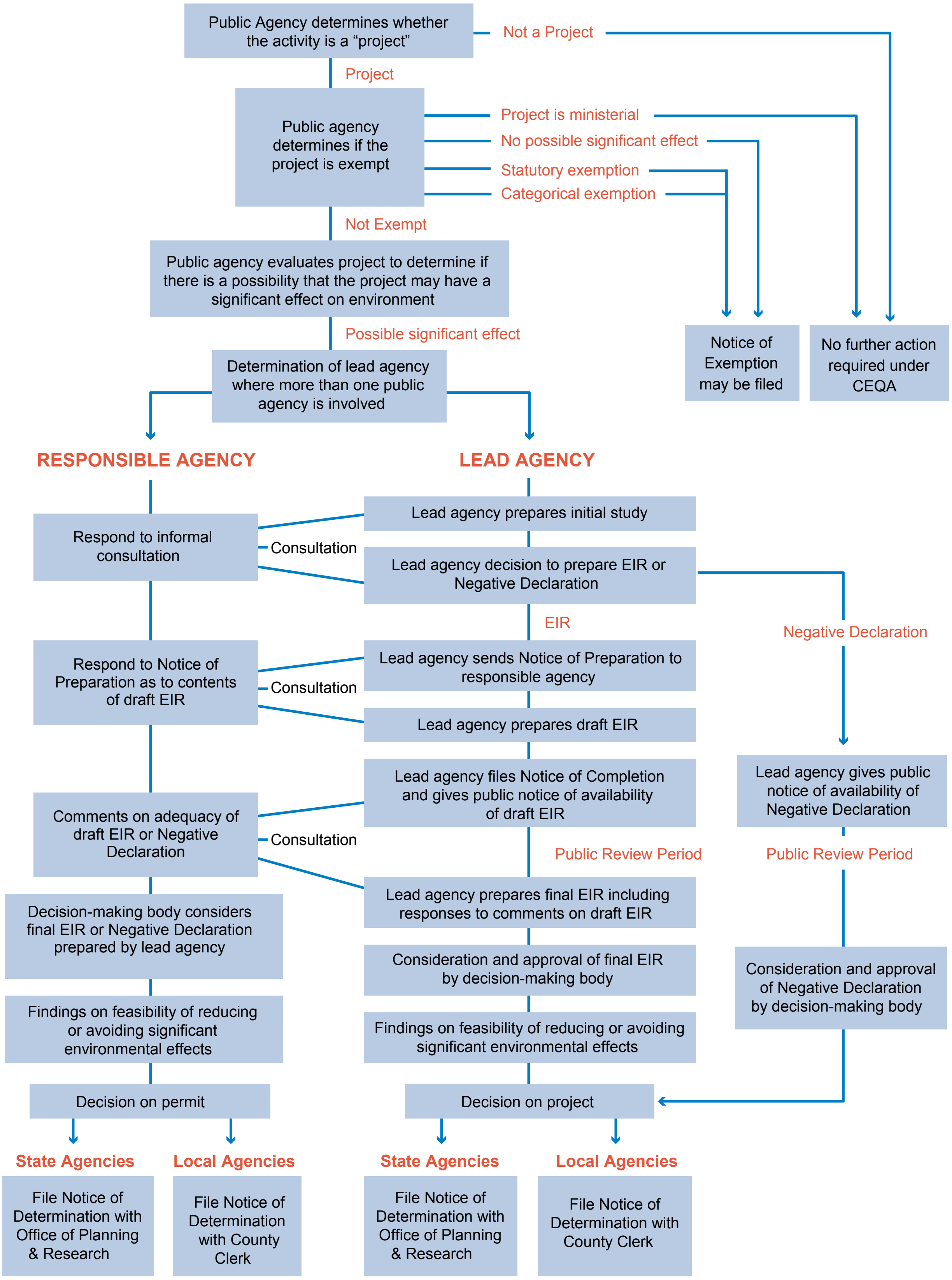
6. See https://www.energy.ca.gov/localgovernment/planning_resources/example_ordinances.html#solar for California’s ordinance.
7. The ERA provides general information on sensitive biological resources that may be present based on information obtained utilizing governmental and industry databases (such as the California Natural Diversity Database [CNDDB], the National Wetlands Inventory [NWI], and the US Geological Society [USGS] quadrangle maps) and a review of aerial photography, aerial signatures, and the professional opinion of a biologist. The ERA also provides a general synopsis of local land use ordinances and/or requirements, zoning, and/or development standards that may affect project costs or scheduling/timelines.
8. Vector control is any method to limit or eradicate mammals, birds, insects or other arthropods (collectively called “vectors”) which transmit disease pathogens (for example, mosquito control).
9. https://www.utilitydive.com/news/floating-solar-offers-unique-bargains-us-utilities-are-missing-out/551693/

FIGURE 5.2 **California Environmental Quality Act process flow chart**



Source: http://resources.ca.gov/ceqa/flowchart/.

might be complicated to implement in reality. Moreover, rules will depend on the type of water body used and its applications. As can be seen from the example of the United States, rules may vary across the country, depending on state laws and county interpretation of those laws. The country case studies attempt to illustrate these differences. So efforts to define a new set of common rules for FPV systems across countries might be premature, but common rules should be considered in the future when the sector gains more maturity and experience in the field.

Especially now, with the technology so new, it is essential to generate evidence on the impacts of such systems on their environment to ensure smooth wider deployment. In general, where potential impact and risks are still being studied, precautionary principles should be followed; under no circumstances, should rules and regulations from one country be blindly applied to another one without proper consideration of the local conditions. Each site where FPV systems can be installed will have a peculiar environmental sensitivity, and they must be evaluated before considering installing FPV systems.

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6 ENVIRONMENTAL AND SOCIAL CONSIDERATIONS

6.1 Overview, scope, and methodology

This chapter summarizes the environmental and social (E&S) issues commonly associated with the development, construction, and operational phases of floating solar photovoltaic (FPV) activities and provides recommendations for their management.

The E&S impacts of FPV projects depend on project size, the technology employed, site characteristics, and other local conditions. Project planners must take all possible impacts into account as they follow international good practices, domestic regulations, and, where applicable, financing institutions' expectations and requirements.

Every FPV development is unique and thus presents its own range of E&S risks. Planners should tailor the recommendations offered in this chapter to the hazards and risks of the specific project, based on an environmental assessment that accounts for site-specific variables (for example, the country context and assimilative capacity of the local environment). The applicability of specific technical recommendations should be determined by qualified and experienced professionals. Where domestic regulations differ from the recommendations presented in this document, it is suggested that projects follow the more stringent of the two. Where less stringent levels or measures than those provided in this document are deemed appropriate (in view of specific project circumstances), a full and detailed justification for each proposed alternative may be included in the site-specific environmental assessment. These justifications should demonstrate that the alternate performance levels chosen protect human health and the natural environment.

During the initiation phase of the project, project developers must assess all relevant direct, indirect, and cumulative E&S risks and impacts of a project throughout its entire life cycle.[1] The E&S assessment should be based on up-to-date information, including an accurate description of the project and associated elements, and E&S baseline data at a level of detail sufficient to inform the characterization and identification of risks and impacts and mitigation measures. The assessment should also examine project alternatives and identify ways of improving project selection, siting, planning, design, and implementation in order to apply the mitigation hierarchy for adverse E&S impacts.[2]

The entire "area of influence" of an FPV project must be assessed. It includes the project's immediate footprint; associated facilities (such as the electrical infrastructure, including substations, electrical transmission lines and towers, dams[3], and other infrastructure); the water body where typical FPV components would be installed, and, depending on the circumstances, upstream and downstream waters and their associated uses/users. There are E&S impacts associated with the construction, operation, and decommis-

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[1] See the World Bank's Environmental and Social Framework (World Bank n.d.) and the International Finance Corporation's Performance Standards (IFC n.d.), which address the management of E&S risks and impacts and stakeholder engagement.

[2] The mitigation hierarchy first emerged in the 1970s. It underpins the World Bank's Environmental and Social Framework and IFC's Performance Standards. The hierarchy prioritizes efforts to anticipate and avoid risks and impacts before moving to efforts to minimize or them to acceptable levels. Where significant residual impacts remain, they should be compensated for or offset, where technically and financially feasible.

[3] When a dam is considered an associated facility (as defined in paragraph 11 of World Bank Environmental and Social Standard 1 or paragraph 8 of IFC's Performance Standard 1) of the FPV project, safety risks to third parties or affected communities should be managed, as outlined in World Bank Environment and Social Standard 4/IFC Performance Standard 4.

sioning of electrical infrastructure (see Environmental, Health, and Safety Guidelines for electric power transmission and distribution in World Bank Group n.d.). The discussion here, however, focuses on impacts, especially on the aquatic environment, that are specific to FPV facilities' installation, operation, maintenance, and decommissioning.

Assessing potential environmental risks and impacts as early as possible in the project life cycle maximizes the range of options available to anticipate and avoid them. Where avoidance is not possible, careful plans must be made to minimize potential negative impacts—and, where residual impacts remain, to compensate or offset them. Baseline assessments should include seasonally representative information (on hydrologic regimes, aquatic or terrestrial ecology, and similar issues), following internationally accepted practices.

In addition to the onshore impact that is similar to that of ground-mounted installations (access roads, construction site, worker facilities, warehouses, transformer stations, substations, transmission lines, and so forth), FPV projects may affect water quality and aquatic-supported biodiversity. The degree of the impact varies dramatically depending on the type of reservoir (natural, manmade, onstream, off-stream) and its uses (hydropower, recreation, conservation, water supply, and so forth). This chapter focuses on deep lakes/reservoirs that are used to provide drinking water and/or support natural flora and fauna and may be downstream of other lakes/reservoirs. Effects associated with water quality and aquatic-supported biodiversity vary depending on multiple factors, including geographic location, seasonality, the size of the water body, the percentage of the water body covered by the FPV system, incoming water sources, and the materials used as part of the FPV installation, to name a few. Table 6.1 compares the environmental and social aspects of floating and land-based photovoltaic (PV) systems.

Research on these topics is taking place in various parts of the world that may lead to more specific guidelines in the future. The following sections focus primarily on the potential impact on water quality and biodiversity as well as occupational and community health and safety considerations and their measures to mitigate them. The potential impact on reduced water evaporation is not addressed; research on this particular topic is ongoing.

6.2 Managing effects specific to floating solar photovoltaic systems

This section summarizes E&S issues associated with FPV facilities and provides recommendations for their managing them. These recommendations are based on the World Bank Group's *General Environmental, Health, and Safety (EHS) Guidelines,* which cover most types of large industrial and infrastructure activities and encompass the construction phase (World Bank Group n.d.). Many of the E&S impacts commonly associated with FPV facilities can be avoided by careful site selection.

6.2.1 Environmental health and safety

Environmental issues specific to the construction, operation, and decommissioning of FPV projects primarily include the following:

TABLE 6.1 Environmental and social aspects of floating and land-based photovoltaic systems

	Floating PV	Land-based PV
Environmental	• Long-term effects on water quality not well-established • Potential impact on biodiversity, including aquatic ecosystems • Potential to reduce algae growth • Potential to reduce water evaporation	• Some adverse impacts during construction • Potential habitat loss or fragmentation
Safety	• Risk of personnel falling into water	• Generally safe

Source: Authors' compilation.

- Landscape, seascape, and visual impacts
- Water quality
- Biodiversity

6.2.1.1 Landscape, seascape, and visual impacts

Depending on the location, the floating modules of an FPV project may be visible from residential areas or tourist sites. Project operations may also change the character of the surrounding landscape and/or seascape.

Impacts on legally protected and internationally recognized areas of importance to biodiversity and cultural heritage are important to consider before construction.[4] It is recommended that wire-frame images and photomontages from key viewpoints be prepared to inform both assessment and consultation processes.

Measures to avoid and minimize landscape, seascape, and visual impacts are largely associated with the siting and layout of floating modules and associated infrastructure. Consideration should be given to the floating modules' layout, size, and scale in relation to the surrounding landscape (including, for example, residential properties and recreational areas/routes). All relevant viewing angles should be considered when considering floating modules' location, including from nearby residential areas.

As for ground-mounted or rooftop PV systems, potential glare should also be analyzed. Hazards from glare brought about by improperly sited (F)PV systems might include temporary disability (flash blindness) or distraction. Although PV modules are designed to reflect as little light as possible (modern PV panels can have less intense reflectivity than still surface water), glare (and glint) may still occur in a few specific situations (Anurag and others 2017). One such real life case of glare is depicted in figure 6.1. When FPV projects are located near airports, for instance, glare analysis is very important for public safety.

6.2.1.2 Water quality

FPV projects affect water quality to varying degrees, depending on their type and design characteristics. For certain reservoirs, solar arrays need to be placed close to or near the main channel such that they are not "beached" or "grounded" during (winter or dry) months, when reservoir levels are lowered. For larger installations, arrays probably need to be elongated and spread along the area between the winter/dry-month pool shoreline and the edge of the navigation channel of the river/reservoir to minimize any disruptions to boater traffic. The following are items of interest in this situation:

- Potentially reduced flow in the areas surrounding the arrays can contribute to increased sedimentation in these areas.
- FPV plants can cause large areas of uneven surface heating, reduced reservoir turnover efficiencies, and degradation of littoral zone plant growth as a result of reduced sunlight.
- Positioning of array systems needs to be studied to understand their effects on the flow patterns of the reservoir/river, which can contribute to shoreline degradation, undesirable morphological changes, and potentially water quality.

Possible impacts of FPV projects on water quality include the following:

FIGURE 6.1 **Glare on Yamakura dam in Japan**

Source: © Kyocera TCL Solar LLC.

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[4] Sites with archaeological, paleontological, historical, cultural, artistic, and religious value.

- Changes to ambient temperature stratification and dissolved oxygen levels can result from the shading of water and/or increased heat generated from the FPV installations, with effects on aquatic life and water quality. These changes could be complementary or opposing, depending on the FPV system type and size.
- Certain areas of the reservoir where these arrays could be sited may create "pockets" of varying water quality, which have been largely unstudied. During special operations, some hydropower reservoirs use "turbine preference" selection withdrawal techniques to capture high dissolved oxygen and/or warmer water temperature from specific layers and specific locations of the reservoir (right bank versus left bank).
- Impacts on water quality and aquatic fauna can result from leaching from materials used as part of the FPV installation.
- The use or accidental release of oil and/or lubricants from boats used during maintenance activities or detergents used to clean panels can affect water quality and aquatic flora and fauna.

Baseline assessment

Few studies have been carried out to understand or quantify the impacts of FPV systems on water bodies. Data collection for both the modelling studies and the baseline assessment is very important to understand the physical/bio-geo-chemical interactions and obtain sufficient modelling inputs. The nature and extent of water quality changes are influenced by a variety of factors, including water residence time; bathymetry; climate; the presence of inundated biomass; catchment geomorphic characteristics; and the level of industrial, agriculture, and resource extraction activities. These factors should be carefully evaluated in the impact assessment phase of the project, using seasonally representative baseline data. In particular, a site-specific water quality survey is needed to establish baseline water quality conditions. It should include an analysis of available data and samples at representative sites as well as within the proposed project footprint area. The data collection should cover a range of parameters over a sufficiently long duration for both local meteorology and in the water. An example of parameters collected for water quality impact assessment of FPV projects in Singapore is presented in box 6.1; water quality modelling tools are presented in box 6.2.

Recommended parameters for the data collection include (but are not limited to) the following:

- Meteorological aspect (to be measured above and below the FPV system and at nearby areas that would represent ambient conditions):
    - Solar radiation (net radiation or short- and long-wave radiation)
    - Air temperature
    - Wind speed and direction
    - Relative humidity
    - Cloud cover.
- Water aspect:
    - Water temperatures at various depths throughout the water column
    - Level of acidity (pH)
    - Dissolved oxygen (DO)
    - Total suspended solids
    - Chemical oxygen demand
    - Biochemical oxygen demand
    - Algal concentrations
    - Chlorophyll-a.

Temperature stratification and dissolved oxygen levels

Temperature stratification (that is, the formation of water layers based on temperature) is most common in deep reservoirs, where relatively deep water remains still for extended periods of time because of limited water flow that does not encourage water mixing. This phenomenon may be greater in reservoirs with limited exposure to wind. Covering lakes/reservoirs with FPV installations can increase stratification and limit water mixing below and in the vicinity of the FPV installation, resulting in lower dissolved oxygen levels. The magnitude of increased stratification would be site-specific and dependent upon the scale of the project according to the ratio "water body covered area/water body total area." For example, a ratio of 3–4 percent would result in a small increase in stratification, which would have a minimum to insignificant impact on water quality.

BOX 6.1

Water quality impact assessment conducted at Tengeh and Kranji Reservoirs, Singapore

In Singapore, PUB, the national water agency, required a strict water quality impact assessment for the proposals of two large-scale FPV systems on its reservoirs in 2018 and 2019 (Request for Information by the Singapore Economic Development Board (EDB) for 100 MWp at Kranji Reservoir and tender for 50 MWp at Tengeh Reservoir by PUB). An example of the scope of work for this assessment is summarized as follows:

1. Collect water and sediment samples in reservoirs. Parameters to be analyzed include, but are not limited to turbidity, dissolved oxygen, chlorophyll-a, temperature, conductivity, Ph, and nutrients.
2. Develop and calibrate the reservoir catchment model (storm water management model or SOBEK) based on data provided by PUB (flows and water levels in drains, rainfall, and so forth).
3. Establish a basic grid for the hydrodynamic model of reservoir based on data provided by PUB (bathymetry, meteorology, inflows and outflows).
4. Develop a heat flux module in the modelling system to account for the observed impact of the FPV system as a result of the modeled water circulation.
5. Develop a most probable heat budget for the climatic year based on the computational fluid dynamics data to be water-quality data and carry out initial one-year scenario simulations to evaluate the likely spread of results attributable to the FPV system. Evaluate the most likely impact of the system on circulation and water quality in the reservoir.
6. Based on modeled data, provide a qualitative—and, where appropriate, quantitative assessment—of the indirect effects arising from the FPV system at the reservoir, including (but not limited to) the effects on reservoir quality over the lifetime of the system and the potential effects arising from the maintenance of the system and from reservoir operations along the corridor between the reservoir edge and the floating solar panels.
7. Recommend avoidance or mitigation measures to reduce overall direct and indirect effects on water quality arising from the presence of the FPV system in the reservoir. The mitigation measures should cover the preconstruction, construction, installation, and operational phases of the project.

Sources: Author's compilation based on EDB and PUB (2018); and PUB (2019).

However, if the ratio is high, the floating solar PV arrays could significantly block the influx of solar radiation at the water's surface (for example, reducing the top layer heating), which could then have several impacts:

- If algae are common to the water body, the lack of sunlight would increase their rate of decomposition and, accordingly, increase oxygen demand at the bottom of the reservoir, potentially causing anoxia of the water body, which would have a significant negative impact on the aquatic species and habitats contained within the reservoir that require dissolved oxygen for survival.
- For hydropower reservoirs, covering significant parts of the surface with FPV could severely limit the ability of operators to satisfy environmental requirements via selective withdrawal techniques, which typically involves pulling warmer water-high oxygen level from the top of the reservoir to increase downstream river temperatures and dissolved oxygen concentrations.
- Especially in river-like sections, the positioning of the arrays within the reservoir may alter surface lateral and vertical flow patterns, which may have local effects of flushing out warm water overbank or reducing dissolved oxygen concentrations during higher flow periods.

BOX 6.2

Water quality modelling tools

Several three-dimensional hydrodynamic and water quality modelling tools (for example, ELCOM-CAEDYM, MIKE, and Delft3D) may be used to understand the effects an FPV system can have on overall water quality. The ELCOM-CAEDYM and Delft3D-FLOW coupled with the Delft3D-WAQ models can be used to evaluate the water quality impacts in lakes and reservoirs; the MIKE3 coupled with the MIKE ECO Lab and the Delft3D-FLOW coupled with Delft3D-WAQ models can be used for estuarine and coastal areas. For a more accurate estimation of surface runoff and a more complete assessment of the water quality, hydrological catchment modelling tools such as MIKE FLOOD/SHE or SOBEK can be used. An example of hydrodynamic and water quality assessments carried out for FPV can be found in STOWA (2018) and Deltares (2018).

Source: Tropical Marine Science Institute at National University of Singapore.

- Top-layer wind mixing plays an important role in the nutrient dynamics of the upper water layers (for example, transfer of heat/cooling and momentum to the lower part of the reservoir). The presence of arrays may hinder this process.

Additional impacts on ecosystems associated with increased stratification and low dissolved oxygen are commonly understood and may include the following (Kirke 2000):

- Negative impact on aquatic life, including fish distress and reduced growth rates
- Anaerobic decomposition of organic materials and metals from bottom sediments, causing changes to water odor and taste and potential health issues
- Increased levels of cyanobacteria (blue-green algae), which can create corrosive conditions for metals (especially racking systems made of steel) (Rossum 2000)

Recommended measures to prevent increased stratification and maintain dissolved oxygen levels include the use of bubble plumes or mechanical aerators to maintain circulation and exchange of water between the surface and lower levels.

Leaching of chemicals

FPV systems often use high-density polyethylene (HDPE) pontoons/floats to support the racking system for the solar panels and other required components (that is, the electrical component housing) as well as for walkways to facilitate future maintenance activities. Although the American Water Works Association has approved its use in potable water, HDPE can leach phenolic compounds related to antioxidants (that is, 2,4-di-tert-butyl-phenol [2,4-DTBP] and butylated hydroxytoluene [BHT]), which can affect taste and cause odor, as well as low levels of endocrine disruptors, which can cause adverse health effects (Skjevrak and others 2003; Yang and others 2011). Brominated flame retardant, a water-soluble hormone disruptor, is added to some plastics; it is generally limited to cable applications and electronics in high-temperature applications (Hansen and others 2013). Other materials may be leached into the water via the corrosion of metals caused by low pH and high total dissolved solids; degradation of plastics from ultraviolet light; and/or breaking/delamination of panels. Recommended measures to prevent leaching of chemicals include the following:

- Prepare a baseline water chemistry analysis.
- Select project materials based on the results of this analysis, with a view to avoid or minimize breakdown into toxic materials or leaching (for example, chemicals that have estrogenic activity, brominated flame retardants, and so forth). Leaching of anti-corrosion/degradation coatings needs to be considered as well.
- When relevant, FPV components that may be in contact with water should meet internationally recognized standards for drinking water systems. In the United States, for instance, any company that manufactures, sells, or distributes water treatment

or distribution products in North America must comply with NSF/ANSI 61: Drinking Water System Components—Health Effects (NSF 2016).

Spill prevention

Other impacts on water quality and thus aquatic flora and fauna could result from contaminants associated with potential oil and lubricant spills from boats accessing the panels for maintenance purposes, as well as detergents used for washing panels when excessive soiling or salt buildup occur. Recommended measures to prevent spills include the following:

- Provide adequate secondary containment for fuel storage tanks and for the temporary storage of other fluids, such as lubricating oils and hydraulic fluids.
- Train workers in the correct transfer and handling of fuels and chemicals and the response to spills.
- Provide portable spill containment and clean-up equipment on site, and train staff in its deployment.
- Use nontoxic detergent or cleaning agents approved by the appropriate governmental agency.

6.2.1.3 Biodiversity

Appropriate site selection is critical to avoiding and minimizing potential adverse impacts on biodiversity. It is suggested that the selection process include the following:

- Consider the proximity of the proposed FPV project to sites of high biodiversity value in the region (including sites located across national boundaries). Early screening can improve macro-level project site selection and the scoping of priorities for further assessment, thus reducing unnecessary impacts to biodiversity and costs in the future.
- For marine FPV projects, review areas of importance to marine life, notably to fish, marine mammals, and sea turtles (for example, feeding, breeding, calving, and spawning areas), and various types of habitats (for example, juvenile/nursery habitats, mussel/oyster beds, reefs, mangroves, or sea grass and kelp beds). Siting would also include a review of productive fishing areas.
- Consult with relevant national and/or international conservation organizations to inform site selection and determine the appropriate study area; methodology (that is, electrofishing, acoustic, autonomous underwater vehicles, scuba divers, bottom-mounted underwater video stations, and so forth); and frequency of sampling (that is, multiple sampling at different times of the year or different times of the day).

Baseline assessment

Following a scoping and desktop study, appropriate site-specific baseline biodiversity information may be needed to inform an environmental and social impact assessment. Where required, baseline biodiversity surveys should occur as early as possible and consider the following elements:[5]

- Site-specific issues: Habitats, geographical location, topography, and vicinity to sites of high biodiversity value.
- Species-specific issues: Species of flora and fauna of high biodiversity value, species with a special international or national conservation status, endemic species, and species that are at elevated risk of impact from FPV facilities.
- Season-specific issues: Certain periods of the year when the project site may have a greater or different ecological function or value (for example, migration season, breeding season, or winter season).

Aquatic flora and fauna

A typical lake/reservoir has three distinct zones of biological communities linked to its physical structure:

- The **littoral zone** is near the shore, where sunlight penetrates all the way to the sediment, allowing photosynthesis to occur. Light levels of about 1 percent or less of surface values usually define this depth. Littoral zones play an important biological role, supporting a diverse community of aquatic plants and animals, which provide a substrate for algae and invertebrates as well as habitat and food sources for fish and other organisms.

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[5] Generic risk assessments and mitigation plans are unlikely to be useful across species and locations.

- The **limnetic zone** is the open water area where light does not penetrate to the bottom. This zone is dominated by plankton (phytoplankton and zooplankton), which are crucial to the food chain as a primary food source for crustaceans, fish, and birds (which in turn may be a food source for other various species, including humans).
- The **benthic zone** is at the bottom. It is typically covered in fine layers of mud, which supports species that burrow and/or attach to it as well as species that move freely within the zone. It is dominated by worms, larvae of chironomid flies, and mollusks and also supports nematode worms and ostracods.

Potential impacts to aquatic flora and fauna could occur for the following reasons:

- The shading of habitats and species from FPV installations within the littoral and/or limnetic zones
- Installation of FPV components within the littoral or benthic zone, causing direct disturbance/mortality (subsurface penetration from mooring systems and disturbance from the placement or movement of underwater electrical cables [that is, increased turbidity])
- Exposure to electromagnetic fields associated with underwater electrical cables
- Impacts on water quality (materials may be leached into the water via corrosion of metals and/or degradation of plastics) that can affect fish and invertebrate species
- Anchoring on the shores (potentially affecting the littoral zone) or at the bottom of the water body (affecting the benthic zone)

Certain float designs can also bring unwanted consequences. Open areas in the middle of the floats that do not involve mounted PV panels, most often along the perimeter of a floating island, create stagnant water pockets, which can become a breeding ground for midges and mosquitoes. Algae growing on the submerged structures or floats provide a suitable habitat for insect larvae to grow, which can lead to a proliferation of insects (see chapter 9 for more details).

Shading

Impacts on aquatic flora and/or fauna that rely on light for photosynthesis, seeking prey, and food production could occur from shading caused by an FPV installation. Studies are not available detailing these impacts, but there is a body of literature on the effects on flora and fauna of attached and floating docks, piers, and moored vessels in lakes/reservoirs. Studies show that shading can reduce and alter ambient light patterns, limiting plant growth and recruitment, reducing surface phytoplankton production, altering flora and fauna assemblages, and affecting animal behavior (Beauchamp, Byron, and Wurtsbaugh 1994; Bolding, Bonar, and Divens 2004; Colle, Cailteux, and Shireman 1989; Garrison and others 2005; Helfman 1981; Rondorf, Rutz, and Charrier 2010; Kahler, Grassley, and Beauchamp 2000, citing White 1975). While structures that create cover and shade may provide habitat, this simple habitat is different from the natural habitat, in that it lacks structural complexity, which prey species rely on for cover. Therefore, overwater structures may increase predators' success rates. Shading also reduces aquatic vegetation and phytoplankton abundance, reducing habitat and primary production.[6]

Specific solutions should be designed on a case-by-case basis and tested on site, as they might work for some geographies but be unsuitable for others. These potential effects to primary production (the product of phytoplankton biomass times phytoplankton growth rate) are in conflict with a commonly discussed benefit, which is that FPV installations reduce the formation of algae. Algae reduction may be a benefit to reservoirs/lakes that experience eutrophication; it would not be a benefit to a reservoir/lake that supports a natural ecosystem. Therefore, effects need to be considered on a case-by-case basis.

Disturbance from the placement or movement of underwater electrical cables

Impacts on the benthic habitat and species could occur as a result of submerged electrical cable movement and/or the installation of mooring systems. Electri-

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[6] In the United States, docks built no wider than 4 feet, with wide board spacing and orientated in a north-south direction have been found to reduce shading impacts (Shafer and others 2008; Burdick and Short 1999).

cal cables that run across the floor of a water body can affect habitat and organisms because of movement caused by wind and/or a change in reservoir levels. Mooring systems directly anchored to the bottom/substrate of a lake/reservoir can also have direct impacts (mortality, increased turbidity) on habitat and species, albeit minor and localized.

Exposure to electromagnetic fields

Submerged electrical cables (alternating and direct currents) emit electromagnetic fields into the surrounding water. An electromagnetic field is exponential and declines rapidly with distance from the source (the cable). Underwater cables associated with FPV projects are assumed to be armored and insulated to prevent leakage of direct current electricity. However, the induced magnetic field would still be emitted in the immediate vicinity of the moving direct current and may affect fish and benthic invertebrates (Gill and others 2005, 2009).[7]

Surrounding flora and fauna

Potential heat plume generated from the FPV installations can spread to nearby flora and fauna, especially in lakes and reservoirs. Changes in air temperature and relative humidity can affect the rate of transpiration. Plants transpire more rapidly at higher temperatures, and a drop in relative humidity increases the rate of transpiration (Štekauerová 2011; USGS n.d.). One possible mitigation measure is to ensure that the FPV system is installed at a certain buffer distance from the nearest flora.

Avian wildlife

FPV installations could affect avian species, specifically water-feeding birds and surface divers that hunt at the surface and pursue fish and forage underwater. For example, failure to detect the difference between project components (such as solar panels) and the water could result in injury and/or mortality from collision with solar panels when birds attempt to land or dive for food.[8] Birds can also get entangled with project components while foraging. To avoid or minimize impacts to avian wildlife, project planners should consider incorporating the following elements into the design of the project:

- Install the FPV system outside the littoral zone to minimize the entanglement of shorebirds.
- Limit surface coverage of the reservoir to minimize the loss of avian habitat.
- Maximize surface contrast in both the ultraviolet and visible spectrum.
- Consider barrier and nonbarrier bird deterrence systems.

Main mitigation measures

Site selection is critical to avoid or minimize potential adverse impacts on biodiversity. Siting the solar

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[7] Laboratory experiments conducted by the Oak Ridge National Laboratory focused on potential behavioral effects on freshwater fish and invertebrates by both direct and alternating currents. These experiments found no behavioral effects associated with direct currents. Temporary effects associated with alternating currents— such as avoidance, altered swimming behavior, and altered axial orientation—were found to lessen with distance or extinguishment of the source (Bevelhimer and others 2013; Cada and others 2011, 2012). The Aquatic Research and Monitoring Section of the Ontario Ministry of Natural Resources and Forestry investigated whether the presence of a high-voltage submarine transmission cable, which carries a maximum of 170 kilovolts, affected the spatial pattern and composition of nearshore and offshore fish at a Laurentian Great Lakes site (Dunlop, Reid, and Murrant 2016). Using electrofishing and acoustic surveys paired with gill netting, the team documented little change between fish communities or density near the cable or the reference transects. The Vantuna Research Group compiled published information on sensitivity to electromagnetic fields in marine fish worldwide from 2010 to March 2015 to complement another literature search on the same subject through 2009 (Claisse and others 2015). Most of the studies reviewed focused on single cables, where effects may not be measurable. However, the literature noted that well-designed baseline (predevelopment) and long-term studies on electromagnetic fields are important both to assess their positive or negative outcomes on populations, communities, or ecosystems as well as their cumulative effects from electromagnetic fields associated with both pilot- and commercial-scale (offshore renewable energy) projects (Claisse and others 2015, citing Gay 2012; Bailey, Brookes, and Thompson 2014; Krägefsky 2014; Leeney and others 2014).

[8] Studies are not available detailing avian conflicts with FPV projects, but studies from land-based solar projects have documented collisions with solar PV panels. Scientists hypothesize that insects, certain species of which use polarized light to detect water, are attracted to PV panels, which also can reflect polarized light (Horváth and others 2010). This in turn attracts insectivorous birds, which could collide with these solar components. Scientists in California have also documented the "lake effect" as a potential cause of avian mortality in land-based installations in the Mojave Desert, in particular among water birds. The hypothesis is that large installations of reflective panels are perceived as water by waterfowl and shorebirds, which can cause injuries when they attempt to land (Kagan and others 2014). While context may play a role (in the desert, for example, where there is a lack of permanent water bodies), it is important to consider that birds rely on open water bodies, especially in known migratory corridors, to hunt and forage.

installation outside the littoral zone can help minimize potential effects to aquatic flora and fauna. Additional mitigation measures include the following:

- Use nontoxic materials for project components and operations and maintenance (O&M) procedures.
- Design the installation to minimize shading to the water body. Whenever possible, leave enough space between rows of PV panels for light to pass through; it is best to limit row widths by setting PV panels in landscape orientation. Spacing can also alleviate potential water quality impacts (temperature, dissolved oxygen) caused by covering the water.
- Design the mooring and electrical system so as to avoid dragging on the bottom substrates, through the use of horizontal directional drilling and/or anchors and floats.
- If, based on the characteristics of the water body, reducing algae growth is a goal, consider PV modules with minimum light transmittance.

6.2.1.4 Decommissioning

Decommissioning FPV systems has not yet started, as most systems are only at the beginning of their life spans. However, appropriate actions and safeguards should be put into place to ensure that system owners or product manufacturers are liable and incentivized to properly decommission and recycle FPV systems at the end of their useful life. Systems include not only the PV modules and their associated electrical equipment but also the floating structures and their anchoring and mooring systems. Most of the floating structures are made of materials that can be recycled, either to manufacture similar products (for example, floats) if the required quality level of the product can be maintained or by reusing the materials for other types of products. While pipes and metals may be used to support PV modules on water, the most common structures are mainly made of HDPE. HDPE is not a biodegradable material, but is easily recyclable, as can be seen in its many applications (packaging, plastic bottles, toys, pipes, 3D printer filaments, and so forth). The typical recycling process consists of large HDPE plastic pieces being shredded and melted into pellets and granules, which can be used again for other purposes. It is advisable to recover the anchoring and mooring system in a way that is the least detrimental to the environment. The appropriate mitigation measures might differ from one water body to the other, depending on the prevalent ecosystem and environmental sensitivity.

For such a circular economy to succeed, adequate and affordable collection systems must also be put into place; often, a certain scale is needed to justify these channels and make them economical. This topic will require further study and development as the floating solar industry matures, in conjunction with the development of enabling frameworks (such as the one imposed by the 2012 EU Waste Electrical and Electronic Equipment Directive) by governments and regulators.

The World Bank Group's General EHS Guidelines (World Bank Group n.d.) provide guidance on the prevention and control of EHS impacts that may occur at the end of a project. Recycling and material recovery of panels and floats are preferable to disposal. Where waste cannot be recovered or reused, treating and disposing of it in an environmentally sound manner is essential. Approaches developed for managing end-of-life PV panel waste include several stages: dismantlement; collection and transportation; and reuse, recycling, or disposal. For PV module recycling, readers can refer to the work on environmental, health, and safety issues published by Task 12 of the International Energy Agency Photovoltaic Power Systems Program (IEA PVPS 2018, n.d.[a], n.d.[b]). Table 6.2 summarizes the potential environmental impact of FPV projects during their entire life cycle.

6.2.2 Occupational health and safety

Most occupational health and safety issues during the construction, operation, maintenance, and decommissioning of FPV projects are common to large industrial facilities, and their prevention and control is discussed in the General EHS Guidelines (World Bank Group n.d.). These impacts include, among others, exposure to physical hazards from use of heavy equipment and cranes and hazardous materials, trip and fall hazards, increasing levels of dust and noise, falling objects, and electrical hazards (from the use of tools and machinery). Occupational health and safety

TABLE 6.2 Potential environmental impact during life cycle of an FPV project

Stage	Impact
Construction and/or decommissioning (short- and long-term impact)	• Short-term air pollution from project construction equipment • Noise, affecting people and wildlife, from project construction equipment • Turbidity from installation and dismantling of mooring and anchoring systems • Potential release of oil and lubricant spills associated with project construction equipment • Loss of habitat and associated species • Creation of waste during construction, transport and dismantling
Operation and maintenance (long-term impact)	• Deterioration of water quality: – Increased temperature/stratification – Decreased dissolved oxygen – Limited mixing – Leaching/chemical risk • Loss of benthic habitat/littoral zone • Impact on primary production • Loss of avian wildlife and habitat • Loss of aquatic species (fish, invertebrates) and associated habitat • Loss of recreational value • Loss of aesthetic value • Creation of waste (that is, replacement of parts, cables, anchors, and so forth)

Source: Authors' compilation.
Note: This list is not exhaustive, and each site will have its own unique characteristics and impacts.

hazards specific to FPV projects primarily include live power lines, electric and magnetic fields, and working over and under water. Management of risks associated with live power lines and electric and magnetic fields is discussed in the EHS Guidelines for Electric Power Transmission and Distribution (World Bank Group n.d.) and is not included in this report.

The risks of working over water must be addressed throughout all phases of FPV operations, especially during routine maintenance. The main risk to avoid is of equipment and operators falling in the water. This and other risks can be exacerbated by wind speed, extreme temperatures, humidity, and wetness. Managing FPV activities requires suitable planning and the allocation of sufficient resources. During the planning and design phases, it is recommended that as few tasks be conducted over water as possible. For example, it is often feasible to assemble the system structure on the ground, then move the completed structure into position over water.

If working over water cannot be eliminated, the following prevention and control measures should be considered:

- Complete a risk assessment to inform safety guidelines for all over-water tasks, and allocate appropriate resources to mitigate the hazards.
- Ensure all operators are trained and competent in the tasks they are expected to undertake and in the usage of all equipment, including personal protective equipment.
- In addition to standard personal protective equipment, as noted above, use approved buoyancy equipment (for example, life jackets, vests, floating lines, ring buoys) when workers are over, or adjacent to, water.
- Where exposure to low water temperatures is likely to lead to the onset of hypothermia, ensure control measures, such as survival suits.
- Train workers to avoid salt spray and contact with waves.
- Provide appropriate rescue vessels with qualified operators and emergency personnel, if required.

Divers installing the anchoring and mooring lines, as well as inspecting them during the O&M phase, are exposed not only to the possibility of drowning but also to a variety of occupational safety and health hazards, such as respiratory and circulatory risks, hypothermia, low visibility, and physical injury from the operation of heavy equipment under water. The type, length, and frequency of the dive, and the type of operation increase the already high risk of this strenuous work. Additional hazards associated with the work include underwater cutting and welding; the handling of materials (for example, anchors, mooring lines); and the use of hand and power tools. Prevention and control measures to manage diving hazards can be found in the US Occupational Safety and Health Administration (OSHA) Commercial Diving Operations Directive.[9]

6.2.3 Community health and safety

Community health and safety hazards during the construction, operation, and decommissioning of FPV facilities are similar to those of most infrastructure projects. Their management is discussed in the General EHS Guidelines (World Bank Group n.d.). Primary community health and safety hazards specific to FPV facilities include water navigation and safety, aviation, and public access.

6.2.3.1 Water navigation and safety

If located near ports, harbors, shipping lanes, or recreational areas, an FPV project may pose risks to shipping safety (for example, collision or the alteration of vessel traffic routes). Such risks are exacerbated during the construction phase, when additional vessels are accessing the site. Collisions may result in damage to floating systems and/or vessels, as well as pollution from spilled oil. Planning the location of floating systems; cable routes; and other associated infrastructure (anchoring, mooring, and rigging) requires careful consideration of factors such as anchorage areas, seabed conditions, archaeology sites, existing cable or pipeline routes, and fishing grounds. Efforts must be taken to minimize any impacts where possible.

6.2.3.2 Aviation

If located near airports, military low-flying zones, or known flight paths, an FPV facility may affect aircraft safety directly through glare. Prevention and control measures to address this risk include the following:

- Use glass with an antireflective coating for PV modules.
- Move the panels' orientation and/or alter their tilt (though the latter action could have a detrimental effect on the yield).

In the United States, to address the risk of glare, the US Federal Aviation Administration (FAA) developed the Solar Glare Hazard Analysis Tool[10] (SGHAT) in cooperation with Sandia National Laboratories. This tool can be used to determine whether a proposed solar energy project may have an ocular impact. Figure 6.2 offers examples of the tool's application.

In 2013 the FAA adopted an interim policy that required anyone proposing a solar project near a federally obligated airport to demonstrate compliance with standards for measuring its possible ocular impact.[11] To obtain FAA approval, the proposed project must meet the following standards (as assessed using the SGHAT tool):

- No potential for glint or glare in the existing or planned airport traffic control tower cab
- No potential for glare or "low potential for afterimage" along the final approach path for any existing or future landing thresholds[12]

According to a solar PV and glare fact sheet put out by the US Department of Energy, modern PV module glass reflects as little as 2 percent of incoming sunlight, about the same as water. Much of the misperception surrounding solar and glare likely comes from

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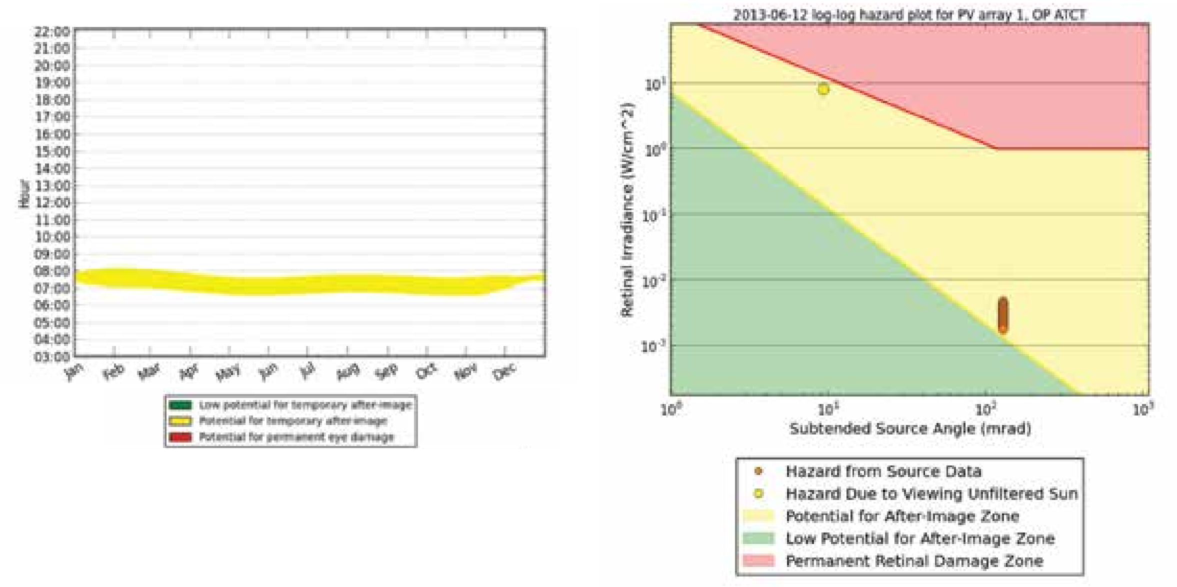
[9] 29 CFR Part 1910, Subpart T—Commercial Diving Operations CPL 02-00-151 (June 13, 2011) provides guidelines for occupational safety and health standards for commercial diving operations (US Department of Labor 2011).

[10] https://share-ng.sandia.gov/glare-tools/.

[11] An airport is federally obligated when the airport owner has accepted federal funds to buy land or develop or improve the airport See http://www.dot.state.mn.us/aero/operations/airportminimumstandards.html.

[12] In the United States, the final approach path is defined as 2 miles (about 3.2 kilometers) from 50 feet (about 15 meters) above the landing threshold using a standard 3° glide path. The analysis for potential ocular impact must be examined over the entire calendar year in one-minute intervals, from when the sun rises above the horizon until the sun sets below the horizon (US Department of Transportation 2013). In addition, the US Department of Defense issued guidance in 2014 requiring relevant solar renewable energy projects to use SGHAT for glare and glint analysis (Office of the Under Secretary of Defense 2014).

FIGURE 6.2 **Sample result charts displaying annual glare duration and ocular impact of each minute of glare**



Source: ForgeSolar (https://www.forgesolar.com/tools/glaregauge/) and Sandia National Laboratories (https://share-ng.sandia.gov/glare-tools/).

confusion between solar PV and concentrated solar power, which uses a system of large mirrors to direct sunlight toward a central tower (NREL 2018).

6.2.3.3 Public access

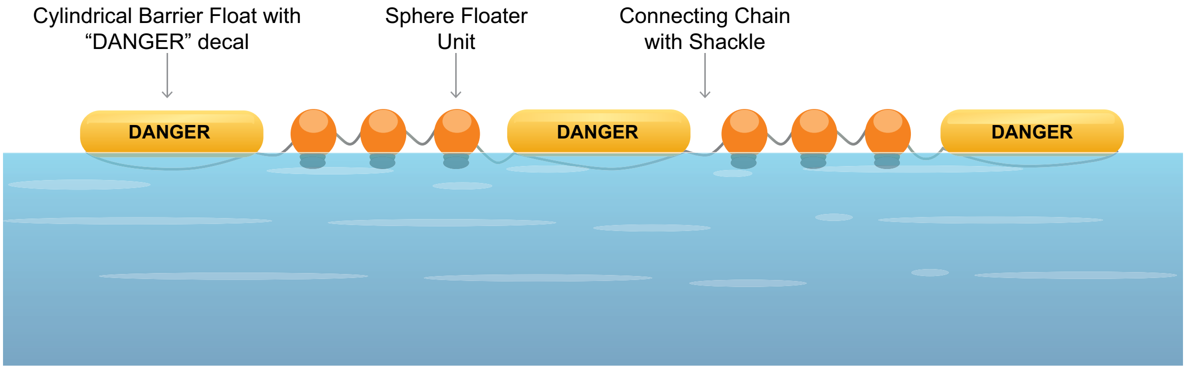
Safety issues may arise where floating modules or substations may be accessed by the public. Any public rights of way located within or close to an FPV project site should be identified before construction and measures taken to ensure the safety of users. To manage public access, the following steps may be considered:

- Use gates on access roads.
- Where there are no current rights of way across a FPV project site, consider fencing the site to prohibit public access.
- Where public access is permissible, install a modular, floating safety barrier around the FPV system to deter the public from going near the system (figure 6.3). Safety barriers must also be designed for cases where the FPV system and barrier would lie on the bottom of the water body.
- Ensure that fencing around the substation meets safety standards (for example, featuring brightly painted signs warning against climbing or entry).
- Post information boards about public safety hazards and emergency contact information.

6.2.3.4 Other social considerations

Other potential effects—including on recreational users of the FPV site (boaters, anglers, and so forth)—as well as changes in aesthetics should be considered by appropriate governmental agencies, nongovernmental organizations, and local stakeholders. For example, FPV systems may reduce the share of the water body available for recreation and sport fishing and increase visual "clutter." Siting a facility in a relatively remote area of a lake/reservoir could alleviate these problems. But in some instances, promoting FPV systems as tourist attractions/educational resources may be beneficial. Given that the FPV industry is in its genesis, public outreach and transparency are critical to gaining public acceptance, as they were to land-based PV some 10–15 years ago (IFC 2007).

FIGURE 6.3 Example of safety barrier float system for the Bedok Reservoir in Singapore



Source: Adapted from PUB 2019.

6.3 Permitting, mitigation measures, performance indicators, and monitoring

Because FPV is a relatively new industry, additional studies, adaptive management, and long-term monitoring will be required to assess and understand effects on water quality and aquatic flora and fauna. Knowledge gained from early projects will be instrumental in informing the industry as it grows, and in developing best practices related to manufacturing project components as well as construction, operation, maintenance, and decommissioning.

6.3.1 Environmental permitting

FPV project developers must obtain various licenses, permits, authorizations, approvals, rights, and clearances from national, regional, and local authorities. They need to understand the applicable national, regional, and local environmental laws to obtain natural resource permits and approvals. Given the infancy of the FPV industry, permitting agencies as well as other interested stakeholders will have elevated concerns about water quality impacts as they relate to the health of people and the aquatic ecosystem.

6.3.2 Potential mitigation measures

For water bodies with significant biodiversity and environmental value, limiting the surface coverage ratio of FPV systems on water bodies could be a key risk mitigation strategy. Large FPV systems could be divided into various patches or islands, separate from one another, to reduce locational environmental impact.

However, there can be cases where strategies to minimize one environmental impact exacerbate another. For instance, spacing out project components to minimize potential impacts to aquatic species from shade/shadow can also alleviate potential water quality issues (temperature, dissolved oxygen), but it could simultaneously exacerbate potential impacts on avian and other aquatic species by creating more places for birds to forage or become entangled. Reduction in the formation of algae (because shading reduces aquatic vegetation and phytoplankton) can have undesirable impacts on aquatic fish species as well as dissolved oxygen levels. Balancing the impacts/benefits requires careful consideration on a case-by-case basis, in consultation with appropriate subject matter experts and stakeholders.[13]

An example of the selected floating solar photovoltaic–related mitigation measures in the Environmental and Social Management Plan (ESMP) for an FPV project in Vietnam is shown in box 6.3.

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13. For example, the Dutch Zon op Water consortium developed an analytical tool to simulate the potential effects of an FPV system on the ecology and quality of water in the Netherlands. The tool (Analysetool ecologie en waterkwaliteit) and related information are available at https://zonopwater.nl/nieuws/i147/handreiking-vergunningverlening-drijvende-zonneparken-op-water (in Dutch only). The tool offers the possibility of reducing potential environmental impacts based on optimized surface coverage and light transmittance, which can be modeled.

BOX 6.3

Floating solar photovoltaic–specific elements of the Environmental and Social Management Plan for the proposed Da Mi project in Vietnam

The Da Nhim–Ham Thuan Da Mi Hydropower Joint Stock Company (DHD) operates three hydropower plants in Southern and Central Vietnam. It is developing a 47.5 MW floating solar photovoltaic power plant on the reservoir of its existing 175 MW Da Mi hydropower plant with support from the Asian Development Bank (ADB). The Initial Environmental Social Examination (IESE) for the project was designed in compliance with ADB's Safeguard Policy Statement. While many elements of the resulting Environmental and Social Management Plan (ESMP) are generic (similar to ESPMs for any other power plant or PV plant), the ESMP contains various points that are specific to FPV in this project and this location. They also take into account that a local floats-manufacturing workshop is expected to be constructed within the project site. The table summarizes selected FPV-related elements of the ESMP. The table is provided only as an example; an ESMP always needs to be project specific and based

Selected floating solar photovoltaic–related mitigation measures in the Environmental and Social Management Plan for the Da Mi project in Vietnam

Predicted impact	Proposed mitigation measures
Noise and vibration management during float manufacturing	• Ensure that the production workshop is constructed with walls, windows, and doors for sound insulation. • Use dashpots for production equipment and machines. • Enhance daily checking and maintenance of equipment, machinery to minimize noise sources. • Minimize the operation of the float manufacturing workshop at night.
Waste generated during float manufacturing	• Provide screens (with diameters of less than 2 millimeters) at all drainage systems in the float manufacturing workshop to ensure that small plastic pieces are prevented from entering the surface water bodies. • Implement a comprehensive housekeeping program to ensure that all small plastic pieces are collected and handled appropriately. • Provide secondary containments and spill kits at all oil storage areas. • Develop and implement an oil spill response procedure.
Disturbance of bottom sediments during construction	• Follow anchor technique during anchor activity.
Reduced water quality during construction and operation	• Paint anchors with waterproof layers or make anchors of stainless steel.
Occupational health and safety during construction	• Ensure safety on the construction site, including when working at height and on surface water. by developing a procedure for these types of job and providing appropriate personal protection equipment.
Aquatic habitat functionality during construction and operation	• Use "glass on glass" transparent floating PV panels, with at least 50 centimeters between panel arrays, and place the arrays at least 20 centimeters above the water surface.
Water management during operation	• Monitor water quality of the Da Mi reservoir regularly.
Occupational health and safety during operation	• Develop and implement occupational health and safety procedures for activities related to the project's activities (working over water, working with electricity, and so forth)

Source: Authors' compilation based on ADB 2018.

6.3.3 Performance indicators and monitoring

As described earlier in this chapter, water quality (including water temperature, dissolved oxygen, total dissolved gases, contaminants, salinity, nutrients and minerals, and turbidity) should be managed on a project-specific basis based on the water quality objectives. Those objectives are usually set based on the planned usage of the water and water body (potable water, recreation, agriculture, and so forth).

6.3.3.1 Environmental monitoring

Environmental monitoring should be conducted during the construction and operational phases of all activities identified as having potentially significant impacts on the environment. The monitoring frequency should be sufficient to provide representative data for the parameters being monitored. Trained individuals should conduct the monitoring, following science-based methods and recordkeeping procedures and using properly calibrated and maintained equipment. Monitoring data should be analyzed and reviewed at regular intervals and compared with operating standards, so that necessary corrective actions may be taken. In the absence of international standards for the monitoring of FPV projects, variables should be based on project-specific environmental assessments. The scope and frequency will depend on project-specific circumstances and may include, when relevant, water quality, aquatic flora and fauna, and avian wildlife. The General EHS Guidelines (World Bank Group n.d.) provide additional information on applicable sampling and analytical methods for emissions and effluents generated during construction or operation.

6.3.3.2 Occupational health and safety performance

Regular monitoring of occupational health and safety performance should cover all workers, including developers, contractors, and subcontractors. Performance reports should provide summary data, as well as data on individual organizations. Performance should be evaluated against internationally published exposure guidelines. Examples include the following:

- the Threshold Limit Value (TLV®) occupational exposure guidelines and the Biological Exposure Indices (BEIs®), published by the American Conference of Governmental Industrial Hygienists (ACGIH n.d.[a], n.d.[b])
- the *NIOSH Pocket Guide to Chemical Hazards,* published by the US National Institute for Occupational Health and Safety (CDC 2005)
- *Permissible Exposure Limits*, published by the US Occupational Safety and Health Administration (OSHA n.d.)
- *Indicative Occupational Exposure Limit Values,* published by European Union member states (EU-OSHA 2009).

Additional indicators specifically applicable to electric power sector activities include the International Commission on Non-Ionizing Radiation Protection (ICNIRP) exposure limits for occupational exposure to electric and magnetic fields, listed in the EHS Guidelines for electric power transmission and distribution (World Bank Group n.d.). Other applicable indicators, such as noise, electrical hazards, air quality, or others, are presented in the General EHS Guidelines (World Bank Group n.d.).

Accident and fatality rates

Projects should try to reduce the number of accidents among project workers (whether directly employed or subcontracted) to zero, especially accidents that could result in lost work time, various degrees of disability, or fatalities. Fatality rates may be benchmarked against the fatalities in developed countries through consultation with published sources (for example, the US Bureau of Labor Statistics [BLS n.d.] and UK Health and Safety Executive [HSE n.d.]). There should be a similar target of zero safety impacts on members of communities adjacent to the development.

Occupational health and safety monitoring

The working environment should be monitored for occupational hazards relevant to the specific project. Accredited professionals should design and implement monitoring as part of an occupational health and safety monitoring program that recognizes post-closure, long-term health concerns.[14] Facilities should also maintain a record of occupational accidents and diseases and dangerous occurrences and accidents. The General EHS Guidelines (World Bank Group n.d.) provide additional guidance on occupational health and safety monitoring programs.

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[14] Accredited professionals may include certified industrial hygienists, registered occupational hygienists, certified safety professionals, or their equivalent.

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7 PROCUREMENT AND CONSTRUCTION

7.1 Overview

Selecting a contractor for EPC (engineering, procurement, and construction) is typically done via a tendering process that considers the candidates' experience, record of engineering accomplishments, knowledge of the relevant country, and financial strength. The EPC contractor assumes responsibility for all design, engineering, procurement, construction, commissioning, and testing. Contractors with experience in floating PV installations are the best candidates. A list of floating photovoltaic (FPV) suppliers is provided in Annex C. This chapter elaborates on the procurement and construction phase of the floating solar project. More general information on EPC contracts and the construction phase common to ground-mounted solar PV projects can be found in the report "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015).

It is important to obtain all the required permits and clearance certificates from various regulators before groundbreaking. The list of permits is dependent on the country's regulation and bylaws applicable to the project site. Some of the required permits are mentioned in chapter 5.

The plant's detailed engineering plans should be completed before construction begins. The design engineering team should issue their drawings with relevant approvals; inspection plans and documents should be in place for quality-control checks. It is essential to control construction quality to ensure contractors are following design specifications to the required levels.

7.2 Managing procurement activities

Procurement must be carried out before construction begins; materials need to be on site on time and as per the specifications in the contracts. Procurement involves the following activities:

- Planning: Determine *what* to procure and *when* and *how* to do it.
- Awarding contracts: Obtain suppliers' responses, select qualified suppliers, and award appropriate contracts.
- Controlling: Manage relationships with suppliers, arrange delivery schedules, and monitor contract performance.
- Closing: Complete and settle each contract or agreement, including the resolution of issues pertaining to warranty clauses.

A procurement management plan includes decisions about which items will be provided internally and which will be outsourced. This information, in turn, will determine the project's budget and financial scope. Key issues when planning procurement activities include:

- High-quality EPC contractors have connections with top-tier suppliers of floating photovoltaic (FPV) components such as float structures, modules, and inverters. These contacts enable cost-effective and timely procurement of materials.
- EPC contractors should evaluate the quality of available suppliers' products, compliance with International Electrotechnical Commission (IEC) certification, manufacturing practices (ISO certification), warranties offerings, and service infrastructure.

- EPC contractors should ensure that the suppliers (module, floating structure, cables, junction boxes, inverters, switchgears, transformers, and so forth) deliver the bill of materials as per the schedule, without damage; they will check the product physically for meeting the specifications listed on the product specification document. It is also advisable to inspect the factory where the equipment is manufactured. Components should be sampled and tested before or after their delivery, based on the project quality plan and depending on the type of component.
- The terms and conditions of major components' manufacturer warranties should be clearly defined. Key data include:
  - Effective start and end dates
  - Definition of defects
  - Clarity regarding the claims' procedure, and who bears responsibility for the cost of testing
  - Agreement on who bears costs related to replacements such as freight or workmanship and whether possible loss of revenue during the replacement is covered
  - Alignment with EPC warranty timeline for workmanship and services
  - Clarity regarding whether the warranty is legally enforceable in the jurisdiction where the FPV plant is being installed
- Packaging and handling requirements, transportation methods, and insurance coverage plans should be stated in every purchase order.
- If the component prices are continuously decreasing, then frequent deliveries in small lots are effective in reducing the total cost of the supply chain. Companies need to find the best trade-off between the management of inventory and frequency of procurement (that is, procurement and deliveries can be planned progressively or in a single batch) according to the project's needs. Some factors to consider are listed below:
  - Price fluctuations over the delivery period
  - Material and local labor cost fluctuations
  - Storage space (floats require a great deal of space)

During procurement, it is a good practice to draft the procurement specifications in the EPC tender documents for all major components; this is a common practice for ground-based PV installations. Procurement specifications exist for PV modules, module-mounting structures, cables, junction boxes, inverters, transformers, and low- and high-voltage equipment. More information on product specifications is available in chapter 3.3 to 3.5 of the report "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" *(IFC 2015)*.

In the case of floating PV, additional specifications could be requested for PV modules, floating structures, anchoring and mooring systems, inverters, launching pads, and safety barriers. For instance, PV modules with double-glass lamination would inhibit the ingress of moisture. For the solar module, if an IP68-rated junction box is preferred; it should be specified. More information on PV module reliability and testing standards is available in section 4.4.

The floating structure is a unique and major component of FPV projects. The tender document should list the project requirements; international standards are under development. Areas to emphasize regarding quality and reliability are described in section 4.2. The document can also describe the preferred design elements such as the best tilt angle for the site, avoiding inter-row shading, incorporating maintenance rows and/or walkways. Furthermore, suitable structure(s) for installing meteorological sensors and equipment, dedicated floating structures for cable routing to land, and so forth, should also be specified. The procurement specification documents should also include provisions for cable trays, cable conduits, and cable clip holders so cables are properly managed above water. The floating structure should have a design life of 25 years.

Often the floating structure suppliers also design, procure, and deploy the anchoring and mooring systems. If a third-party is involved, the interfaces as well as roles and responsibilities need to be clearly defined. Apart from load considerations, construction materials for anchoring and mooring lines are another important factor, together with determining water quality, to ensure that mooring lines do not easily corrode or get damaged. Anchors can be placed in the reservoir bed or attach to the banks. A civil engineering company should undertake soil and geotechnical studies as a prerequisite. More details on anchoring and mooring system can be found in section 4.3.

If central inverters are used, containerized solutions would be best. These consist of a centralized inverter, a step-up transformer, and other ancillaries all installed on a floating platform using a steel- or concrete-based barge. The container should be anti-corrosive, weatherproof, and well ventilated.

For the construction of the floating PV island, it is highly preferable to have a launching pad on the slope of the water body. Hence, this requirement shall also be captured in the procurement specification document.

To deter water users from accidently reaching the FPV system perimeter, operators could set out floating buoys and outfit them with lights that blink at regular intervals to provide a visual warning; this could be requested in the procurement documentation.

Design aspects relevant to the FPV plant, as detailed in chapter 4, can be specified in the procurement specification document; the details must be decided by the developer.

7.3 Managing construction activities

The starting point for proper management of this phase is a detailed construction plan for the FPV system. This plan contains work packages and detailed milestones, task interdependencies, the project-critical path, and the duration of each activity. During the course of the project, progress can be tracked against this plan to ensure that the project is completed on time and without delays.

A number of stakeholders are involved during the construction phase. It is important that the site construction head manages all the contractors, subcontractors, suppliers, machinery operators, and the owner to ensure smooth implementation of all the construction activities. Managing stakeholder interface is of central importance. It keeps momentum up and ensures on-time delivery of the project. Proper installation and good workmanship are important at every step. EPC contractors should provide daily, weekly, and monthly progress reports to the owner. They should plan and implement in-process quality checks; these facilitate the early identification of issues that can arise during construction to avoid redoing the work or repairs. The owner and the lender (possibly assisted by the owner's engineer or lender's engineer) are advised to regularly monitor construction progress and the quality of implementation. As compared to land-based PV, some areas where FPV construction would differ is highlighted in table 7.1.

Workers should be aware of construction management policies:

- Compliance with engineering design (anchoring and mooring, tilt, orientation, string design, cable size, inverter design, electrical protection, etc.) and with manufacturers' installation manuals
- Usage of appropriate tools (like crimping tools for connectors and torque wrenches)

TABLE 7.1 Floating and land-based photovoltaic systems: A comparison of construction phase

	Floating PV	Land-based PV
Installation and deployment	• In general, easy assembly, but highly variable depending on location and workforce availability • Transportation of bulky floats to site is difficult; favors local production • Needs suitable launching area • May need specialized equipment or divers to install anchoring system	• Efficiency of assembly varies depending on location and workforce availability • Needs heavy equipment and land preparation • Complexity and costs depend on soil quality

Source: Authors' compilation.

- Condition of equipment
- Suitability of anchoring and mooring equipment to subsurface soil conditions and extreme local conditions (wind, snow, ice, water-depth variations, waves, and so forth)
- Compliance with E&S (environmental & social) and HSE (health, safety, and environment) management plans.

This helps to facilitate the early identification of issues that can arise during construction. Some of the key focus areas during the deployment of an FPV system include, but are not limited to, site preparation, material (floats) delivery, floating structure assembly, mooring and anchoring system deployment, as well as cable routing, electrical equipment installation, and grid connection.

7.3.1 Site preparatory works

Project implementation begins with site preparation, when the EPC contractor starts building access roads for equipment delivery, clears the site, and removes objects that might impede construction. Usually all the activities related to site clearance, landfill, evacuation, and debris removal is done during this phase. In addition, the EPC contractor establishes site security and a security office and erects fencing and gates.

7.3.2 Delivery of materials and storage

Most floats are manufactured through a blow-molding process that uses high-density polyethylene (HDPE). When inflated with air or foam, they occupy a lot of storage space (figure 7.1). Plan carefully for ideal, just-in-time delivery for installation and also to have enough storage space near the site. For large-scale projects (tens of MW), the float manufacturer should explore local manufacturing production lines to supply floats in batches; this will help with the management of onsite storage space, turnaround times, and exorbitant logistics costs. Floats can be unpacked and stored at the launching site with a sufficiently large staging area. Electrical equipment like inverters, LV switchboards, and transformers should be stored indoors or under a canopy to protect them from dust or rain until their deployment.

7.3.3 Preparation of launching area

Before construction begins, identify a suitable launching area by the water body with a gentle slope. This important supporting infrastructure is where the floating structure is assembled and launched. In general, working on land is easier than assembling the components directly on water. The launching area always needs some preparation. A launch ramp can be constructed on the bank's natural slope into the water body. This temporary infrastructure could be built with metal or wooden scaffolding and slats at minimal investment (figure 7.2). Although not mandatory in all cases, a launch ramp can ease deployment efforts and reduce float damages; hence, it is highly recommended. Workers can gently push the assembled floats into the water, so lifting machinery is not necessary. There are, however, other assembly and launch methods: assembling on land, then lifting and launch into water. The system could also be assembled on

FIGURE 7.1 Storage space earmarked for floats and accessories

Source: © Akuo Energy.

FIGURE 7.2 Construction of a launch ramp

Source: © SERIS.

FIGURE 7.3 **Two ways to assemble and launch floating PV structures: on a ramp or in the water**

Source: © Profloating. *Source:* © Texel4trading, Solar.

water, depending on the floating structure design and ease of construction works. For floating structures with cement[1]/concrete-based platforms,[2] assembly could be done directly on the water body. In these cases, machinery or infrastructure may be required in the launching area. Figure 7.3 illustrates these various methods of assembling.

7.3.4 Assembly of floating structures

Once the materials are delivered onsite, the assembly work of the floating structure commences. Assembly is usually done as smaller single blocks of floating units. Single units are assembled first by multiple teams of workers. The construction varies depending on the floating structure design. The floating structure supplier usually provides a method-statement document that describes the assembling activity. The following steps are carried out for the construction of a single block of floating units:

- Layup of floating component
- Assembly of floats together and interconnection of floats, where relevant
- Assembly of module support structures (metal or HDPE plastic)
- Installation of modules

Once assembled, the single units are linked together. After a few units are linked, the entire row is pushed partially into the water. Subsequent rows are built and launched until the floating island is completed (figure 7.4). The next steps of construction could be outlined as:

- Interconnection of single units/block to a larger row
- Electrical interconnection as per the single-line diagram (SLD)[3] to form the string
- Launching or sliding into water
- Towing to designated position
- Mooring and anchoring

Upon completion, the entire FPV island is towed to its final location by motor boat (figure 7.5). The system is ready for mooring and anchoring.

Differences exist depending on the types of floating platforms; these must be taken into consideration during construction (table 7.2).

7.3.5 Management of cable routing

The solar modules are interconnected in accordance to the single-line diagram on land (usually on a ramp) to form strings. Three DC interconnections must be done during the floating structure assembly process in the order shown below:

1. Interconnection between solar modules

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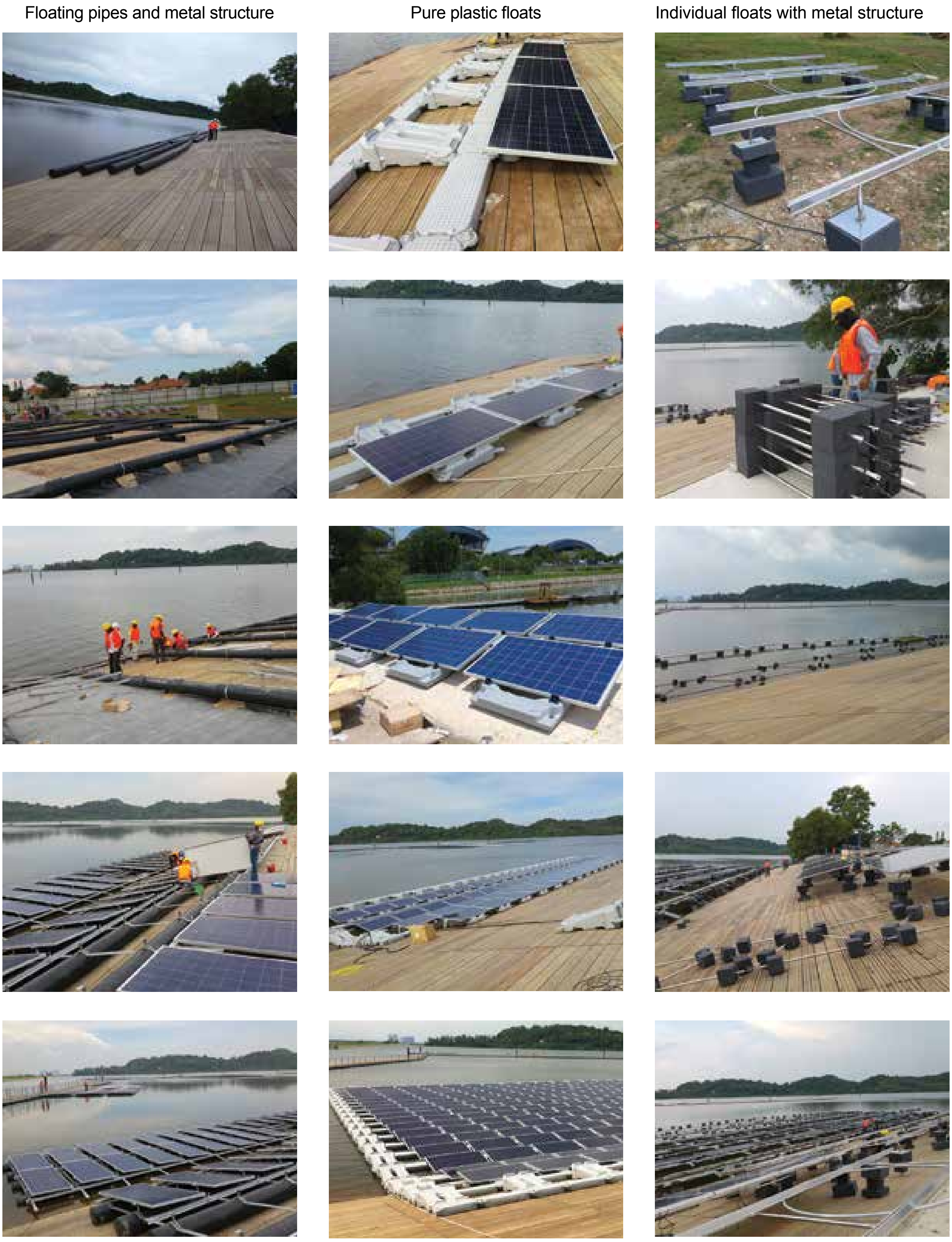
[1] https://adtechindia.com/solar-energy/floating-solar/
[2] https://www.solarfloat.com/
[3] The single-line diagram, or SLD, is a simplified graphic representation of a three-phase electrical distribution system.

FIGURE 7.4 **Construction sequence of three types of floating structures (from top to bottom)**


Floating pipes and metal structure

Pure plastic floats

Individual floats with metal structure

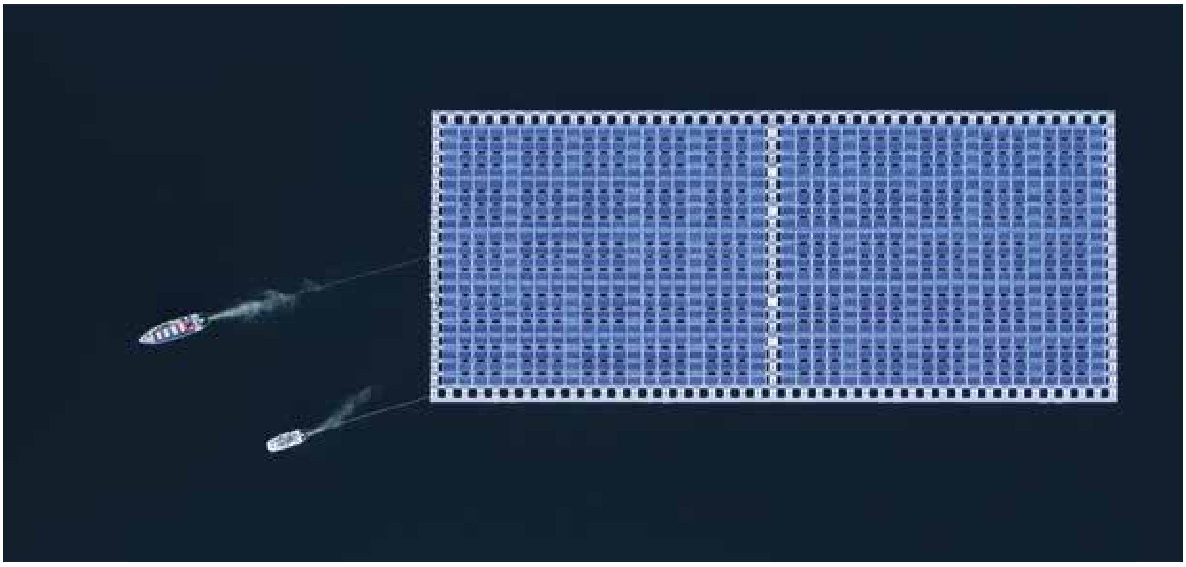
Source: © SERIS.

TABLE 7.2 **Floating structure types and their main construction differences**

	Floating pipes and metal structure	Pure plastic floats	Individual floats with metal structure
Storage space	Low— Pipes can easily be stacked and packed	Large— Floats occupy large volume	Medium— Individual floats can be stacked and packed
Tools and tackles	Possible welding involved to join the pipe rafts	Simple hand-held tools – Screwing, drilling, bolting, torqueing involved	Simple hand-held tools – Screwing, drilling, torqueing involved
Ease of assembly	Moderate complexity	Simple	Moderate complexity
Throughput*	Medium	Fast	Medium
Boat requirement	No	No	Yes

Source: Authors' compilation.
Note: *Assuming similar number of workers or teams are employed.

FIGURE 7.5 **Floating PV island being towed by a boat to its final anchoring location**



Source: © Pixbee/EDP S.A.

2. Interconnection from the string to the DC junction box
3. Interconnection from the junction box to the string inverter (in cases where string inverter is mounted on the same floating island)

These DC connections are made during the float-and-module assembly works and are usually carried out on land on the launching ramp.

All these connections must be well managed to ensure that DC cables and connectors stay above water at all times (assuming submersible-grade cables are not being used). It is important that cables have sufficient slack; if they are too taut, they might snap or rupture. Taking into account the differences in PV module dimensions and float dimensions, as well as the orientation of the modules (portrait/landscape), the standard cable length from the junction box to the module should allow for at least 15–20 cm of slackness. DC cables touching the water could deteriorate the cables' key properties and increase the risk of corrosion (figure 7.6). Cables, while usually UV-resistant, should also be protected by wiring trunks when exposed to direct sunlight in order to optimize their longevity. All the DC cables/conduits should be secured with proper cable ties or clamps to avoid water contact. Figure 7.7 shows the use of C-clamps in suspending cables along the surface of floats.

In some cases, central inverters are placed on dedicated floating platforms located at some distance from the FPV islands. In such a scenario, the cables from each combiner box are merged to form a main cable trunk. Then the main trunk cables to the central inverters are laid out on top of dedicated floats with protective conduits. Similarly, the AC cables routed from the central inverters to the shore/bank are also laid out on separated and dedicated floats, or submarine cables are used for the connection to the main electrical infrastructure onshore.

If routed above the water, the main cable trunk should use a larger conduit (floating by itself or on top of a plastic float) with sufficient slackness (like an S-curve) (figure 7.8). Cables with insufficient slackness could rub against metal fasteners. This friction over time could rupture their protective cladding and cause short-circuiting/arcing, a potential fire hazard.

7.3.6 Anchoring and mooring deployment

Bathymetry studies and site conditions determine the most appropriate anchoring and mooring solution. These schemes are chosen during the design engineering stage—anchoring to the bank or to the bottom of the water body. The mooring and anchoring system can be prepared while the floating platform is assembled. For example, sinkers can be cast and deployed using special barges together with the required mooring lines (figure 7.9).

If it is decided that the floating island will be anchored at the bottom of the water body, professional divers and/or specialized barges may be employed to moor and anchor them (figure 7.10). Buoys can be used to keep the mooring connection point afloat, which would be later connected to the floating structure.

FIGURE 7.6 Examples of cables in contact with water

Source: © SERIS.

FIGURE 7.7 Clamps used to guide cables along the upper surface of floats

Source: © SERIS.

FIGURE 7.8 Main cable trunk routed to shore using floats (left), and floating by itself (right)

Source: © Sungrow. *Source:* © Texel4trading, Solar.

Similarly, anchors can be prepared and installed in parallel for FPV system designs requiring anchoring to the bank (figure 7.11).

The mooring lines (such as ropes, chains, wires, elastic rubber hawsers, or a combination thereof) are coupled to the floating PV islands in various ways depending on the floating platform designs and recommended methods by the supplier. Some examples are shown in figure 7.12 while additional examples can be found in section 4.3.

FIGURE 7.9 Barge used to lower concrete sinkers

Source: © SERIS.

7.3.7 Substation construction and onshore electrical works

In many projects, substations (figure 7.13) are dedicated to house inverters not deployed on water; the substations house low-voltage (LV) or medium voltage (MV) switchgears and transformers for interconnection to the grid. Civil works are carried out in accordance with applicable country-specific electrical standards. The overall electrical works resemble those in use for ground-mounted PV systems. More information can be obtained from the report, "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015).

FIGURE 7.10 Professional divers tie knots, install marker buoys, and anchor an FPV system (left); special barge used for anchoring and mooring system (right)

Source: © SERIS.

Source: © Ciel & Terre International.

FIGURE 7.11 Land-based anchoring on the banks

Source: @ Ciel & Terre International.

Source: @ Ciel & Terre International.

FIGURE 7.12 Mooring to the floating PV platform using D shackle with ropes (left) and using a spreader bar and chains (right)

Source: © SERIS.

Source: @ Ciel & Terre International.

FIGURE 7.13 A substation under construction

Source: © SERIS.

To summarize, it is important for the construction process to finish on time according to schedule and without cost overruns. As-built drawings shall be produced and documented after completion. The end of the construction period marks the beginning of the testing and commissioning phase, described in chapter 8, after which the PV plant begins commercial operations.

7.4 Checklist for procurement and construction

Critical elements to consider in the procurement and construction of an FPV system are summarized in table 7.3.

TABLE 7.3 Procurement and construction checklist

• Obtain permits ahead of time to avoid delay in starting construction.
• Ensure detail design is complete and all the drawings are issued prior to construction.
• Proper coordination must occur among subcontractors, machine operators, suppliers, logistics company, site approving authority (e.g. owner's and/or lender's engineer), and the owner.
• Establish milestones to verify progress against plans, and measure variance.
• Plan labor and machinery needs meticulously to achieve daily, weekly and monthly targets without delay. For FPV, boats are likely to be needed during the construction phase.
• Allocate sufficient storage space for floats as they occupy considerable volume.
• Prepare launching area for efficient and safe assembly and launch.
• To assemble the floating platform, workers should follow a written method-statement, and quality checks should be in place.
• Ensure cable and connectors are routed above the water body at all times and proper cable management procedures are followed.
• Ensure anchoring and mooring construction is carried out exactly as per design specifications. Quality checks and verification methods shall be implemented.
• Prepare and vet as-built drawings; discuss plan for demobilizing plant and machinery with owner.

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IFC (International Finance Corporation). 2015. "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide." Washington, DC: IFC.

https://adtechindia.com/solar-energy/floating-solar/

https://www.solarfloat.com/

© Sungrow.

8 FIELD TESTING AND COMMISSIONING

8.1 Overview

Once the project is mechanically complete and connected to the grid, testing and commissioning is performed or observed by qualified electrical inspectors, such as licensed electrical workers or certified professional engineers. For a system to feed electricity into the grid, certain documents must be submitted as specified by law or regulation in the country where the system is located. Some common examples are:

- Single line diagram of the photovoltaic (PV) system
- Layout diagram of the PV system
- Module test reports or certificates
- Inverter certificate of compliance and declaration of conformity to standards
- Power quality report
- PV module and inverter data sheet

The commissioning test for the floating PV (FPV) system is normally based on IEC 62446, compliance with the local grid code, and other relevant country-specific standards. These tests are performed before the commercial operation date. Procedures for commissioning tests are usually submitted, reviewed, and agreed upon between the owner and the contractor responsible for engineering, procurement, and construction (EPC).

System verification involves a thorough visual inspection, followed by a verification of electrical measurements to ensure their compliance with the requirements of the EPC contract. Well-documented testing and commissioning reports serve as a baseline reference to ensure all the components are functioning in accordance with design calculations and specifications. Testing and commissioning considerations for floating PV compared with land-based PV systems is shown in table 8.1.

8.2 Solar PV modules and inverters

At the component level, the solar modules should be tested by accredited testing laboratories under relevant standards such as IEC 61215, IEC 61730, among others (see section 4.4.2 on testing standards for floating PV modules for more detail). It is preferable for modules to be further certified by a Certification Body or Certification Body Testing Lab. The developers should follow the country-specific requirements. Although not mandatory, certificates are often a pre-requisite for obtaining financing from lenders.

Inverters should be compliant with grid standards from the country where the systems are located as well as international standards such as IEC 60364, IEC 61000, IEC 61727, IEC 62109-1/2, IEC 62116, IEC 62920, and IEEE 1547. Inverters should meet the output power quality requirements of the country's electric transmission codes. The grid code parameters are set during the commissioning activity. Power quality requirements are usually defined using the following parameters:

TABLE 8.1 Floating and land-based photovoltaic systems: A comparison of testing and commissioning aspects

	Floating PV	Land-based PV
Testing	• No international standards exist for verifying floats	• Testing and commissioning procedures are well-established
Grounding	• Grounding module frame or mounting structure may be challenging if constant motion causes bonding conductor to loosen or snap	• Grounding module frame or mounting structure is well-established

Source: Authors' compilation.

- Permissible levels of injection of DC current
- Voltage imbalance
- Voltage fluctuation and flickering
- Harmonics

8.3 Floats and anchoring

Because international standards for the manufacturing and field-testing of floats and their accessories have yet to be established, the industry usually refers to country-specific standards. For example, floats' tensile strength and maximum elongation have been tested in Japan in accordance with JIS K 6922-2. Generally, independent third-party lab tests are also accepted. Professional engineers qualified by the country's board of engineers need to endorse the design calculations and drawings for the floating structure and for the mooring and anchoring system. Verification is carried out during the testing and commissioning stage against these foundational documents.

8.4 Safety labelling

Proper safety labelling is to be applied throughout the installation of an FPV system, thereby fulfilling the requirements of IEC 62446-1 (see examples in figure 8.1).

8.5 Surge/lightning protection

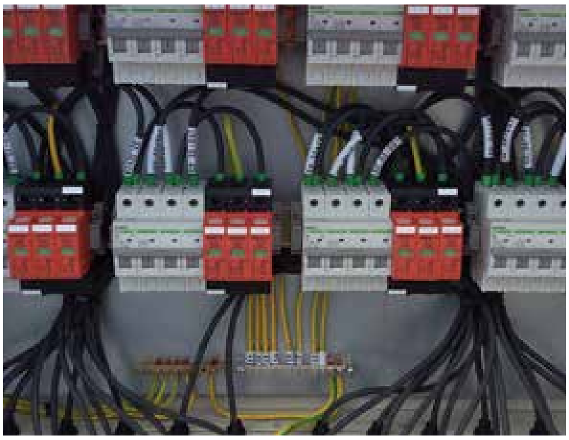
Lightning is a location-specific, probabilistic event, and the required risk mitigation levels are determined based upon a project's risk matrix. Surge protection devices (SPDs) are used in both DC and AC electrical circuits to parry electrical surges and spikes, including those caused by lightning. An example of a DC electrical circuit protected by SPDs is shown in figure 8.2. These are to be installed in a manner consistent with IEC standards and verified during field testing and commissioning.

All extraneous conductors (such as structural metal parts, module frames, and junction boxes) should be bonded and grounded to the reservoir bed/water surface for protection against lightning (figures 8.3 and 8.4), based upon specified requirements. Since the internal lightning protection system covers only equipment and not personnel, work on FPV systems should not be performed during inclement weather.

FIGURE 8.1 Safety warning labels

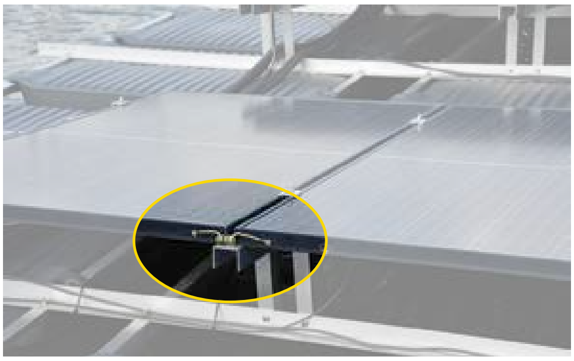
Source: © SERIS.

FIGURE 8.2 DC cabinet with surge protection devices (red-orange)



Source: © SERIS.

FIGURE 8.3 Equipotential bonding conductor



Source: © SERIS.

FIGURE 8.4 Grounding to reservoir bed

Source: © SERIS.

8.6 DC electrical system

The following electrical measurements are a minimum requirement for the DC electrical subsystem:

- Continuity of grounding and equipotential bonding conductors
- Polarity
- String short-circuit current
- String open-circuit voltage
- Insulation resistance of DC circuits

Apart from the electrical measurements listed above, checks are also carried out on DC connections (figure 8.5), including the array frame grounding, cable runs, and DC terminations, to ensure that they have been installed in accordance with the single line diagram of the electrical system.

Overcurrent protection devices (fuses) should be installed as per standards (if not built into the inverter) (figure 8.6).

FIGURE 8.5 Solar professional performing continuity tests

Source: © SERIS.

FIGURE 8.6 DC distribution board with fuses and grounding cables terminated with markings

Source: © SERIS.

FIGURE 8.7 DC isolator switch at bottom of the inverter, and neatly terminated cables with labels

Source: © SERIS.

FIGURE 8.8 **LED indicating grid supply and FPV supply**

Source: © SERIS.

FIGURE 8.9 **AC subboard with surge protection device**

Source: © SERIS.

FIGURE 8.10 **AC isolator**

Source: © SERIS.

FIGURE 8.11 **AC isolator with emergency shutoff**

Source: © SERIS.

A DC isolator to disconnect the DC FPV systems should be available at an accessible location (figure 8.7). Double-insulated PV-grade cables must be used to minimize the risk of grounding faults, short-circuits, and electric shocks. All cable strings should be clearly labelled at their termination point. Recorded observations should be included in the testing and commissioning reports.

8.7 AC electrical system

AC connections should adhere to IEC 62446-1 (Section 5.2.9—Verification of AC System), wherever applicable. On the AC electrical distribution board, at the point of interconnection, electricity is supplied from the grid as well as from the FPV system. For that reason, it is important to have all isolation and switching devices connected such that the FPV installation is wired to the "load" side and the public supply (electricity from the grid) to the "source" side. LED lamps should be installed (figure 8.8) to provide a visual indication of grid supply and FPV electricity supply. AC-side surge protection devices are also installed (figure 8.9). Isolators should be provided as emergency shutoff measures (figures 8.10 and 8.11). In some jurisdictions, residual-current devices must be installed on AC circuits to which solar inverters are connected.

8.8 Acceptance tests

Once the testing described in the previous sections and commissioning is completed, the EPC contractor must demonstrate the performance of the plant using some of the following metrics:

- Energy yield (MWh/year)
- Performance ratio (%)
- Capacity utilization factor (%)
- Plant availability guarantee (%)

The demonstrated values must match or exceed the minimums specified in the contract for the short term (days) and long term (years). The duration of the performance test is specified in the contract. Short-term tests provide early indicators of system performance that can be used as a baseline to solve faults or enhance system performance. They also help determine whether the EPC contractor may begin to demobilize in anticipation of the commencement of the O&M phase. Long-term performance tests are conducted to detect other problems with shading, soiling, inverter clippings, and component degradation.

IEC TS 61724-2 and 3 are used as references for performance testing. Other references include NREL (2013) and IEA-PVPS (2018).

Typically, all of the commissioning tests must be completed before the owner of the plant can begin exporting electricity to the grid.

After performance is assured, the project enters into commercial operation. This marks the beginning of the O&M phase, when the O&M contractor takes over for the lifetime of the project.

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IEC 61000-3-12: 2011
Electromagnetic compatibility—Part 3-12: Limits—Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤ 75 A per phase

IEC 61000-3: 2018 SER
Electromagnetic compatibility—Part 3: Limit—All parts

IEC 61000-6-2: 2016 RLV
Electromagnetic compatibility (EMC)—Part 6-2: Generic standards—Immunity standard for industrial environments

IEC 61000-6-3: 2006 and AMD1: 2010 CSV
Electromagnetic compatibility (EMC)—Part 6-3: Generic standards—Emission standard for residential, commercial and light-industrial environments

IEC 61000-6-4: 2018 RLV
Electromagnetic compatibility (EMC)—Part 6-4: Generic standards—Emission standard for industrial environments

IEC 61215: 2016
Terrestrial photovoltaic modules—Design qualification and type approval (Parts 1 and 2)

IEC 61727: 2004
Photovoltaic systems—Characteristics of the utility interface

IEC 61730: 2016
Photovoltaic module safety qualification (Parts 1 and 2)

IEC 62109-1, 2: 2010/2011
Safety of power converters for use in photovoltaic power systems—Part 1: General requirements and Part 2: Particular requirements for inverters

IEC 62116: 2014
Utility-interconnected photovoltaic inverters—Test procedure of islanding prevention measures

IEC 62446-1: 2016 and AMD1: 2018 CSV
Photovoltaic systems—Requirements for testing, documentation and maintenance—Part 1: Grid connected systems—Documentation, commissioning tests and inspection

IEC 62920: 2017
Photovoltaic power generating systems—EMC requirements and test methods for power conversion equipmen

IEC TS 61724-1, 2, 3: 2016/2017
Photovoltaic system performance—Part 1: Monitoring
Photovoltaic system performance—Part 2: Capacity evaluation method
Photovoltaic system performance—Part 3: Energy evaluation method

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9 OPERATIONS AND MAINTENANCE

Given the short track record of floating photovoltaic (FPV) systems globally, operations and maintenance (O&M) guidelines for FPV are relatively insubstantial. But experience with O&M at the Singapore testbed, operating since 2016 and containing multiple FPV designs, has produced solid information about best practices. As the numbers of FPV systems deployed globally grow over time and this market segment matures, O&M experience will accrue accordingly, and across different sites and climates. The collection of best practices set out in this chapter will therefore continue to get refined and fine-tuned.

9.1 Overview

After attaining commercial operation, an FPV project moves into the O&M phase. In general, with few moving parts, solar photovoltaic (PV) plants have minimal maintenance and servicing requirements; PV plants are designed for an expected lifetime of 20 to 25 years. As with the O&M of any type of PV system, the aim is to maximize the electricity generation yield through the system's efficient operation while minimizing the costs through careful system maintenance that ensures the longevity of its components. Maintenance also ensures a safe working environment for O&M personnel.

The scope of work and the deliverables of the O&M phase are usually defined in an operations and maintenance contract. It is common practice for solar PV projects that O&M is carried out by a principal O&M contractor who is responsible for all aspects of O&M, including works performed by subcontractors (if any). Different options exist to find an appropriate O&M contractor:

- Continue using the EPC company or the system integrator who built the system
- Develop and train an in-house O&M team
- Outsource to a third-party O&M service provider
- Alternatively, a combination of the above

An O&M contract seeks to optimize the energy yield of the plant and guarantee a certain level of performance through agreed-on targets (for example, yield, plant uptime, and performance ratio [PR]). For more information on the O&M contract and its obligations, readers can refer to chapter 11, sections 11.2 and 11.7, of the report, "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015).

FPV systems are relatively new, with most systems having been in operation for only a few years. The maintenance of FPV systems requires new skillsets, techniques, and procedures. Accessibility, soiling, corrosion, and stress from the continual flexing present O&M providers with challenges beyond the ones encountered for land-based PV installations. Furthermore, stringent safety protocols involved in transmitting power onshore from the water surface must ensure that FPV structures and their components remain "touch safe" at all times.

Table 9.1 highlights aspects relevant for O&M activity in FPV systems as compared with land-based PV systems. Careful O&M planning is essential. The subsequent sections will elaborate on key know-how regarding FPV O&M activities.

9.2 O&M approach and activities

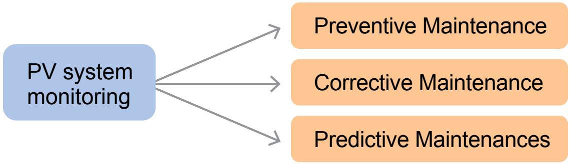
Under the O&M contract, the principal contractor responsible for monitoring the PV system usually performs three types of maintenance—namely, preven-

TABLE 9.1 Floating and land-based photovoltaic systems: A comparison from an O&M perspective

	Floating PV	Land-based PV
Technical	• Harder to access and replace parts • More mechanical wear and tear due to wave action • Likely to have biofouling • High-humidity environment may accelerate corrosion/oxidation of metal parts • More maintenance for structural elements • Easier access to water for cleaning • Lower risk of theft/vandalism	• Generally easy to access • More vegetation • Easier to deploy automated cleaning routines • Less maintenance for civil work and ground foundations
Safety	• Constant movement of floats poses walking hazards • Risk of personnel falling into water	• Generally safe, with stable ground for walking

Source: Authors' compilation.

FIGURE 9.1 O&M approach and activities



Source: Authors' compilation.

tive maintenance (PM), corrective maintenance (CM) and/or predictive maintenance (figure 9.1).

Preventive maintenance entails routine inspection and servicing at predetermined intervals. It is planned with the goal of preventing the occurrence of damage and breakdown. Preventive maintenance should be scheduled regularly; the requisite frequency (for example, monthly, quarterly, or yearly) depends largely on site-specific conditions. Typical elements include:

- General site maintenance
- Cleaning of PV modules
- Cleaning of floating pontoons
- Inspection and management of soiling (mostly from bird droppings)
- Mitigation of midges and vector control
- Inspection for equipotential bonding, cables, and connectors
- Inspection of balance-of-system
- Periodic recommissioning checks
- Upkeep of data acquisition and monitoring systems

Corrective, reactive, or unscheduled maintenance mitigates downtime when components break down. It occurs on an as-needed basis and should be minimized through proper monitoring and preventive maintenance. Because plant owners may seek to minimize the upfront costs of preventive maintenance, however, equipment will malfunction from time to time. Speed of response and repair times are important metrics in this maintenance category. Unscheduled maintenance work on FPV systems typically includes, but is not limited to:

- Resetting tripped inverters, usually caused by insulation resistance faults
- Replacing blown fuses
- Tightening cable connections or loosened connectors due to float movement
- Repairing equipotential bonding wires broken due to float movement
- Repairing communication (data acquisition and transmission) dropouts

Predictive maintenance uses real-time data to monitor the power plant and predict possible failure modes, which in turn helps to prioritize tasks and allocate resources. It has higher upfront costs and is subject to the quality of the monitoring system and its granularity, but it can reduce maintenance costs over time and saves money. Predictive maintenance is believed to be one of the most efficient methods of sustaining the long-term efficiency of a solar power plant (Betti and others 2019).

Predictive maintenance often serves as an early warning system for individual failure events—easily identifying maintenance patterns related to seasonal effects, configuration changes, system breakdowns, or unplanned downtimes, in addition to problems with recording instruments.

9.2.1 PV system monitoring

The continuous monitoring of operating conditions at an FPV plant requires a robust PV system monitoring solution. At the design phase of the project, sufficient care must be taken to ensure:

- Quality of the monitoring equipment. For more information on quality benchmarks, measured and calculated parameters, sensor choice, and requirements, please refer to IEC 61724—photovoltaic system performance
- Compatible measurement protocols (SCADA-based) across various brands of instruments
- Remote or on-site support after installation
- Ease of use regarding graphical user interface (GUI) and detailed report generation features

As a minimum requirement, it is essential that the monitoring system should be able to measure and report with sufficient granularity: irradiance (plane of array, kWh/m^2), temperature (ambient, module) and other environmental parameters, power and energy delivery (kW, kWh), performance ratio, system availability, inverter efficiency, sudden or unexpected losses (e.g. from soiling), and other electrical and meteorological data.

In the case of FPV, the meteorological station could be stationed on the floating platform (for large-scale projects above 5–10 MWp) or on land for smaller projects, in which case it should be as close as possible to the project site (figure 9.2-a). The number of meteorological stations to be deployed depends on the size and layout of the project.

Recommended essential sensors (shown in figure 9.2-b to figure 9.2-f) include:

- Pyranometer (horizontal)
- Si-sensors (horizontal and in-plane)
- Gauges of meteorological conditions such as ambient temperature, wind speed and direction, humidity and precipitation

These sensors measure critical meteorological parameters that are normally used to analyze the performance of the PV system.

Special attention should be paid to measuring in-plane irradiance. Over time, some floaters may lose their buoyancy, causing panels to deviate from their expected inclination angle. In addition, if the irradiance sensor is mounted on its own at the outer rim of the platform, its tilt angle may deviate from the designed tilt angle and its irradiance measurements will be inaccurate. It is therefore preferable to fix irradiance sensors directly adjacent to the module frame (figure 9.3) of a centrally located module to ensure that its tilt angle aligns with those of most of the panels on the platform.

Module temperature is useful in gauging the cooling effect on a particular type of floating PV island. Figure 9.4 shows several ways to install module temperature probes. Module temperature sensors with an accuracy of ±1ºC are affixed in a manner suitable for long-term outdoor use on a body of water (for more information please refer to section 8.4 of NREL 2016: *Best Practices in Photovoltaic System Operations and Maintenance*). Because floating systems tend to move a lot, temperature-measuring probes can be dislodged more easily than in ground-mounted systems. The readings should be checked and the appropriate location and installation verified in case the readings seem to deviate from the norm.

It is recommended that the chosen data-acquisition systems deployed over time are able to time synchronize their collection of electrical parameters, energy, and incident solar irradiation (and other meteorological parameters).

If it is desirable to have a direct comparison with a land-based PV system (for example for benchmarking), a reference ground-mounted array can be installed nearby. The array should be of the same module type and also have at least Si-sensors to measure global

FIGURE 9.2 Meteorological station close to FPV system (a) and types of sensors: (b) wind speed sensor, (c) humidity sensor, (d) pyranometer, (e) Si-sensor, and (f) wind direction sensor

Source: © SERIS.

horizontal irradiance (GHI) and plane of array (POA) irradiance. These help to determine differences in performance and degradation and to reveal any abnormalities associated with the floating installation.

Soiling losses can be monitored and/or inferred by comparing the performance against regularly cleaned reference solar modules, or by carefully analyzing long-term performance data.

For a meaningful and in-depth analysis of the measured performance, operators need to verify that on-site weather monitoring stations are working correctly, the collected data are correct and uninterrupted, and the module temperature readings carry the least possible uncertainty. Any missing data could trigger false events and/or lead to meaningless comparison. Hence, it is important to:

FIGURE 9.3 **Irradiance sensor installed in the plane of the solar modules**

Source: © SERIS.

- Calibrate the instruments/sensor as recommended by the manufacturer
- Clean irradiance sensors at regular intervals to avoid false baselining
- Check for any detached temperature probes due to constant motion of the floats
- Verify sensor operations and monitoring circuits

Compared to ground-mounted systems, FPV systems are not easily accessible. Barges and/or boats need to be permanently stationed for O&M. A boat trip to identify an underperforming string or array requires effort and expense. Hence, it is important to monitor the DC voltage and current of the PV strings with as much granularity (at combiner box level) as possible. It would be advisable to invest upfront and install equipment to monitor current and voltage at each string level.

FIGURE 9.4 **Examples of module temperature probes**

Source: © SERIS.

State-of-the-art string and central inverters are able to sweep IV curves and monitor DC string voltage and current values. Alternatively, collect IV data with handheld IV tracers at selected intervals. Inverters are also capable of reporting alternating current (AC) cumulative energy (kilowatt hours), AC current, and voltage readings. Inverter manufacturers have off-the-shelf string monitoring sensors and devices. Inverters are also capable of communicating with the deployed SCADA system. Under normal circumstances, these types of inverters should be sufficient to gather energy generation data from the solar power plant. For the entire data acquisition and communication network, operators should consider using a standby alternative power source (that is, battery/diesel genset) to avoid loss of data. Overall, efficient system monitoring is vital to O&M. For more information on the PV system monitoring topics, readers can refer to chapter 7.7 of the report, "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015).

9.2.2 PV modules

Regular inspections will ensure that solar modules are not being shaded by surrounding objects (for example, nearby trees). Any shade-causing objects should be removed or relocated. FPV installations face fewer shading issues than ground-mounted systems, since the water surface is flat and systems are often distant from buildings or vegetation.

Soiled PV modules are the greatest concern for O&M, and bird droppings cause significant soiling for FPV systems. Floating structures naturally attract avian wildlife. They use them as landing and resting points. Bird droppings (figure 9.5) reduce power output and performance through partial shading and hot spots, which can cause substantial loss of production (Deign 2017). Soiled solar panels need frequent cleanings, which leads to higher maintenance costs. In the long term, bird droppings may cause permanent degradation of solar cells and modules, especially in systems near bodies of water that are regularly visited by seabirds. This issue needs to be considered and addressed during the planning/engineering phase and through the operation of the plant to avoid potential productivity losses.

Bird droppings often contain seeds, which can sprout in floats and mooring cable joints; the resulting vegetation growth (figure 9.6) may subsequently attract more birds or other animals. These small plants have to be weeded out on a regular basis.

FIGURE 9.5 Severe bird droppings at a testbed in Tengeh Reservoir, Singapore

Source: © SERIS.

Bird deterrence systems, barrier and nonbarrier, should be deployed. Techniques that deter birds from gardens (such as fishing lines) may also work for FPV systems (Knight 1999). Similarly, a single strand of monofilament wire tied to either end of a row may be effective (they should not cause shading on solar modules). Various nonbarrier methods like ultrasonic devices, sonic repellers, or visual scare devices can also be used. The environmental and social impacts of such solutions should be investigated and documented at the planning/engineering phase. The use of laser systems has been shown to reduce bird landings by 75 percent (Bird Control Group n.d.).

FIGURE 9.6 Vegetation growth due to the spreading of seeds by air, water, or bird droppings

Source: © SERIS.

Monitoring systems, including dedicated DC string measurements, make it possible to see if a certain segment of a system is underperforming, which might indicate that incident sunlight is being blocked, in this instance by bird droppings.

The thermal imaging of large-scale installations from an unmanned aerial vehicle (drone) is now common and can be used to quickly identify issues caused by damaged panels or soiling. Otherwise, a lightweight handheld thermal camera can also be employed for regular inspection of the solar panels. Figure 9.7 shows a hot spot due to bird droppings on an FPV installation.

The effects of dust are less severe for FPV systems located on inland freshwater bodies than for ground-mounted ones, but still should be considered when optimizing the module-cleaning schedule. Modules' tilt angle, for example, can help reduce the required frequency of cleanings through periodic "self-cleaning" by rain, depending on the climatic conditions.

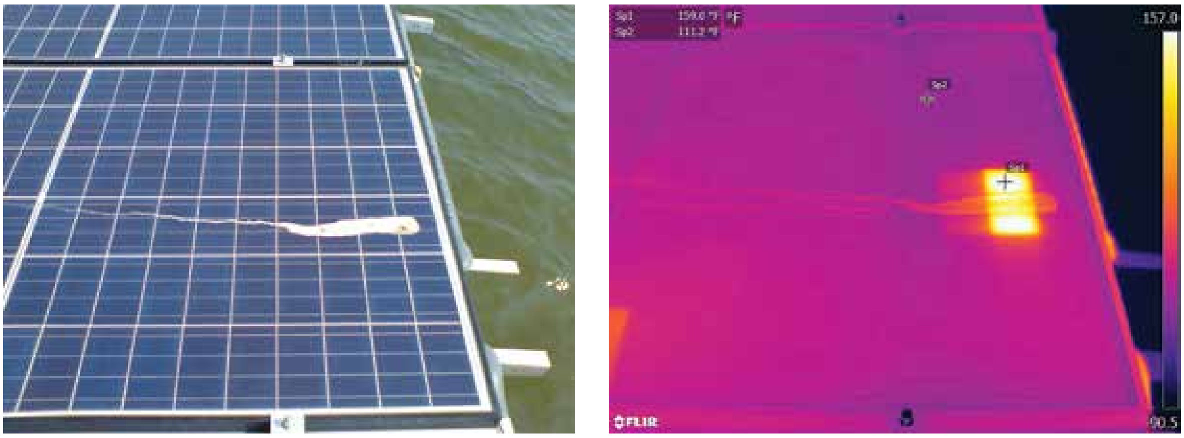
Cleaning should be carried out at times of the day when the modules have not reached very high operating temperatures to avoid unnecessary thermal stress. O&M workers should ensure to not step on the panels while carrying out inspection and/or cleaning. Independent of the float islands' layout, module cleaning remains labor-intensive. Properly training module cleaning technicians is essential to prevent O&M personnel from accidental falls onto the panels or into water while they are cleaning.

Workers often use soft sponges, nonabrasive brushes, or cloth to lightly wipe affected areas. The use of chemicals or pressure and steam cleaners is discouraged because of concerns for both the modules and the water body.

Module can be cleaned with water from the water body on which the system floats, a practice that can reduce O&M costs. The rinse water is typically environmentally benign and can be allowed to drain back into the water body. FPV plants built on corrosive types of water (like seawater) will require alternative sources of cleaning water. A typical module-cleaning activity might involve a team of six workers working four days to clean one MWp.

Table 9.2 outlines a preventive maintenance plan for modules in an FPV installation. For a detailed list of activities, readers can refer to Appendix B, Service Descriptions for Preventive Maintenance Selections, in NREL (2016). Damaged solar modules would require replacement as part of corrective maintenance. These repairs involve planning and effort, starting with transporting the solar modules by boat and accessing the mounting structures while standing on the floats (shown in figure 9.8). The removal of a broken solar module and installation of the new one should follow the standard operating procedure issued by the float and module manufacturers. Floating solar panels are in general more difficult to clean, inspect, repair, and replace than ground-mounted ones.

FIGURE 9.7 **Thermal image taken by handheld infrared camera showing a hot spot from bird droppings**



Source: © SERIS.

TABLE 9.2 **Solar module maintenance plan**

Monthly	Quarterly	Yearly
• Visually inspect for objects that are casting shadows on the solar modules and thus affecting the power output of the system. • Verify the cleanliness and integrity of the solar PV module surfaces.	• Spot clean as required without the use of hard water or detergents. • Visually inspect for defects such as: – Cracks – Fractures in glass – Discoloration – Delamination – Moisture penetration – Frame corrosion	• Conduct annual recommissioning of the PV systems to compare performance from year to year. • Compare voltages and currents across individual strings. If large deviations are found, sample modules may be sent for indoor flash testing, and results compared with initial module performance as measured before deployment. • Conduct thermal (infrared) imaging of the solar modules using an unmanned aerial vehicle. • Perform UV fluorescence scan of the solar modules if required or if cracks/snail trails are suspected • Perform EL if potential induced degradation is suspected

Source: SERIS.

FIGURE 9.8 **Replacement of a damaged solar module**

Source: © SERIS.

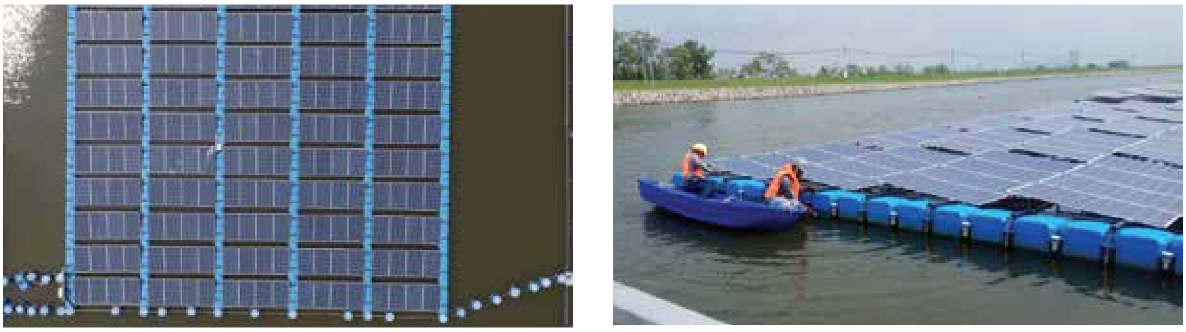
Many floating installations built to date have maintenance walkways, which ease access to solar panels (figure 9.9). Without walkways, trained O&M personnel need special equipment and boats to access the panels (figure 9.10), which likely adds time and expense to regular maintenance. A cost-benefit analysis of the extra floats used for walkways should be undertaken at the design-engineering phase of the project.

Working on water bodies requires special equipment such as life jackets, boats, boat driving permits/licenses, and wireless radios, and personnel must be properly trained to handle all equipment. These and other

FIGURE 9.9 Floating islands constructed with walkways (left), and its maintenance (right)

Source: © SERIS.

FIGURE 9.10 Floating islands constructed without walkways (left), and its maintenance (right)



Source: © SERIS.

recurring O&M costs should be factored into layout decisions during the design phase of the project.

9.2.3 Floats and mounting structures

9.2.3.1 Biofouling

The design and climate at the installation site play an important role in influencing the degree of biofouling. General cleaning of the float surface—removing accumulated dirt, algae growth, bird droppings, and midge/mosquito egg masses—should take place at appropriate intervals depending on site conditions. Open areas of each float (if applicable) that are not covered by PV panels (most often along the perimeter of a floating island) create stagnant water pockets that can become breeding grounds for midges and mosquitoes. Floats upon which PV modules are mounted are observed to be less susceptible to this problem. Algae growing on the submerged structures or floats (figure 9.11-left) provide a suitable habitat for insect larvae and proliferating insects; larvae also constitute a food source for birds. If the electrical enclosures have insufficient ingress protection (figure 9.11-right), tiny insects can infest cabinets and cause long-term damage. Moreover, insect breeding may violate local environmental regulations and should therefore be controlled. For example, the hot and humid climate of the tropics is conducive to insect swarms and increased levels of biofouling.

9.2.3.2 Buoyancy and structural integrity

Loss of buoyancy can be caused by poor float quality or by punctures and holes introduced (but unnoticed) during installation or O&M. Inspect the buoyancy of the floating structure periodically. Corrective maintenance is required in case of loss of buoyancy. Also, float interconnections need regular checking and retightening as indicated in the float supplier's O&M manual.

Float design will affect the amount of work involved in replacing individual sinking floats. It is easier to remove floats in a modular design involving a metal structure, as shown in figure 9.13 (left), for example. But interlinked/interwoven floats with interlocking mechanisms using nut and bolts take more time and effort to remove and replace (figure 9.13, right).

BOX 9.1

Solutions to prevent biofouling

With its tropical climate, Singapore and its FPV systems are vulnerable to biofouling. The following are some methods for mitigating biofouling based on the experience from Singapore FPV testbed:

- Install floats without any open areas at the perimeter of the floating island.
- Floats made of cross-linked, smooth-surface polyethylene foam tend to inhibit algae growth.
- For some floating platforms suppliers use sheet-like membrane materials to counter the wind load. Avoid submerging membrane materials as they aggravate the problem.
- Install water pumps/rotors to prevent water from stagnating in pockets.
- Use sealing tape to cover exposed pockets of stagnant water present in the floats (figure 9.12) to help prevent midges and mosquitoes.

FIGURE 9.12 Sealing tape to cover open areas in floats

Source: © SERIS.

FIGURE 9.11 Midges, algae, and mosquito larvae

Source: © SERIS.

Keep in mind that these faulty floats will become much heavier with soaking or seepage, requiring additional personnel to lift and haul. It is recommended to follow the standard operating and maintenance manual of the float supplier for replacement of the floats. Figure 9.14 shows O&M personnel replacing a float. It is also recommended that a few spare floats be kept on hand as temporary substitutes during the replacement process.

Constant water movement will increase the risk of loosening the joints and bolts that connect the floats. Inspectors should check for signs of damage and looseness to prevent floating structures from disintegrating. Mounting structures for PV inverters and other electrical components on water (such as combiner boxes) might suffer from similar issues too, leading to risks of components falling into water.

FIGURE 9.13 Floats on left side: modular and detachable from support structure; floats on right side: interlinked, aligned, and secured to neighboring floats with a nut and bolt

Source: © SERIS.

FIGURE 9.14 Corrective maintenance carried out on the float

Source: © Ciel & Terre International.

9.2.3.3 Corrosion and degradation

Watch for early signs of rust and corrosion in the metal frame and mounting structure (where applicable), including fasteners and cable clips attached to the structure or to the solar modules. Any damaged parts need to be replaced or repaired to reinstate the original system's integrity and specifications. Table 9.3 shows a preventive plan for inspecting the floats and support structures. Generally, one worker working for two days can check the floating structures of a one MWp FPV system.

9.2.4 Mooring lines and anchoring systems

The failure of the mooring and anchoring system can have a catastrophic impact. It is important to verify every component of an anchoring system, including the wire or mooring chain, shackle, and anchor.

The inspection and verification of the system components that are close to the surface can be accomplished with less effort from the floating platform. For submerged parts of the system, inspection is usually undertaken by professional divers who employ specialized tools and tackles.

For the components near the surface (like the shackles, chain, and cable), a visual inspection may be done from the floating platform by pulling the rope/wire a few centimeters above the water. Factors contributing to the degradation of the mooring system include cyclic loading, wet/dry cycling, ultraviolet exposure, chemical and environmental exposure, temperature, abrasion, creep, and fatigue (Weller and others 2015). Mooring lines should be inspected for marine growth and general fouling, which add weight and contribute to further corrosion and degradation. A visual inspection of the chain links and contact points is also important. It is advisable to look for broken wires, loose strands, corrosion, and frayed crimp points. Chafing is common where the chains or ropes rub against each other or against the floating structure. If the diameter of the mooring line is reduced significantly or worn out by wear and tear, then it should

TABLE 9.3 **Floats and mounting structure maintenance plan**

Monthly	Quarterly	Yearly
• Visually inspect condition of floats and their buoyancy. • Check for surface damage or growth of algae and insect eggs/larvae.	• Inspect for galvanic corrosion between two dissimilar metals in module mounting structures (when structures are made of metal). • Inspect for rust on frame supports, cable clips, and fasteners (if applicable). • Clean the floats of algae or other aquatic growth on the float surface.	• Verify strength, tightness, and integrity of bolts and other fasteners in the mounting structures. Irregularity in the panel mounting or slope may indicate that the supporting structure is not properly positioned. • Manually inspect tension between components and fastening of bolts for the floats. • Check for loose connectors, rust, and overall system integrity.

Source: SERIS.

TABLE 9.4 **Anchoring and mooring system maintenance plan**

Half yearly	Biennially
For components above and/or close to water surface like the shackles, the chain, and cables	For submerged components like anchors, underwater shackles, and mooring ropes/cables
• Visual inspection for marine growth, corrosion, and degradation. • Visual inspection for broken wires, loose strands, corrosion, and frayed crimp points. • Measurement/inspection for diameter of the mooring line. • For anchors located on the banks, visual inspection can check initial position, possible bending or lift up from the ground.	• Employ certified divers to visually inspect the shackles, mooring lines, and the anchors. • Verify mooring line tension.

Source: SERIS.

be reported to qualified designers for a reevaluation. Based on the advice of the qualified personnel, the lines can be replaced or augmented. For the onshore anchors, a visual inspection can check its initial position for possible bending or lifting up from the ground.

For the submerged components like anchors, underwater shackles, and mooring ropes/cables, it is recommended to employ certified divers for inspection. A biennial inspection of the anchor and measurement of tension of mooring line can be done as part of the preventive maintenance routine. Table 9.4 shows a preventive plan for inspecting the mooring and anchoring systems.

9.2.5 Inverters

O&M of inverters includes responding to an inverter's faults. Inverters typically provide error messages that help diagnose possible causes of the faults, as well as inverter logs. Consult the inverter manufacturer's manual for more details on how to interpret error logs and decide the appropriate corrective action.

If string inverters are located on the water surface, the ingress protection (IP67) rating of the inverter is important. Inverters should not have vents or fans that would permit water ingress. In addition, the codes and regulations for AC-carrying conductors routed on a water surface should be addressed at the time of commissioning. The IP code classifies and rates the degree of protection provided against intrusion, dust, accidental contact, and water by mechanical casings and electrical enclosures.

Usually, when central inverters are used in large-scale FPV plants, they are installed on large floating platforms. It is essential to have a maintenance platform or working area around the central inverter.

When inverters are installed on land with an IP65 rating, prevent water ingress by installing them under shelter and perform periodic checks for signs of humidity, corrosion, or water ingress. Clean the filters and test the proper operation of the fans (if any).

PV inverters have different warranty options, including complete life-cycle services, spare part provisions, preventive maintenance, and service contracts. Inverters should be inspected on an annual basis, and aging components like cooling fans should

TABLE 9.5 **Inverter inspection plan**

Monthly	Quarterly	Yearly
• Download error log files from the inverter database and check for any major downtime or repeating error code.	• Clean and make sure the ventilation is adequate during normal operation. • Dismantle inverter fans* and clean any dirt or dust that could cause blockage. • Record any inverter fault codes, deformation, burn marks, or signs of overheating to the manufacturer.	• Check the anti-islanding function of the inverters annually by disconnecting the main supply to the inverter. The inverter must disconnect itself and shut down, preventing any power from being sent back to the grid. This ensures the safety of the system.

Source: SERIS.

Note: *applicable for IP65-rated inverters deployed on land under a canopy or shelter.

FIGURE 9.15 **Connectors and cables submerged in water**

Source: © SERIS.

be replaced periodically. Inverter failure and consequent system downtime can be minimized by entering into service contracts with suppliers for parts replacements.

Table 9.5 outlines a checklist for the preventive maintenance of inverters.

9.2.6 Cables

All the cables (DC and AC) and connectors should be secured above the water surface, unless they are submarine grade. Nevertheless, connectors and cables tend to get submerged (figure 9.15) intermittently or permanently, by constant wave action, wind, wave amplitudes, mismatch in module cable length and float dimensions, low clearance from water surface, and cable ties and clamps loosening or breaking over time.

Water immersion of connectors or cable leads to leakage and low insulation resistance, degradation (corrosion) of cables, and eventual loss of power. Submerged cables are also susceptible to biofouling (figure 9.16). The prolonged effects of biofouling on cables could be detrimental as well.

FIGURE 9.16 **Biofouling on submerged connectors and cables**

Source: © Lightsource BP.

Hence, during the O&M phase, is it important to check for such situations and immediately mitigate the risk by taking the cables out of water, clean if required, reroute the cable and fasten the cable with cable ties, clips or conduits. Monitoring insulation resistance is useful for early problem detection. Insulation resistance tends to be low for systems with cables in contact with water. Frequent slow starts for inverters is a sign of insulation resistance that is too low, so proper performance monitoring can help to spot the cable issues.

Slack cables connecting the floating island to the land (figure 9.17) can also be submerged to accommodate platform movement. This could pose an electrical safety risk and possibly lead to leakage currents. Hence, during maintenance it is good to inspect the cables returning to shore.

Because the cables are often rubbing against moving parts, the cable sheath is vulnerable to chafing (figure 9.18); ultimately the cable may expose its leads or snap. During maintenance routines, it is important to check places where cables are rubbing against other moving parts. Damaged connectors, cables, and/or conduits must be immediately replaced.

Table 9.6 indicates the preventive check plan for connectors and cables.

9.2.7 Balance of system—junction box, protection devices, and components

FPV installations are close to the water surface therefore IP ratings of all the cabinets should be maintained IP65 or above. Both the DC and AC combiner boxes should be sufficiently well secured on the floats, so that they cannot slide and fall into the water. Protection from water ingress is important; defective seals, cable glands, and boxes must be replaced or repaired to maintain original IP performance specifications. Figure 9.19 shows a DC junction box's compromised sealing, leading to water ingress and corrosion.

Faulty fuses, electrical circuit breakers, residual current devices, safety isolation switches, or surge pro-

FIGURE 9.17 Maintenance on cables returning to shore

Source: © SERIS.

FIGURE 9.18 Conduit and cable sheath wear out

Source: © SERIS.

FIGURE 9.19 Water ingress and IP integrity compromised

Source: © SERIS.

TABLE 9.6 Connectors and cables inspection plan

Monthly	Quarterly	Yearly
• Check if cables and connectors are still secured above water or if they are submerged.	• Verify mechanical and watertight integrity of cable conduits and/or cable trays. • Inspect cables for signs of biofouling, chafing, degraded insulation or exposed conductors. • Inspect cable runs to ensure the appropriate amount of slack is present to prevent stress, while still keeping the connectors away from the water.	• Carry out thermal inspection of wiring and connectors. • Perform and verify the insulation resistance of DC cables. Megger test equipment can be used to measure and identify weakened insulation resistance.

Source: SERIS.

TABLE 9.7 Junction box inspection plan

Monthly	Quarterly	Yearly
• Visually inspect for obvious damage to the junction box.	• Inspect DC junction boxes located on floating platform for: – Tightness of connections – Water accumulation and water damaged boxes – Integrity of water/lid seals – Integrity of cable entrance, cable glands, and/or conduit sealing – Integrity of fastening • Inspect junction box isolator switches or circuit breakers for signs of electrical or water damage and water penetration.	• Verify for any defects in the: – Integrity of DC fuses – Circuit breakers and residual current devices/ miniature circuit breakers – Earth fault protection devices – Solar array isolation switching device(s) – Lightning protection system (surge) devices – Conduct a thermal inspection of fuses and connectors.

Source: SERIS.

tection devices require the immediate shutdown of the corresponding DC and AC electrical subsystem; faulty components should be replaced to maintain original project performance specifications. Table 9.7 lists the action plan to maintain the junction box and other protective device component integrity.

9.2.8 Earthing and equipotential bonding

Another major potential issue relates to equipotential bonding. Equipotential bonding takes two forms, as stated in IEC 62548: (i) main equipotential bonding is the connection of exposed conductive parts to the main earthing terminal; and (ii) supplementary equipotential bonding is the connection of the exposed conductive paths to extraneous conductive parts. PV array frame bonding (an exposed extraneous conductive path) is essential. Grounding regulations vary from country to country, so it is necessary to adhere to the prevailing local standards.

The constant movement of the floating platform induces mechanical stress at the joints of rigid structures. This is especially so for platform designs where relative movements between modules are frequent. Most of the bonding tape and wires are subjected to this constant stress due to waves and wind, which can lead to snapping or breaking of equipotential bonding tape (figure 9.20) across the metallic elements in the array.

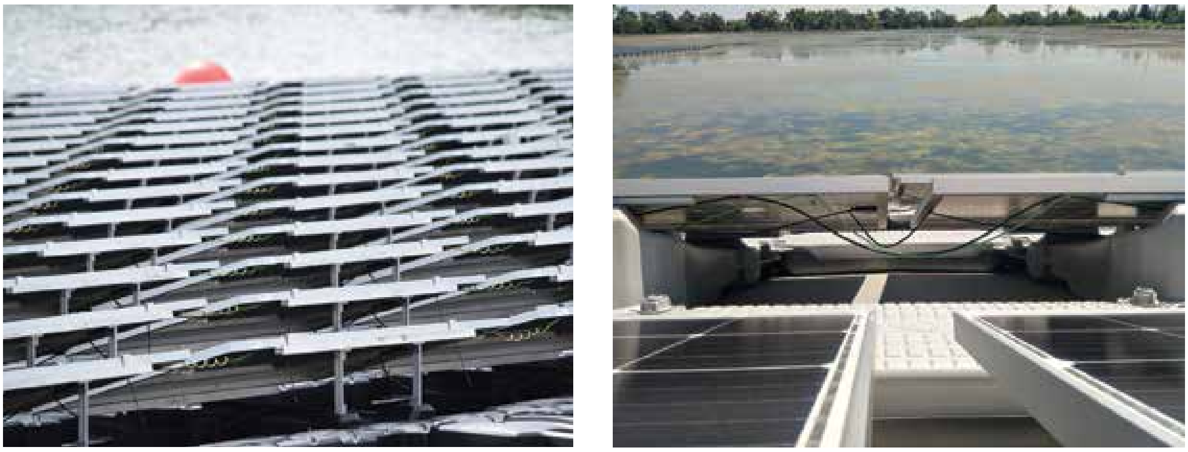
During the construction phase, the module frames are interconnected through grounding cables attached to dedicated slots provided in the module. Usually, if sufficient slack (15–30 cm) is allowed, then snapping of the earth cables can be avoided. Nevertheless, during maintenance, it is important to periodically check and verify that the module frames and metallic mounting structures are grounded.

A typical problem with series-grounding connection methods is that bonding is lost as soon as one connection breaks (figure 9.21, left). Therefore, an alternate main grounding cable could be laid in parallel on the floats, with each PV module's grounding cable then tacked onto this main cable (figure 9.21, right) Thus, each of the module frames is independently connected to the main grounding cable. This helps to maintain continuity even if there is a cable break (as compared with series grounding), effectively increasing the reliability.

FIGURE 9.20 **Bonding tapes/wires snapped due to constant motion of floats and excessive slackness**

Source: © SERIS.

FIGURE 9.21 **Grounding cable run—series layout (left) and parallel layout (right)**



Source: © SERIS.

Source: © Ciel &Terre International.

TABLE 9.8 **Earthing and equipotential bonding inspection plan**

Monthly	Quarterly	Yearly
• Verify that the cabling for equipotential bonding is still in good condition. This is especially important for floats that do not have a frame, and undergo more wave action. • Verify that the main grounding cable/rod is in good condition.	• Check earthing connections for: – Tightness of connections – Corrosion – Cable fastenings	• Check earth pit and its resistivity depending on regulations. (for cases where the earth cable returns to shore) • Check the earthing material (rod/tape) for corrosion. (for cases where earthing is done on the reservoir water or to the reservoir bed)

Source: SERIS.

It is also important to check the earth pit and its resistance if earth cables are returning to the shore. These checks are implemented according to each country's regulations. 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. Table 9.8 shows a maintenance plan for earthing and equipotential bonding.

9.2.9 Risks posed by wildlife

During the planning stage of the project, undertake a careful site survey for fauna and flora. There could be associated risks from the aquatic animals on the floating PV system (figure 9.22). Sometimes animals may vandalize structural components or cables. Proper mitigation strategies, such as barriers at the periphery, should be in place in consultation with environmental agencies.

FIGURE 9.22 **Animal visits**

Source: © SERIS.

During the O&M phase of the project, it is important to maintain barrier methods to prevent animal visits. Nonbarrier methods, like laser-beam equipment, might also be an option. It is important to maintain such equipment per the supplier's recommendation. Where relevant it may also be necessary to store anti-venom at the O&M site office and identify the nearest medical center for emergency visits to mitigate snakebite risks. It is important to maintain both the equipment and personnel safety at all times.

9.2.10 Spare parts inventory

A spare parts inventory in the event of equipment failure is essential. It minimizes downtime during corrective maintenance. The cost of maintaining an inventory is justified by the benefit brought by reducing plant downtime and avoiding revenue loss, after consultation with manufacturers on estimated component lifetimes and failure rates. It is recommended that spare parts be kept on site in a permanent storage area or in a nearby warehouse.

Engineering product design and specifications are typically updated multiple times over a plant's life cycle. Some original parts may no longer be available within a few years of manufacture (or might require an upgrade). Detailed discussion with each of the suppliers is essential during procurement stage of the project. Based on their recommendations and know-how, stock sufficient numbers of spare parts.

In general, adequate supplies of the following essential components should be maintained for FPV systems:

- Floats—loss of buoyancy could require replacement floats during the lifetime of the project.
- Module mounting structure pieces—along with the float replacement, associated mounting structures would need to be replaced.
- Fasteners—all fasteners exposed to water might require replacement owing to corrosion/oxidation or accidental submersion.
- Modules, in case of damage.
- Spare string inverters (if these are being used).

For a more detailed list of PV spare parts, similar to lists for ground-mounted PV projects, readers can refer to chapter 11.5 of the report "Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide" (IFC 2015).

9.3 Warranties and performance guarantees

The O&M contractor is liable for meeting the plant performance guarantees and maintaining the asset value during the project life. The project financiers will also be interested to ensure that plant is well secured with product warranties and performance guarantees.

During the initial years (one to five years), the warranty from the EPC contractor may cover the failures arising from civil, structural, and electrical workmanship; product warranties cover most of the critical components of the PV plant. Product warranty protects the purchaser against failures arising from manufacturing defects.

Most solar panel manufacturers provide product warranties for 10 years and a long-term performance warranty for 25–30 years. Performance warranty guarantees a certain power output that declines over time, usually ending up at 80 percent of the initial rating after 25 years.

The materials and products supplied by the floating platform supplier shall be guaranteed free from defects for at least five years. Currently, float manufacturers are providing a product warranty of five to ten years. It is also important that the anchoring and mooring system be covered by a warranty for the same period as the floating structure.

Inverter manufacturers typically provide a five-year warranty with various options for an extended warranty beyond five years, up to ten.

It may be a good practice to ask for a third-party inspection before any warranty liability transitions during the lifetime of the FPV plant.

With regard to performance guarantees, targets for the energy yield, performance ratio, and plant availability are normally used as metrics. Each of the metrics calculated must be specified in sufficient detail; standards such as IEC 61724, parts 1, 2, and 3, can be used for such purposes. The O&M contractor is expected to undertake periodic performance tests and reports.

The *measured* plant energy (in kWh) is compared against the amount of the *expected* plant output in kWh. The terms and conditions of any shortfall need to be clearly defined. Under situations where the yield is not meeting the requirement, liquidated damages (LD) are triggered, as agreed upon before an O&M contract commences. Plant owners should have a yield report based on an acceptable model, and then use that model to benchmark actual performance, based on measured irradiance and other prevailing environmental parameters in the reporting period.

In the case of FPV, it is important to consider the measurement of irradiance and environmental factors more carefully. Some uncertainties could arise in:

1. Tilt, azimuth, and in-plane irradiance
The floating platform is constantly moving due to wind and waves (figure 9.23). The water level changes could allow the system to drift from its original orientation. This in turn would affect the amount of solar irradiation received by the active area of the solar panel.

Hence, it is recommended to measure the in-plane irradiance on the float and as close as possible to the solar panel to get a good estimate of solar resource. For large, MW-scale FPV plants, more than one sensor is normally installed.

2. Module temperature
It is recommended to determine the temperature-related losses, normally measured with a temperature sensor affixed to the back of the solar module. Solar modules close to the water surface are expected to be cooler. As FPV systems are in constant motion, these sensors might easily dislodge and fall into the water. Periodic inspection is necessary if unexpected shifts in module temperature are observed. Module temperatures can also vary based on their location in the floating island. The perimeter solar modules could be operating at a different temperature as compared with the one in the center of the island due to varying convection mechanisms. Consider adding more sensors at different locations around the floating island.

3. Ambient temperature, wind speed, and wind direction
Measure the environmental factors as close as possible to the floating island or on the island itself, as these are

FIGURE 9.23 Varying tilt angle induced due to wind and waves

Source: © SERIS.

representative of the solar array conditions. The ambient temperature sensor, wind speed, and direction sensors are then placed accordingly without shading the modules on the FPV island itself.

9.4 Operations and maintenance checklist

Critical aspects of operations and maintenance are summarized in table 9.9.

TABLE 9.9 Operations and maintenance checklist

- EPC and O&M provider interests are aligned for smooth handover and takeover.
- O&M contract contains clear descriptions of scope of work and deliverables.
- O&M contractor is suitably experienced; familiar with floating PV installations.
- PV system monitoring is able to measure and report relevant electrical data and meteorological data with sufficient granularity.
- For FPV, the meteorological station could be built on the floating structure close to the conditions experienced by the solar array.
- Types of FPV maintenance and maintenance plans are clear and comprehensive.
- Soiling from bird droppings is monitored.
- Standard operating procedures for module and float replacement are respected.
- Biofouling on the floats and cables are considered.
- The mechanical integrity of connecting parts of the floating platform and mounting structures are regularly checked.
- The anchoring and mooring lines are periodically inspected.
- Above-water cables are maintained.
- Adequate plans are made to handle issues related to animal activities.
- Floats and related parts are covered by warranties and spare parts kept in stock.

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ANNEX A

FLOATING PV MODULE FAILURE MODES AND TESTING RECOMMENDATIONS

A.1 Overview

Table A.1 shows environmental stresses that are higher for PV systems in a floating environment compared to temperate, desert and tropical operating environments. Based on what is known of failure modes and tests, one important question to ask is: can we simulate a 25-year lifetime to develop models and data so FPV has the same bankability as land-based PV? Furthermore, given the rapid pace of installations, can such tests be performed in a timely manner that successfully minimizes risk without stymying time-to-market?

For moderate stress (the baseline for ground-mounted PV), multiple groups (including NREL in the United States), have noted that 1,000 hours of damp heat is adequate for the majority of locations; but industry has chosen to market 3,000 hours duration (3x IEC 61215) with a Highly Accelerated Stress Test (HAST) (120°C/100 percent RH) used as a further acceleration particularly at the product development phase. The same approach can be applied for PID, for which 85°C/85 percent RH with bias (1000-1500V) is now the IEC 62804 standard; however, accelerated conditions such as HAST with bias may also be of value (Rowell, Coughlin, and Harwood 2013). Care must be taken in extrapolating what a given test (particularly a much-accelerated test) equates to. For example, the desert conditions in Arizona (the United States) and the tropical conditions in Singapore would be very different, and moisture causes multiple failure modes

TABLE A.1 Accelerated testing for floating solar module failure modes in various operating environments

Environmental stresses	Failure mode	Moderate stress	Higher stress	Highest stress
Moisture	- Corrosion - Hydrolysis - PID	Test at 85C/85% RH, 1,000hrs, Salt mist	Test at 85C/85% RH, 2,000hrs	Test at 85C/85% RH, 3,000hrs+ 120C/100%RH
		●	▼	▨
Mechanical stresses	- Interconnect fatigue - Cell cracking	Static mechanical load test 5,400Pa	Dynamic mechanical load test, 1000Pa/1000cyc	Shock/Vibration/HALT test
		●	▼	▨
Hot-spot/shading	- Arcing - Melting/cracking - Diode failure	Temperature test Diode test	Extended shading tests	High temperature operating life test
		●	▨ ▼	◆

● Temperate environment ◆ Desert environment ▼ Tropical environment ▨ Floating environment

Source: Harwood 2018.
Notes: PID = potential induced degradation; C = degree Celsius; RH = relative humidity; hrs = hours; Pa = Pascal; HALT = Highly Accelerated Life Test; HTOL = high temperature operating life.

such as corrosion of both cells and ribbons and backsheet degradation. For mechanical stresses, interconnect fatigue and cell cracking are the primary issues observed but the amplitude and frequency of those stresses have a different impact on the two. Panels returned from the field for ground-mounted applications have sometimes shown cracks and ribbon fatigue; dynamic mechanical load testing has been relatively successful in reproducing those failures in the lab (Bosco and others 2014). Panels mounted on rigid floats may see a stress profile similar to ground-mounted panels. But a flexible panel dealing with wave motion would see a different stress spectrum.

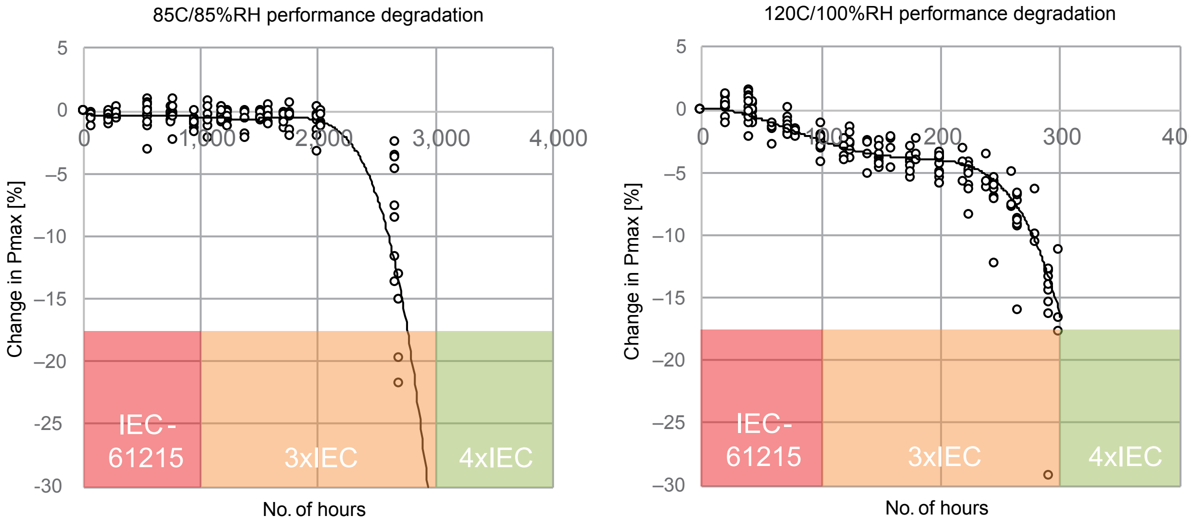
For hotspots, multiple failure modes on cells, ribbons, and diodes exhibit different activation energies. While modules may run cooler on or in water, they are also more likely to be soiled. It is not clear whether cooler temperatures mitigate the higher likelihood of hotspots.

A.2 Moisture-induced failure modes

In general, the conventional solar industry has argued that qualification tests such as the traditional IEC 61215 standard should not indicate 25-year lifetime, and certainly not for all environments (Wohlgemuth and Kurtz 2014). But for the FPV industry, the IEC 61215 damp-heat test (1000hrs 85°C/85 percent RH) has proved closer to a lifetime test and perhaps even an overstress of real-world operations even for high-temperature, high-humidity land locations (Wohlgemuth and Kempe 2013). This damp-heat test looks at sample field modules, accelerated-degradation testing, and modeling that assume moisture levels are low when the cells are on-sun but higher at night. In figure A.1, the change in power is compared as a function of test duration for the traditional damp-heat condition using the same construction through an accelerated test of 120°C/100 percent RH that yields an acceleration factor of about 10x. Note that this is based on a performance change for the module caused by corrosion of cell metallization, but other failures can occur much sooner. For example, although the mean-time-to-failure in figure A.1 is around 250hrs in HAST for a 5 percent change in power, the PPE backsheet for these modules exhibited hydrolysis-induced cracks by 150 hours of exposure, which would involve a severe safety risk for electrocution and arcing despite only a minimal change in module power.

Another failure mode, potential induced degradation (PID), is relevant to floating solar for several reasons, not just because PID can be accelerated by moisture

FIGURE A.1 Comparison of change in module performance through IEC 61215 damp-heat testing and highly accelerated stress testing (HAST)



Source: Harwood 2018.

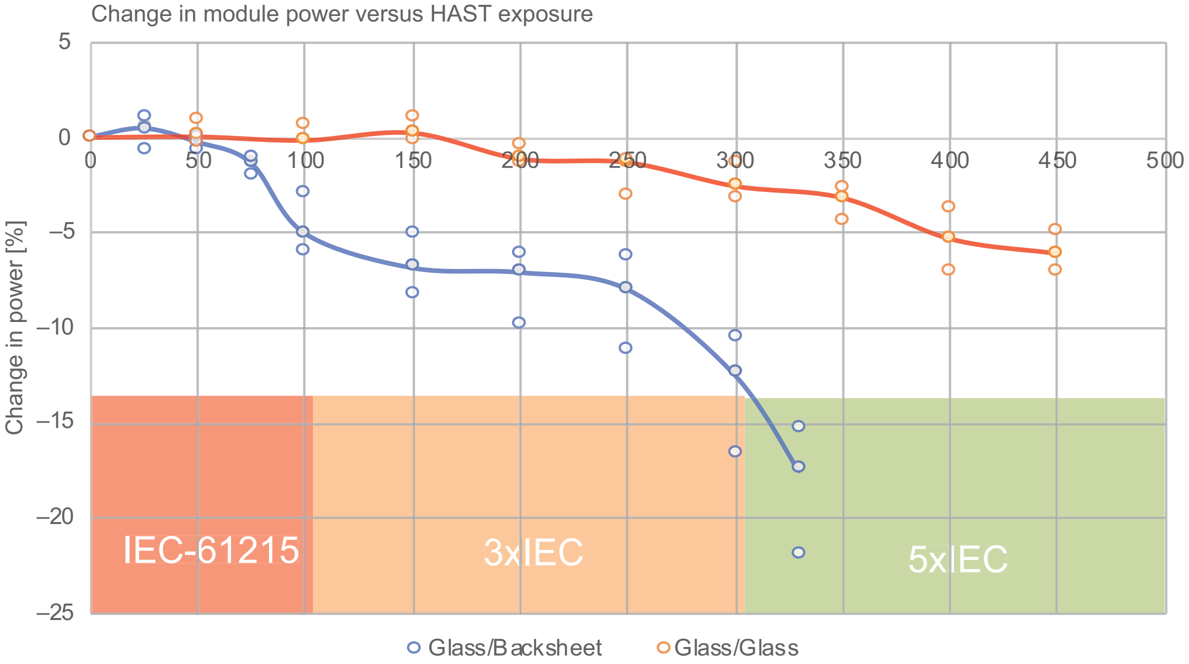
(particularly liquid water). Existing test standards do not identify PID, which causes significant and sudden field failures linked to module design and bill-of-materials (Hacke 2015). PID occurs when sodium ions migrate under bias from the modules' superstrate glass and cause cells to shunt. Grounding the module frame creates a potential difference between the glass and cell junction (up to the maximum voltage of the array) by driving ion migration from inside the glass, through the encapsulant, to the cells. Observations of early stages of PID noted that cells adjacent to the frame degraded first. In cases where the surface of the glass meets increased humidity (especially liquid water), the conduction path makes the glass surface equipotential with the frame. The current IEC 62804 standard provides a test method for evaluating and characterizing PID. While relative humidity does affect the degradation rate, it is driven more by the relative humidity around the module than by humidity inside the laminate/encapsulant. Most relevant for FPV, soiling caused by sea salt on the panel surface showed a 500x increase in the potential induced degradation rate (Hacke and others 2015). Care should therefore be taken with the selection of so-called PID-resistant panels, both with respect to material choice and water composition.

One approach to improve resistance towards moisture is to use glass-glass modules. Research had shown improved performance (figure A.2) over a traditional glass-backsheet module designed for harsh climates (Xu and others 2016). Other moisture-hardening approaches include the use of low-water-vapor transmission encapsulants and metalized backsheets.

A.3 Mechanical stresses

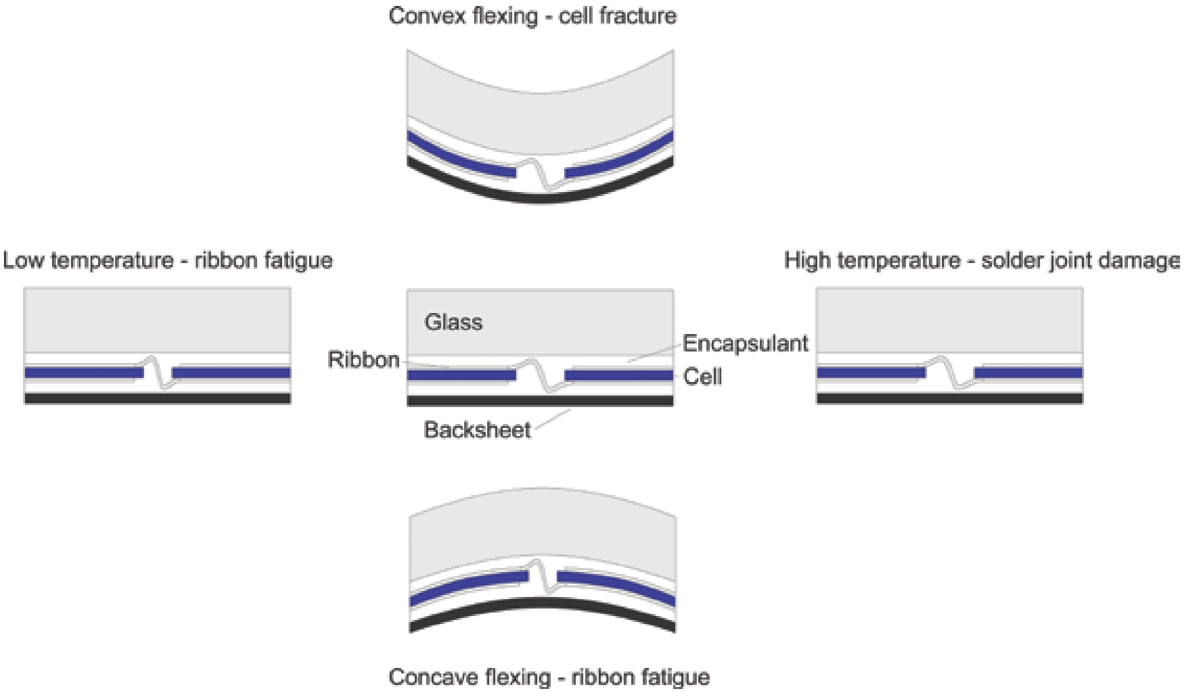
Solder-coated copper ribbon is the traditional method for connecting solar cells (figure A.3); it has been used for well over three decades and is generally reliable. Any failures are typically caused by mechanical stresses where temperature or flexing changes the cell spacing; temperature cycling can also create cumulative stress damage to the cell/ribbon solder joints (Bosco 2012). The ribbons buckle under compression, and their lifetime is defined by the number of cycles to failure at a given strain. In contrast, modules flexed in a concave manner place the silicon cells in tension, which leads to cell breakage or crack growth defined by the fracture rate versus cell stress (Sander and others 2012).

FIGURE A.2 Comparison of performance change during HAST for a glass-backsheet and glass-glass module



Source: Harwood 2018.

FIGURE A.3 **Influence of temperature and mechanical stresses on module materials**



Source: Harwood 2018.

A.4 Soiling and shading effects

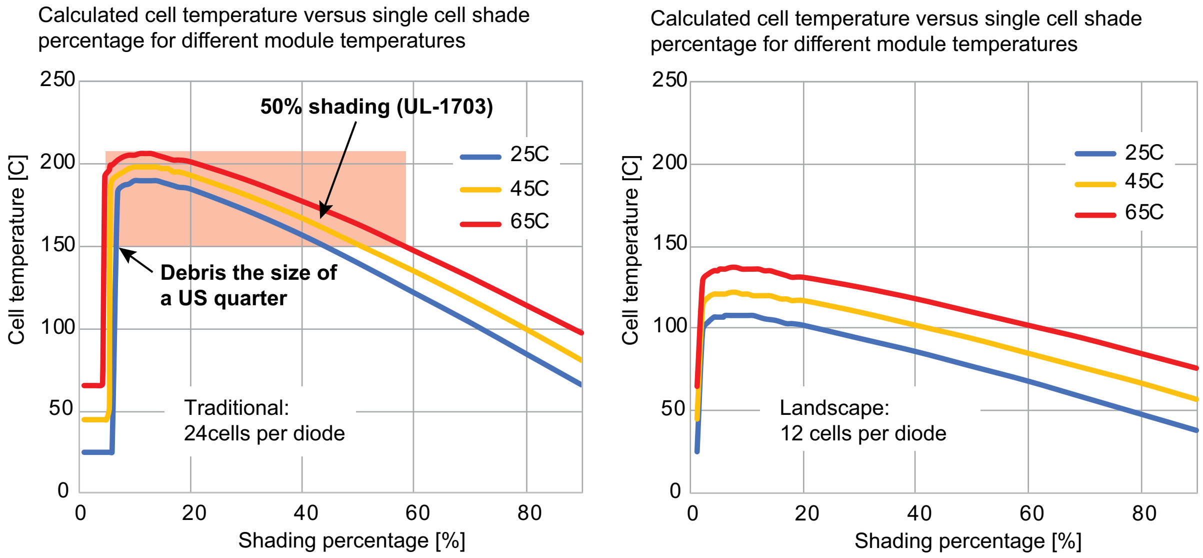
Soiling and hotspots constitute the last of the three risks highlighted in table A.1. Researchers have shown that modules will self-clean in relatively high-humidity environments. But data indicate localized soiling may be more prevalent with water-mounted panels. Localized, small areas of shade—as might be observed with bird droppings—can represent a worst-case situation for modern solar panels because of their high fill factors. In figure A.4, cell temperature was calculated for a generic 72-cell module (6 x 12 cells) with one bypass diode per 24 cells. One cell is shaded at short-circuit conditions—a worst-case, but not unrealistic, scenario demonstrating the impact of shading on cell temperature. Just a little shading (the size of a U.S. quarter) can cause temperatures to rise more than 150°C to 200°C and stay there until shading increases to approximately 50 percent, after which the temperature falls below 150°C. The left plot shows the traditional 24 cells per diode; the right plot shows a module with the cells strung in the other direction, placing 12 cells on a diode. In this way, the problem is mitigated with temperatures staying below 150°C.

High temperatures can cause degradation of encapsulants and backsheet materials. A cracked, melted, or burned backsheet is a serious safety risk. In contrast, glass can withstand temperatures well in excess of 200°C without causing a dielectric failure, although the performance of the underlying cells and encapsulant may be compromised. The resulting moisture exposure can reduce a module's durability and decrease its power output over time. It can also create catastrophic reliability or safety issues, such as dielectric failure and arcing in the event of backsheet hydrolysis or cracking. Similarly, localized hotspots may have a negligible impact on power degradation, but a melting backsheet would be a significant safety risk.

A.5 Extended qualification testing

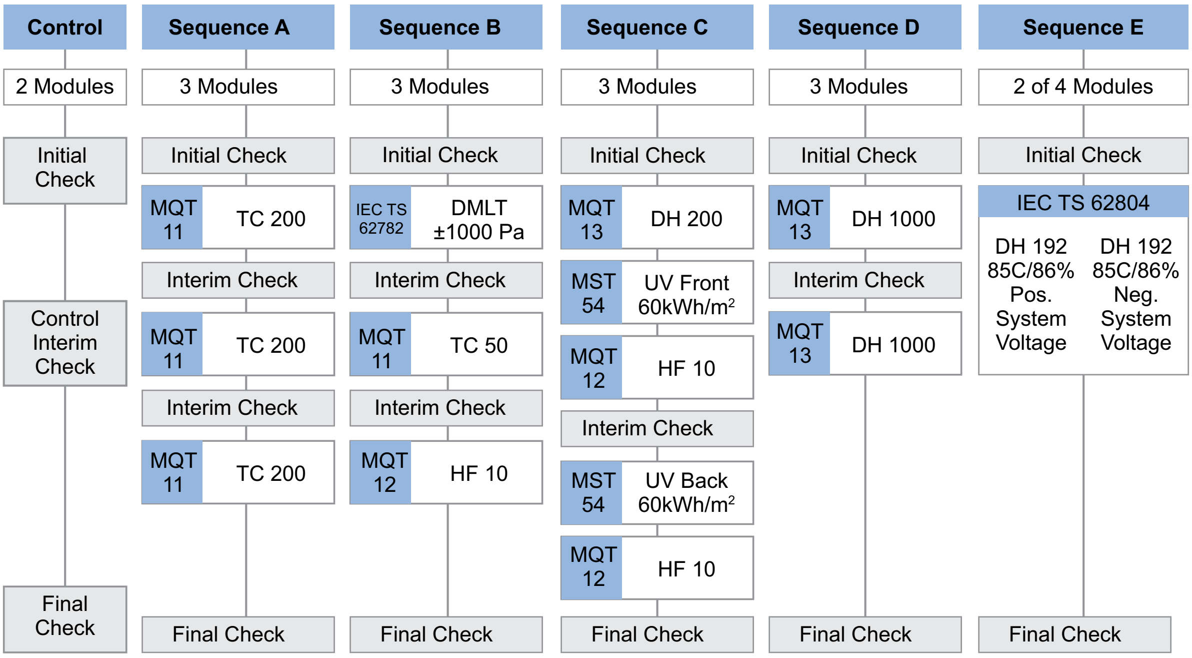
Given the challenges of a floating environment, developers may also consider extended qualification testing (Kurtz and others 2013), for example, using the ANSI-C450 standard shown below in figure A.5.

FIGURE A.4 Comparison of predicted maximum cell temperature versus shading percentage



Source: Harwood 2018.

FIGURE A.5 Test sequence for ANSI-C450



Source: Dana 2017.

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ANNEX B

COSTS OF FLOATING SOLAR

This annex is based on chapter 5 of the "Where Sun Meets Water: Floating Solar Market Report" (World Bank Group, ESMAP, and SERIS 2019). It provides a comparison of theoretical costs of floating and ground-mounted photovoltaic (PV) systems using average figures based on industry feedback and publicly available data. Since floating PV (FPV) systems are not as common or widespread as ground-mounted systems, it remains difficult to have data about their capital and operating costs that could be generalized, a more detailed analysis would need to be performed on a project level, for a complete picture of how FPV compares to ground-mounted in given circumstances.

The average total investment cost of an FPV system in 2018 varied between $0.8/Wp and 1.2/Wp, depending on the system's size and location. The CAPEX of large-scale but relatively uncomplicated FPV projects (around 50 MWp) was in the range of **$0.7-$0.8/Wp** in the third and fourth quarters of 2018, depending on the location and the type of modules involved. The CAPEX of a hypothetical 50 MWp FPV installation is laid out in table B.1, by component, and also compared with a ground-mounted system (both fixed tilt) at the same location. Assumptions regarding the average cost per component consider a hypothetical 50 MWp FPV system on a freshwater, inland reservoir with a maximum depth of 10 meters and minimal water level variation.

TABLE B.1. A comparison of capital investments: Floating vs. ground-mounted photovoltaic systems

CAPEX component	FPV 50 MWp ($/Wp)	Ground-mounted PV 50 MWp ($/Wp)
Modules	0.25	0.25
Inverters	0.06	0.06
Mounting system (racking)*	0.15	0.10
BOS**	0.13	0.08
Design, construction, T&C	0.14	0.13
Total CAPEX	0.73	0.62

Source: World Bank Group, ESMAP, and SERIS 2019.

Note: *For FPV, the mounting system includes a floating structure, and anchoring and mooring system. **Including monitoring system. BOS = balance of system; CAPEX = capital expenditure; MWp = megawatt-peak; PV = photovoltaic; T&C = testing and commissioning; $/Wp = U.S. dollar per watt peak.

Capex figures in table B.1 exclude grid interconnection costs. Details on operating expenditures, insurance costs, and costs of inverter replacement can be found in chapter 5 of the "Where Sun Meets Water: Floating Solar Market Report" (World Bank Group, ESMAP, and SERIS 2019) and are reflected in table B.4 below.

The key difference between FPV and ground-mounted PV projects is the modelling of the cooling effect due to water evaporation. It has been reported across the world that FPV systems have a higher energy yield than ground-mounted PV systems under similar conditions. Therefore, the irradiation level and ambient temperatures where the project is located are key variables that will influence the energy yield and thus the LCOE of projects. Preliminary results show that in hotter climates, the energy yield gain of an FPV plant over a ground-mounted one is higher than in temperate climates, since the cooling effect of water makes a great difference to their relative efficiency. This means that in certain regions of the world, the energy yield gain could be around 10 percent (typically in warmer regions with a global horizontal irradiation higher than 1,600 kilowatt-hour per square meters per year [kWh/m^2/year]) while in other regions it would be only about 5 percent (typically in colder regions or where irradiation is lower than 1,600 kWh/m^2/year). However, more studies are needed to verify this assertion and to more accurately quantify the correlation between energy yield gains and various climates.

Three types of climates are considered in the LCOE calculations: temperate, tropical, and arid/desert.

The representative "average" P50 global horizontal irradiance and performance ratio for ground-mounted PV figures has been estimated for each climate zone (table B.2). The performance ratio of FPV systems under similar conditions is estimated to increase by 5 percent in the conservative scenario and 10 percent in the optimistic scenario. The bold PR values are the "likely" cases per climate zone.

Table B.3 shows the energy output of hypothetical 50 MWp ground-mounted and FPV plants in their first year, across the three climates.

As of the end of 2018, there are no sufficient records yet for the degradation rates of FPV systems. Generally, crystalline silicon modules degrade at a rate of no greater than 0.8 percent to 1.0 percent per year. It is assumed here that the annual system degradation rate is 1 percent (Ye and others 2014) in a tropical climate, 0.7 percent in an arid/desert climate (Copper, Jongjenkit, and Bruce 2016), and 0.5 percent in a temperate climate (Jordan and Kurtz 2013).

Assumptions used in levelized costs of electricity calculations are summarized in table B.4.

Ideally, to fine-tune this analysis, system prices, O&M costs, insurance, and inverter warranty extension costs should also be varying by location/climate. Without empirical data on these particular variables, the analysis considers their costs to be similar across the three climate zones.

TABLE B.2. Representative average global horizontal irradiance and performance ratio, by climate zone

			Floating PR (%)	
	GHI (kWh/m^2/year)	Ground-mounted PR (%)	Conservative (+5%)	Optimistic (+10%)
Tropical	1,700	75.0	78.8	**82.5**
Arid/desert	2,300	75.0	78.8	**82.5**
Temperate	1,300	85.0	**89.3**	93.5

Source: World Bank Group, ESMAP, and SERIS 2019.
Note: GHI = global horizontal irradiance; kWh/m^2/year = kilowatt-hours per square meter per year; PR = performance ratio.

TABLE B.3. First year's energy output, by climate

		Floating PV (GWh)	
	Ground-mounted PV (GWh)	Conservative (+5%)	Optimistic (+10%)
Tropical	63.8	66.9	**70.1**
Arid/desert	86.3	90.6	**94.9**
Temperate	55.3	**58.0**	60.8

Source: World Bank Group, ESMAP, and SERIS 2019.
Note: GWh = gigawatt-hour; FPV = floating photovoltaic; PR = performance ratio.

TABLE B.4. Summary of assumptions used in calculations

General assumptions	Ground-mounted	Floating
System size (MWp)	50	50
System price ($/Wp)	0.62	0.73
O&M costs ($/Wp/year)	0.011	0.011
Yearly insurance (in % of system price)	0.3%	0.3%
Inverter warranty extension	Year 5: 20% of prevalent price Year 10: 45% of prevalent price Year 15: 60% of prevalent price ~$0.004/Wp	Year 5: 20% of prevalent price Year 10: 45% of prevalent price Year 15: 60% of prevalent price ~$0.004/Wp
Debt equity ratio	80:20	80:20
WACC	6% / 8% / 10%	6% / 8% / 10%
Debt premium (%)	4%	4%
Maturity of loan (years)	10	10
Surface lease cost ($/year)	—	—
Inflation (%)	2%	2%
Years of operation	20	20

Source: World Bank Group, ESMAP, and SERIS 2019.
Note: For both cases authors assume no lease cost, no contingency costs, same inverter replacement methodology, same insurance cost, same O&M costs, same system degradation rate and is calculated on a pretax basis.

Climate-related assumptions	GHI (kWh/m^2/year)	System degradation rate (%)	Ground-mounted PR (%)	Floating PR (%)	
				Conservative (+5%)	Optimistic (+10%)
Tropical	1,700	1.0	75.0	78.8	**82.5**
Arid/desert	2,300	0.7	75.0	78.8	**82.5**
Temperate	1,300	0.5	85.0	**89.3**	93.5

Source: World Bank Group, ESMAP, and SERIS 2019.
Note: GHI = global horizontal irradiance; kWh/m^2/year = kilowatt-hour per square meter per year; MWp = megawatt-peak; O&M = operations and maintenance; PR = performance ratio; $/Wp = U.S. dollar per watt-peak; WACC = weighted average cost of capital.

In the conservative scenario (+5 percent PR), the LCOE of the FPV system is between 8 and 9 percent higher than the LCOE of the ground-mounted PV system, while in the optimistic scenario (+10 percent PR), the FPV LCOE is only 3–4 percent higher than the ground-mounted LCOE. This difference is likely to reduce, become zero, or even reverse as FPV volumes grow and anticipated cost reductions are realized.

The LCOE calculation represents only a "break-even" analysis—that is, if the tariff were set at the LCOE, the net present value of the project would be zero. Equity investors would presumably require a higher tariff from the offtaker to make the project economically viable for them, assuming debt financing was accessible.

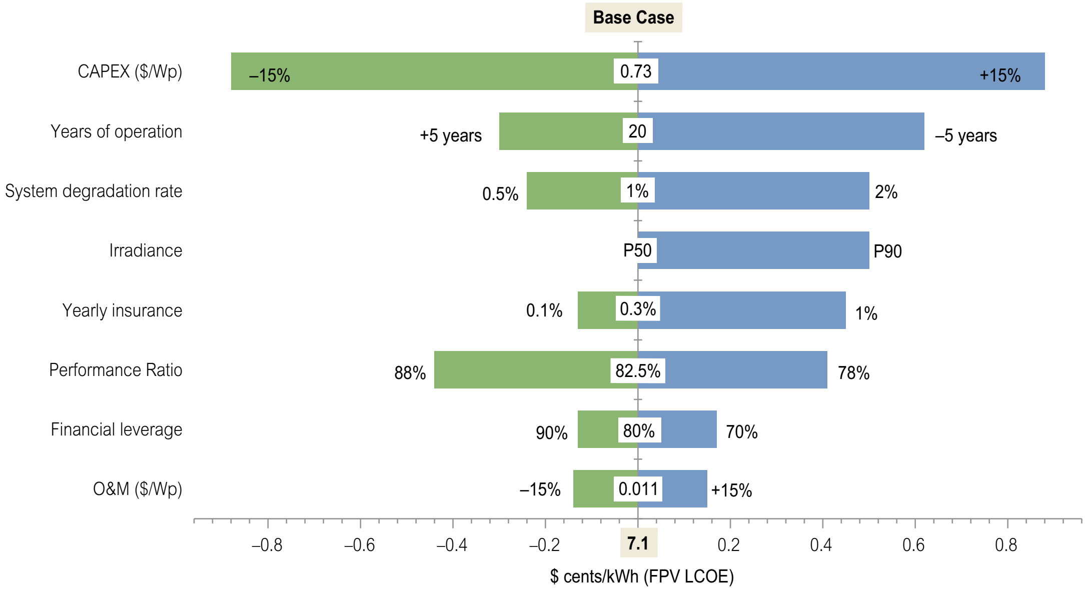
When performing sensitivity analysis, reduced CAPEX (-15 percent) and a higher performance ratio (88 percent) will have the highest positive impact on LCOE, as depicted in figure B.1. A 2 percent change in the WACC, even though not reflected in the figure but calculated in table B.5, will also have a significant impact on the LCOE, almost as important as a 15 percent change in CAPEX. This highlights the fact that concessionary financing from multinational lenders could boost FPV adoption.

TABLE B.5. Results of (before tax) calculations

LCOE ($cents/kWh)			Ground-mounted PV 50 MWp	Floating PV 50 MWp	
				Conservative (+5% PR)	Optimistic (+10% PR)
Tropical	WACC	6%	6.25	6.77	**6.47**
		8%	6.85	7.45	**7.11** base case
		10%	7.59	8.28	**7.91**
Arid/desert	WACC	6%	4.52	4.90	**4.68**
		8%	4.96	5.39	**5.15**
		10%	5.51	6.01	**5.74**
Temperate	WACC	6%	6.95	**7.53**	7.19
		8%	7.64	**8.30**	7.93
		10%	8.49	**9.26**	8.85

Source: World Bank Group, ESMAP, and SERIS 2019.
Notes: kWh = kilowatt-hour; LCOE = levelized cost of electricity; MWp = megawatt-peak; PV = photovoltaic; WACC = weighted average cost of capital. The bold LCOE values are the “more likely” cases per type of climate.

FIGURE B.1. Levelized cost of electricity sensitivities vs. base case



Source: World Bank Group, ESMAP, and SERIS 2019.
Note: CAPEX = capital expenditure; FPV = floating photovoltaic; LCOE = levelized cost of electricity; O&M = operations and maintenance; $/Wp = U.S. dollar per watt-peak; $ cents/kWh = U.S. dollar cents per kilowatt-hour.

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ANNEX C

NONEXHAUSTIVE LIST OF FPV SYSTEM SUPPLIERS AS OF DECEMBER 2018

Company name	Country of origin	Services offered				Location of completed FPV projects	FPV technology	Total FPV capacity installed (MWp)	Total FPV capacity under development/ construction (MWp)	Website
		(Co-) Owner	Turn-key EPC	O&M	Others					
MAJOR FPV SYSTEM SUPPLIERS (INSTALLED CAPACITY ≥ 5 MWp)										
Ciel & Terre International	France	●	◐	●	Floating system design and procurement	Worldwide	Specialized pure HDPE floats	319	330	https://www.ciel-et-terre.net/
Jintech New Energy	China	●	●	○	Floating system design and procurement	China	Specialized pure HDPE floats	150	80	http://www.jnnewenergy.com
Kyoraku Co.	Japan	○	◐	○	Floating system design and procurement, tracking	Japan, Taiwan, China, Thailand	Specialized pure HDPE floats	51	N/A	http://www.krk.co.jp/
LG CNS	Korea, Rep.	●	●	●	Floating system design and procurement	Korea, Rep.	Floating island + racks	6	80	http://lgcns.co.kr/
LS Industrial Systems Co.	Korea, Rep.	N/A	●	●	Floating system design and procurement	Korea, Rep., Japan	Floating island + racks	30	250	http://www.lsis.com/ko/
NorthMan Energy Technology	China	●	●	○	Floating system design and procurement	China	Specialized pure HDPE floats	230	N/A	https://netsolar.solarbe.com/
SCG Chemicals	Thailand	●	●	●	Floating system design and procurement	Thailand, Singapore	Specialized pure HDPE floats	5	N/A	https://www.scgchemicals.com/en
Scotra Co.	Korea, Rep.	N/A	●	●	Floating system design and procurement	Korea, Rep., Japan, Taiwan, China, Philippines	Floating island + racks	40.3	19.3**	http://www.scotra.co.kr/en/
Sumitomo Mitsui Construction Co.	Japan	●	●	●	Floating system design and procurement	Japan, Singapore, Thailand, Taiwan, China	Specialized pure HDPE floats	9.7	100	https://pv-float.com/english/
Sungrow	China	●	●	●	Floating system design and procurement, specialized platform for central inverters. Full turnkey	China, Germany, Israel, Japan, Philippines, Singapore, Thailand, Taiwan, China	Specialized pure HDPE floats	500	600	https://en.sungrowpower.com/product_category?id=22
Xiamen Mibet New Energy Co.	China	●	◐	●	Floating system design and procurement, float supplier, tracking	Brazil, China, Germany, Israel ,Japan, Southeast Asia, Spain, Taiwan, China,	Specialized pure HDPE floats	30	120	https://www.mbt-energy.com/

○ = No   ◐ = Limited support   ● = Yes   N/A = Not available

Company name	Country of origin	Services offered				Location of completed FPV projects	FPV technology	Total FPV capacity installed (MWp)	Total FPV capacity under development/ construction (MWp)	Website
		(Co-) Owner	Turn-key EPC	O&M	Others					
OTHER FPV SYSTEM SUPPLIERS (INSTALLED CAPACITY < 5 MWp)										
Floating Solar	Netherlands	N/A	●	●	Floating system design and procurement, tracking	N/A	Floating island (with pipes) + frames, optimal solar tracking	N/A	N/A	https://floatingsolar.nl/en
ISIGENERE	Spain	○	◐	◐	Floating system design and procurement	Spain, Chile	Specialized pure HDPE floats	1.9	50	https://isifloatingcom.wordpress.com/
Koiné Multimedia (Upsolar Floating)	Italy	○	●	○	Floating system design and procurement, tracking, concentration	Singapore, Italy, Korea, Rep.	Floating island (with pipes) + frames	0.4	N/A	http://www.koinemultimedia.eu/wp/
NRG Energia	Italy	○	●	●	Floating system design and procurement	Italy, Iran, France, India, Canaries Island	Floating island + racks	1	10	http://www.nrg-energia.it/index-en.html
Oceans of Energy	Netherlands	○	○	○	Floating system design and procurement, mooring systems	Netherlands	Offshore floating systems ***	N/A	N/A	https://oceansofenergy.blue/
Ocean Sun	Norway	○	●	○	Floating system design and procurement	Norway, Singapore	Floating island + membrane ***	0.1	2.2	http://oceansun.no/
ProFloating	Netherlands	○	◐	○	Floating system design and procurement	N/A	Specialized pure HDPE floats	N/A	N/A	https://profloating.eu/en/
4C Solar	USA	N/A	N/A	N/A	Floating system design and procurement, tracking	Singapore, Chile, Maldives	Floating island (with pipes) + frames, one-axis tracking + offshore	N/A	N/A	https://www.4csolar.com/
SolarisFloat	Portugal	N/A	N/A	N/A	Floating system design and procurement, tracking	N/A	Modular floating platforms with two-axis tracking ***	N/A	20	https://www.solarisfloat.com/

○ = No ◐ = Limited support ● = Yes N/A = Not available

Company name	Country of origin	Services offered				Location of completed FPV projects	FPV technology	Total FPV capacity installed (MWp)	Total FPV capacity under development/ construction (MWp)	Website
		(Co-) Owner	Turn-key EPC	O&M	Others					
OTHER FPV SYSTEM SUPPLIERS (INSTALLED CAPACITY < 5 MWp)										
Solaris Synergy	Israel	○	●	○	Floating system design and procurement, tracking	Israel, Singapore, USA	Special island design with HDPE floats + frames	1	50	http://www.solaris-synergy.com/
Sunengy	Australia	○	○	○	Floating system design and procurement	India	Plastic concentrators with tracking, mounted on rafts (Liquid Solar Array) ***	N/A	N/A	http://sunengy.com/
Sunfloat	Netherlands	N/A	N/A	N/A	Floating system design and procurement, tracking (bifacial)	Netherlands	Floating island (with pipes) + aluminum frames	N/A	N/A	http://www.sunfloat.com/
Sun Rise E&T Corporation	Taiwan, China	○	○	○	Floating system design and procurement	Japan	Floating island (with pipes) + frames	N/A	N/A	http://www.srise.com.tw/v2/
Swimsol	Austria	●	●	●	Floating system design and procurement, floating substructure supplier	Maldives	Offshore modular floating platforms ***	0.2	0.4	https://swimsol.com/
Takiron Engineering	Japan	N/A	N/A	N/A	Floating system design and procurement	Japan	Floating island + racks	N/A	N/A	https://www.takiron.co.jp/english/

○ = No ◐ = Limited support ● = Yes N/A = Not available

Source: World Bank Group, ESMAP, and SERIS 2019.

Notes: HPDE = high-density polyethylene. *O&M for own projects only. ** Under construction, excluding bidding projects. *** R&D or early stage of commercialization.

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