Floating PV systems – an overview of design considerations

System design | Floating solar has huge potential in areas where difficult terrain or land constraints make ground-mounted systems impractical. Gijo George and Pranav Patel of DNV GL explore some of the technical challenges in designing and building floating PV projects

Credit: Lightsource BP

Floating solar design and installation pose considerable technical challenges

DNV GL's 2018 Energy Transition Outlook forecasts that by 2050 solar photovoltaic (PV) will provide 40% of global electricity generation, corresponding to 19.1TW of global solar PV capacity [1]. We estimate that 70% of this PV capacity will be realised as ground-mount systems, which would require approximately 400,000 square km of land. Non-availability of land in some locations and multipurpose use of land could make land acquisition difficult for energy projects. Considering this, it is important to explore any potential technology application that:

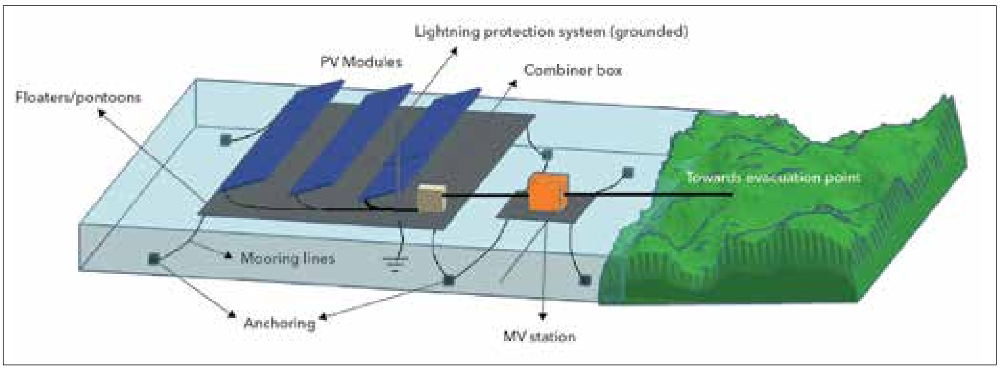
- Optimises existing man-made infrastructure and suitable natural resources;
- Improves water conservation;
- Increases renewable energy generation given the background of climate change and water shortage.

Floating solar PV projects (FSPs) can satisfy the above conditions by providing an alternative deployment option for PV modules, namely on bodies of water such as lakes, lagoons, reservoirs, ponds, canals, etc. As a relatively new concept that combines the intricacies of both solar and floating technologies, the specific deployment drivers of FSPs can find application when factors influencing a project might include:

- Densely populated countries
- Limited area for large-scale, ground-mounted PV
- Mountainous terrain compared to largely available water bodies
- Innovation-driven necessity
- Requirement for higher specific yields (kWh/kWp)
- A need to reduce water evaporation, especially in dry areas

Floating solar installations consist of floats/pontoons, module mounting structures, mooring system, PV modules, inverters, and balance of system (BOS) components. PV modules, which are the main components of FSPs, are mounted on top of floats, which are fundamentally buoyancy units used to keep the panels floating on the water surface. PV modules, which convert the incident solar irradiation into electricity, can be mounted either directly or in combination with frames on the floaters. A mooring system is used to keep the floats in place. The system is similar to a spring, where displacement of the floater from a neutral equilibrium position causes a restoring force to react to the applied loading. The choice of mooring system depends primarily on the location,

Representation of a floating solar plant




Floaters with module mounting structure

depth of water, geotechnical parameters and reservoir bed profile. Such mooring systems mainly consist of two components, namely the mooring lines and the anchoring mechanism. The direct current (DC) power generated by PV modules is converted to alternating current (AC) power by inverters. For small-scale floating plants close to shore, it is possible to place the inverters and BOS components on land. Otherwise, both central or string inverters can be installed on specially designed floats along with other BOS components.

Even though there are several advantages of using FSP installations, there are also several challenges in using this technology, which should be assessed on a case-by case-basis. These installations are vulnerable to storms, waves, currents, etc. that could adversely affect the life of the plant. Such dynamic loads can result in floats getting overturned during adverse weather events, or the increase in motion can induce stresses on the mounting structure.

Unlike ground-mounted systems, the environmental dynamic loads in FSPs result in higher fatigue loads that need to be addressed in the design of physical connections. Floats that are connected to the mooring lines experience higher forces, and floats on the periphery need to be designed for possible impact loads as well. Mooring systems should be configured such that the lateral movement and rotation of the plant is minimal, while allowing for variation in water level. This means that the mooring lines should neither be too tight nor too slack. Finding the right balance between the two can be very challenging, especially if the water level variation expected at the site is significant.

FSP installations have additional challenges due to their local environment. For example, there is an increased risk of corrosion and hence a possible reduction in the design life. Inverters and BOS components are exposed to high humidity environments and movements due to the waves. Preventive measures ensuring that the chosen equipment has an adequate ingress protection (IP) rating and has undergone environmental tests for the saline marine conditions should be taken into consideration during the design and installation stages. Additional safety measures that address risks related to the use of electrical equipment in such environments should be put in place as well. Depending on the design and site constraints, installation and maintenance costs may be higher relative to onshore PV plants. Furthermore, environmental impacts should be taken into consideration. For example, by preventing the penetration of sunlight into the water, these installations have the potential to affect the aquatic life and biodiversity of the site.

The design of FSPs can be a long and complex process. Each of the components in a floating solar system faces a plethora of challenges, some of which are discussed above. In addition to these challenges, understanding the interactions between components is essential for a stable system design. The external design parameters including environmental conditions that influence the system design will vary between different sites. As a result, preparing a universal solution might not be feasible and each project will need to be dealt with on a case-by-case basis. Although challenges in FSPs are different from conventional ground-mounted or rooftop solar projects, similar challenges have been encountered in other fields such as maritime, oil & gas, and offshore wind projects, where floating systems are used based on proven technical grounds. Hence, parallels can be drawn from these fields and adapted for the FSP application. The FSP design process broadly includes following activities:

Site surveys

Site surveys should include bathymetry, geotechnical investigation, hydrology study, metocean study and collection of historical data. These surveys should be conducted as a preliminary step to arrive at the baseline for the environmental and climatic conditions that the FSP will need to be designed for. *Bathymetry* is the study of underwater depth of lake or ocean floors and helps to map the reservoir bed. *Geotechnical investigations* need to be undertaken to understand the stratigraphy, engineering properties, behaviour and composition of the soil. *Hydrology* is the study of flow and storage of water in the environment, which provides valuable insights on expected variation of water level as well as water flow. The combined wind, wave, current and other climatic conditions that are prevalent in the site are called the 'metocean' characteristics of the site. A *metocean study* where these characteristics are monitored can help arrive at appropriate design values for wind, temperature, humidity, water level variations, storm surges, seiches, wave parameters and water currents. Historical data, whenever available, should be used to supplement and validate the data obtained from site.

Environmental conditions

FSPs need to be designed for different environmental conditions such as wind, wave, currents and water level variations. The design environmental conditions can be established from site surveys and historical data.

Similar to ground-mounted solar systems, the site-specific wind condition is one of the prominent environmental conditions that govern the design of FSPs. The wind acting on the system generates suction, pressure and drag forces on the system's components. The varying nature of wind also generates dynamic loads on FSPs.

Waves generated in waterbodies can interact with FSPs, and the motion induced by waves will generate inertial forces on the system. In addition, the varying nature of waves results in dynamic loads on the structure, similar to wind loads in FSPs and in traditional ground-mount systems. Wave heights can vary from a few centimetres to a few metres depending on various site conditions. The properties and behaviour of the waves are typically influenced by the size, shape and depth of the waterbodies, the wind velocities and the fetch distance. Thus, the effect of waves can be negligible for small waterbodies of shallow depth compared to large deep reservoirs with long fetch distances. The different wind wave models available can be used to predict the waves, which can be validated from a combination of the metocean study and historical data. The output of the models will be a spectrum of waves with a significant wave height and characteristic time period.

Water level variation and water currents are also of significance in the design of FSPs. The hydrology study in combination with metocean data, historical data and reservoir design criteria can be used to determine their effects.

Loads and load combinations

The different components in FSPs are exposed to diverse load types, which arise due to the normal operation and local environmental conditions. Components should be designed for probable combinations of these loads.

Similar to any other structure, FSPs should also be designed for dead and live loads acting on it. Dead loads are the permanent loads acting on the system such as the self-weight of the components and weight of the panels etc. Live loads are the variable and dynamic loads that are expected to act on the system, primarily during normal operation of the floating solar plant.

Winds can generate dynamic effects such as vortex shedding on the structure. Studies on utility-scale ground-mounted solar panels systems have shown that the dynamic loads can be several times the normal loads; and a similar phenomenon can be expected for floating solar projects, depending on the type, configuration and material choices for the system. The presence of wind will also have a significant impact on the cyclic loads applied to the floaters.

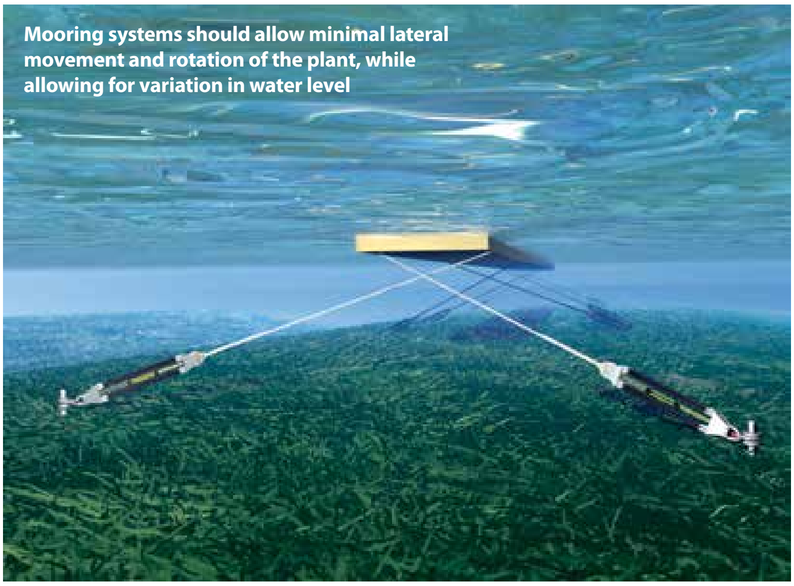
Stresses can be developed in FSP components due to the action of waves. The submerged components will be subjected to lateral forces due to the motion of water whereas the floating components experience vertical and horizontal motion, which will induce internal forces on the floaters. The cyclic nature of waves can result in dynamic loads on the structure, modules, inverters and BOS as well.

Waves generated in inland waterbodies are generally due to the action of wind, and hence maximum wave loads can act simultaneously with maximum wind loads. In addition, the simultaneous actions of wind and waves can lead to complex behaviour of the floating system, which can only be determined if the wind and wave phenomena are simulated simultaneously.

Currents prevalent in reservoirs can apply a lateral load or drag force on the structure. Large submerged components can also develop dynamic loads on the structure due to vortex shedding caused by the flow of water past a non-streamlined body. The variation of current near the surface and bed of water bodies can create additional forces and combinations.

In addition to the loads listed above, construction-related loads such as forces applied on the system when the FSP is tugged to the location of installation, and accidental loads such as the impact of a vessel onto the floating system or impact on the system due to a loss of buoyancy of random modular floats should also be considered in the design.

FSP systems should be designed in a way to perform adequately even under the worst possible situation envisaged during the design life of the project. This is generally achieved by designing for a combination of loads. Load combinations should consider the strength and serviceability conditions of the system – the design should be performed not only for different load combinations, but also for different configurations and boundary conditions that the system can adopt. For example, inclination angles of mooring lines will change as the water level changes, and hence should be designed for extreme water levels (i.e. lowest and highest water levels) as well as for intermediate water levels. Similarly, boundary conditions of the system during operation can be different from the boundary conditions during construction or maintenance phase. Directional variations of loads should also be considered in the design.



Mooring systems should allow minimal lateral movement and rotation of the plant, while allowing for variation in water level

Credit: Seaflex

Materials and durability

Materials used in FSP system components should be selected to satisfy the structural and functional requirements for the entire lifecycle. In addition, selected materials should also satisfy requirements related to degradation, environmental stress cracking, UV stabilisation, exposure to water, salinity, humidity, algae growth, toxicity, impact on ecosystem biodiversity and end-of-life recycling aspects.

Analysis and design

The analysis and design of any system is an iterative process, where the effect of external actions (loads) on the system and the resultant response (reactions) are studied to provide a solution that satisfies the functional safety and durability requirements. Being a relatively new field of engineering, there are very limited standards that can be directly used for analysis and design of FSPs. However, parallels can be drawn from several mature and established fields such as offshore oil & gas, offshore wind, coastal engineering, onshore solar and so on.

FSPs can be subjected to several different loads which can also be dynamic in nature. The different components within floating systems will also interact with one another. These characteristics of a floating solar project make it a highly complex system that is inherently nonlinear and dynamic. The choice of method for analysis and design will depend on the type of structure, complexity of the system and level of accuracy required.

Simplified methods such as equivalent static analysis can be used to arrive at approximate solutions for these complex problems, but an effect such as vortex shedding cannot be captured in these methods. Advanced computer-aided design techniques such as finite element method (FEM) and computational fluid dynamics (CFD) that use mathematical models of the systems to simulate their behaviour can give much more accurate results. However, these methods are often computation-, time- and cost-intensive.

FEM and CFD can also be used to simulate complex phenomena such as simultaneous interaction of wind and waves with FSPs, which might not be possible to simulate in a (scaled) model testing due to physical constraints. (Scaled) model tests such as atmospheric boundary layer wind tunnel testing and wave pool testing can be used to study the effect of the structure under different wind and wave flow regimes. They can provide very accurate values for force coefficients and dynamic behaviour when performed adequately and coupled with modal analysis and a dynamic sensitivity study. The design of the components can also be performed with the help of testing (design assisted by testing) where the test results are compared with design requirements established using the methods described above. These test results can also be used to validate the results obtained from CFD and FEM.

Installation & maintenance

As FSPs need to remain in operation as per the specified time horizon for each project, proper installation and maintenance is required. The layout of the FSPs needs to be such that it is easy to install components in a safe manner with minimal impact on the environment. Care needs to be taken to avoid permanent damage to the land and environment during construction activities on the shore. Precautions need to be taken to ensure the safety of personnel and to avoid any incidents, particularly considering the specialised requirements for installation (e.g. divers working underwater for a prolonged time). Power plants should be designed and installed taking into account ease of maintenance, accessibility and replaceability of the components. End-of-life disassembly and removal of the plant parts should be possible with minimal impact on the environment.

Energy simulations

It is necessary to assess the yield of FSPs, to check the feasibility and profitability of each project. There is a huge range of energy gains reported up to 25%, compared to ground-mount or rooftop systems. Thus, it is necessary to understand the water body and its thermal behaviour along with the type of floating systems used for realistic energy estimates for FSPs. PV modules are rated at standard test conditions, which is $1,000W/m^2$, 25°C and air mass 1.5. The module generation is reduced whenever the module surface temperature is above 25°C and vice versa. Due to cooler air temperature over water surface during the day, this can lead to lower temperature loss compared to a ground-mount system.

In one study, the capacity utilisation factor (CUF) of two floating plants of 100kW and 500kW installed in the same reservoir as well as an overland PV system of 1MW, which was 60km away, were compared [3]. The gains in CUF reported were 13.5% and 10.3% for the 100kW and 500kW systems, respectively. However, a direct CUF comparison is not suitable here as there would be different Global Horizontal Irradiation (GHI), different plane of array gains due to difference in the diffuse component, site specific shading loss and different system losses for the two systems. In another study conducted by the Solar Energy Research Institute of Singapore (SERIS) [3], eight floating systems were compared to one another, and an additional system with a rooftop reference system was installed on a building just next to the water body. It was concluded from the study that the performance ratio varied across different floating systems, and on average the best performing floating systems were similar to the rooftop reference system of the test bed. It was noted, however, that the floating systems studied had roughly 5-10% gain in performance ratio compared to a typical rooftop system installed in Singapore; though again it is not suitable to make generic comparisons, given the detailed aspects that contribute to the performance of any given system.

The quantum of energy gain depends upon the size of water body, type of floaters used, system layout (extent of coverage of the water surface), location of the system on the water body, module tilt angle and pitch distance between module rows. The increase in generation due to improvement in efficiency could be offset by lower than optimal tilt angle of the floaters, changes in orientation due to movement of the floating system, increased mismatch losses, soiling losses depending on the location of the installation and system availability due to issues with components, improper installation, faults, response time, etc.

Mitigation of adverse effects is possible through a properly conducted site survey, design methodology and selection of components suitable for the location and application. ■

References

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