Offshore floating solar – a technical perspective

Offshore PV | With floating solar on lakes and reservoirs well on the way to becoming a mainstream concept, attention is now turning to the possibilities offered by offshore systems. Børge Bjørneklett describes some of the pioneering R&D work being undertaken in the race to take solar to the open seas

Over recent years floating solar has rapidly emerged as a new frontier for photovoltaic systems. In areas with limited space on land, the possibility of floating solar on lakes and reservoirs opens up vast possibilities. The use of floating solar on hydro power reservoirs is particularly interesting. Here the grid infrastructure is readily available and facilitates an interplay between solar and hydro power. The potential energy in the reservoir can be utilised much better. The predictable output from the water turbine fits well with the inherent intermittency of solar power. A floating solar system will also limit evaporation from the reservoir. Although this new hydro power and solar hybrid market is huge by itself, the application area is still limited on a global basis, restricted to regions with favourable topology and water catchment.

In large power consumer areas as in the big cities, rooftop solar is an attractive solution. The technique is well established over decades. The drawbacks are more related to limited surface for large installations, ownership and competition with other good initiatives such as rooftop gardens or terraces. Rooftop PV installations are also sometimes subject to poor airflow, which causes relatively high operating temperatures in the modules and subsequently low yield. Soiling by smog is another potential problem in cities with high pollution.

Ocean Sun pilot system in the fjord next to the Osterøy island, Norway. Offshore PV offers further opportunities in the floating solar segment

Most of the world's mega cities are located along the coast lines. Historically they evolved at trading centres with good harbour conditions, in bays, river deltas or in between archipelagos offering sheltered waters for the trading ships. Despite today's busy ship lanes, recreation areas, aquaculture and fisheries, huge surface areas in coastal regions are virtually unused. If this space can be exploited for floating solar power, transmission of power to major consumer groups is shorter than for most land-based installations.

Arguably, the most attractive sites for utility-sized PV plants have already been taken. Ground-mount PV installations on farmable land are controversial and banned in many countries. Consequently, the search is widened to more desolate areas further from the grid. The penalty for remote power plants is poor transmission infrastructure and consequent high costs for power delivery over long distances. Hence, with the ever-increasing manufacturing capacity and high output of solar modules, installers need to find new surfaces. A cost effective and reliable method for installing PV on water bodies will create a new era for solar power. Potentially, huge population groups can be given access to abundant renewable energy.

Offshore solar is in many ways different from offshore wind power. The best conditions for wind power are found some distance offshore in regions with steady winds. The visual impact is strong with turbines towering up to 200 meters high, potentially interrupting scenic ocean views. On the other hand, floating solar is essentially flat and less invasive since systems would drop below the horizon at relatively shorter distances. With near proximity to consumers the transmission cost for solar power is a lot cheaper than offshore wind power.

If various floating PV designs struggle to achieve necessary bankability and conformance to established standards, the notion of offshore floating solar is even more challenging. The larger waves and saltwater add considerable technical difficulties. Albeit the sound scepticism, Ocean Sun has tested prototypes in Norway and Singapore with satisfactory results. It is absolutely within reach to install large floating PV plants on seawater. The practical results from Ocean Sun's testing of the new patented concept look promising.

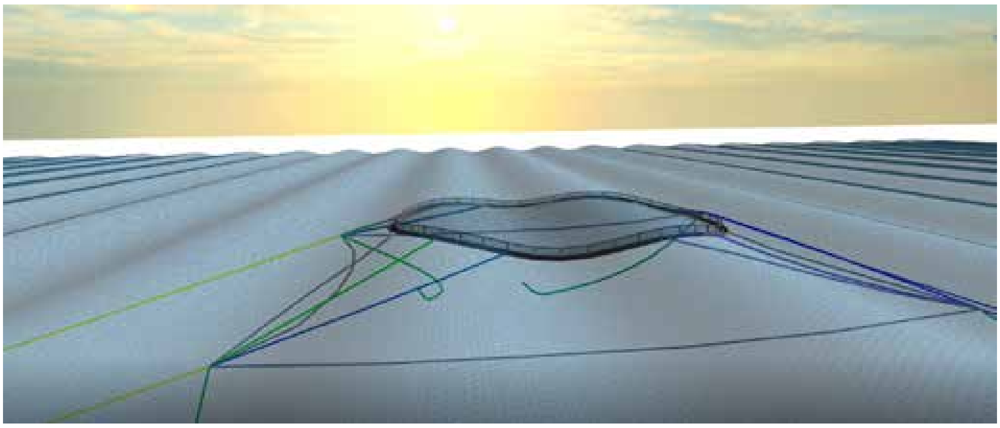

Figure 1. Computer model of floating torus with surface membrane

The floater architecture

The PV industry is notoriously driven by cost. Hence, to move to the water surface, a successful floater design must use minimal amount of material, have good robustness and offer a protective environment for the solar modules.

Attempting to address all parameters, Ocean Sun designs floaters consisting of thin reinforced membranes suspended in a buoyant double torus structure. The membrane is fully hydroelastic and prevents breaking of waves underneath the structure. The effect is not unlike the well-known phenomenon of oil on troubled water. Historically, the method was widely used among seafarers to dampen rough waves during rescue operations, or when navigating treacherous straits in severe weather. A reinforced polymer membrane spread out on the water can achieve much of the same effect. The sea is calmed and only the regular waves, typically with longer wavelengths travel across the membrane. Such hydroelastic membranes can be made large and can serve as an ideal surface area for solar modules. Practical experience has shown that the floating membrane offers a good and safe working environment for installers and the modules can be securely attached at high speed. The hydroelastic design is also found in nature among aquatic plants relying on photosynthesis. The giant water lily, Victoria Amazonica, is a good example.

For most floating PV systems, the buoyancy is distributed uniformly, supporting one or several PV modules, typically by using individual polymer buoys that are interconnected, either directly linked or via rails. This design is flexible, but the motions are concentrated to the connections between the individual buoys, making these points vulnerable to stress, wear and fatigue.

When dealing with strong current, at sea, on rivers or on hydroelectric reservoirs, it is favourable to position the buoyancy at the perimeter of the floater. Otherwise, the system is more easily dragged under by the mooring arrangement in strong currents. In the Ocean Sun design, the dual torus provides buoyancy and the interior membrane serves as the installation surface for the modules.

The principle has been tested in the basin laboratory at the Marine Technology Centre in Trondheim, Norway. The sea-keeping capabilities were tested for a range of wave conditions using a 1:16 model of a 2,000 sqm membrane. Due to the high flexibility, the membrane easily follows even several meters high waves and dampens out irregular wave motion. The design limitations for the model were found at the freeboard, which must prevent intrusion of irregular waves washing over the system. A relatively large freeboard is necessary in big waves and a porous structure must be designed to prevent high slamming forces. However, without further design modification, the model worked well for a significant wave height up to 1.5 meters. Statistically, in this sea state individual waves may reach a height of about 3 meters.

The mooring system is derived from fish farming and follows the rather stringent NS9415 standard. This standard has been developed to prevent ecological disasters following mechanical failure and the potential escape of up to 200,000 salmon from a single fish cage. For a floating torus with a fish cage, the mass and particularly the drag forces are significantly higher than for the floating solar installation with only the surface membrane. In a hydrodynamic analysis of the floating solar installation, the mooring forces were found to be only a fraction of the forces acting on a torus equipped with a fish cage. Further work on hydrodynamic modelling, using the finite element method, has been initiated to downsize the system optimally for FPV in more benign waters. Careful material selection of durable polymers with good UV and hydrolysis resistance is crucial for the robustness and longevity.

In many regions, strong winds represent a major challenge for floating solar, particularly in the typhoon belt where wind speeds can approach 300km/h. Cases have been reported where floating solar arrays have been partially damaged in typhoons, e.g. at the Umenoki Furugori Water Reservoir, Japan, where 152 modules were damaged in 2016.

In a computational fluid dynamic model, the Ocean Sun design was simulated with a wind speed of 275km/h. At a strong wind force, the leading edge of the floater experiences uplift while the trailing edge is pressed downwards. The forces are primarily generated by the wind load on the freeboard and the exposed torus over the waterline. It is, however, relatively easy to account for the uplift in the ballast and mooring arrangement. A certain draft must be maintained at the rim of the floater to prevent air from entering under the membrane. Due to the rotational behaviour of typhoons, the wind successively attacks from all directions and the circular floater geometry is then ideal with no weak broadsides or vulnerable corners.

Module integrity

In the basin test (Figure 2), the membrane was equipped with 740 modules modelled to scale in the form of thin aluminium shims. Several modules were instrumented with strain gauges to measure the deflection. The stiffness of the modules was scaled to match the stiffness of the common dual-glass 60-cell utility module. The degree of deflection is important for the mechanical integrity of the modules and the potential hazard of micro-fracturing of solar cells. The micro-cracking phenomenon is typically characterised under electroluminescence of solar modules and can be a major contributor to reduced power output over time, as fractions of cells eventually become isolated. Micro-cracking of cells may occur due to strong wind, snow load or e.g. careless stepping on the front glass on frame mounted modules. In the basin laboratory tests, the modules showed small deflections on the floating membrane and significantly less than the deflection that can be observed during e.g. wind load testing according to IEC 61215. The maximum up-scaled stress value in the modules for the steepest wave travelling across the membrane was much less than the bending stress limit calculated from the standard wind load test. The stress distribution in modules lying flat on the flexible membrane is fundamentally different, and less critical than the stress concentrations that can occur with typical four-point clamping fixation on conventional rails.

Figure 2: Laboratory basin model

Figure 3. Fish farm outside Singapore with floating solar installations

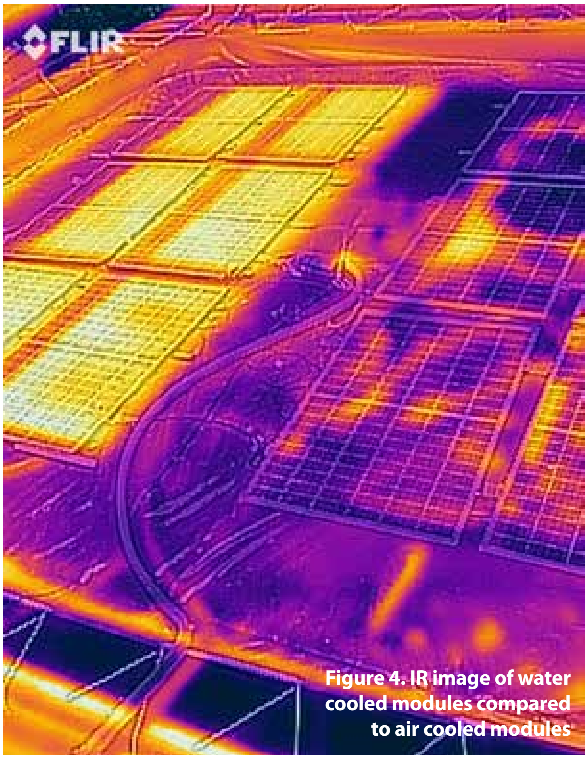

Figure 4. IR image of water cooled modules compared to air cooled modules

Another degradation mechanism in solar modules is the thermally induced stress caused by temperature fluctuations between day and night. The metallic busbars soldered onto the solar cells have a high coefficient of linear thermal expansion while the silicon material itself is more thermally stable. When subjected to high temperature differences this cause a sheer force between busbar and the cell, potentially adding to the micro-cracking. This problem is avoided in the Ocean Sun design since the solar modules are thermally connected to the membrane and the water body itself, resulting in small temperature variation between day and night in the module.

Water will accumulate on the surface of the membrane during rain. The water is removed by small bilge pumps that are placed in shallow recesses, evenly distributed around the surface of the membrane. In very heavy rain the modules can be partially submerged for short periods and the dual glass type module offers good resistance to water ingress. Additional water ingress protection and measures against PID can be achieved with e.g. butyl rubber lining or other sealants along the module edges protecting the exposed EVA. The environment is not necessarily more challenging than for example rooftop modules covered by ice and snow. Junction boxes should be IP68.

Module performance

An important aspect of the Ocean Sun concept is the thermal coupling to the water that gives a significant contribution to the electrical performance of the modules. The floating membrane acts as an efficient heat sink and several tests have shown that the module operating temperature only reaches a few degrees Celsius higher than the water temperature. For crystalline silicon solar modules, the temperature coefficient is typically around 0.4% per degree Celsius. In a pilot installation outside Singapore, the air-cooled modules reach well over 600C on an average day, while the direct water-cooled modules sitting on the membrane operate at 35^{0}C, only a few degrees over the water temperature of 32^{0}C. See Figures 3 and 4. The difference of around 25 degrees means that direct cooling gives roughly 10% higher output compared to modules in conventional air-cooled floating PV systems.

In the lower latitudes, the effect of the direct water-cooling contributes more than having the perfect module inclination. At higher latitudes, the loss caused by the horizontal orientation becomes more pronounced. The pivot-point is not simply given by latitude but also involves insolation, water temperature, wind speed, ambient air temperature and to some extent water current. In practice, floating solar installations with steep module inclination face other problems with expensive structural design, limited wind resistance and shading effects between modules causing inefficient utilisation of the floater space.

Pilot installations

Ocean Sun has tested the concept of floating membranes in several installations. System size has ranged from a few modules tested in swimming pools and up to a 100kWp installation in the sea outside Bergen, Norway. The first moored installation was positioned in the fjord next to Osterøy island in Norway (see main image). The floater has been in operation for 1.5 years and has been subjected to several storms, precipitation of up to 110mm in one day, minus 10^{0}C with ice on the fjord and heavy snow fall.

While Norway offers varied conditions for testing the seaworthiness and mechanical integrity of floating solar system designs the insolation is moderate and very limited during the winter. To better demonstrate the cooling effect through the membrane, a system was installed close to equator in Singapore.

Several large fish farms in Norway obtain power from diesel generators. Energy consumption is mainly driven by pneumatic feeding systems delivering pellets for salmon or trout. The fish only eat during daylight and consequently the energy demand fits well with solar power. An off-grid 2,000sqm floater was installed next to the main barge (see Figure 5).

Figure 5. Off-grid installation powering a large fish farm at the west coast of Norway

Commercialisation

Ocean Sun has plans for even larger units in the MW range (see Figure 6), and multiple units will form large solar power plants. However, floating solar power has a long way to go before reaching the technical maturity of the ground mount installation. Competing floater designs make standardisation and certification more complex and the marine environment places new demands on the solar modules.

Introducing the flexible membrane as a mounting surface for the standard dual- glass module is highly unconventional. Still, the principle offers a sound thermal and mechanical environment which in many aspects is better than traditional installations. The low cost of the floater combined with the increased yield obtained by stable and effective cooling is difficult to ignore.

New floating solutions will rock the boat in the established PV industry, and the prospect of supplying cheap renewable energy to coastal regions will drive development of new standards and certificates, eventually creating a fundament for bankable systems. Meanwhile, the pioneers in the FPV industry are prepared to take initial higher risk.

Author

Børge Bjørneklett is co-founder of Ocean Sun and the inventor of a new floating solar concept. Børge has experience with R&D from the automotive (Norsk Hydro), solar (REC Solar) and offshore O&G (Aker) industries. Børge has a doctorate degree in materials science from NTNU. He has authored 10 patents.

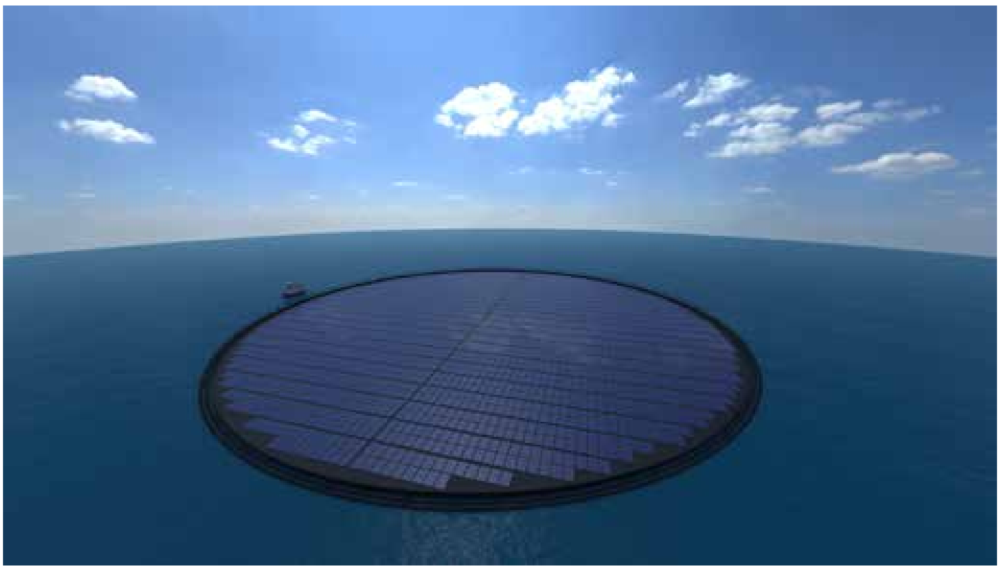

Figure 6. Illustration of a 1MW floater with a diameter of 100 meters