Where Sun Meets Water

FLOATING SOLAR MARKET REPORT

EXECUTIVE SUMMARY

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

This report was researched and prepared by the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS), under contract from the World Bank, with inputs and editing from staff and consultants at the World Bank and the International Finance Corporation (IFC). The work was funded by the Energy Sector Management Assistance Program (ESMAP), Government of Denmark, and the World Bank, and also benefited from in-kind contributions from SERIS.

Attribution—Please cite the work as follows:
World Bank Group, ESMAP and SERIS. 2018. Where Sun Meets Water: Floating Solar Market Report—Executive Summary. Washington, DC: World Bank.

Front Cover: © SERIS
Back Cover: © Pixbee/EDP S.A.

Where Sun Meets Water

FLOATING SOLAR MARKET REPORT

EXECUTIVE SUMMARY

WORLD BANK GROUP
THE WORLD BANK | IFC International Finance Corporation

ESMAP
Energy Sector Management Assistance Program

SERIS
Solar Energy Research Institute of Singapore

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 (NUS), National Research Foundation (NRF) and the Singapore Economic Development Board (EDB). 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 EDB. 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

CHINA © Sungrow

EXECUTIVE SUMMARY
FLOATING SOLAR MARKET REPORT

Why floating solar?

Floating solar photovoltaic (PV) installations open up new opportunities for scaling up solar generating capacity, especially in countries with high population density and competing uses for available land. They have certain advantages over land-based systems, including utilization of existing electricity transmission infrastructure at hydropower sites, close proximity to demand centers (in the case of water supply reservoirs), and improved energy yield thanks to the cooling effects of water and the decreased presence of dust. The exact magnitude of these performance advantages has yet to be confirmed by larger installations, across multiple geographies, and over time, but in many cases they may outweigh any increase in capital cost.

The possibility of adding floating solar capacity to existing hydropower plants is of particular interest, especially in the case of large hydropower sites that can be flexibly operated. The solar capacity can be used to boost the energy yield of such assets and may also help to manage periods of low water availability by allowing the hydropower plant to operate in "peaking" rather than "baseload" mode. And the benefits go both ways: hydropower can smooth variable solar output by operating in a "load-following" mode. Floating solar may therefore be of particular interest where grids are weak, such as in Sub-Saharan Africa and parts of developing Asia.

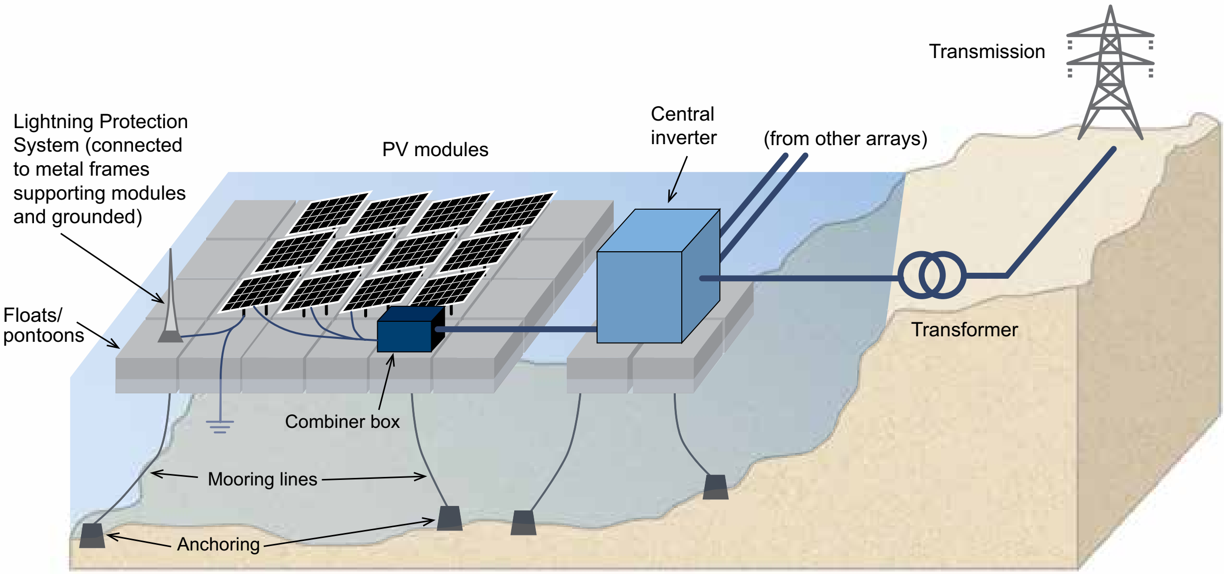
Other potential advantages of floating solar include:

- Reduced evaporation from water reservoirs, as the solar panels provide shade and limit the evaporative effects of wind
- Improvements in water quality, through decreased algae growth
- Reduction or elimination of the shading of panels by their surroundings
- Elimination of the need for major site preparation, such as leveling or the laying of foundations, which must be done for land-based installations
- Easy installation and deployment in sites with low anchoring and mooring requirements, with a high degree of modularity, leading to faster installations.

An overview of floating solar technology

The general layout of a floating PV system is similar to that of a land-based PV system, other than the fact that the PV arrays and often the inverters are mounted on a floating platform (figure 1). The direct current (DC) electricity generated by PV modules is gathered by combiner boxes and converted to alternating current (AC) by inverters. For small-scale floating plants close to shore, it is possible to place the inverters on land—that is, just a short distance from the array. Otherwise, both central or string inverters on specially designed floats are typically used. The platform, together with its anchoring and mooring system, is an integral part of any floating PV installation.

FIGURE 1 **Schematic representation of a typical large-scale floating PV system with its key components**



Source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS).

Currently most large-scale floating PV plants are deployed using pontoon-type floats, with PV panels mounted at a fixed tilt angle. Typically, the floating structure can be made of so-called pure floats or floats that are combined with metal trusses (figure 2). A pure float configuration uses specially designed self-buoyant bodies to which PV panels can be directly affixed. This configuration is the most common. It is available from several suppliers and claims an installed capacity worldwide of several hundred megawatts. Another type of design uses metal structures to support PV panels in a manner similar to land-based systems. These structures are fixed to pontoons whose only function is to provide buoyancy. In this case, there is no need for specially designed floats. 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.

The floating platform can generally be anchored to a bank, to the bottom, to piles, or to a combination of the three. The developer selects a design suitable to the platform's location, bathymetry (water profile and depth), soil conditions, and variation in water level. Bank anchoring is particularly suitable for small and shallow ponds, but most floating installations are anchored to the bottom. Regardless of the method, the anchor needs to be designed so as to keep the installation in place for 25 years or more. Mooring lines need to be properly selected to accommodate ambient stresses and variations in water level.

The current global market for floating solar

The first floating PV system was built in 2007 in Aichi, Japan, followed by several other countries, including France, Italy, the Republic of Korea, Spain, and the United States, all of which have tested small-scale systems for research and demonstration purposes. The first commercial installation was a 175 kWp system built at the Far Niente Winery in California in 2008. The system was floated atop a water reservoir to avoid occupying land better used for growing grapes.

Medium-to-large floating installations (larger than 1 MWp) began to emerge in 2013. After an initial wave of deployment concentrated in Japan, Korea, and the United States, the floating solar market spread to China (now the largest player), Australia, Brazil, Canada, France, India, Indonesia, Israel, Italy, Malaysia, Maldives, the Netherlands, Norway, Panama, Portugal, Singapore, Spain, Sweden, Sri Lanka, Switzerland, Taiwan, Thailand, Tunisia, Turkey, the United Kingdom, and Vietnam. Projects are under consideration or development in Afghanistan, Azerbaijan, Colombia, Ghana, and the Kyrgyz Republic, as well as other countries.

FIGURE 2 The most common float types: pure float (top) and pontoons with metal structures (bottom)

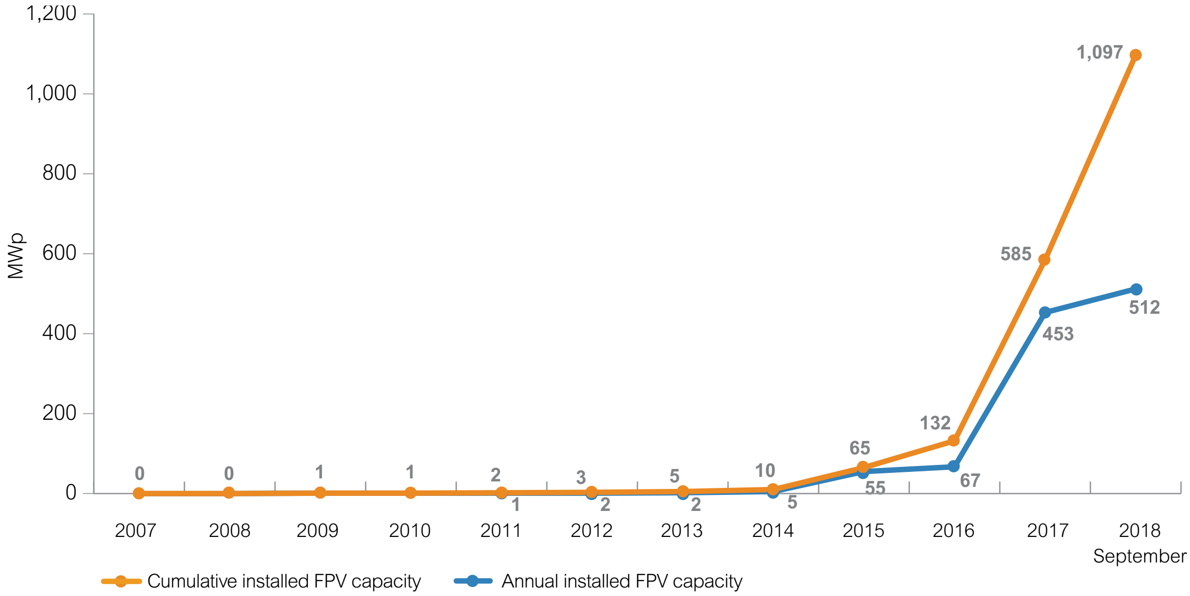
INDONESIA © Ciel & Terre International

INDIA © NB Institute for Rural Technology

Recently, plants with capacity of tens and even hundreds of megawatts have been installed in China; more are planned in India and Southeast Asia. The first plant larger than 10 MWp was installed in 2016, and in 2018 the world saw the first several plants larger than 100 MWp, the largest of which is 150 MWp. Flooded mining sites in China support most of the largest installations (box 1). With the emergence of these new markets, cumulative installed floating solar capacity and annual new additions are growing exponentially (figure 3).

As of mid-2018, the cumulative installed capacity of floating solar was approaching 1.1 gigawatt-peak (GWp), the same milestone that ground-mounted PV reached in the year 2000. If the evolution of land-based PV is any indication, floating solar could advance at least as rapidly, profiting as it does from

FIGURE 3 Global installed floating PV capacity



Source: Authors' compilation based on media releases and industry information.

BOX 1

China's collapsed coal mines turned into a solar opportunity

There are dozens of flooded coal mines in China. Spurred by China's "Top Runner" program, solar developers are turning these environmental and social disasters into an opportunity. Anhui Province is home to the world's largest floating solar installations to date, ranging from 20 megawatts (MW) to 150 MW per site.

Local people who just a few years ago worked underground as coal miners are now being retrained as solar panel assemblers and maintenance personnel. They are earning better wages and are no longer exposed to harmful mine conditions known to cause lung disease.

Producing solar power in mining regions while scaling back coal-based power production is one way to improve local air pollution issues in several regions of China.

Source: Authors' compilation based on Mason (2018) and BBC (2018).

all the decreases in costs attained by land-based PV deployment. Most of the installations to-date are based on industrial basins, drinking water reservoirs, or irrigation ponds (figure 4), but the first combinations with hydropower reservoirs, which bring the added benefits of better utilization of the existing transmission infrastructure and the opportunity to manage the solar variability through combined power output, have started to appear (box 2). In these installations, special attention needs to be paid to possible effects on the downstream flow regime from the reservoir, which is typically subject to restrictions related to water management (in case of cascading dams), agriculture, biodiversity, navigation, and livelihood or recreational uses.

FIGURE 4 Floating solar installations in Malaysia, and Japan

MALASIA © Ciel & Terre International

JAPAN © Ciel & Terre International

BOX 2

Hydropower-connected solar PV systems

The development of grid-connected hybrid systems that combine hydropower and floating photovoltaic (PV) technologies is still at an early stage. Only a small system of 218 kilowatt-peak (kWp) has been deployed in Portugal (see photo) (Trapani and Santafé 2015). But many projects, and of much greater magnitudes, are being discussed or developed across the world.

The largest hybrid hydro-PV system involves ground-mounted solar PV. This is the Longyangxia hydro-connected PV power plant in Qinghai, China (Qi 2014), which is striking for its sheer magnitude and may be considered a role model for future hybrid systems, both floating and land-based.

The Longyangxia hydropower plant was commissioned in 1989, with four turbines of 320 megawatts (MW) each, or 1,280 MW in total. It serves as the major load peaking and frequency regulation power plant in China's northwest power grid. The associated Gonghe solar plant is 30 kilometers (km) away from the Longyangxia hydropower plant. Its initial phase was built and commissioned in 2013 with a nameplate capacity of 320 megawatt-peak (MWp). An additional 530 MWp was completed in 2015.

The PV power plant is directly connected through a reserved 330 kilovolt (kV) transmission line to the Longyangxia hydropower substation. The hybrid system is operated so that the energy generation of the hydro and PV components complement each other (Choi and Lee 2013). After the PV plant was added, the grid operator began to issue a higher power dispatch set point during the day. As expected, on a typical day the output from the hydro facility is now reduced, especially from 11 a.m. to 4 p.m., when PV generation is high. The saved energy is then requested by the operator to be used during early morning and late-night hours. Although the daily generation pattern of the hydropower has changed, the daily reservoir water balance could be maintained at the same level as before to also meet the water requirements of other downstream reservoirs. All power generated by the hybrid system is fully absorbed by the grid, without any curtailment. This system shows that hydro turbines can provide adequate response as demand and PV output varies.

Source: Authors' compilation based on Trapani and Santafé (2015); Qi (2014); and Choi and Lee (2013).

First-ever hydropower-connected floating solar operation, Montalegre, Portugal

PORTUGAL

Marine installations are also appearing. The deployment of floating solar technologies near shore may be of strong interest to populous coastal cities. Indeed, it may be the only viable way for small island states to generate clean solar power at scale, given the limited availability of land suitable for ground-mounted PV installations.

Still at a nascent stage, near-shore solar PV is conceptually similar to deployment on inland water bodies. But the offshore environment poses additional challenges:

- Water surface conditions are much rougher (larger waves and higher winds)
- Mooring and anchoring become even more critical amid large tidal movements and currents
- Salinity tests the durability of components
- The accumulation of organisms on equipment ("bio fouling") can interfere with functionality.

The harsh near-shore environment imposes stringent requirements on floats, anchors, moorings, and components. Alternative design and technological solutions may be required, drawing on the rich experience of existing marine and offshore industries. Compared to the open sea, coastal areas such as lagoons and bays are relatively calm and thus more suitable for floating PV, however, installations must still be able to withstand waves and high winds. On the other hand, some lagoons and bays can be environmentally sensitive, which may limit the possibility for floating solar deployment in certain areas.

The biggest uncertainties are long-term reliability and cost. Marine-grade materials and components are critical for these installations, which must withstand rough weather. Operation and maintenance costs for near-shore PV are also expected to be higher than for inland installations.

In the Maldives, near-shore solar PV is powering a tourist resort; in Norway, a large fish farm (figure 5). Future systems will likely fulfill needs that are additional to energy production, such as the generation of hydrogen or the solar-based desalination of water.

Policy and regulatory considerations

Currently, even in countries with significant floating solar development there are no clear, specific regulations on permitting and licensing of plants. Processes for the moment are assumed to be the same as for ground-mounted PV, but legal interpretation is needed in each country. In some countries, drinking water reservoirs or hydropower reservoirs are considered national-security sites, making permitting more complex and potentially protracted.

As highlighted in this report, floating solar deployment is expected to be cost-competitive under many circumstances and therefore not to require financial support. Nevertheless, initial projects may require some form of support to overcome barriers associated with the industry's relatively limited experience with this technology.

So far, a number of countries have taken different approaches to floating PV. Typical policies currently supporting floating solar installations can be grouped into two categories:

Financial incentives:

- Feed-in tariffs that are higher than those for ground-mounted PV (as in Taiwan, China)
- Extra bonuses for renewable energy certificates (as in the Republic of Korea)
- A high feed-in tariff for solar PV generally (as in Japan)
- Extra "adder" value for floating solar generation under the compensation rates of state incentives program (as in the U.S. state of Massachusetts).

Supportive governmental policies:

- Ambitious renewable energy targets (as in Korea and Taiwan)
- Realization of demonstrator plants (as in the Indian state of Kerala)

FIGURE 5 Near-shore floating installations in the Baa Atoll of the Maldives, and off the west coast of Norway

MALDIVES © Swimsol

NORWAY © Ocean Sun

- Dedicated tendering processes for floating solar (as in China, Taiwan, and the Indian state of Maharashtra)
- Openness on the part of the entities managing the water bodies, such as tenders for water-lease contracts (as in Korea).

However, for most countries hoping to develop a well-functioning floating solar segment of a wider solar PV market, the following policy and regulatory considerations need to be addressed:

- Unique aspects of permitting and licensing that necessitate interagency cooperation between energy and water authorities. This also includes environmental impact assessments for floating PV installations.
- Water rights and permits to install and operate a floating solar plant on the surface of a water body and anchor it in or next to the reservoir.
- Tariff setting for floating solar installations (which could be done as for land-based PV, for example, through feed-in tariffs for small installations and tenders or auctions for large ones).
- Access to existing transmission infrastructure:
  - How will this be managed?
  - Who will be responsible?
  - What permits/agreements will be required?
- Special considerations for hydro-connected plants:
  - Whether the hydropower plant owner/operator is allowed to add a floating solar installation
  - Whether the hydropower plant owner/operator is allowed to provide a concession to a third party to build, own, and operate a floating solar plant
  - Management of risks and liabilities related to hydropower plant operation and weather events that can affect the solar or hydropower plants
  - Rules of dispatch coordination of the solar and the hydropower plants' outputs.

Market opportunities

There are more than 400,000 square kilometers (km^2) of man-made reservoirs in the world (Shiklomanov 1993), suggesting that floating solar has a theoretical potential on a terawatt scale, purely from the perspective of the available surface area. The most conservative estimate of floating solar's overall global potential based on available man-made water surfaces exceeds 400 GWp, which is equal to the 2017 cumulative installed PV capacity globally. Table 1 provides a summary of the man-made freshwater bodies supporting this very

TABLE 1. Peak capacity and energy generation potential of floating solar on freshwater man-made reservoirs, by continent

Continent	Total surface area available (km^2)	Number of water bodies assessed	Floating PV potential (GWp) — Percentage of total surface area used: 1%	5%	10%	Possible annual energy generation (GWh/year) — Percentage of total surface area used: 1%	5%	10%
Africa	101,130	724	101	506	1,011	167,165	835,824	1,671,648
Middle East and Asia	115,621	2,041	116	578	1,156	128,691	643,456	1,286,911
Europe	20,424	1,082	20	102	204	19,574	97,868	195,736
North America	126,017	2,248	126	630	1,260	140,815	704,076	1,408,153
Australia and Oceania	4,991	254	5	25	50	6,713	33,565	67,131
South America	36,271	299	36	181	363	58,151	290,753	581,507
Total	**404,454**	**6,648**	**404**	**2,022**	**4,044**	**521,109**	**2,605,542**	**5,211,086**

Source: SERIS calculations based on the Global Solar Atlas and Lehner et al. (2011a, 2011b).
Note: GWh = gigawatt-hour; GWp = gigawatt-peak; km^2 = square kilometers; PV = photovoltaic.

conservative estimate. Considering global irradiance data on significant water bodies, and assuming 1 percent to 10 percent of their total surface area as used for floating solar deployment, an estimate of potential peak capacity was derived using the efficiency levels of currently available PV modules and the surface area needed for their installation, operation, and maintenance. Then, to estimate potential electricity generation, the capacity estimate was multiplied by the expected specific energy yield, with local irradiance used alongside a conservative assumption of an 80 percent performance ratio. These estimates use very low ratio of coverage of the reservoir. In reality, many existing projects implemented on industrial or irrigation reservoirs cover much more significant portions of the reservoirs, after environmental studies confirm no expected impact on the aquatic life in the reservoirs. The situation from one reservoir to another can differ significantly, however.

There are individual dams on each continent that could theoretically accommodate hundreds of megawatts or, in some cases, gigawatts of floating solar installations. Examples of such reservoirs are provided in table 2. While hydropower and solar capacity do not provide the same type of power production (solar typically has a lower capacity factor and generates variable power), the table compares the surface needed for a PV plant having the same peak capacity as the hydropower reservoir.

Costs of floating solar and project structuring

Capital costs

The capital costs of floating PV are still slightly higher or comparable to those of ground-mounted PV, owing chiefly to the need for floats, moorings, and more resilient electrical components. The cost of floats is expected to drop over time, however, owing to better economies of scale.

Total capital expenditures for turnkey floating PV installations in 2018 generally range between USD 0.8–1.2 per Wp (figure 6), depending on the location of the project, the depth of the water body, variations in that depth, and the size of the system. China is the only country that has yet built installations of tens to hundreds of megawatt-peak in size. The costs of smaller systems in other regions could vary significantly.

As reflected in figure 6, Japan remains a region with relatively high system prices, while China and India achieve much lower prices, a pattern that can also be seen in ground-mounted and rooftop solar systems when compared to the global average.

TABLE 2. Reservoir size and estimated power generation capacity of selected hydropower dams, and potential of floating PV to match the dams' hydropower capacity

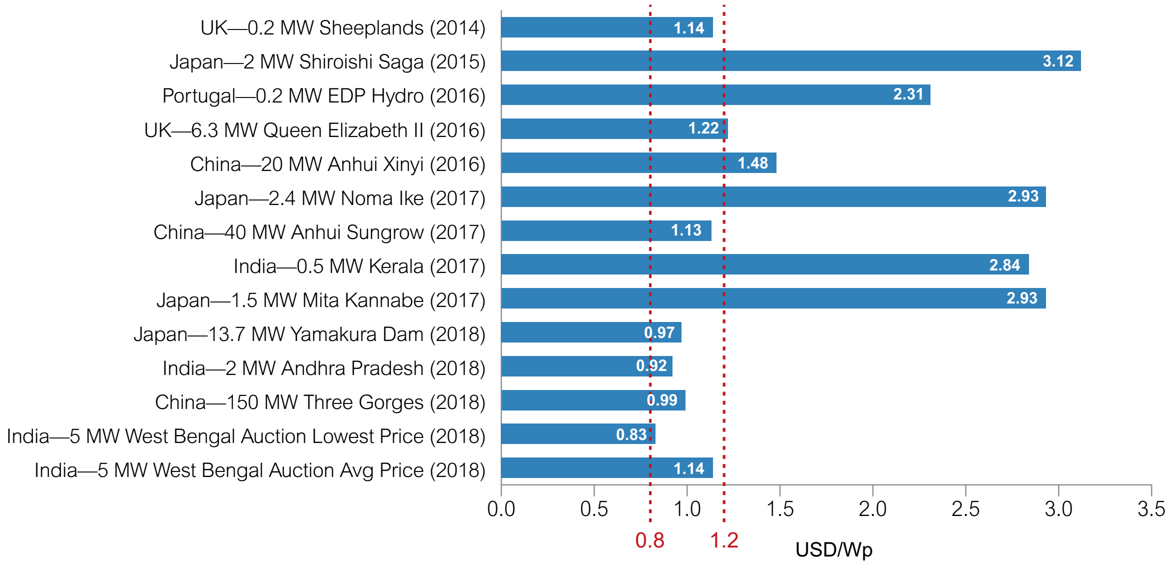
Dam/reservoir	Country	Reservoir size (km^2)	Hydropower (GW)	Percentage of reservoir area required for floating solar to match dam's hydropower capacity (%)
Bakun Dam	Malaysia	690	2.4	3
Lake Volta	Ghana	8,500	1.0	<1
Guri Dam	Venezuela	4,250	10.2	2
Sobradinho "Lake"	Brazil	4,220	1.0	<1
Aswan Dam	Egypt	5,000	2.0	<1
Attaturk Lake and Dam	Turkey	820	2.4	3
Narmada Dam	India	375	1.5	4

Source: Authors' compilation.
Note: GW = gigawatt; km^2 = square kilometer; PV = photovoltaic

JAPAN

© Sungrow

FIGURE 6 **Investment costs of floating PV in 2014–2018 (realized and auction results)**



Source: Authors' compilation based on media releases and industry information.
Note: Using the 2017 USD annual exchange rates, as released by OECD. PV = photovoltaic; USD/Wp = U.S. dollars per watt-peak.

Levelized costs of electricity, including sensitivity analysis

Calculated on a pretax basis, the levelized cost of electricity (LCOE) for a generic 50 MW floating PV system does not differ significantly from that of a ground-mounted system. The higher initial capital expenditures of the floating system are balanced by a higher expected energy yield—conservatively estimated at 5 percent, but potentially as high as 10–15 percent in hot climates. This result holds at a range of discount rates, as shown in table 3. Both projects have the same theoretical financial assumptions and irradiance. However, the main differentiating factors are system price (a floating system is considered 18 percent more expensive), insurance costs (0.4 percent of the floating system price vs. 0.3 percent for ground-mounted systems), and performance ratios (5 percent higher for floating systems).

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.[1] Equity investors would presumably require a higher tariff from the off-taker to make the project economically viable for them, assuming debt financing was accessible.

If the performance ratio of a floating solar project is assumed to be 10 percent higher than that of a ground-based project (instead of 5 percent), a sensitivity analysis shows that the LCOE for the base case decreases to USD 5.3 cents per kWh, almost equivalent to the LCOE of the ground-mounted PV project.

Project structuring

To understand how floating solar projects are typically financed, it is useful to classify them into two main categories: those with an installed capacity of 5 MWp or lower, and and those with an installed capacity greater than 5 MWp. Table 4 summarizes typical financial structures for these categories, which are similar to financial structures for land-based PV deployment. To gain trust in the technology, public grants are often

1. The discounted payback period is 20 years, and the equity internal rate of return is set at the discount rate.

TABLE 3. Comparing the levelized cost of electricity from a 50 MWp floating with that from a ground-based PV system

	Ground-mounted PV (fixed tilt)	Floating PV (fixed tilt)
Electricity produced (first year), GWh *Increase in performance from ground-mounted fixed tilt*	75.8	79.6 *5%*
LCOE (U.S. cents/kWh)		
at 7% discount rate (base case)	5.0	5.6
at 8% discount rate	5.2	5.7
at 10% discount rate	5.4	6.0

Source: Authors' compilation.
Note: GWh = gigawatt-hour; kWh = kilowatt-hour; LCOE = levelized cost of electricity; MWp = megawatt-peak; PV = photovoltaic.

TABLE 4. Financing structure vs. size of floating solar system

System size (MWp)	Business model	Ownership	Financing structure
≤ 5	Self-generation	Commercial and industrial companies	Pure equity and/or corporate financing (or "on balance sheet" financing). Owner would typically be an energy-intensive commercial or industrial company with ponds, lakes, or reservoirs on its premises and willing to install a floating solar system for its own use.
> 5	Power sold to the grid	Independent power producers and public utilities	Mix of debt and equity (typically 80:20); on balance sheet or non-recourse project finance. The latter is still rare, however, because such project finance structures make sense only for projects of a certain size (generally larger than 10 MWp). Future large projects will likely have financing structures similar to the ones used for utility-scale ground-mounted PV projects.

Source: Authors' compilation.

provided to finance R&D and pilot projects (<1 MWp), which are often run by universities or public research institutions.

Given their small size (except in China), most floating solar projects are financed in local currencies and mainly by local or regional banks. Japan, Taiwan, and a few other areas have seen an increased involvement of local commercial banks seeking to take advantage of favorable long-term feed-in tariffs available for floating solar. The involvement of large international commercial banks, and of multilateral development finance institutions in developing countries, is expected to grow as larger projects become more common in areas outside China.

Challenges

While enough large-scale projects have been implemented to permit floating solar technology to be considered commercially viable, there are remaining challenges to its deployment—among them the lack of a robust track record; uncertainty surrounding costs; uncertainty about predicting 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). The experience of other technologies operating in aquatic environments, including near-shore environments, offers good lessons in the last of these areas.

HONG KONG, SAR CHINA

ed to permitting and commercial aspects include: a lack of clarity on licensing/permitting (especially concerning water rights and environmental impact assessment); difficulties in selecting qualified suppliers and contractors; difficulties in designing insurance policies that include liabilities for potential damage of the hydro plant; and uncertainties about the adequacy of warranties of the performance or reliability of critical components. In most countries, the policy and regulatory framework needs to be adjusted to provide more clarity in some of these areas.

Conclusions and next steps

The deployment of floating solar looks set to accelerate as the technologies mature, opening up a new frontier in the global expansion of renewable energy and bringing opportunities to a wide range of countries and markets. With a global potential of 400 GW under very conservative assumptions, floating solar could double the existing installed capacity of solar PV but without the land acquisition that is required for ground-mounted installations. At some large hydropower plants, covering just 3-4% of the reservoir with floating solar could double the installed capacity, potentially allowing water resources to be more strategically managed by utilizing the solar output during the day. Additionally, combining the dispatch of solar and hydropower could be used to smooth the variability of the solar output, while making better use of existing transmission assets, and this could be particularly beneficial in countries where grids are weak.

When combined with other demonstrated benefits such as higher energy yield, reduced evaporation, and improved water quality, floating solar is likely to be an attractive option for many countries. Although the market is still nascent, there are a sufficient number of experienced suppliers to structure a competitive tender and get a commercial project financed and constructed, and the additional costs appear to be low and are falling rapidly.

The priority over the next few years should be to carry out strategic deployments of floating solar at sites where it is already economic, while applying the "precautionary principle" when it comes to possible environmental or social impacts. This may include initial limits on the portion of the water surface that is covered and efforts to avoid installations in the littoral zone near shore, where plant and animal life may be more abundant. In addition, 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 floating solar over those of ground-mounted systems, makes early installations in developing countries a strong candidate for concessional climate financing.

To support market development, an active dialogue among all stakeholders, public and private, is required to further global understanding of floating solar technologies and to spread lessons learned from early projects across a wider area. Through this market report and an upcoming handbook for practitioners, the World Bank Group and SERIS hope to contribute to this goal, and we look forward to working with governments, developers, and the research community to expand the market for floating solar by bringing down costs, supporting grid integration, maximizing ancillary benefits, and minimizing negative environmental or social impacts.

In addition to the financing of public and private investments, the World Bank Group is committed to supporting the development of floating solar as well as hydro-connected solar by generating and disseminating knowledge. Publications and tools planned for the *Where Sun Meets Water* series are:

- A floating solar market report
- A floating solar handbook for practitioners
- Global mapping of floating solar potential (a geospatial tool)
- Proposed technical designs and project structuring for hydro-connected solar.

REFERENCES

BBC (British Broadcasting Corporation). 2018. "Solar Farm Means 'I Can Breathe More Easily.'" Video story, BBC News, April 24. https://www.bbc.co.uk/news/av/business-43881280/solar-farm-means-i-can-breathe-more-easily.

Choi, Y.-K., and N.-H. Lee. 2013. "Empirical Research on the Efficiency of Floating PV Systems Compared with Overland PV Systems." CES-CUBE 25: 284–89.

Global Solar Atlas: https://globalsolaratlas.info/

Lehner, B., C. Reidy Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J. C. Robertson, R. Rodel, N. Sindorf, and D. Wisser. 2011a. "Global Reservoir and Dam Database, Version 1 (GRanDv1): Reservoirs, v1.01." NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY. http://sedac.ciesin.columbia.edu/data/set/grand-v1-reservoirs-rev01.

———. 2011b. "High-Resolution Mapping of the World's Reservoirs and Dams for Sustainable River-Flow Management." *Frontiers in Ecology and the Environment* 9: 494–502.

Mason, Pauline. 2018. "Meet the Ex-Miners Who Are Now Walking on Water." BBC News, April 27. https://www.bbc.co.uk/news/business-43864665.

Qi, S. 2014. *The Analysis of Complementation in PV Grid-Connected Part of Longyangxia 320 MWp, in Engineering.* Xi'an: University of Technology.

Shiklomanov, Igor A. 1993. "World Fresh Water Resources." In *Water in Crisis: A Guide to the World's Fresh Water Resources,* edited by Peter H. Gleick. New York: Oxford University Press.

Sungrow: https://en.sungrowpower.com/reference?id=22&ref_cate_id=30.

Swimsol: https://swimsol.com/.

Trapani, K., and M. Redón Santafé. 2015. "A Review of Floating Photovoltaic Installations: 2007–2013." *Progress in Photovoltaics: Research and Applications* 23 (4): 524–32.

UNITED STATES

Funding gratefully acknowledged from

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

ESMAP
Energy Sector Management Assistance Program

MINISTRY OF FOREIGN AFFAIRS OF DENMARK