TKI WIND OP ZEE
Topsector Energie

Challenges and potential for offshore solar

By TNO (Wim Soppe, Aldo Kingma, Martijn Hoogeland, Ruud vd Brink, Jan Kroon, Wiep Folkerts)

1 February 2022

Disclaimer

This report was commissioned by RVO (Netherlands Enterprise Agency) on the request of the TKI Wind op Zee (TKI Offshore Wind). The opinions expressed in this report are entirely those of the authors (TNO) and do not reflect the views of the TKI Wind op Zee. TKI Wind op Zee is not liable for the accuracy of the information provided or responsible for any use of the content.

Table of contents

Introduction

The Dutch top sectors strengthen the economy through innovations that target to help solving important societal challenges such as the energy transition. In this approach the societal and economic goals go hand in hand.
Recently this has substantiated in so called mission-driven innovation. For the energy transition 13 multi-annual mission-oriented innovation programs (MMIP’s) have been formulated.

MMIP 1, titled “Renewable electricity at sea”, has the goal to contribute to the mission A: a CO2-free electricity system in 2050. For this, a massive upscaling of renewable electricity generation is needed, which has to start as soon as possible.
That upscaling leads to a number of serious challenges. The MMIP1 focuses on addressing these challenges by innovation. This MMIP is part of the IKIA (Integral Knowledge and Innovation Agenda), which is part of the Dutch Climate Agreement.

The TKI Wind op Zee supports the Top Sector Energy on shaping and execution of MMIP 1. The TKI WIND OP ZEE stimulates, connects, and supports Dutch enterprises and knowledge institutes in the development and application of innovations for a rapid transition to a sustainable, reliable, and affordable energy system centred around the massive upscaling of offshore wind energy. The TKI Wind op Zee is a member of the core team that develops the MMIP 1 and keeps it up to date.

The past few years there is an increasing attention for the development of offshore floating solar. The technology has a very large power generation potential when applied in the Dutch Exclusive Economic Zone (EEZ), in particular in the areas used by offshore wind farms.
In some scenarios 45 GWp solar power in the Dutch part of the North Sea has been projected in 2050[1]. The most important underlying reasons are:

- Insufficient suitable and available area and network congestion for the generation of sustainable energy on land and inland water;
- Decline of societal support for the generation of sustainable energy on land and inland water;
- Potential benefits related to the combined application of solar energy and wind energy on the same area (complementarity, connection capacity).

In the Routekaart Zon op Water[2], sent to parliament by the Minister of Economic Affairs and Climate Policy in 2021, also a number of relevant challenges concerning this technology are discussed. The Routekaart concludes that in 10 - 12 years large scale application of offshore solar on the North Sea could offer possibilities, but it also expresses major concerns about the technical and economic challenges of offshore floating solar systems.

---

[1] Wiep Folkerts et al, Roadmap PV systemen en toepassingen, SEAC december 2017.

[2] Brief aan de Tweede Kamer,van minister B. van ’t Wout; 2 februari 2021

There are substantial technological challenges to build and operate floating solar systems in a harsh maritime environment, with wave heights up to 15 m. Significant innovation in this field by commercial enterprises will only be undertaken if there is enough perspective for a profitable business case in a large market. This is only possible if technical problems are likely to be solved, and costs can be decreased considerably.

Nevertheless, several companies (especially in the Netherlands and Norway) started investing in system developments that may lead to feasible and affordable solutions for offshore solar. Some smaller scale pilots have been established or planned.

At the same time, there are major challenges on system design, O&M schemes, grid connection and cost.
For the further development of the MMIP1, the TKI WIND OP ZEE needs a further analysis of the challenges related to offshore floating solar. RVO approached TNO to deliver an initial analysis for this.

TNO Energy Transition is leading in innovation for floating solar. In 2016 TNO together with Rijkswaterstaat initiated the National Consortium Floating Solar. This consortium organized several innovation projects in The Netherlands and built up an international network of organizations working on the topic.

Figure 1: Mail stamp of PostNL, indicating the public awareness of the potential of floating solar.

Among the projects were the first pilot on challenging inland water (i.e. De Slufter on the Maasvlakte) and a study on permit criteria for floating solar. Recently, TNO created a new field lab for floating solar at the Oostvoornse Meer. TNO works together with many companies on floating solar.

TNO Buildings, Infrastructure and Maritime addresses the technical challenges related to maritime and offshore structures and built a strong technology base in, amongst others, offshore wind and safety of novel maritime applications such as alternative fuels and crashworthiness of ship structures. Numerical and experimental analyses form the basis for long term reliability of structures.

This report is based on publicly available knowledge and on TNO insights. It does not contain information that has been received by TNO under a confidentiality agreement.

1 State of the art

Offshore floating PV is not a fully developed technology yet, but there are several concepts under development and the most important ones will be discussed in this chapter. In the wake of these developments, a few overview papers have recently been published and have served as additional source of information[3],[4].

1.1 System concepts

There are four major conceptual development directions at the moment according to TNO:

1.1.1 The pontoon concept

The pontoon concept is based on floating pontoons. The pontoons are substructures that are mechanically coupled into a massively modular structure. The complete floating structure is moored. Solar panels are mounted on the pontoons, and are positioned relatively close to the water level. The advantage is that the wind load on the panels and the structure is relatively low.

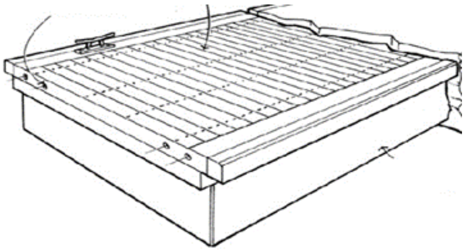


Figure 2: schematics of a floating pontoon.

1.1.2 The truss concept

A truss structure is equipped with floaters and mooring. A platform with solar panels is placed on the truss structure, supported by floating elements. The platform is located on a certain height above the waterline. Waves can move underneath the truss structure. The concept avoids the direct contact between (slamming) waves and the solar panels. This may lead to advantages compared to a pontoon concept: the mechanical load on the solar panels (because of waves) will be less, and the fouling of the solar panels due to sea water residues on the panel surfaces may be smaller.

---

[3] Sara Oliveira-Pinto, Jasper Stokkermans, Marine floating solar plants: an overview of potential, challenges and feasibility, Proceedings of the Institution of Civil Engineers – Maritime Engineering 173(4): 120–135

[4] Thi Thu Em Vo, Hyeyoung Ko, Junho Huh and Namje Park, Overview of Possibilities of Solar Floating Photovoltaic Systems in the OffShore Industry, Energies 2021, 14, 6988

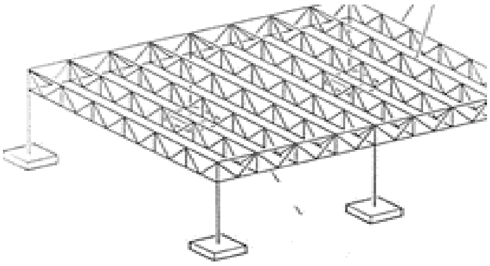


Figure 3: Schematics of a truss concept for floating solar

1.1.3 The fish farm concept.

The fish farm concept builds on experience from near shore fish farming. Especially in Norway there is expertise on this approach. A floating ring equipped with a membrane is moored. The solar panels are mounted on the membrane.

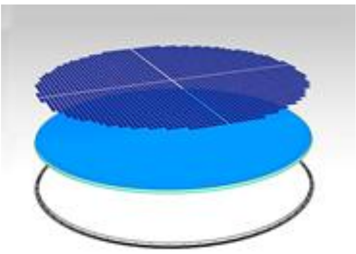


Figure 4: schematics of the fish farm concept.

1.1.4 The soft & flex concept.

The basic idea of the *soft & flex* concept is to let the floating structure move with the waves as much as possible. The transfer of mechanical energy from the waves to the structure will therefore be smaller, compared to for instance the pontoon concept, reducing mooring forces. This could lead to an advantage because the structure needs less strength and therefore achieve a lower cost structure. Solar panels are mounted on the floating body and must be able to follow the deformation of floater. During high waves part of the structure may be overflown. Being near the water surface, it is less sensitive to wind loads.

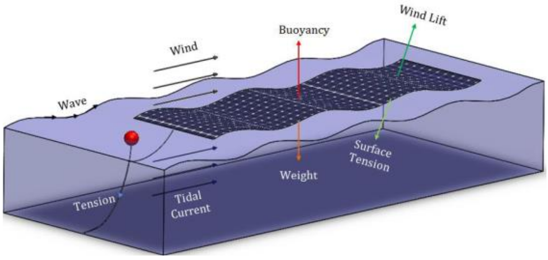


Figure 5: Schematics of a soft&flex concept and the forces that the structure experiences[5].

---

[5] K. Trapani, D. L. Millar, Hydrodynamic Overview Of Flexible Floating Thin Film PV Arrays, Conference Paper OSES 2016

1.2 Overview of offshore floating solar system developers in Europe

We have identified seven different solar system suppliers in Europe, which develop concepts for offshore application. Based on public information, we have estimated the nature and the technical matureness of the concept.

For the Technical Matureness of the concept, we use the following criteria:

TRL3 – scale model tests accomplished
TRL4 – full size in test basin (e.g., Marin) accomplished
TRL5 – pilot on open water, with island operation, accomplished
TRL6 – pilot on open water, grid connected, accomplished
TRL7 – demonstrator on open water, with proven reliability of at least one year.
TRL8 – market introduction accomplished with limited bankability
TRL9 – market introduction accomplished with full bankability

Further, we discriminate between two categories of wave exposure: “medium exposure” H_s=3m, H_{max}=6m” and “high exposure”: H_s=7m, H_{max}=14m, whereas “high exposure” is representative for the North Sea

System developer	Country	Concept	TRL medium exposure	TRL high exposure
Oceans of Energy	NL	Pontoon	5	4
Bluewater	NL	Soft&Flex	4	4
Solar Duck	NL	Truss	5	4
Tractebel-Engie	Belgium	Truss	4	4
Swimsol	Austria	Truss	8	n.a.
Moss Maritime	Norway	Pontoon	4	4
OceanSun	Norway	Fishfarm	8	5

Oceans of Energy

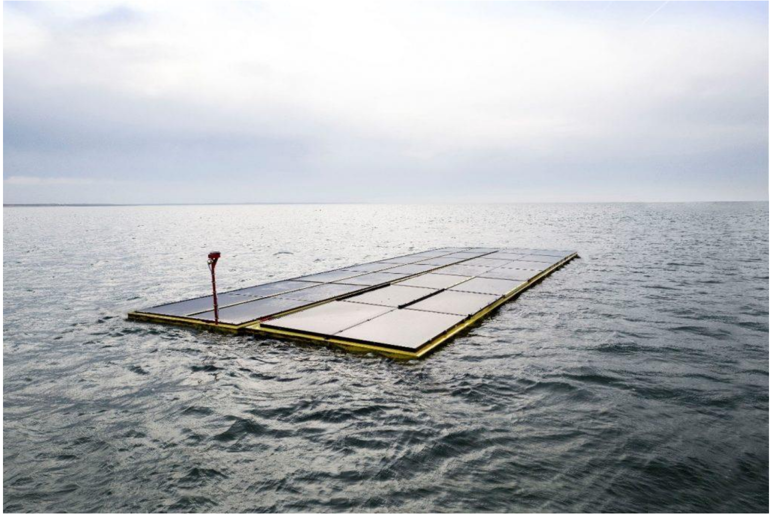


Figure 6: Pilot system of OoE near the Brouwersdam

The core of the concept developed by OoE is the construction of the pontoons and the connection between the pontoons[6]. The pontoons are shallow draught pontoons, and the solar panels are laid flat on the deck.
OoE has built and installed a small pilot near the Brouwersdam (see picture above) and will install a 1 MWp system in 2023 at the location Noordzeeboerderij, near Scheveningen, as part of a DEI project. In the EU project EU-SCORES, OoE will build and install a 3 MWp system near the Belgian coast. This system will be located in/ near an existing wind farm.

Bluewater

Figure 7: 20 kWp demo system of the Bluewater consortium in the Oostvoornse Meer

---

[6] Allard Pieter van Hoeken, “array of pontoons for solar panel and connection modules therefor”, NL patent NL2019956B1

The concept that is developed by Bluewater and partners is based on lightweight flexible floaters and PV modules (Soft&Flex concept). The first development steps were made in the TKI-Urban Energy project Solar@Sea. Further development took place in the project Solar@Sea-II, which has resulted in the installation of a 20 kWp system at the Fieldlab Oostvoornse Meer in November 2021. The concept is based on the usage of inflatable mattresses as floaters, waterbags as stabilizers and flexible thin film PV modules. Water basin tests have shown that these flexible and lightweight structures result in very low mooring forces, allowing a simple and low-cost mooring system. Bluewater has developed a dedicated underwater interconnection and mooring system for this concept.

SolarDuck

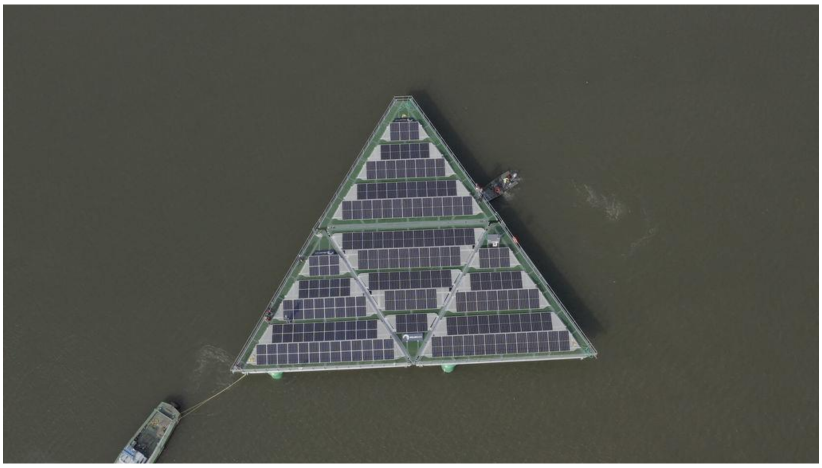


Figure 8: SolarDuck's floating solar demonstrator installed in IJzendoorn

SolarDuck is a spin-off of Damen Shipyards. The concept of SolarDuck is based on the usage of tri-angular shaped truss-like platforms, which float a few meters above the water on cylinders. The structure is made of aluminium. The PV modules are tilted mounted positioned in East-West direction. In the spring of 2021 a first pilot of four units was installed on the river Waal, near IJzendoorn. Plans for an offshore pilot of 500 kWp near Oostende are under development. Recently a MoU with project developer Pondera has been signed for the development of 555 MWp floating PV systems in South-east Asia[7].

---

[7] https://solarmagazine.nl/nieuws-zonne-energie/i25457/overeenkomst-pondera-en-solarduck-voor-555-megawattpiek-drijvende-zonnepanelen-op-zee

Tractebel-Engie

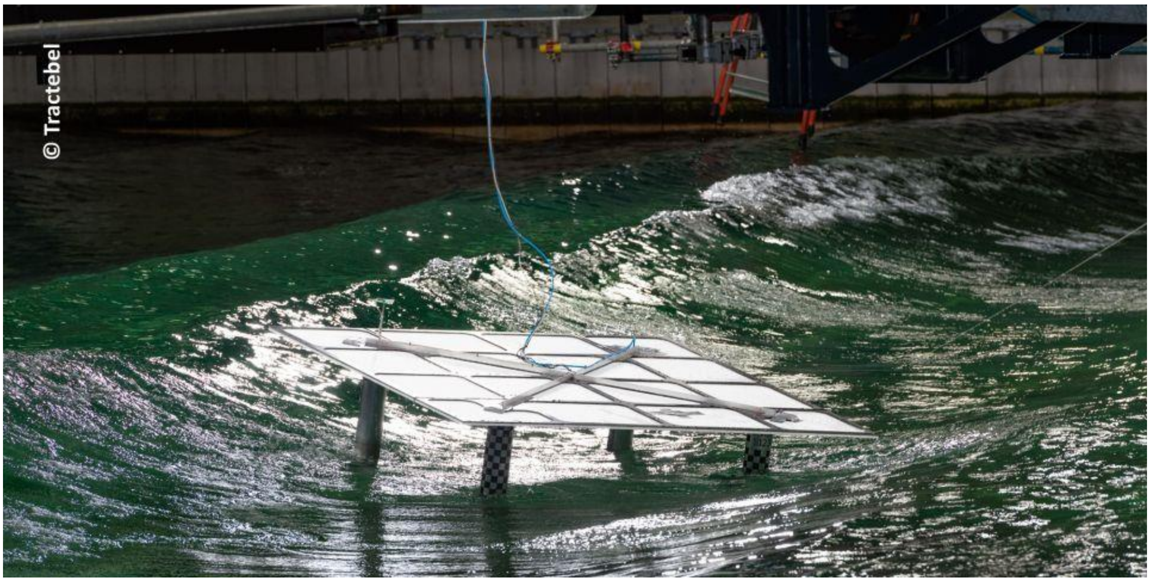


Figure 9: Scale model test of Tractebel system in a wave basin.

Tractebel-Engie is already for a longer time active in inland based floating PV systems. Recently they installed a 1 MWp system on an artificial lake Terhills Resort next to the Hoge Kempen National Park (Belgium). In 2020 they announced that they will develop the basic design of three floating PV arrays with 30 MW of capacity at the 52.2 MW Batalha hydropower project, which is owned by Brazilian state-run power company Eletrobras Furnas.

In 2019 a consortium of Tractebel, Jan De Nul Group, DEME, Soltech and Ghent University announced the launch of an innovative project in the field of marine floating solar technology. The consortium, led by Tractebel, was set up in the framework of the Flemish Blue Cluster and is strongly supported by VLAIO. Total budget is 2 M€, and the project should result by the end of 2021 in the installation of an offshore floating PV system (capacity unknown) near the port of Zeebrugge.
From the limited information, the concept qualifies as a truss concept, having an elevated deck and buoyancy elements.

Swimsol

Figure 10: Illustration of the Swimsol concept

Swimsol is an Austrian company, located in Vienna. It developed several floating PV systems for near-shore operation at the Maldives. It qualifies as a truss concept, although the solar panels are located near the water surface. For sheltered waters that is sufficient to avoid damage by wave slamming. Main application so far is to supply hotels on these islands with electricity, partly replacing the electricity from more expensive, noisy and polluting diesel generators. The concept of Swimsol is designed for low and medium wave exposures. Preparing the concept for high wave exposure, such as in the North Sea, would require a drastic re-engineering and the company has indicated that they do not have the ambition on the short term to do so.

Moss Maritime

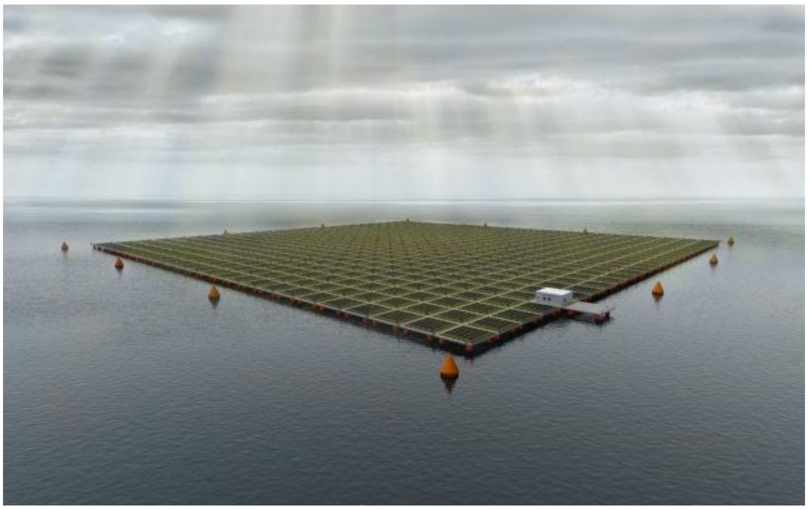


Figure 11: Artist impression of the Moss Maritime concept

Moss Maritime is a Norwegian engineering company and owned by the Italian EPC contractor Saipem. Moss Maritime is active in the offshore oil & gas and renewable energy sector. It has developed a concept based on 10x10 m^2 floating PV platforms. It is a truss concept, with square decks and cubic buoyancy elements. The units are connected in a flexible manner to larger systems. The flexible connections allow the system to adopt the surface to waves with long wavelengths.
Moss Maritime has conducted 1-13 scale model tests with 64 interconnected floaters in a wave basin at Sintef and is preparing a pilot floating power plant, together with Equinor This pilot will span 80 by 80 meters, and tower less than 3 meters over the sea surface[8].

OceanSun

OceanSun is also a Norwegian company. Their concept basically consists of a membrane that floats on the water and that is fixed by a large floating ring and follows therefore the fish farm concept.

Track record:

- two pilots in Norwegian fjords: 7 kWp Skafta; 100 kWp Kyrholmen
- one pilot 220 kWp at a hydropower plant on the Philippines

---

[8] https://www.offshore-energy.biz/sintef-ocean-on-point-for-moss-maritime-equinor-floating-solar-model/

- one pilot 2 MWp at a hydropower plant in Albania (with issues)
- one pilot planned/ committed near Canary Islands
- signed technology license agreement with Korea for minimum 100 MWp, intention 500 MWp
- September 2021: Ocean Sun has signed an agreement with Sunneng Technology for a 1 MWp FPV pilot in Yantai, China. The project is fully funded by String Capital.

Figure 12: Photographical impression of the OceanSun concept

1.3 Material aspects

The concepts described above are made of the readily available construction materials: Steel, Aluminium and Plastics. Plastics are mainly used for floating elements, and are single component, like High Density PE (HDPE). Composite materials, i.e. combination of fibres (Glass or Carbon) and a plastic (e.g. Vinylester or Epoxy) are not yet common. The material of the tarpaulins supporting the PV panels for the Fishfarm concept (OceanSun) are not known to the authors, but are most likely based on the tarpaulins as used to cover water basins (typically polyolefin). The materials choice for the Soft&Flex concept is not finalized yet.

Steel has the advantage of being readily available and commonly used, both in offshore and shipping and is very suitable for one-off structures. The challenge for Offshore Floating Solar is longevity. Steel needs to be protected against corrosion and fatigue damage. The floating structures are supposed to stay offshore for the design life of minimum 20-25 years and maintenance shall be minimised. Aluminum may be a solution to minimize weight and material loss due to corrosion, but is more prone to fatigue. Both metals can be re-used using common technologies. Plastics are considered light weight, but have challenges regarding recycling, aging and may cause pollution by small plastic particles. The benefit for plastics and composites come when you can make multiple products from the same mould, allowing low-cost mass production.

Most concepts are now in demonstrator phase, and longevity and cost are addressed in less detail. The demonstrators are great means to better understand the specific conditions on offshore floating PV installations and construction cost.

1.4 PV system components

PV panels are exposed to environmental loads specific to offshore conditions, such as impact by water and aging in salty conditions. As PV panels are composite structures, numerical and experimental assessments are both necessary to understand and predict the behaviour.

Power cables connecting the floating PV systems with a power hub are exposed to dynamic loads, and are therefore called dynamic cables. For stationary power generation installations, such as wind turbines, the motions are limited. However, for floating wind and solar the motions, are larger due to the motions of the floater itself (so-called excursions), but also due to the potential vortex induced vibrations (VIV), as studied in Cable JIP[9].

1.5 Design, structural integrity, construction, transportation and installation

All concepts mentioned in the first section have been tested in wave basins to validate the representative mechanical loads for which they are designed. Numerical analysis for multibody systems are established, but are not fully mature for all cases yet. This is especially true for concepts in which very elastic materials are used. Assemblies of pontoons and truss structures are more similar to existing offshore structures, however interaction of more than two, non-moving items are rarely studied. In wave basins scaled models are used, and with little full-scale experience, essential effects may be insufficiently covered.

The largest ships sailing today are about 400 m in length and 70 m wide. Floating offshore PV installations are supposed to be larger than that. This cannot be achieved as one floating unit in case of pontoon and truss type concepts. Hence, multiple floaters are to be assembled on site. Individual units could be constructed at shipyards and moved to the operation site to be assembled at that location. The logistics may be comparable to the installation of an offshore wind farm, but one specific difference is obvious: single PV floater elements need to be assembled to one large installation, while the (floating) wind generators are stand/ float alone units. Individual elements are to be optimised as individual unit, but also in its role in the construction and assembly.

1.6 Mooring aspects

The figure below shows a generic overview of various mooring concepts that are being used or proposed for offshore floating platforms[10]. This overview makes a distinction

---

[9] CABLE JIP joint industry project (CABLE JIP), Openbaar Eindrapport 2020, TKI Wind op Zee

[10] Josh Davidson and John V. Ringwood, Mathematical Modelling of Mooring Systems for Wave Energy Converters—A Review, Energies 2017

between Single Point Mooring (Taut, Catenary anchor leg mooring (CALM), and Single Anchor Leg Mooring (SALM)) and Spread Moorings: Catenary mooring, multi-catenary mooring, and taut spread mooring. Each concept has its specific advantages and disadvantages depending on the circumstances (water depth, tidal changes in water depth, water currents etc.

In addition, new mooring concepts are under development, fuelled by the needs of deployment of floating wind turbines[11].

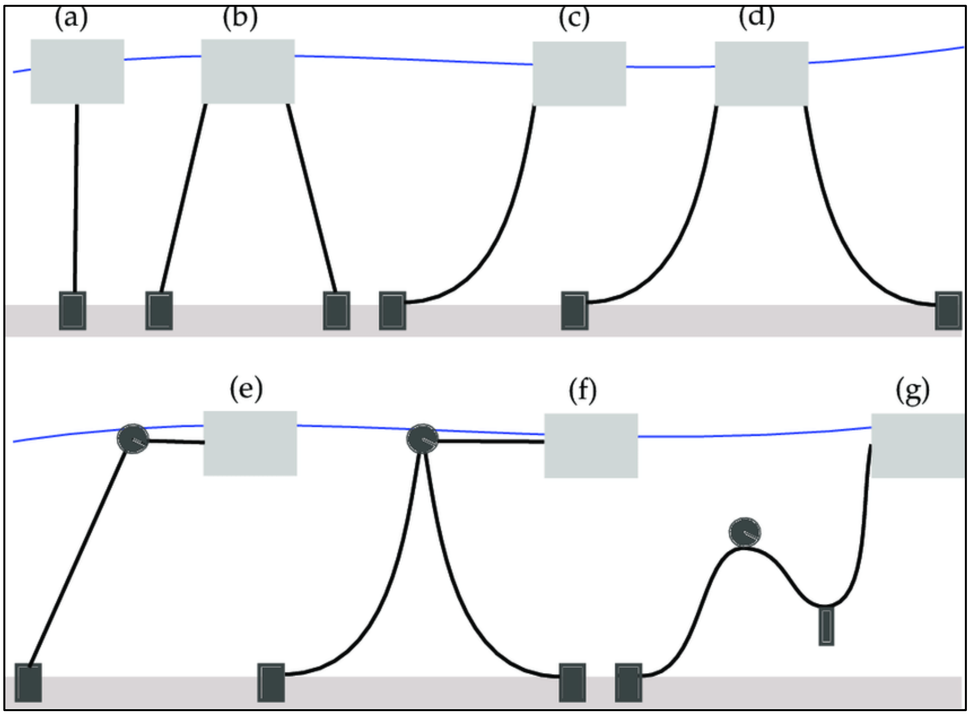


Figure 13: schematic overview of different mooring concepts: (a) Taut; (b) Taut spread; (c) Catenary (d) Multi-catenary; (e) SALM; (f) CALM; and (g) Lazy-S.

---

[11] https://www.energyglobal.com/special-reports/03112020/floating-wind-what-are-the-mooring-options/

1.7 PV system performance

The electricity production of the floating PV systems is determined by various parameters. The most important are:

Insolation

The insolation on the North Sea is quite similar to that of the coastal regions of the Netherlands. It is somewhat higher than the average insolation of the entire Dutch land area by about 4-8%[12].

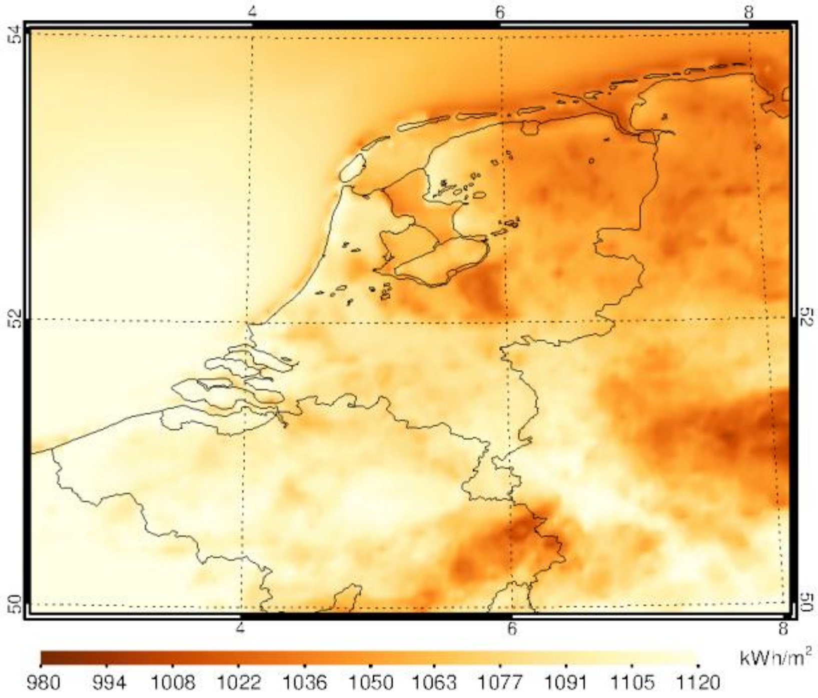


Figure 14: Irradiance levels based on satellite data in the period 2005-2017. Source: (Meirink, 2018)

Orientation of the PV modules

Ideally, the PV modules track the sun. This is particularly true for regions where the ratio between direct and diffuse sunlight irradiation over the year is high. Current tracking systems, however, are not suited for offshore conditions and it is questionable whether they can ever be made cost effective for these conditions.

For static systems the maximum annual production can be achieved when the PV panels are oriented towards the south and have a tilt angle that depends on the latitude of the location of the PV system (about 40 degrees for the Netherlands). However, to achieve a more even distribution of the production over the day, often an East-West orientation is chosen[13].

A tilt angle, however, also makes the PV system more vulnerable for wind. Many offshore PV concepts therefore have zero tilt angle. This leads to a much lower peak production at noon, but a larger production in the early morning and late afternoon partly compensates this. On an annual basis the flat orientation in the Netherlands leads to about 10% less annual power production than for an ideal tilt angle.

---

[12] Jan Fokke Meirink, Willem Koetse, Corné Oudshoorn, KNMI-activiteiten Zon Op Water, 2018

[13] Bas van Aken; Ashish Binani; Kay Cesar, TOWARDS NATURE INCLUSIVE EAST-WEST ORIENTATED SOLAR PARKS, TNO-2021-R11087

Land based systems can also make use of bi-facial solar modules to harvest sunlight from the rear side. This is an attractive option if the land on which the modules are mounted has a high albedo. The albedo of seawater, however, is very low. Under ideal conditions (no shadow effects of the mounting structures), the increase of the panel efficiency is between 3 and 12%[14]. Unless special provisions are made to increase the albedo of the floating structures, the usage of bi-facial PV modules for offshore applications may not be cost effective.

Temperature

The output voltage, and with that, the output power of PV modules decreases with increasing temperatures. Therefore, a cooling by wind or water could have a positive impact on the performance of offshore floating PV. The real cooling effect though is very much dependent on the construction and the materials usage of the floating structures on which the PV modules are mounted[15].

Effects of waves and movements

If the PV panels are mounted on flexible floaters or on floaters with length smaller than the length of the sea waves, the movement induced by wave-forces, makes that panels have different orientations. So it happens that the Maximum Power Point (MPP) of the individual panels within a string will vary, which can lead to mismatch losses and therefore to a reduced power production of the system. First model studies show that these losses can amount to up to about 7% for NorthSea conditions[16] for systems that use one floater per PV module. For structures holding a larger amount of PV modules, the effect is expected to be lower.

Soiling and Fouling

Dust, salt and biological fouling (bird droppings) can lead to serious performance losses. In general, this leads not to permanent damage and after cleaning the PV modules will perform correctly again. Local fouling, e.g. on one solar cell in a module only, can lead to more permanent damage through the formation of hot spots[17].

Degradation

PV cells and modules are subject to various forms of degradation, and they are very dependent on the materials choice for cells and modules. Well known degradation mechanisms are Light (& Temperature) Induced Degradation (L(&T)ID) in c-Si and Potential Induced Degradation, but there are various other degradation or failure modes. The figure below shows a Pareto chart of the most frequent degradation modes observed in a large study of land-based systems installed in a period of more than 20 years[18].

The origin of these degradation modes is for most cases well understood and controlled by the module manufacturers. Common practice is that the manufacturers

---

[14] Ahmed Hasan, Ibrahim Dincer, A new performance assessment methodology of bifacial photovoltaic solar panels for offshore applications, Energy Conversion and Management, Volume 220, 15 September 2020, 112972.

[15] Maarten Dorenkamper, Arifeen Wahed, Abhishek Kumar, Minne de Jong, Jan Kroon, Thomas Reindl, The cooling effect of floating PV in two different climate zones: A comparison of field test data from the Netherlands and Singapore, Solar Energy 219 (2021) 15–23

[16] M. Dörenkämper, D. van der Werf, K. Sinapis, M.M. de Jong, W. Folkerts, Influence of Wave Induced Movements on the Performance of Floating PV Systems, 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille, France 2019.

[17] https://www.pveducation.org/pvcdrom/modules-and-arrays/hot-spot-heating

[18] Dirk C. Jordan, Timothy J. Silverman, John H. Wohlgemuth, Sarah R. Kurtz and Kaitlyn T. VanSant, Photovoltaic failure and degradation modes, Prog. Photovolt: Res. Appl. 2017; 25:318–326

give a panel's performance warranty and an equipment warranty. The performance warranty will typically guarantee 90% production at 10 years and 80% at 25 years. An equipment warranty will typically guarantee 10-12 years without failing. This however is the practice for land-based systems.

Offshore application of PV panels can introduce new degradation modes caused by strong mechanical loads on the panels, corrosive environment, soiling and fouling. A few module manufacturers have recently announced the start of production of PV modules dedicated for floating systems (Hanwa Qcells, Solarge, Soltech). These modules will not automatically be suited for offshore application too.

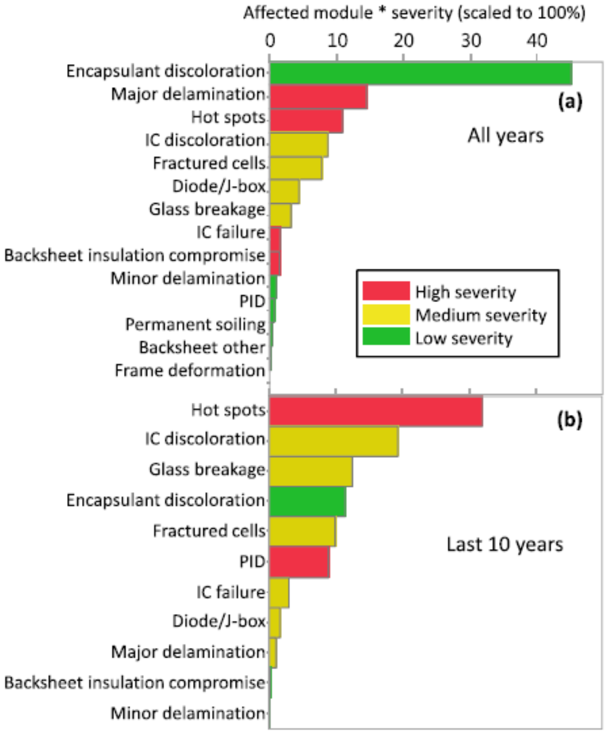


Figure 15: Pareto chart of the most frequent degradation modes of land based PV systems. The colors indicate the severity of the degradation.

1.8 Grid connection aspects

The power output of PV panels is DC. Commonly PV modules are connected in series and build a string. The maximum number of PV modules that can be connected in one string is determined by the maximum system voltage. Commonly the maximum system voltage is 1000 V, but modern PV modules and components are designed for a maximum system voltage of 1500 V. The string is then typically connected to a string inverter that transforms the power from DC to 400-800 V AC. On inland floating PV systems, the inverters are usually installed on the same floaters on which the PV modules are mounted, and each inverter serves a number of strings, with a Maximum Power Point (MPP) tracker for each string. The capacity of these string inverters is in the range of 25 to 250 kWp.

The 400-800 V AC power from the inverters then is forwarded to a medium voltage transformer station that can be installed on a separate floating structure or onshore. For offshore operation of floating PV, the conditions for the grid connection are not settled yet and will be site dependent. Cable pooling with wind farms seems an attractive option ("the power output of offshore wind turbines and FPV systems is significantly smoothed when both are combined, with a 68% reduction in the power output variability relative to a stand-alone wind farm"19) and in that case the grid connection will be designed for both the wind farms and the floating PV systems.

1.9 Aspects of operations & maintenance

A major difference between offshore and onshore PV systems is the accessibility. Distance and weather dependency make that monitoring of the operation, inspection and maintenance are more difficult for offshore PV systems, especially in the harsher conditions. The design of the offshore PV system should take these aspects into account, e.g., by incorporating redundancy of critical components and reliable monitoring systems.

1.10 Interaction between solar and wind production on joint locations

Wind turbines can cast shadow on PV modules in their vicinity. Two types of shadows need to be discerned:

1. slowly changing shadow by the monopoles
2. dynamic shading by the rotating blades.

Together with project partners Heliox and Zwanendal and solar energy producers Vattenfall and Solarfields, TNO has started a project in 2021 to investigate the effects of shade on the energy yield of solar parks on land. Results of this project will presented by the end of 2022, but an earlier TNO study, in which dynamic shading was investigated on a small scale, showed that a dynamic shadow can lead to greater energy loss than an equally large slowly moving shadow.
On the other hand, the presence of large floating PV systems may also influence the production of offshore wind turbines since the PV systems change the roughness of the water surface and therefore may change the wind flow at larger altitudes as well.

1.11 Societal aspects

The main aspects of societal acceptance of floating PV systems are:

- *Aesthetic appreciation*; landscape and horizon pollution

At eye height (1.75 m) the horizon appears at a distance of 4.7 km. Any object with the same height will therefore be "behind the horizon" if the object is at a distance of twice 4.7 km. So, we can safely assume that floating PV systems cannot be seen from distances larger than 10 km.

---

19 Mario López, Noel Rodríguez and Gregorio Iglesias, Combined Floating Offshore Wind and Solar PV, J. Mar. Sci. Eng. 2020, 8, 576; doi:10.3390/jmse8080576

- *Ecological effects*

Here, we discern two aspects: the risk of pollution and the effect on underwater life. The PV systems can cause pollution if they leach poisonous materials, or if they lose parts, e.g. in heavy storms. A careful design of the systems should prevent this to happen.

The effect on underwater life will be very site dependent. Shadow of the floaters might have a detrimental effect on the ecology underneath the floaters but the growth of algae and barnacles on the floaters may have a positive effect. Both effects, however, are hypothetical at the moment and need further research.

- *Common use of the sea area*

Stakeholders meet each other in the Community of Practice (CoP) Noordzee. Using water areas for offshore floating PV might generate additional conflicts of interest with e.g., commercial shipping, fishing, sand extraction, military use, and recreational sailing.
These conflicts may be mitigated by putting constraints on the design of the floating PV systems to minimize the “forbidden” area, but in the end, it is up to the policy makers to make rules for joint use of the water areas[20].

---

[20] Jan Matthijsen, Ed Dammers and Hans Elzenga, The future of the North Sea - The North Sea in 2030 and 2050: a scenario study, PBL Netherlands Environmental Assessment Agency The Hague, 2018 PBL publication number: 3193

2 Technical challenges

2.1 Materials aspects

In view of the large areas required for cost efficient solar PV, material selection plays an important role. In traditional maritime and offshore applications, strength and fatigue are important criteria. Steel meets those criteria at low cost. Most maritime and offshore applications are able to go to a dock for inspection and maintenance. Permanently moored floating structures have already experienced the change to on-site inspection and maintenance, resulting in under water inspection techniques, as well as remote inspection methods.

For offshore floating solar, a next step is required, to limit total lifetime cost. OPEX is considered to be the main cost driver, and CAPEX shall be optimized for long term service. In comparison with offshore wind, there are less moving parts but more distributed components involved. Two main tracks of development are therefore identified:

1. Material selection with superior longevity
2. Tools allowing for remote Structural Health Monitoring (SHM)

It is noted that there are material requirements for the floaters, mooring, connections, and topsides. This section focuses on the materials for floaters.

2.1.1 Superior longevity

Metal materials may suffer from corrosion; hence the corrosion protection is important. Offshore FPV can benefit here from developments elsewhere. Most corrosion protection systems (coating, cladding21) have a limited lifetime and may render ineffective after more than 10 years of operation, or when damages occur. Developments are necessary to include self-healing aspects. ArcelorMittal developed for instance Magnelis22, an Aluminum-Zinc-Magnesium coating for structural steel. Such a metal coating is self-healing. Other options exist, such as the conventional galvanizing or epoxy-based coatings, or may be developed for better performance against corrosion and/ or ecological footprint.

Connectors and mooring attachments may involve rotating mechanical parts (axles, bearings). Especially the connection between floaters may be subjected to intermittent wet and dry conditions, increasing the risk of corrosion damage and salt deposition. Friction will be increased when salt enters the bearings, and wear will accelerate. For this purpose, specific developments in analysis and testing of corrosion and tribology (friction and erosion/ abrasion) aspects is required. Offshore repair of mechanical parts is considered as very costly, and efforts shall be directed to avoiding the need of any repair.

Repetitive, long term loads lead to slow degradation, known as fatigue and creep. The susceptibility depends on the material. Analysis methods and establishing strength limits are research subjects with a long history. For large floating solar structures, new aspects may be of importance though. New aspects include materials not used for this

---

21Wiki: Cladding is the application of one material over another to provide a skin or layer. In construction, cladding is used to provide a degree of thermal insulation and weather resistance, and to improve the appearance of buildings.

22https://industry.arcelormittal.com/Magnelis

purpose before such as plastics (HDPE), influence of seawater and the actual loads acting on the weak points in the structure. Connectors like hinges may move around a certain neutral position, increasing the risk of making a dent in the contact surfaces. Some concept developers rely on the use of composites or plastics. These materials may degrade over time and leech particles in the sea. This is undesired and research is required to quantify the leeching, and most of all, avoid any leeching at all.
Circularity principles require that possible destination of the materials after end of life need to be identified. An important criterium for material selection is the reusability of the material after abandonment of the structure (cradle-to-cradle). Ideally, the selected materials have had a previous life. Design shall also be made such that separation of individual material is possible or not needed. Life Cycle Assessment is a good method to address this and future research project should contain such assessment, especially when it involved material selection and/ or development. In the wind energy industry, the re-use or recycling of wind blades is an important research topic, and for plastics used for offshore solar similar approaches are required.
For all material aspects, it is noted that developments include testing, and maybe new methods or procedures for representative testing. Numerical methods complement the testing, and may reduce the need for actual testing in the long run, especially when the methods results in design code. Such an approach is valid for all materials used, so also the PV panels and mooring.

2.1.2 Fouling

Deposition of minerals or biological material may limit the PV efficiency and is therefore unwanted. Further, the underwater parts of the system will be a breeding ground for algae and barnacles. This may decrease the buoyancy of the floaters and increase the mooring forces. These types of fouling can be avoided by the right selection of materials. Progress is made with development of material that reduce the amount of fouling by e.g., non-stick surfaces, based on for instance nano-particles. Deposition avoidance needs more development.
Adequate fouling removal (e.g. clean robots or sweep installations) is a useful addition to fouling remedies. These systems are not yet tailored for offshore PV installations.

2.1.3 Tools for remote Structural Health Monitoring

Certain components of floating PV systems will not survive the technical or economical lifetime of the total system. Basically for all critical components an End-of-Life criterion needs to be defined. For instance, currently, in maritime and offshore structures a thickness reduction of 25% is seen as a criterion for renewal. However, for the survivability of the structure, it may well be acceptable to reduce thickness locally even more. Or renewal may be required at less thickness reduction. Reliability methods shall be introduced and utilized to dynamically assess the actual elapsed life time and provide a “fit-for-purpose” classification. Design assumptions and as-built information need to be updated with the actual measurements and feedback from monitoring and inspection. To make optimal use of SHM, the design and safety guidelines should contain goal-based design criteria. Such criteria can be defined as a maximum allowable annual probability of loss of a floater. Design criteria, and also inspection and maintenance strategies can be tailored for this approach.. Such criteria can be defined as a maximum allowable annual probability of loss of a floater. Design criteria, and also inspection and maintenance strategies can be tailored for this approach.

Sensors that provide the input for the dynamic fit-for-purpose analyses, should be robust and reliable. Although this is not specific for offshore solar, current issues with sensors are the endurance, i.e. will the sensor deliver information at all times and for the full life time? Ingress of water, external loads and “normal” degradation all threaten the delivery of reliable data. The challenge is to separate the unreliable data from the reliable data and determine the current health status of the structure or system, e.g. by introducing probabilistic methods, alongside machine learning based solutions. Further, developments are required to make sure the monitoring systems provide reliable results over long period of time by (a combination of) improving the sensors, smart selection of the location where sensors are installed and introducing redundancy. For the offshore solar applications, efforts should be directed towards suitable locations and redundancy.

2.2 Reliability of PV system components

2.2.1 Current knowledge on reliability of FPV

As the first FPV plant was installed in 2007 and significant growth of FPV installations worldwide started only after 2015[23], there has been limited opportunity to gather field data from which to derive relevant failure modes for such systems. Also, the largest cumulative capacity is installed in China and Japan, from where only limited amounts of field data have become available since installation. During the period from 2007-2013 only systems on inland waters have been installed[24], which means most of the ‘oldest’ data available does not see effects of offshore reliability issues. Of course, the actual design and location of the system play an important role in the largest safety risks and dominant degradation modes. Although some failure modes can be derived from other applications of PV or educated guesses can be made based on the relevant environmental conditions, actual long-term field data is indispensable for accurate identification of failure modes and the design of appropriate testing.

2.2.2 Observed issues in FPV (pilot) systems

Some incidents have been observed in pilot studies and at FPV plants that were installed on near shore locations and on inland waters in the past decade (see also paragraph 1.7). Issues that have come to the attention of the authors are:

- Severe damage in frameless glass/glass modules, due to wave slamming
- Flipping over of (part of) floaters in FPV installations due to heavy winds/tornados
- Anchoring issues
- Failing floater interconnections
- Failing grounding provisions
- Cable damages
- Severe soiling and as a consequence hotspot formation due to partial shadowing from bird droppings. In floating PV this was found to be a larger problem than on land (i.e. larger than 3% loss), since floating PV installations can provide nesting places for birds at sea. The likelihood of birds nesting at a

---

[23] M.M. de Jong, M. Dörenkämper, K. Sinapis, W. Folkerts, An Overview of Floating PV Worldwide, 35th EUPVSEC, 2018, no. September, pp. 1437–1439.

[24] K. Trapani and M. R. Santafé, “A review of floating photovoltaic installations: 2007-2013,” Ieee Trans Fuzzy Syst, vol. 20, no. 6, pp. 1114–1129, 2012, doi: 10.1002/pip

floating PV installation was found to be higher in case of lower tilt angles of the modules at the tests in the Slufter lake in The Netherlands[25].
- Corrosion of junction boxes with inadequate (< IP68) water proofing, due to humid and salty environment.
- Insulation failures of different electrical components, caused by the humid environment.

2.2.3 Identified potential risks in Offshore FPV installations

From the typical environmental conditions in which offshore FPV installations are located (i.e. humid, corrosive environments) several parties have started to design accelerated aging conditions in indoor testing. The most relevant driving forces for degradation in floating PV structures that are more severe than in land-based systems are: high moisture, potentially high salinity, mechanical loading, shading and hotspot formation due to fouling (especially bird droppings). The main identified risks associated with these driving forces are:

- Issues in electrical safety/isolation due to PV modules and cabling constantly being in vicinity of water, in a corrosive and typically harsh environment. Due to the occurrence of high winds and waves, PV modules and components initially not intended to be submerged might become submerged over the course of the lifetime of the plant. The mechanical loading (wave and wind loads) might also result in damage to cabling and connections.
- Longer term damage to the PV modules due to constant or varying mechanical loading (solder joint fatigue, microcracking of cells)
- Corrosion of the PV cells due to failing insulation from the highly corrosive environment.
- It is suggested that modules in floating PV installations may suffer more from potential induced degradation due to the humid environment[26].
- Collisions between floating platforms due to drifting caused by winds.
- Mismatch losses due to drifting of islands with modules, differences in solar insolation or differences in tilt angles due to waves have been found more relevant in FPV systems. Wave induced mismatch losses were modeled to possibly lead to 3-9% yield loss[16].
- Wind loading of the PV modules. This also depends strongly on the tilt angles of the modules (higher tilt angles allow to capture more wind) and the free space underneath.

In consideration of the above described risks, the most relevant IEC tests/guidelines to take into consideration for FPV panels are:

- IEC 61215 – module design
- IEC 61730 – module safety (especially wet leakage resistance, water proofing)
- IEC 62790 – junction box safety (especially wet leakage resistance, water proofing)
- IEC 62852 – connector safety (insulation, water proofing)
- IEC 61701 – salt-mist corrosion
- IEC 62804 – potential induced degradation

---

[25] World Bank Group, ESMAP and SERIS. 2019. Where Sun Meets Water: Floating Solar Handbook for Practitioners. Washington, DC: World Bank.

[26] Haohui Liu, Vijay Krishna, Jason Lun Leung, Thomas Reindl, Lu Zhao, Field experience and performance analysis of floating PV technologies in the tropics, Prog Photovolt Res Appl. 2018;26:957–967.

A number of companies has already developed a ‘home-made’ recipe for specific testing of PV modules for FPV applications.

PV module producer REC has set up a test scheme consisting of[27]:

- Component salt spray, in excess of ISO9227
- Panel vibration (> 324.000 cycles without rubber damping)
- 1 m immersion > 2 weeks
- Salinity wet leakage, up to 65 mS/cm
- PID testing, in excess of IEC62804
- UV exposure, in excess of IEC 61215

March 2021, Classification Society DNV has published the first ‘recommended practice’ for FPV installations[28], including minimal requirements for the PV modules, though meant for inland and near shore, sheltered waters only.

It is noted that there is no regulatory framework in place for the design, construction and operation of offshore floating PV. Related rules and guidelines are available, but a coherent and applicable set for offshore floating solar is not available. Also the government is lacking a comprehensive set of guidelines for evaluating permit requests.

2.3 Design, structural integrity, construction, transportation and installation

Regarding design, several technical challenges are expected. Some of them are applicable in general for floating offshore solar systems and others are dependent on the considered system concept, as described in Chapter 1. Those challenges are elaborated in the following two subsections.

2.3.1 General technical challenges

All system concepts have in common that on the long term a large area in the horizontal plane is required, i.e. in order magnitude of square kilometers, and they are relatively flat (i.e. height is small compared to surface area). Furthermore, topside weight caused by PVs and associated equipment on those large areas are relatively small. This is different compared to current offshore (floating) structures like wind turbines and oil and gas platforms with footprints in order of (tens up to hundreds) square meters and structures which are much taller and heavier (e.g. ten thousands of tons for a single oil and gas topside).

Modular concepts (i.e. floating modules which are connected and form together a large structure) are required, due to the large dimensions in the horizontal plane. Without splitting the total assembly in smaller units, design is not feasible, at least for economic viable levels.

Design aspects concern structural integrity, construction/constructability, transportation and installation. The current technology for floating offshore (energy) applications is mainly focused on and developed for offshore applications consisting of a single floater

---

[27] REC Group, “Riding the Wave of Solar Energy: Why Floating Solar Installations are a Positive Step for Energy Generation,” REC Sol., vol. 2018, pp. 1–4, 2018.

[28] DNV-RP-0584, “Recommended practice: Design, development and operation of floating solar photovoltaic systems,” no. March. 2021.

like semi-submersibles, tension leg platforms, FPSO's, SPAR's etc. Those floating structures are usually deployed on locations with relative large water depths (at least 50m). For smaller water depths usually bottom fixed structures are applied like jackets, jack-ups and gravity based solutions (up to 120m). In the overlap, both options exist and preference is based on local conditions.
The main technical challenge for very large systems is to develop cost effective massively modular concepts which are able to cope with the harsh environmental (metocean[29]) conditions. Note that the scope of this document is focused on the North Sea.

To meet these challenges, system developers have the following objectives:

- Develop a method to determine the "sweet spot" between rigidity and structural flexibility of offshore floating solar farms. This is important since e.g. a very large rigid structure results in large internal- and mooring forces and needs therefore to be stronger, larger and therefore more expensive. On the other hand, when a structure is very flexible and following the waves the forces reduce, but the massive modular structure is much more sensitive for excessive deformations and/or wrinkling phenomena. This results in other technical challenges. Those challenges are system concept specific and elaborated in next sections.

Note that the optimum between rigidity and flexibility depends on a combination of metocean conditions, soil conditions and desired solar farm capacity (i.e. size).

- Develop floater connections. If the rigidity/flexibility requirements are more clear, those connections can be developed based on those requirements. Those connections should be able to withstand forces between substructures and mechanisms that can deal with the relevant traction and torsion forces ("hinges", "connection bars"). One could also think of develop plastic-metal connections. Another method which could be used might be topology optimization to minimize the material use for a specific design load set.

- Develop (calculation) methods to ensure the structural reliability over the design lifetime, especially due to cyclic loading of the floaters, connections, but also the PV's. This is also related to the FLS as mentioned before.

- Develop safety philosophy and translate this into design loads and criteria. The safety philosophy might be slightly different compared to the oil and gas industry, since no people are permanently based on the floating solar farms. This item is overlapping with and strongly related to the development of rules and regulations described in the next item.

- Recommended practices and/or rules and regulations need to be developed. An example of this is the DNV guideline for inland (!) floating solar applications2. Those regulations should/could include:

---

[29] Metocean refers to the combined conditions of the meteorology (e.g. wind, temperature) and oceanography (waves, currents, bathymetry).

    - Design loads in terms of serviceability limit state (SLS), ultimate limit state (ULS), accidental limit state (ALS) and fatigue limit state (FLS) in combination with the relevant material and load factors;
    - Relationships between the size of the substructure (i.e. connected floaters, supporting the PVs) and the wave conditions;
    - Scaling relationships for up-scaling the current and near future solutions to larger solar farms.

In order to reach those objectives the following is required:

- Develop and validate numerical/ calculation models which are able to describe fluid structure interaction of multi-body dynamics. Those models should describe:
    - The hydrodynamic interaction with the (multi-body) structure exposed to waves, wind and currents;
    - The global structural (dynamic) response, local structural response of each floater and forces on connections and mooring system;
    - The interaction between before mentioned items, as the flexibility of each element influence the hydrodynamic behavior.
- Measurement campaigns are required for validation of (numerical) models:
    - Towing tank and/or model basin testing;
    - Full scale test in offshore conditions;
    - Fatigue and ultimate strength testing of connectors and new materials used for floaters.
- Develop a method to determine the amount of expected (biological) fouling over time.
    - Weight: The total expected additional weight due to fouling is affecting the structural reliability w.r.t. buoyancy of the system during the lifetime. A floating solar farm is more sensitive for additional weight compared to structures applied in the oil and gas industry, since the typical weights of the floating solar structures is much lower;
    - Drag: Marine growth is causing an increased (submerged) surface. This means that drag due to currents, and therefore mooring loads, are increasing over the life time;
    - Further it is noted that the type and amount of fouling is very geographic dependent.

2.3.2 Challenges specifically related to different system concepts

The specific challenges for each system concept as mentioned in Chapter 1 are briefly discussed in this section.

Rigid structures

- Pontoon concept:

A rigid pontoon results in larger 2nd order wave forces (drift) compared to a flexible structure (following waves) with the same footprint. Those drift forces results in large mooring forces and may lead to a heavy and expensive structure. The current demonstrators based on the pontoon concept involve individual pontoons with limited size and limited amount. By connecting multiple rigid structures, one obtains a larger structure which is as a whole a flexible system moving along with the waves. That however results in another challenge, namely a reliable design of such a system supported by a decent structural analysis.

- Truss concept:

Using a truss concept also the challenge regarding the multi-body dynamics is applicable. Next to that, typical for a SWAMH concept is that there is space between the bottom of the deck (supporting the PVs) and Still Water Level (SWL), the so called airgap. This has two consequences for the environmental loading on the structure:

  - Prevent waves hitting the deck (slamming). This is important since slamming may result in large peak loads, damaging the structure and equipment on top of the deck. A combination of two methods are usually applied. First, ensure sufficient airgap so the waves can run underneath the deck. Second, optimize the dynamic behavior in the design such that the floaters moves along with the wave elevation. The later item depends on the site specific wave spectrum and the eigenfrequency of the floating structure.
  - Take into account the wind load between the deck and SWL which may cause the platform to behave like a kite. Since the structure (topside) is relative light weight this could become a relevant design parameter, especially in areas with extreme environmental conditions like the North sea.

Flexible structures

- General flexible structures (both Fishfarm and Soft&Flex concept)

From material point of view the challenge is to select appropriate materials for flexible concepts. The material which will be used for flexible solutions should be able to cope with a large amount of loading cycles during the entire life time, since it deforms along the wave elevation. Since it is likely that less conventional materials will be used for flexible solutions, less knowledge regarding material behavior is available yet, especially considering that those material are exposed to a saline, aggressive seawater, environment). Another effect is that, as described before, fouling will have a larger influence on a light weight structure compared to a heavier one, in terms of buoyancy.

- Soft & flex concept
  One can imagine that a flexible structure has lower weight compared to rigid structure and consequently a light weight structure is much more sensitive for (uplift due to) wind, gusts and strong gradients in wind speed and direction. Especially in combination with steep waves a second effect is that wind could come underneath the structure. The main challenge is to quantify the wind loads on a structure close to the water surface and the interaction with the flexible structure. The complexity is mainly caused due to the interaction of the wind (gusts) with the waves and moving structure.
- Fish farm/ Membrane concept

Academic research w.r.t. wrinkling behavior of large floating offshore structures has recently started but needs to be translated into relevant engineering methods and models. An example of a project regarding the membrane concept is FlexFloat[30]. This

---

[30] Dr. Ing. Sebastian Schreier (TU Delft), Dutch Research Council (NWO), “FlexFloat: Efficient hydroelastic loading and response modelling of Very Flexible Floating Structures”, NWO Domain Applied and Engineering Sciences (AES), Open Technology Programme

project is a collaboration between MARIN, TU Delft, Heerema Marin Contractors, HyET Solar and TNO. The project signals that wrinkling is critical for solar modules and can lead to structural collapse. Therefore nonlinear Fluid-Structure Interaction simulations are required. Therefore the ambition of the project FlexFloat is to develop suitable models:

- Which include relevant failure modes associated with very high width to thickness ratios. An example of such a failure mode is the wrinkling of the membrane;
- Develop design criteria to avoid wrinkling;
- Which include relevant wave parameters and quantify the effects on the (structural) design;
- Which include material properties of the considered membrane. Those materials behave usually less straightforward compared to common applied materials like steel.
- Validate those models by wave basin experiments using state of the art measurement systems to investigate the influence of wave and structure parameters on the response of the membrane structure.

2.4 Mooring aspects

2.4.1 General

The goal of a mooring system is station keeping. This means that the excursions are supposed to be limited by the mooring system.

The local (environmental) conditions are relevant for the choice and design of the mooring systems. The most considerations for mooring layout selection and design depends on:

- Local waterdepth and bathymetry;
- Water level variations (like tidal ranges and storm surges) w.r.t. the waterdepth;
- Currents;
- Wave conditions;
- Footprint (how much space is required/desired);
- Maximum allowable excursions of the floaters;
- Soil conditions (for anchor selection);

2.4.2 Mooring concepts

A brief overview of potential mooring layouts are presented in this section, which are partly based on inland solutions for floating solar. For each mooring solution the pros, cons and applicability are indicated. The subdivision and explanation of the mooring is based papers discussed previously[4,28].

According to Vo et al, mooring aspects can be subdivided in:

- Mooring Layout, which will be addressed further in this section:
    - Catenary mooring system, see Figure 11
    - Taut mooring system, see Figure 12
    - Hybrid mooring system, see Figure 13
- Mooring Makeup (see Vo et al. for an overview):
    - Chains31

---

31 DNVGL-OS-E302 – Offshore mooring chain

  - Wire Ropes32
  - Synthetic Fiber Ropes33
- Anchoring (see Vo et al.):
  - Deadweight
  - Drag anchors
  - Plate Anchors
  - Pile anchors

With respect to the Mooring Layout; there is one additional mooring layout that is not mentioned by Vo: namely the use of spud piles (similar to monopile).

Further DNVGL-RP-0584 is also considering solutions related to shore mooring, however this is only applicable for inland solutions. Shore moorings are therefore omitted in this section.

2.4.3 Mooring layout

A schematic overview of the catenary mooring system is depicted in Figure 16. The station keeping of this system is provided by the self-weight of the mooring cable or chain and its friction with the seabed. This mooring system requires a relative large footprint to limit to keep the floating object in position. Nevertheless relative large excursions (few up to a few tens of meters) in the horizontal plane can be expected when a catenary mooring solution is applied. This solution is favorable if water level variations are large compared to the water depth. A drawback, especially when upscaling floating solar to large surfaces, is that the design of the entire mooring configuration is a major challenge. The mooring lines could interfere with each other or neighboring offshore structures and infrastructure, especially since a synergy with offshore wind farms is expected like projects as Hollandse Kust Noord.

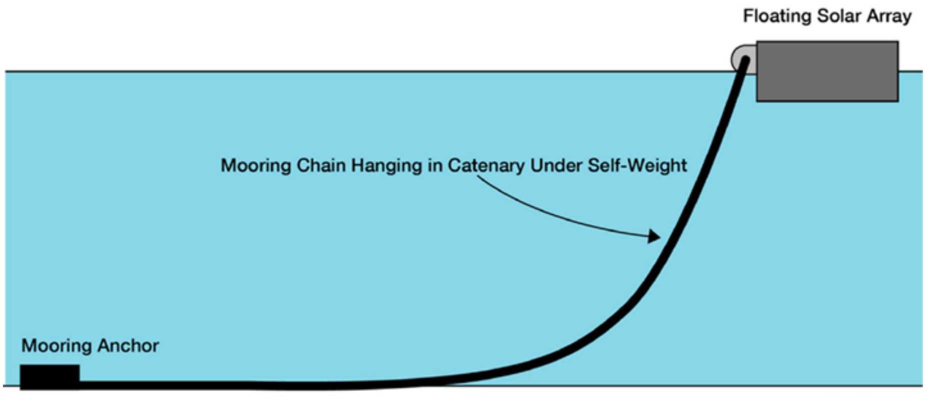


Figure 16: Catenary mooring system, Vo et al.

A schematic overview of the taut mooring system is depicted in Figure 17. The station keeping of this system is provided by the tension which is applied in the mooring lines. The lines can be oriented both vertical as inclined. A taut leg solution is usually applied on locations with a large water depth, since in that case the water level variations are relative small compared to the water depth. A much smaller footprint is required when

---

32 DNVGL-OS-E304 – Offshore mooring steel wire ropes

33 DNVGL-OS-E303 – Offshore fibre ropes

applying a taut mooring system. The first generation of offshore floating solar farms is expected to be on locations near bottom fixed windfarms with limited water depth (20-40m) like HKN and Blue Accelerator site in Belgium by Oceans of Energy[34].

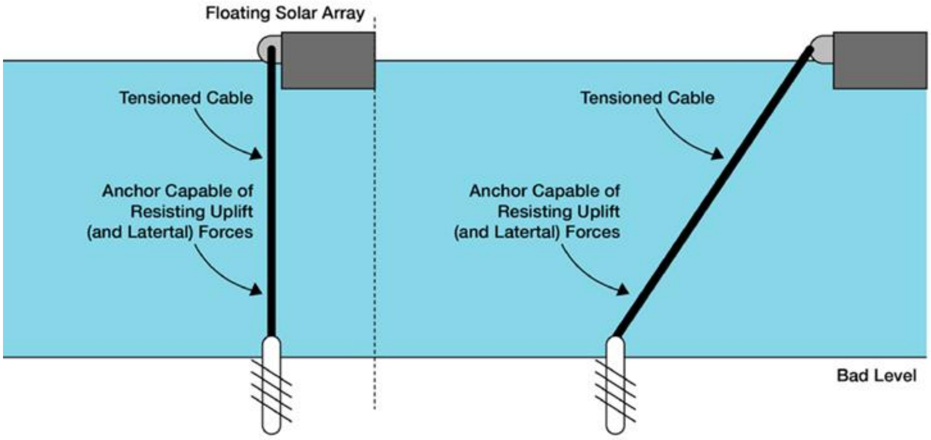


Figure 17: Taut mooring system, Vo et al.

A schematic overview of the hybrid mooring system is depicted in Figure 18. This solution is a combination of the beforementioned options. To provide (pre)tension in the cable either a mooring buoy (near the water surface) or a submerged weight is added to the mooring line. Doing so the footprint is reduced compared to a catenary system and the water level variations can be accommodated by the catenary shaped part of the mooring line. A remaining challenge for this solution is the mooring arrangement for large surfaces, since the mooring lines could interfere with each other.

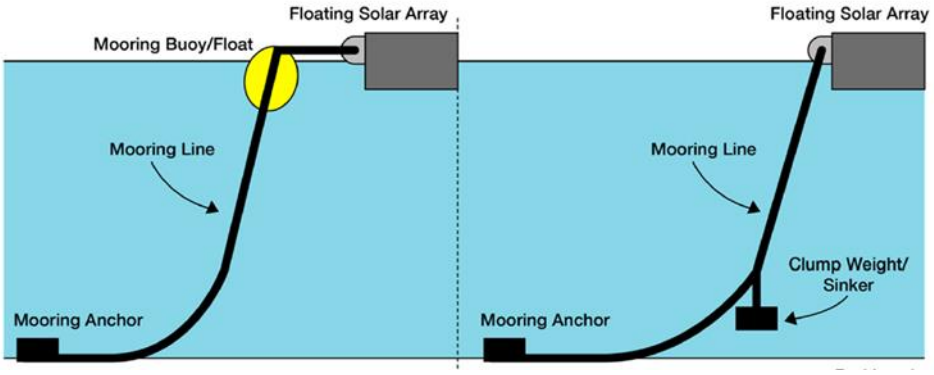


Figure 18: Hybrid mooring system, Vo et al.

The last option is mooring the floaters to spudpiles. This can be tubular piles which fix the floater in the horizontal plane, but allow the floater to move in the vertical direction. The spudpiles are fixed in the seabed, similar to a wind turbine monopile. This option is not applied yet for offshore applications but are applied for example for inland floating houses, see Figure 19. This solution provides a footprint which is similar to the footprint of the floaters itself and there are less issues with the configuration. One can imagine those spudpiles are especially favorable in relative shallow waters in the North Sea and for concepts that exert small mooring forces.

---

[34] https://oceansofenergy.blue/2021/09/01/eu-scores-project-aims-to-deliver-world-first-bankable-hybrid-offshore-marine-energy-parks/

Figure 19 Example of a spudpile solution applied for floating house

2.4.4 Mooring Challenges for the North Sea

The Dutch Economical Zone of the North Sea is a relatively shallow water area. Technically this is not the most challenging sea area for mooring a floating system and we have seen that there is a large variety of mooring concepts available.

Space requirement is considered as a major challenge: space on the water and space on the sea bed.

Most of the floating PV concepts require a multitude of mooring lines. In particular catenary mooring lines create an additional zone around the floating systems where shipping is not possible. And irrespective of the mooring concept, the mooring anchors need space on the sea bed. This may create conflicts of interest with owners of sea cables and with commercial fishery.

Next to that: the existence of various mooring concepts does not guarantee that a cost effective **and** reliable solution of mooring of an offshore floating PV system is possible. We foresee a lot of development efforts to optimize these two aspects in the near future.

2.5 Grid connection aspects

The picture below shows a generic overview of a floating PV system on inland waters. An offshore system will look similar, only with the transformer located at sea too.

A general challenge for offshore floating PV is to achieve a reliable electrical connection between the Combiner box and the Central inverter, and between the Central inverter and the Transformer. Wave induced motions put a heavy mechanical load on the interfaces between the cables and these components and the cables themselves for the floating sections (so called dynamic cables).

Recommended practice for cables, connectors, transformers and other electronic components is described in DNV-RP-0584[28].

In practice, the total connection scheme will be very site dependent; depending e.g. on the presence of a wind farm (cable pooling), the nearest vicinity of a TenneT

transformer platform. But also hybrid solutions are possible in which the electric power from the PV system is used to generate hydrogen at the same location, such that no or only a part of the PV power will be fed into the grid.
All these options require tailor made solutions for the grid connection.

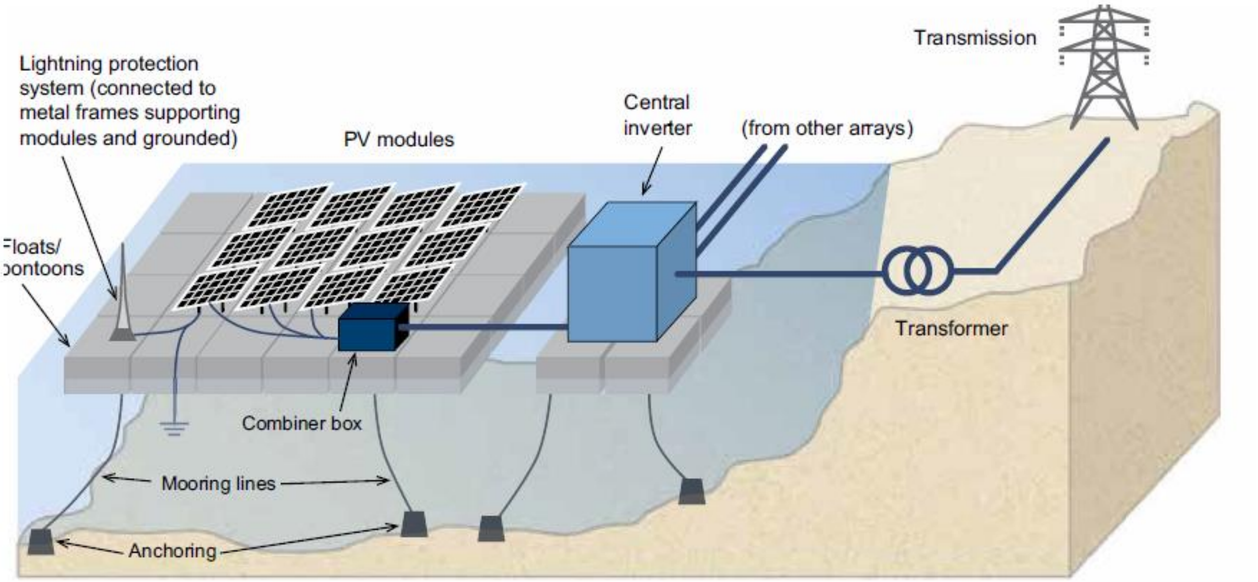


Figure 20: Schematic representation of a typical large-scale FPV system with its key components (source: World Bank Group, ESMAP and SERIS. 2019. Where Sun Meets Water: Floating Solar Handbook for Practitioners. Washington, DC: World Bank)

2.6 Aspects of operations & maintenance

High transportation costs and limited weather windows make that maintenance operations on the floating PV systems need to be minimized and concentrated. Experience in this has to be built up in practice in the next years, but a proper design of the system will facilitate effective maintenance.
For land based PV systems, cleaning robots have been developed. For offshore systems, such robots do not exist yet, and it is questionable whether reliable automatic cleaning systems will ever become available for offshore application. Therefore antifouling measures are necessary for offshore floating PV systems.
Adequate monitoring of the performance of the PV system is also mandatory to detect failures of PV modules or components in an early stage. Digital twinning can be a helpful tool for this.

3 Cost of electricity

3.1 Introduction

The levelized cost of electricity (LCOE), is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. It is used for investment planning and to compare different methods of electricity generation on a consistent basis. The LCOE "represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle", and is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered[35].

The mathematical formula for the LCOE is

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n}[OPEX(t)/(1+WACC_{Nom})^{t}]}{\sum_{t=1}^{n}[Utilisation_{0} \cdot (1-Degradation)^{t}/(1+WACC_{Real})^{t}]}$$

where
t = time (in years)
n = economic lifetime of the system (in years)
CAPEX = total investment expenditure of the system, made at t=0 (in €/kWp)
OPEX(t) = operation and maintenance expenditure in year t (in €/kWp)
$WACC_{Nom}$ = nominal weighted average cost of capital (per annum)
$WACC_{Real}$ = real weighted average cost of capital (per annum)
$Utilisation_{0}$ = initial annual utilisation in year 0 without degradation (in kWh/kWp)
Degradation = annual degradation of the nominal power of the system (per annum)
and $WACC_{Real} = (1 + WACC_{Nom}) / (1 + Inflation) - 1$
where Inflation is the annual inflation rate.

3.2 LCOE of land based PV and inland floating PV

The LCOE of PV systems in general has dramatically dropped in the last decades. The picture below shows that the costs of electricity by Utility Scale PV systems can be in the range of 30-40 $/MWh, and comparable with the LCOE of wind.

---

[35] Lai, Chun Sing; McCulloch, Malcolm D. (March 2017). "Levelized cost of electricity for solar photovoltaic and electrical energy storage". Applied Energy. 190: 191–203. doi:10.1016/j.apenergy.2016.12.15

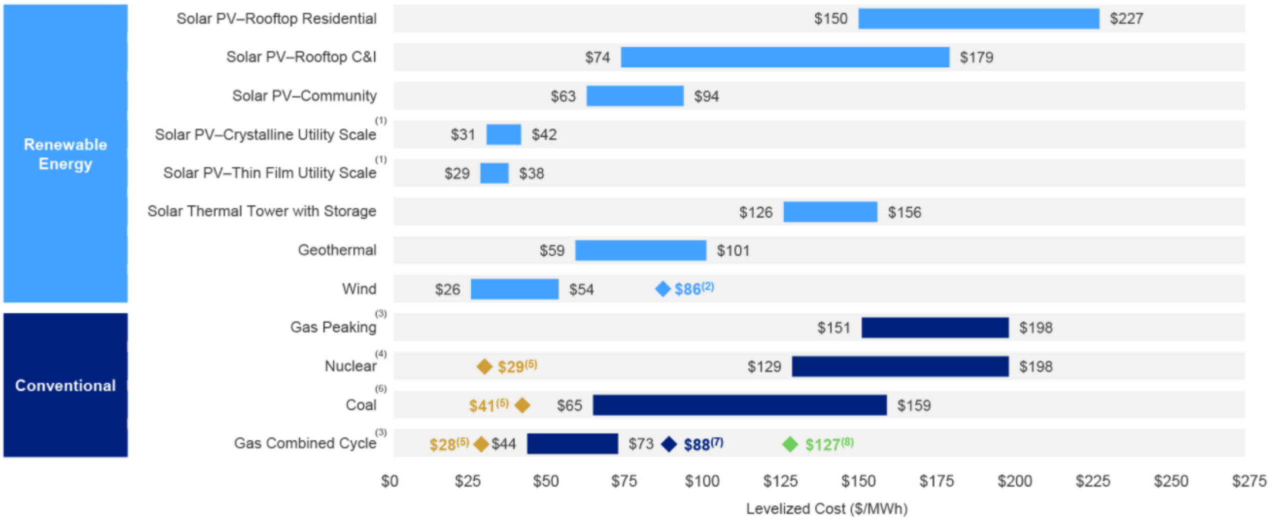


Figure 21: Present Levelized Costs of Electricity for various generation sources[36].

The LCOE of solar electricity of course is very much dependent on the annual yield of the PV system, and with that, of the location of the system. The minimum costs of 30 $/MWh can presently only be achieved in regions with the highest annual insolation, like deserts.

SERIS made an estimation of the LCOE of inland floating PV systems and compared them with on-land based systems, for various locations: the tropics; deserts and moderate climates[37]. The results are shown in the table below and are differentiated for various WACCs (weighted average costs of capital). They arrive at slightly higher costs than Lazard (45.2 $/MWh for desert based systems, but also conclude that electricity from (inland) floating PV is only marginally (about 10%) more expensive than that from ground-mounted PV.

Table 1: LCOE of (inland) floating PV compared with ground-mounted PV for various climate regions.

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

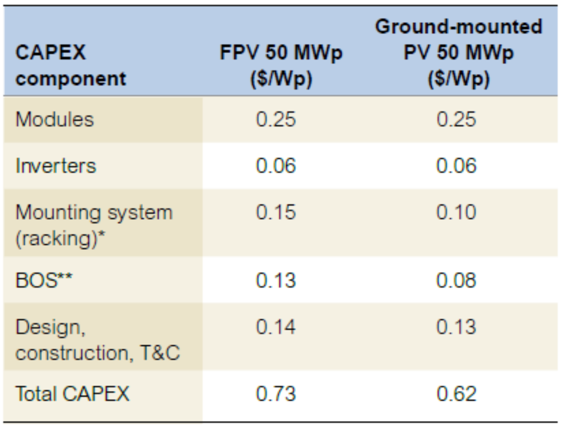
---

[36] Lazard's annual Levelized Cost of Energy Analysis (LCOE 14.0) (2020)

[37] SERIS, Where Sun Meets Water, Floating Solar Market report (2019)

The main reason for the (slightly) higher LCOE of floating PV in comparison with ground-mounted PV is the higher CAPEX costs. As shown in the table below, SERIS estimates the CAPEX of ground based system about 0.62 $/Wp and 0.73 $/Wp for floating PV systems.

Table 2: Comparison of capital investments required for floating PV systems and ground-mounted PV 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

A TNO study, carried out in 2019, estimates the CAPEX costs of inland floating PV in the Netherlands, in the range of 0.8 – 1.0 €/Wp and arrived at a LCOE value of 0.09 – 0.11 €/kWh[38].

Another relevant publication is from NREL[39]. They estimate the CAPEX for a 2 MWp FPV plant at 1.5 €/Wp and for a 10 MWp FPV plant at 1.1 €/Wp. For a 10 MWp FPV plant at the geographical location of Kansas (with 1500 kWh/kWp annual yield) and a WACC_{Nom} = 5%, they calculate the LCOE to be 0.05 €/kWh. If we translate this number to an annual yield of 1000 kWh/kWp, we arrive at an LCOE of approximately 0.075 €/kWh.

Rosa-Clot and Tina[40] [4] published an analysis for a 1 MWp FPV plant in Dubai. They estimate the CAPEX to be 0.5 – 0.7 €/Wp and arrive at a calculated LCOE of 0.025 - 0.03 €/kWh (with 1600 – 2200 kWh/kWp annual yield). If we translate these numbers to an annual yield of 1000 kWh/kWp, we arrive at an LCOE of approximately 0.06 €/kWh. In conclusion we see that for inland floating PV plants there is a substantial variation in the financial estimates from different sources. In the table below we summarized our view on LCOE of inland floating solar, that took into account the publications as referenced here.

Table 3: Financial estimates for inland floating solar in North West Europe

CAPEX (1 MWp)	0.7 – 1.1 €/Wp
CAPEX (10 MWp)	0.5 – 0.9 €/Wp
LCOE (1 MWp)	0.07 – 0.11 €/kWh
LCOE (10 MWp)	0.05 – 0.09 €/kWh

---

[38] De Jong et.al: Zon op Water (2019).

[39] Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies: Ramasamy and Margolis, NREL (2021).

[40] Rosa-Clot and Tina: Floating PV Plants, Chapter 10. Elsevier Inc. publishers (2020).

3.3 LCOE of offshore floating PV

For offshore floating solar, not many data have been published. According to the World Bank report[37] the system of Swimsol for offshore floating PV at medium exposure (significant wave height 3 m) can produce electricity at costs as low as 0,11 €/kWh. This number is based on an economic lifetime of 30 years (n = 30), which is an assumption that has not yet been substantiated.

Based on an analysis of an early pilot from Oceans of Energy the LCOE for offshore solar has been estimated at 3.54 €/kWh in 2019[41]. We believe that this calculation is not very relevant as it relates to an early case in which substantial development cost have been taken into the CAPEX.

For offshore floating PV at high exposure no other data or publications are available yet. It is therefore difficult to define a state of the art when it comes to LCOE.

It is however clear that high exposure circumstances such as at the North Sea require substantial higher CAPEX levels compared to the medium exposure case. We estimate that CAPEX would be a factor 2-3 larger today compared to the medium exposure case.

For a small system (1 MWp) that would be contracted in 2022 and delivered in 2024 we estimate a CAPEX of 3 - 6 €/Wp and an LCOE of 0.8 – 1.3 €/kWh. Furthermore, we assumed n=10 and OPEX = 4% x CAPEX for small systems.

For a medium size system (10 MWp) there will be scale advantages in CAPEX and OPEX. We assume OPEX = 2% x CAPEX for medium size systems. We estimate that for a medium size system CAPEX would be 2 – 4 €/Wp and LCOE would be 0.6 – 0.9 €/kWh.

Table 4: Summary on TRL and LCOE - best estimates for northwest Europe

	Low exposure	**Medium exposure**	**High exposure**
Definition	Hmax = 2 m, HS = 1 m. mostly inland waters	Hmax = 6 m, HS = 3 m.	Hmax = 14 m, HS = 7 m.
Development status	Approx 2 GWp installations worldwide. Ongoing developments on reliability, cost and O&M. No full bankability yet. TRL 8.	Several pilot projects have been realized. TRL 4-6.	Initial developments. TRL 2-4. Pilots have been planned.
CAPEX (1 MWp)	0.7 – 1.1 €/Wp	1.5 – 2.0 €/Wp	3 – 6 €/Wp
CAPEX (10 MWp)	0.5 – 0.9 €/Wp	1.0 – 1.5 €/Wp	2 – 4 €/Wp
LCOE (1 MWp)	0.07 – 0.11 €/kWh	0.15 – 0.22 €/kWh	0.8 – 1.3 €/kWh
LCOE (10 MWp)	0.05 – 0.09 €/kWh	0.11 – 0.16 €/kWh	0.6 – 0.9 €/kWh

---

[41] Witteveen & Bos, CE Delft. (2019). Perspectieven elektriciteit uit water. Nationaal potentieel voor 2030 en 2050.

3.4 Perspective on LCOE of offshore floating PV

We believe that the two most important mechanisms for substantial cost reduction of offshore PV are: scale and reduction of overengineering.

Scale
Today the pilot experience for offshore solar is on the kWp scale. Plans are in place for the 1 MWp scale. However, several cost factors depend largely on the size of the system. Mooring cost, offshore installation cost, logistics cost and OPEX are expected to decrease substantially (calculated per Wp) for larger systems. We expect that this size-effect will approximately saturate at the 100 MWp scale. On top of that is the learning curve effect based on the cumulative installed capacity.
Related to scale are cost advantages that will be obtained when offshore FPV develops from a niche market to an international mass market with more competition between component manufacturers and service providers.

Reduction of overengineering
In the engineering process for an offshore FPV system model calculations are made on mechanical strength and structural integrity of the system in relation to the various types of loads. These calculations have a limitation on accuracy and therefor the common practice is to apply safety factors in the engineering.
When the field of offshore PV will become more mature, the validation of the model calculations will improve and therefore the accuracy of the calculated predictions. This will lead to a safe reduction of the overengineering factor on these systems and therefore contribute substantially to the cost reduction potential.

Our estimate is that these factors will drive the LCOE of offshore solar in 2030 to 0.25 - 0.3 €/kWh for a 10 MWp system and to 0.15 - 0.2 €/kWh for a 100 MWp system.

4 Potential for the Dutch industry

The Dutch industry is or can be involved in many links of the value chain of offshore floating PV. Most important links are End users; System Suppliers and EPCs; Project Developers, and Material Suppliers.

4.1 End users (utility and energy companies)

Dutch companies like Shell, Eneco and Delta are already active in the exploitation of offshore wind farms and are potential end-users of offshore floating PV too. Shell and Eneco have formed a joint venture Crosswind which will build a new wind farm at Hollandse Kust Noord. In the frame of this project, they will also carry out a demonstration project of floating PV of 500 kW, to be installed at that same site.

4.2 System Suppliers and EPCs

Several Dutch system suppliers are developing a concept for offshore floating PV. In ranking of matureness we list Oceans of Energy, SolarDuck and Bluewater. All three companies are ambitious with plans to build demonstration systems of several megawatts. Besides these companies, other companies who are active now as System Supplier for inland floating PV systems, like Texel4Trading, Sunfloat, Groenleven are keen to step in to offshore floating PV too as soon as they see economically feasible ways to overcome the technological hurdles.
Since there is no commercial market yet for offshore floating PV, there are no dedicated Engineering, procurement, and construction (EPC) companies either. Presently the demonstration systems are built by the System Suppliers themselves. However, when the market for offshore floating PV becomes more mature, dedicated EPCs will become active in this field.

4.3 Project developers

Project developers will step into the market of offshore floating PV as soon as there is a profitable business case.

4.4 Material suppliers and contractors

Materials for the offshore floating PV systems can be divided in a few categories: PV modules, Electronic components; Floaters; Mooring.

- PV modules
  Presently the system suppliers use standard PV modules with IP68 rating. The extreme weather conditions and the desire to use lightweight PV modules to save costs for the floating structures, opens the opportunity for Dutch module

makers to produce dedicated PV modules for this market. The startup company Solarge is already exploring this market.

- Electronic components
  We foresee that on the short and middle long term standard electronic components will be applied. For the electrical connections with the grid, however, dedicated dynamic cables are required. This provides new opportunities for cable manufacturers like TKF.
- Floaters
  Various concepts for the floaters are under development currently but tend towards simple robust constructions. In order to avoid huge transportation costs, the manufacturing should not be remote from the launching sites (harbors). This provides opportunities for Dutch construction companies.
- Mooring
  All floating PV concepts require a dedicated mooring system. Several of the system suppliers are owned or connected to Dutch offshore companies with huge experience in mooring, like Bluewater, SBM, van Oord, Damen Shipyard, Franklin offshore and Boskalis. For these companies, offshore floating PV will provide new business opportunities for mooring, but also in a broader sense: as EPC.

5 Conclusions and Advice

5.1 Present and near future status of OFPV

Offshore Floating PV is a technology with substantial potential for emission-free production of electricity for the Netherlands, but it is still in a relatively early stage of development. The challenges to arrive at a state of development that is in terms of costs, energy yields and reliability competitive to other technologies for renewable electricity production are huge. Utility-scale PV systems are proven technology on land and floating PV is applied increasingly on inland water. Energy production costs (LCOE) for floating PV on inland waters are approximately 10% higher than land-based PV systems. The step to offshore systems is, however, a challenging one.
The major challenges that we have identified are:

1. Reduction of LCOE (increase yield, decrease CAPEX and OPEX, increase economic lifetime)
2. Reduction of risks (failures, degradation of system and components, societal acceptance)
3. Improvement of circularity of materials and components

Four different technology concepts (pontoon, truss, fish farm and soft&flex) for offshore FPV are currently under development. For each concept, one or more companies in The Netherlands and in other European countries are developing prototypes and demonstrators. All these concepts have a low to medium TRL (TRL 4-5). Public information on the technical and economical details of the concepts is scarce. At this stage it is not possible to predict the future market success of the various concepts. For all concepts there are significant technological hurdles to pass and several system suppliers have presently financially to deal with the “valley of death”. We foresee that the parallel development of different concepts for offshore FPV will continue for the next couple of years.

Offshore PV is still in an early stage of development. For medium exposure locations, the first two companies introduced their system to the market, although limited data about field reliability and lifetime are available. For high exposure locations such as the North Sea, the TRL is in the TRL 2-4 range. On the topics of technical feasibility, economic perspective and societal acceptance, there are important challenges to be addressed.
We believe that public support for innovation over a broad range of topics, and for demonstration projects for offshore FPV will be important for the years to come.

We have identified two types of innovation questions: (1) questions specific to the various concepts and (2) generic knowledge questions relevant for all FPV developments.
Examples of specific innovation topics for the specific concepts are:

- Capex reduction potential of the FPV structure (see section 3.4)
- Reliability and integrity of the FPV structure under offshore conditions,
- Fouling and degradation

- Design of mechanical interconnections between substructures

Examples of generic innovation topics (a larger list is provided in Annex 1):
- Reliability and lifetime of PV system components under offshore conditions
- Calculational modelling of electricity yield and LCOE
- Materials circularity of FPV
- Societal acceptance
- Grid integration and electrical interfaces
- Operation & maintenance strategies
- Mooring concepts

5.2 Recommendations for cost effective solar offshore electricity

Most relevant questions for the reduction of the LCOE of offshore FPV are those which are specific for offshore application and will not be addressed for land based and inland water based PV. In order to get a grip on the LCOE of offshore solar electricity, and to effectively steer the LCOE reduction, it is important to build validated yield models and validated models for the direct cost components. Both are needed to build a reliable business case that will attract investors.

5.2.1 Validated yield models

Yield modelling and yield prediction for PV systems on land is well established. For offshore floating PV, there are some additional aspects that need to be integrated into the existing models. These are related to movements of the system, the effect of the large water body on the module temperature, specific pollution effects at sea and potential higher degradation rates at sea. The advanced yield modelling has to be validated by extensive yield monitoring of pilots and demonstration projects.

All these aspects are dependent on the design of the floating system, the mooring design and the design of the PV system components.
We recommend to stimulate pre-competitive generic research on yield modelling, yield monitoring, degradation of PV modules and electronic components (including cables), and (avoiding of) fouling and pollution effects.

5.2.2 Direct cost

CAPEX
CAPEX is largely driven by the cost of the floating system and the cost of mooring and installation. Further development of experimental and calculational tools for hydrodynamic responses of the systems and their structural integrity will lead to the design of more cost effective systems. Cross learning projects with related developments such as floating wind turbines, can be effective.

OPEX
Today there is very limited knowledge about cost for operation and maintenance (OPEX) for offshore solar farms. Besides OPEX factors that are also manifest for solar parks on land, specifics on preventive maintenance and repairs are important. We recommend to stimulate multiyear demonstration projects that gather big data on the

performance and O&M and utilize a digital twinning approach to build up the required knowledge base.

5.3 Recommended approach

A recommended way to support the development of offshore FPV is to stimulate cooperation projects of system developers and knowledge partners performing research on generic innovation topics. In Annex 1 we have listed the generic topics that we encountered in our analysis of the innovation system of offshore FPV. The Dutch offshore FPV systems currently under development are in TRL 4-5. In the next phase it is important that research pilots are performed at an offshore location. Knowledge sharing of the (pre-competitive) results of such research pilot projects is expected to benefit the development of the sector.

Cooperation between concept developers and knowledge institutes can be further enhanced by the creation of a national North Sea FPV field lab, which will host such pilot projects and offer facilities for data collection and analysis. Another recommendation is to establish a working group “offshore FPV” under the existing network organization of the “Nationaal Consortium Zon op Water”.

ANNEX 1

Research Topics for offshore FPV:

- **Construction of offshore solar systems**
    - Reliable connectors for connecting substructures
    - Choice of materials balancing cost, longevity and ecological footprint
    - Structural integrity of the complete installation including the mooring
    - Reliable dynamic power cable connections
    - Minimization of non-access area
    - Calculation methodologies for interaction of wind and wave loads and structural behavior

- **Operation and Maintenance**
    - Design of PV modules and electrical components for offshore applications
    - Monitoring and digital twinning of offshore PV systems
    - Preventive and reactive maintenance schemes
    - Fouling prevention and fouling removal strategy

- **Power Production and LCOE**
    - Development of power yield models for offshore solar
    - Development of LCOE models for offshore solar
    - Optimization of the combined production of solar, wind, H2 production and
    - Power transfer and electrical storage at one offshore site (cable pooling)
    - Mutual interaction effects of Solar and Wind on production
    - Options for lower Capex by re-use of existing assets (e.g. oil platforms)

- **Societal acceptance**
    - Circularity of systems and components
    - Ecological effects
    - Permitting aspects
    - Inclusion of stakeholders and communities depending on maritime economic activities

TKI WIND OP ZEE
Topsector Energie

Postadres
postbus 24100
3502 MC Utrecht

Bezoekadres
Arthur van Schendelstraat 550
Utrecht

T +31 30 73 70 541
E secretariaat@tki-windopzee.nl
T www.tki-windopzee.nl