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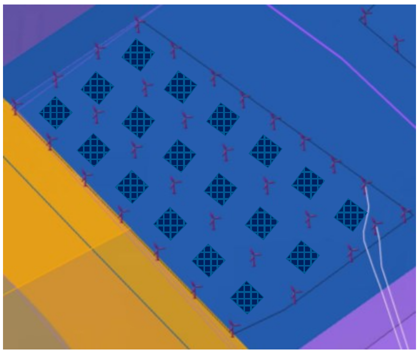
"MarineSPOTS"

Marine Solar POtential and Technology Study

Summary Report



Project binnen het

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List of acronyms, abbreviations, and definitions

AC	Alternating Current
BEM	Boundary element method
BoM	Bill of Materials
CF	Capacity Factor
DC	Direct Current
ECMWF	European Centre for Medium-Range Weather Forecasts
FF	Fill Factor
FMEA	Failure Modes and Effects Analysis
(O)FPV	(Offshore) floating photovoltaics
HDPE	High density polyethylene
MPP(T)	Maximum power point (tracking)
NTC	Net Transfer Capacity
RES	Renewable Energy Source
SWOT	Strengths, Weaknesses, Opportunities, Threats
TYNDP	Ten-Year Network Development Plan
Wp	Watt peak
(HA)WT	(Horizontal Axis) Wind Turbine

1 Introduction

The MarineSPOTS project lays a fundamental scientific basis for the roll-out of solar energy installations in the North Sea, with a theoretical potential power of several gigawatts. This is done by modeling the specific conditions including waves and storms, and performing research on modified photovoltaic cells, floating structures, and the electrical systems including power electronic converters and system integration. Attention is paid to reliability and a minimization of the impact on the marine environment ecology.

When starting out with the proposal for the current project in late 2020, first concepts had emerged for OFPV technology and were approaching tests in protected waters. This project was thus conceived to map the boundary conditions in a bottom-up, low TRL approach. A key aim of the project is to provide scientific backing for an estimation of the electricity generation potential of OFPV. The analysis conducted allows to determine curtailment losses as a function of scaling relative to the power of a given wind farm, and thus an economic calculation of the potential earnings based on target costs. This is complemented by a grid analysis that takes into account the evolution of the electricity generation, consumption and pricing in the grid over the next decades; clearly this is based on current assumptions and variable by nature. On the positive side, OFPV in wind farms allows for the installation of large units in one go, while essentially no surface area is taken away from other uses, since offshore wind farms are off limits to most other uses, and e.g. fishing can continue regardless while maintaining sufficient safety distance. In this sense, it represents a benign way of deploying electricity generation technology. The biggest challenge, apart from various technical issues that need to be solved and environmental concerns, is to reduce the costs to a point where deployment becomes financially viable.

In this report, we are summarizing the main results of our research conducted between November 2021 and October 2023. We are finally suggesting some conclusions of the work of the last two years in this project, and some future directions of research.

2 Factors constraining size and power

From the outset, it is the goal of the project to combine OFPV with offshore wind farms, since they occupy large areas which are already off limits to shipping and most other uses. This enables the co-utilization of their existing grid connections, which represent a major cost item. When comparing the two types of systems, it becomes clear that solar systems can deliver a peak power per horizontal surface area of solar modules of approximately 180 W/m^2. This assumes that the modules are placed nearly horizontally; the reason lies in the cost relation between modules and carrying structure, and mechanical constraints. Existing Belgian wind farms have power densities between 7.5 and 18 W/m^2 relative to the total surface area. That said, the capacity factor (CF) of wind farms is much higher, reaching values of 32% to 45% for today's systems, and even up to 56% for novel, larger turbines. The CF of an OFPV system is approximated to be 10…12%.

The electricity generation by OFPV is to a high degree complementary to that by wind turbines, owing to opposing annual trends and the fact that times with high wind speeds tend to be less sunny and vice versa. We analyzed the time trends of wind and solar resources in detail at various time scales. Figure 1 shows this for monthly and weekly averages, respectively, for the Belgian Eastern wind zone. Details can be found in [1].

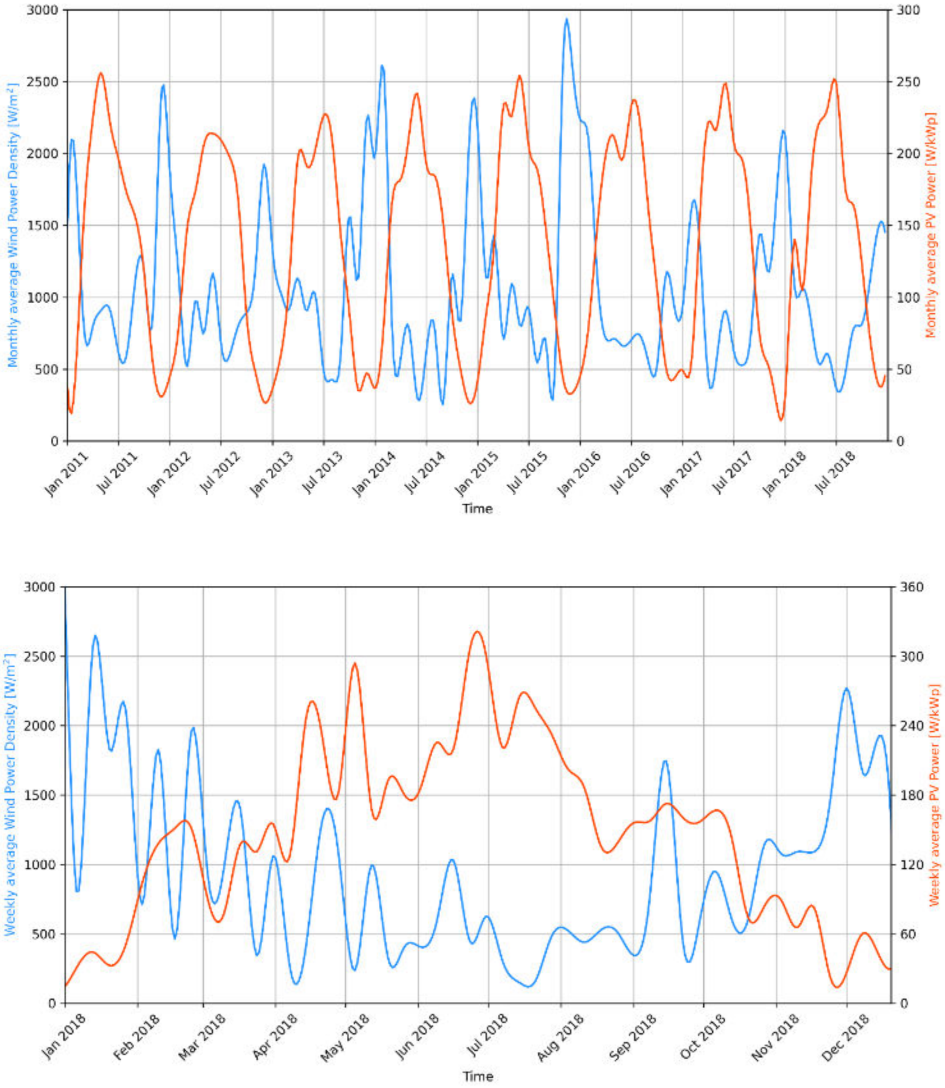

Figure 1: Examples of time trends of wind (blue) and solar (red) resources for the Belgian Eastern zone. Top: Monthly averages, years 2011…2018; bottom: weekly averages, 2018. From [1]

However, it is obviously impossible to fill the area entirely with solar panels owing to numerous reasons:

- The module area per area of structure is limited. Mutual shading has to be avoided, and areas for technical installations and maintenance access have to be foreseen.
- A safety distance to wind turbines needs to be maintained.
- A safety distance to shipping lanes for maintenance access to both the wind turbines and the OFPV system, and possibly for other uses, is necessary.
- Since a fixed ground-mounted installation seems prohibitively expensive, flotation and mooring systems have to be used which allow for some lateral motion due to drift and wind forces; both the extension of the mooring and the range of motion add to the safety distances.

- The grid connection imposes power limitations, leading to curtailment of power at times when both wind and PV power are high. They could only be overcome by installing additional transformers and cables to shore, albeit at high cost. – In principle, temporary offshore storage could alleviate the constraint, but this is both technically difficult and expensive. Note that we are considering the curtailed power as part of the PV power since the system was originally planned for wind turbines and we are aiming to work out the additional electricity generation by OFPV.
- Aside from offshore transmission limitations, congestion in the onshore grid may force the curtailment of offshore generators, lowering the number of hours that solar (and wind) power systems can supply electricity to the onshore grid and thus generate income. Onshore grid reinforcement is therefore of paramount importance for the scalability of offshore generators.
- There may be a maximal coverage of the surface for which biological impacts remain acceptable.

Assuming that we accept the limit imposed by existing grid connections, this represents the strictest limitation for installation in existing systems (“brown field”). For newly planned installations (“green field”), additional cable capacity can be foreseen in principle. In that case, given the low capacity factor of PV, a too high PV/wind power ratio would lower the capacity factor of the cable and thus increase the grid connection cost per unit of electricity, effectively creating a financial limitation of the viable share of OFPV in combined farms. Without added cable capacity, grid curtailment losses would increase since newer wind turbines with greater height and higher power feature higher capacity factors up to 56%. It is thus safe to assume that an area coverage by OFPV of more than 12% of the wind farm area is not beneficial. This means that the installable power per total surface area of PV is similar to that of wind turbines; more detailed analysis shows that a factor of 1.5 x may be achievable. Proactive thermal modelling of transmission cables is essential in this context to maximize the transmission of electricity and optimally allocate transmission space for solar and wind generators.

3 Categorization of design options

Across the world, different approaches for the structural design of OFPV systems are being followed. What became clear from the start is that structures that are used in inland waters are not applicable. There, mostly structures that use one flotation device per one or few PV modules are used. They generally lack the strength to cope with high waves and strong winds.

We conducted a comprehensive analysis of the published concepts for OFPV. Of the OFPV approaches being tested, low-lying pontoon types can be found, where the PV panels are placed near the water level. Further, there are various approaches with raised elevated truss structures, with the goal that the panels are protected from the impact of waves. Elevating the panels above the storm crest height should protect them from the impact of waves, thus lowering the requirements towards mechanical strength of the PV modules. Conversely, the requirements towards the stability of the structure may increase. A further design criterion is segmentation: some structures are built in single units, others are made to be combined into larger articulated structures, bringing up the need for flexible interconnectors that can withstand the forces they are exposed to.

Regarding placement of the PV modules, a south orientation is optimal to generate high energy yield per surface area of modules. However, for OFPV the structure is considerably more expensive than the modules, and in an overall optimization it is more important to generate the highest amount of energy per capex, shifting the maximization goal to energy yield *per area of structure*. South-facing modules at an angle of about 30° bring about a large aerodynamic drag, increasing the requirements towards the strength of the structure, and possibly the modules. They can also not be packed densely; a significant distance has to be kept between rows to limit mutual shading at low solar angle. These criteria lead us to favor horizontal or near-horizontal placement of the modules. An east- and west-facing configuration is thus chosen to broaden the daily time profile. We opted for an angle of 15° to ensure water run-off under all circumstances to limit soiling; the impact on energy yield is minimal. Furthermore, this configuration spreads the power generation in time throughout the day, aiding in keeping power peaks below the curtailment limit.

4 Placement of structures

There are several constraints relevant for the placement of OFPV systems in wind farms, with no definite rules in place as of yet. We inquired with several wind farm operators regarding limitations they see. Note that for the case of a PV-to-wind power ratio of 1:1, in an existing wind farm with 7 MW turbines, six of the 84-m OFPV structures would have to be placed per WT, whereas in a future system with 15 MW turbines it would be 13 units.

- OFPV systems should not be placed too close to wind turbines to limit shading losses, especially on the north side of the wind turbines.
- The OFPV structures must be placed at a safe distance from the wind turbines, such that even in the event of failure of a mooring line no contact can be made.
- Similarly, the OFPV structures may not come into contact with each other. This favors larger connected structures, since otherwise extra safety distance must be foreseen to account for horizontal movement.
- The mooring lines in their lower part (which could touch the ground) may not cross the cables that connect the wind turbines to the substation; these typically run along a chain of turbines, not necessarily in a straight line. This means that the OFPV systems have to be placed between these cables, i.e. a mooring line length (200 m) away, or they can be placed above the cables.
- Access to the wind turbines must be possible with crew vessels for maintenance, but also with large jack-up ships in case of major repairs, necessitating a maneuvering space around the WT. This can possibly be limited to one side (semicircle) of the turbine.
- A further complication arises from the distribution of wind turbines according to ground conditions and other limitations, i.e. the fact that they are not uniformly spaced.
- Shipping lanes for transportation outside the wind farm have a defined safety distance based on the potential deviation of ships from course and the size of ships

used. This is usually measured from the outermost turbines; consequently no OFPV systems can be placed on the part of the outer perimeter of the wind farms facing towards shipping routes.

- Shipping corridors need to be foreseen for all vehicles needing to reach the WTs, with a width of e.g. 200 m.
- Shipping within wind farms has to be allowed to a certain extent. E.g. the Dutch Code of Conduct allows access for ships of up to 24 m overall length. Safety distances of 50 m from wind turbines and 500 m from substations have to be maintained. Similarly, a safety distance will have to be defined for OFPV systems taking into account their possible movement.

Overall, these limitations present serious complications for the placement of a sufficient number of OFPV structures in a given wind farm, especially if the wind turbines are small and spaced closely. E.g. within the Rentel wind farm with its 42 wind turbines of 7.35 MW, about 230 of these structures would have to be placed. Rules will have to be devised for safe placement and operation.

5 Energy yield

We calculated the energy yield of OFPV systems based on bottom-up physical models, with the primary intention to determine the impact of environmental variables that are different from known conditions on land. While the lack of measured irradiances offshore as the biggest source of uncertainty cannot be fixed in this project, we were able to determine other impacts with an estimated accuracy of around ±1%. The combination of lower ambient temperature and higher wind speeds offshore compared to land has a positive effect of 1.6% in annual energy yield. In contrast, the bifaciality of the modules brings about no appreciable positive effect. Given that we aim for a large rigid OFPV structure, the swaying motion has little impact on the incidence angle and reduction of the average irradiance. Its reducing effect is estimated to be a small fraction of 1%.

Of larger impact is the shading by nearby wind turbines. Its negative effect is estimated to be between 1% and 1.5%. When the PV system is placed at a short distance north of the wind turbine, it could amount to 6%, which should be avoided for obvious reasons. Uncertainties in the factors mentioned above amount to another 1…2% uncertainty in the overall energy yield. Yield estimates are based on a combination of irradiance data measured onshore with satellite data. Similar measurements for land-based locations show an RMSE value of 9%. Should offshore irradiance meteorology become available, this value is expected to reduce considerably, with data recalibrated through onshore measurements reaching 1...2%. Note that, for generated electricity, this is of limited importance since the main limitation stems from the grid connection capacity. Influences do exist on the nominal power sizing, hence on costs, as well as on the time distribution of generation and corresponding time-dependent value, and on the exact onset of curtailment. Accounting for the fact that the costs of the floating structure are expected to be a small multiple of the costs of the PV modules, we consequently optimized performance per area of structure instead of module area.

6 Structural design

Based on a detailed analysis of information we were able to gather about the existing design approaches, we opted for a modular concept of square elements that can be combined to large structures. Given the limitation in PV string voltage, a useful size of one element is 14 x 12.5 m², with one element carrying one pair of strings of 25 modules each. They are arranged in five double rows of east- and west-facing modules with an inclination of 15°; between them are walkways to make the surface accessible and provide spacing to reduce mutual shading in the early morning and late evening. A favorable size of one deployable structural unit is then 6 x 6 elements, i.e. 84 x 75 m². The nominal (DC) PV power of such a structure amounts to 1173 kWp assuming a module efficiency of 21.6% (PERC modules). The maximal attainable power is about 80% of that owing to the angle of irradiance and temperature effects. Thus an inverter can safely be designed for approximately 875 kW (75% of the nominal PV power) without significant clipping losses. One central inverter has to be placed on each structure together with a transformer, occupying one of the 36 elements.

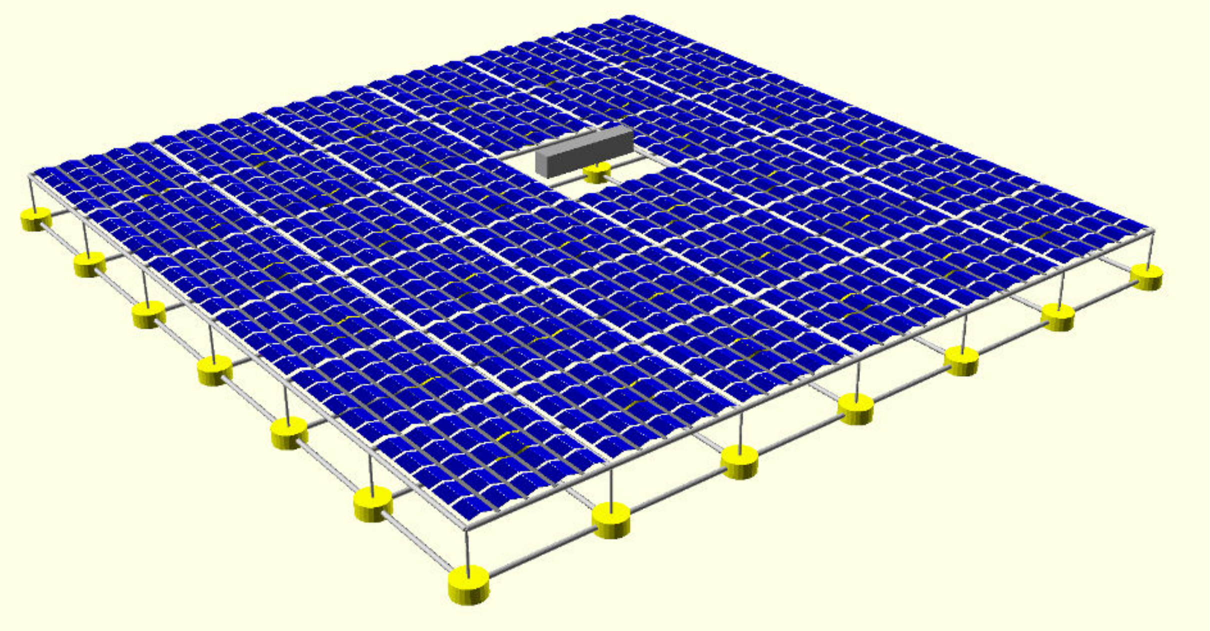

Figure 2: Full structure consisting of 36 base units

We opted for a raised design with a PV platform 7 m above the bottom of the floaters, and 6 m above the water level. Dynamic modeling predicts that the structure withstands the maximal wave motion expected for the Belgian sea with a 50-year wave height of 6 m, whereby the sway (horizontal) motion reaches up to 10 m and the heave (vertical) up to 4 m. The model is corroborated by tests that were conducted in the newly opened Coastal & Ocean Basin in Oostende with a structure scaled by 1:30, see Figure 3. The area covered by the system is considerably larger than the structure itself. We planned for a taut mooring, with lines extending 200 m radially from the corners of the structure. This entails that by the effect of drift and waves the structure can move laterally by a distance dependent on the water depth, e.g. ±20 m for a typical water depth of 20 m.

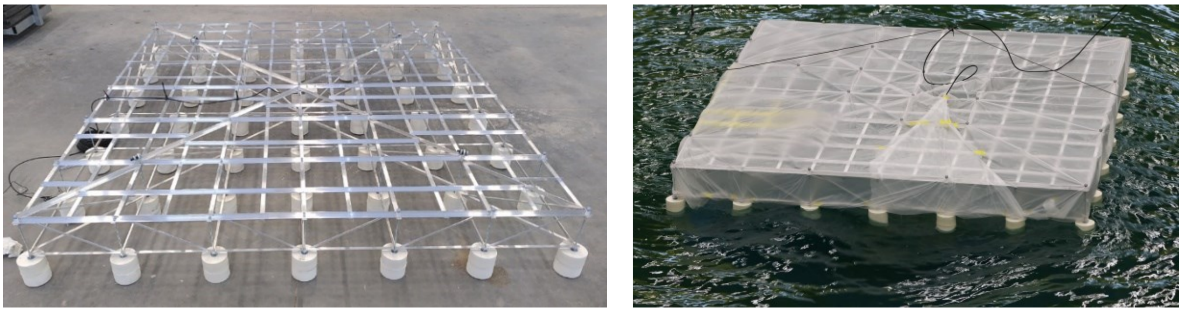

Figure 3: Built scaled model for hydrodynamic tests in the COB. Left: Aluminum structure with floaters. Right: Model under wave loads, equipped with tilt sensor and motion capture markers.

7 PV-electrical design

Generally, the fabrication of PV modules has been improved over the last two decades with respect to reliability, with more attention being paid to testing and qualification of design features as well as production monitoring. However, some recent trends in the design are critical with respect to reliability. This includes lower glass thickness, which increases the stress on cells under mechanical load and can lead to glass cracking, and thus eventual isolation failure. Further, lower cell thicknesses, larger cell areas, cut cells (with potential micro-cracks induced by cutting) and the reduction in silver quantity make cells more susceptible to cracks, contact delamination and power losses. Moreover, cell gaps are getting smaller, and contacts between wires and cell edge are possible with even a slight movement between stringing and lamination. On these design features, a somewhat conservative approach is recommended to ensure high reliability and long lifetime in the marine environment where repairs or replacement would be extremely cumbersome and costly, to the point where it would not be performed for few units, but rather as an overhaul of an entire system.

Towards realization, we are suggesting a structure that would allow deployment with moderate changes to the PV-electrical components compared to land-based systems, backed by our reliability analysis. This is important since any change in design triggers a cost increase, at least the module laminate should remain the same. We envision adding an edge sealing to the standard double-glass design in order to minimize moisture penetration and hence corrosion of the internal metal, and possibly the use of beams made from marine grade aluminum glued behind the modules rather than an edge frame. Most importantly, the standard “MC4” connector plugs need to be eliminated, since their design is problematic even for land-based systems and the sealing would not withstand a marine environment. To determine realistic costs of such a system, actual industrial design and procurement would be needed, which is not something the academic partners of this project can deliver. However, we believe that the suggested changes only trigger moderate cost increases if modules are purchased in sufficient quantities.

8 Environment

Environmental impacts have been screened and listed qualitatively, and quantified more precisely as concerns the impact of shading on primary production (as the reduction of solar radiation below water surface limits the photosynthesis by microalgae cells). Regarding the impact of shading, realistic OFPV deployment scenarios have been assessed in the frame of a tri-dimensional hydro-biogeochemical model of the southern North Sea, resolving primary production dynamics under realistic tidal, riverine, atmospheric and bathymetric influences. In summary, the impact of shading on water environmental variables (e.g. nutrient concentration, primary production, key elements of the carbon cycle) is reasonably low and amounts to perturbations of their natural seasonal cycle by fractions of a percent only. This is mostly due to the dynamic nature of the pelagic environment (water column) as tidal excursion ensures that the shading only affects a given parcel of water for a limited fraction of daytime. In contrast, local shading impacts on benthic state variables (i.e., related to the seafloor), such as the reduced deposition of organic matter following lower local primary production, might accumulate over years in the OFPV concessions, and lead to an offshore transfer of benthic carbon stocks that remains to be evaluated at decadal time scales. Yet, careful judgement and assessment in demonstration systems will be needed to further address aspects not considered quantitatively in this project.

In particular the introduction of a large amount of submerged hard structural surfaces is concerning, as these will be colonized by “hard substrate” organisms that do not originally belong to these locations and of which some are known for the intensity of active ecological functions (e.g. filtering by mussels). First scaling computations show that the total submerged surface of OFPV deployment projects might reach 20 times that of current wind farm projects, where a significant impact of hard substrate organisms has already been documented. From a technical perspective, surfaces that do not have a technical function may be exposed to settlement of species, especially since there are hardly any proven, environmentally benign, methods of preventing it. Only for active components, prevention or removal is necessary. This concerns obviously the active PV surface, but also ropes, cables, doors, hatches, hinges and fixtures.

Clearly, this should be the focus of the next investigations in this field, before large deployments are committed: Firstly, to study in an integrative way (regional scale, interactions with other environmental components) the effect of introducing organisms and ecological functions in a place where there are currently absent (near surface in OWF concessions); second, from there, to derive how to mitigate the negative impact (e.g. by removing them), and potentially how to exploit positive impacts in the frame of nature-based design concepts; third, how to clean surfaces that need it in a technically safe and environmentally benign way.

9 Electricity generation and finances

We have provided a methodology for estimating the optimal size of OFPV installations based on the expected future revenues that can be achieved as well as the cost of installation of OFPV plants. For the analysis at hand, which is based on the market assumptions of the ENTSO-e TYNDP 2020, a positive business case for OFPV can only be observed if the cost of investment and installation can be kept below 1.6 M€ / MWp as seen at the connection point of the offshore substation transformer. If the costs can be kept below 1.3 M€ / MWp, OFPV plants and offshore wind farms can both be sized up to the rated capacity of the grid connection. For having a positive business case the LCOE of the OFPV would need to be kept below 66 € / MWh under the taken market assumptions. However, such analysis needs to be repeated with more up to date pricing information for actual investment decisions, which could be done using the developed optimization models. From the results we can observe that for any range of investment and installation cost OWFs are lucrative to be installed up to the available connection capacity. For OFPV installations there is a point where the investment and installation costs do not allow for a positive business case. Thus, there is a long way to go before OFPV can reach power levels akin to offshore wind.

Table 1: Summary of generation potential of OFPV in the Belgian EEZ compared to current consumption and generation for two power ratios

Nominal OFPV power vs. wind		1:1	1.5:1
Electricity consumption, BE, 2022	TWh/a	87	
Current installed capacity, wind	GW	5,3	
Current installed capacity, PV	GW	8,6	
Electricity generation, wind, 2022	TWh/a	12,07	
Electricity generation, PV, 2022	TWh/a	7,35	
Total OFPV potential power, Belgian EEZ	GW	5,8	8,6
Total OFPV potential energy generation, Belgian EEZ	TWh/a	4,75	6,26
Curtailment losses (of PV energy)		9%	20%
OFPV coverage of energy consumption		5,5%	7,2%
Energy yield ratio vs. wind		19,9%	26,2%
CO_2 emissions avoided (estimate)	kt	380	501

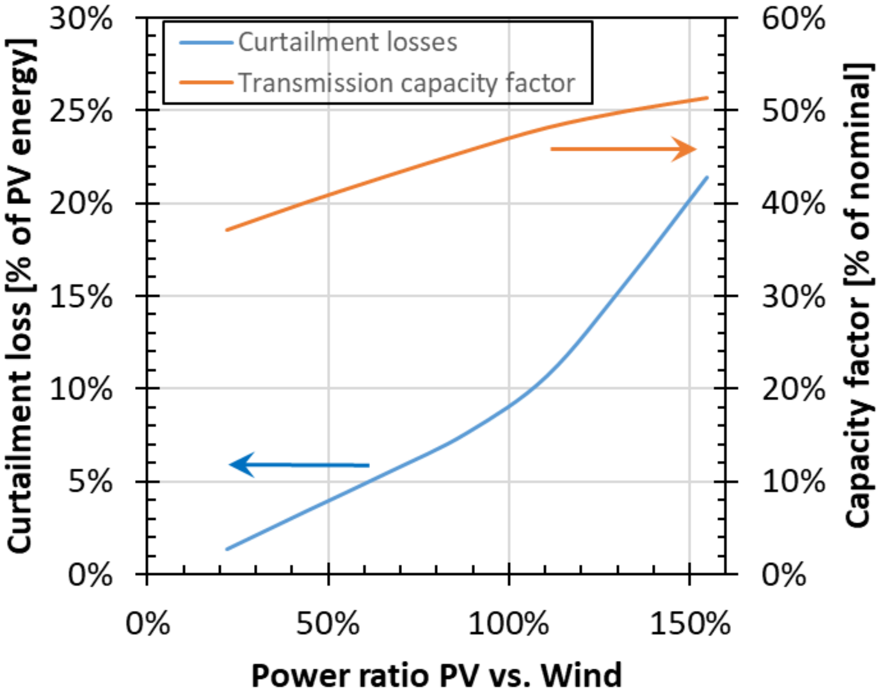

Figure 4: Curtailment losses and cable capacity factor as functions of the power ratio with the nominal power of wind farms equalling 100%, assuming a fixed cable load limit

If OFPV plants would be installed in all Belgian wind farms in both the Eastern (existing) and the planned Western (Princess Elisabeth) zones with the same nominal power as that of the wind turbines, an additional 4.7 TWh of electricity could be generated per year. If the scaling factor relative to wind was 1.5, this would even reach 6.6 TWh/a, compared to 7.4 TWh/a generated by all existing PV installations to date. I.e. OFPV could cover 5.5% respectively 7.2% of the Belgian electricity consumption of 2022 (87 TWh), adding 20…28% to the electricity generated by offshore wind farms. Table 1 puts these values in comparison with existing electricity generation and consumption. According to our study, curtailment losses would be approximately 9% or 16%, and the systems would cover 7% or 10% of the area of the wind farms, respectively. Smaller installations would suffer less from curtailment, since its dependence on the power scaling is slightly superlinear, as Figure 4 shows.

10 Future directions

Within the present project, we did the possible within the scope and resources at hand. Yet, there is need for more research and development in several areas:

- The development of prototypes for OFPV by several companies has progressed in the last two years, thus our SWOT assessment would deserve an update informed by first results of the test installations, to identify the most promising concepts.
- Placement constraints need to be worked out in more detail; this will require the input of several stakeholders to derive rules for safe and practical deployment.
- The work on design-for-reliability of the PV modules should proceed to prototyping and testing of modules with new features.
- More work is needed on mooring and anchoring in order to find solutions that take up less space, are efficient to install and environmentally benign.
- The effect of dynamic shading by wind turbines needs to be analyzed in detail, to resolve the dynamic impact on losses, necessary adaptations of the power converter and potential impact on reliability.
- Environmental effects need to be studied further with respect to the large submerged surface that OFPV systems generate and organisms growing on it, both by modeling and, ideally, testing.
- Cleaning of active surfaces is a necessity, and ways must be found to do this in safe, benign and automated way.
- The cables to shore have dynamic limitations, allowing for higher power transmission for short times, but limiting power below nominal values over long periods. A more concise thermal model is needed to account for this and refine the curtailment limit for an optimal dynamic operation of the transmission capacity.
- OFPV power generation should be integrated into national and supranational grid planning to identify limitations and account for impact on value generation.
- OFPV should be considered as an option when planning new wind farms, as well when considering repowering of existing ones that reach the end of their useful life, by foreseeing proper connection points and transmission capacity.
- Electrical architectures enabling efficient and reliable power conversion for such hybrid offshore solar-wind systems are not established and require further study.

- Lastly, local meteorology to determine the solar resource offshore with better accuracy is highly desirable.

Given the results and the identified need for regulations, we are aiming to give input to the Marine Spatial Plan 2026+ in order to put OFPV firmly on the map and define boundary conditions that allow deployment of this powerful technology while maintaining safety and minimizing the environmental impact.

Acknowledgements

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[1] Oscar Delbeke, Jens D. Moschner, Johan Driesen, The complementarity of offshore wind and floating photovoltaics in the Belgian North Sea, an analysis up to 2100, Renewable Energy 218, 2023; https://doi.org/10.1016/j.renene.2023.119253

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