Deltares

Impact of offshore floating solar on the marine environment

Review

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Client	Merganser-DEI Project Consortium
Contact	D. Hoogendoorn
Reference	
Keywords	OFPV, solar energy, environmental impact, literature review

Document control	
Version	1.0
Date	25-10-2023
Project nr.	11208338-000
Document ID	11208338-000-ZKS-0008
Pages	31
Classification	
Status	final

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Summary

This literature review aims to identify the main impacts of offshore floating photovoltaic (OFPV) installations for the marine environment, with a focus on the southern North Sea. It discusses the impacts on hydrodynamic processes, suspended sediments and oxygen, primary producers, primary consumers, and higher trophic levels. In addition to the impacts on the natural system, the review also considers the impacts on other offshore users (offshore wind farms, aquaculture farms, sports and recreation as well as fisheries).

Implications of OFPV include the blocking of wind and solar radiation, changes in turbulence and mixing within the water column, and the associated impacts on sediment resuspension near the seabed. These could affect the light- and nutrient-availability experienced by the primary producers, and result in the blockage of feeding appendages or burial of some marine species. The OFPV structures may also provide new habitat for sessile species including primary or secondary consumers, which could shift the competition within the entire food web. Furthermore, the new habitats may result in increased connectivity between different populations, which could increase their vulnerability to parasites, viruses or exotic species. For species at higher trophic levels the construction and maintenance of the OFPV installations may disturb their foraging and migration behaviour. It may, however, also provide additional resting spaces for birds or shelter for fish, which may locally attract them, but may in turn also have consequences for the local lower food web.

This review highlights that OFPV may have many different, opposite, and interactive implications on the environment, while only little relevant literature is available. This makes it currently very difficult to draw general conclusions even about the net direction of the impacts. For the primary producers, the various implications largely depend on the OFPV design as well as on the local situation, and particularly on scale, but the local net effect is likely to be either neutral or negative. For planktonic primary consumers a (neutral or negative) local effect is expected, since they depend on primary producers as their food source. For sessile primary consumers, there may be neutral or negative effects due to impact on the food, but there may also be positive effects due to more available settling habitat high up in the water column. For higher trophic species, the net impact will largely depend on their taxon or ecological guild and the associated foraging or migration behaviors.

In addition to their local effects, OFPV installations may also have consequences for downstream areas. Similarly, for higher trophic levels, a local change in individuals may (or may not) have consequences at the population level. Moreover, the net impacts, positive or negative, will also very likely be strongly scale dependent. The many knowledge gaps stress the need for pilot studies and data collection, as well as for integrative modelling studies.

With respect to the interactions with other users, it should be noted that OFPV installations are not suitable for direct co-location with all types of users, like aquaculture, water sports, and some types of fisheries. OFPV could affect fisheries also indirectly via their influence on fish populations. When OFPVs are co-located within wind farms, as is the planning in the Netherlands, the interaction with tourism will be limited.

Although the above stated difficulties in drawing general conclusions on the environmental impacts of OFPV, the literature review does serve as a basis for providing several recommendations and guidance notes on mitigation.

Contents

1 Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states a continued rise of total net anthropogenic greenhouse gas (GHG) emissions. To limit warming to 1.5 °C, global GHG emissions should peak at the latest before 2025 and immediate actions towards climate mitigation should be taken (IPCC, 2022). Consequently, the EU has set targets to cut GHG emissions by at least 55% by 2030 (compared to 1990) and to be fully carbon neutral by 2050 (European Commission, 2023). The transition from fossil fuels to renewable energy is seen as one important pathway to reach those targets (European Commission, 2018).

However, several obstacles are still in the way of a successful energy transition. The most obvious ones are space availability, the amount of generated renewable energy, the supply chain and acceptance by the public. Floating photovoltaic could offer a solution to some of those obstacles. Floating photovoltaic can either be installed on inland water systems or offshore. The development and deployment of inland floating photovoltaic has already been tested over the past decade, while offshore floating photovoltaic (OFPV) is still a new research field. Therefore, a short introduction to both inland and offshore floating photovoltaic will be given below.

In addition to the benefits, it is important to consider the environmental implications of OFPV installations and to decide if their benefits outweigh their costs within a marine system. Currently, the Merganser-DEI Project Consortium is running an R&D program on the Merganser design which includes such an environmental impact study. In this context, the consortium has asked Deltares to identify the main implications of OFPV installations on the marine environment by means of a literature review, which can be found in this report. Most of the described implications would apply to any marine system, but a particular focus in this review is on the southern North Sea. Also, OFPV installations have a range of designs, which may again have similar impacts on a marine system. However, this report focuses on a design with panels that are not in direct contact with the sea surface, but instead are elevated by floating devices (e.g. Figure 2b). In addition to the impacts on the natural system (Chapter 2), also the interactions of OFPVs with other users are being discussed (Chapter 3).

1.1 Inland Floating Photovoltaic

Over the past few years, a significant growth in the deployment of floating PV systems has been observed worldwide, from an installed capacity of 10 MWp in 2014 to about 2.6 GWp in 2020 (Bax *et al*. 2022). In the Netherlands, approximately 230MWp of floating solar have been installed by 2022 (TNO internal database). In some scenario’s this may increase to 70 GWp by 2050 of which 45 GWp would be located offshore (TNO and TKI Urban Energy). A Watt-peak is a unit of electrical power to quantify the total energy output from solar or nuclear plants, for example. It is the maximum electrical power that can be supplied by a photovoltaic panel under standard temperature and sunlight conditions. Currently, the larger part of the floating solar panels is implemented on inland waters. The implementation started with small water bodies, such as sewage treatment plant basins, that do not directly impact larger water bodies and nature reserves. Nowadays, also larger isolated water bodies such as sand pit lakes have been selected to accommodate floating PV parks. The expectation from organisations such as STOWA, Unie van Waterschappen and Rijkswaterstaat is that also water systems with other functions, such as recreation, will be designated as locations for floating PV systems.

Despite existing concerns on the effects of floating PV systems on water quality and ecology, the speed of implementation exceeds that of the production of knowledge of their impacts. The few case studies show the following effects of inland floating PV: 1) a decrease of water temperature (Chateau *et al*. 2019; de Lima *et al*. 2021; Ziar *et al*. 2021), 2) a decrease in oxygen production (Chateau *et al*. 2019; Andini *et al*. 2021; Al-Widyan *et al*. 2021), 3) a decrease in evapotranspiration (Al-Widyan *et al*. 2021; Kumar & Kumar 2020), and (4) a decrease in aquatic plants, algal biomass and/or chlorophyll concentrations (Andini *et al*. 2021; Al-Widyan *et al*. 2021; Ziar *et al*. 2021). Effects on organisms of the (higher) food web are not yet reported in scientific literature (Exley *et al*. 2021).

However, impacts of inland floating PV are expected to be different from those of OFPV, since inland floating PV are typically located in relatively small, shallow, and/or enclosed water bodies without a current. Under these conditions, a higher solar panel coverage may be achieved relative to the water body, but also within the (inland floating) PV farm itself (because smaller mooring and safety zone areas will be required). Higher coverage will lead to larger impacts, because in general, the greater the proportion of surface area covered, the greater the influence (Jones 2018). Also, in enclosed and/or stagnant water bodies, the local impacts are not diluted by or compensated in surrounding waters. Furthermore, inland water systems are usually more eutrophic than offshore areas, leading to a larger oxygen demand which in combination with a reduced air-water exchange will be more likely to result in anoxic conditions. Overall, it can be hypothesised that the relative impacts of inland floating PV will on average be larger than those of OFPV. It must be noted, however, that some of the above arguments may change as a result of new technologies (when e.g. resulting in coverage ratios for OFPV that are similar to inland PV), or under conditions of upscaling (which may cancel out the benefits of exchange with surrounding waters).

1.2 Offshore Floating Photovoltaic (OFPV)

Compared to inland floating PV, the development, deployment and research into the effects of OFPV are still in its infancy. In general, the offshore environment is deeper as well as rougher with stronger waves, surges, wind and currents. This means that the structures to which the panels are attached need to be larger, more weather- and corrosion resistant, and different associated impacts on the offshore ecosystems are expected (see Chapter 2). Furthermore, by being located offshore, the OFPV would also not be visible from land to disturb the coastal landscape.

Within Europe, there are multiple companies leading the field of OFPV: SolarDuck, Oceans of Energy, OceanSun, SeaVolt, Bluewater and Moss Maritime. The technical implementations of OFPV vary between these companies and may result in different impacts on the marine ecosystem. In general, a solution with a smaller light blocking area (solar panel + walkways) is expected to result in a smaller environmental impact (Jones 2018). In general, a solution with elevation is expected to result in lower disturbance of the wave and sea-air interaction and will block less indirect light.

SolarDuck designs OFPV as flexible connect triangles that are elevated to avoid wave impacts (Figure 1a; SolarDuck, 2023), while SeaVolt and Moss Maritime develops rectangular, elevated floating structures (SeaVolt, 2023; Moss Maritime, 2023). OceanSun's OFPV mimic aquaculture rings and float directly on the water surface on a think membrane (Figure 1b; OceanSun, 2023), while Oceans of Energy and Bluewater install OFPV on rectangular matrasses that also float directly on the water surface (Oceans of Energy, 2023, Bluewater, 2023). Figure 1presents different technical implementation of OFPV.

A) b)

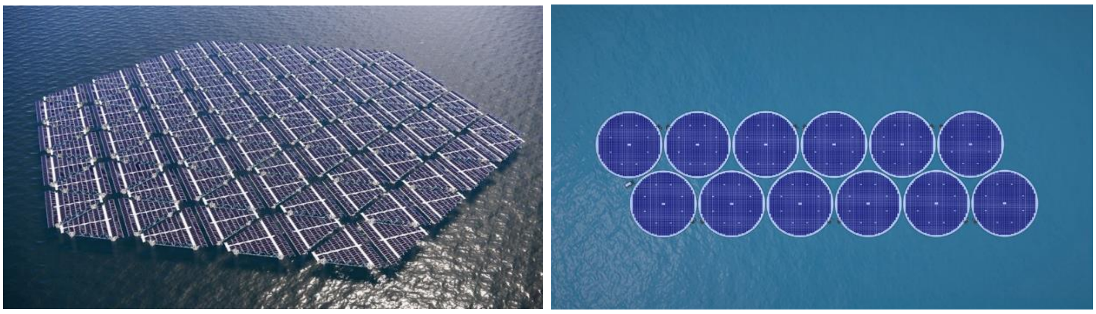

Figure 1: A comparison between the SolarDuck design (a) (10 MW – triangular elevated solution existing of 96 connected platforms, source: SolarDuck) and the OceanSun design (b) (7,8 MW – 12 floating membranes of 0,65MW per membrane. source: https://oceansun.no/our-products/). The SolarDuck OFPV are elevated above the sea level, while the OceanSun OFPV are floating on the water surface.

2 Impacts of OFPV on the Marine Environment

The base of marine ecosystems is primarily driven by hydrodynamics, which in turn are influenced by tides, density differences in the water column and by meteorological conditions. Furthermore, interactions between the different ecological compartments play a vital role in the functioning of a marine ecosystem. Figure 2 presents a simplified overview of the environmental and ecological interactions that influence the functioning of a marine systems, once without OFPV (Figure 2a) and once including an OFPV installation (Figure 2b).

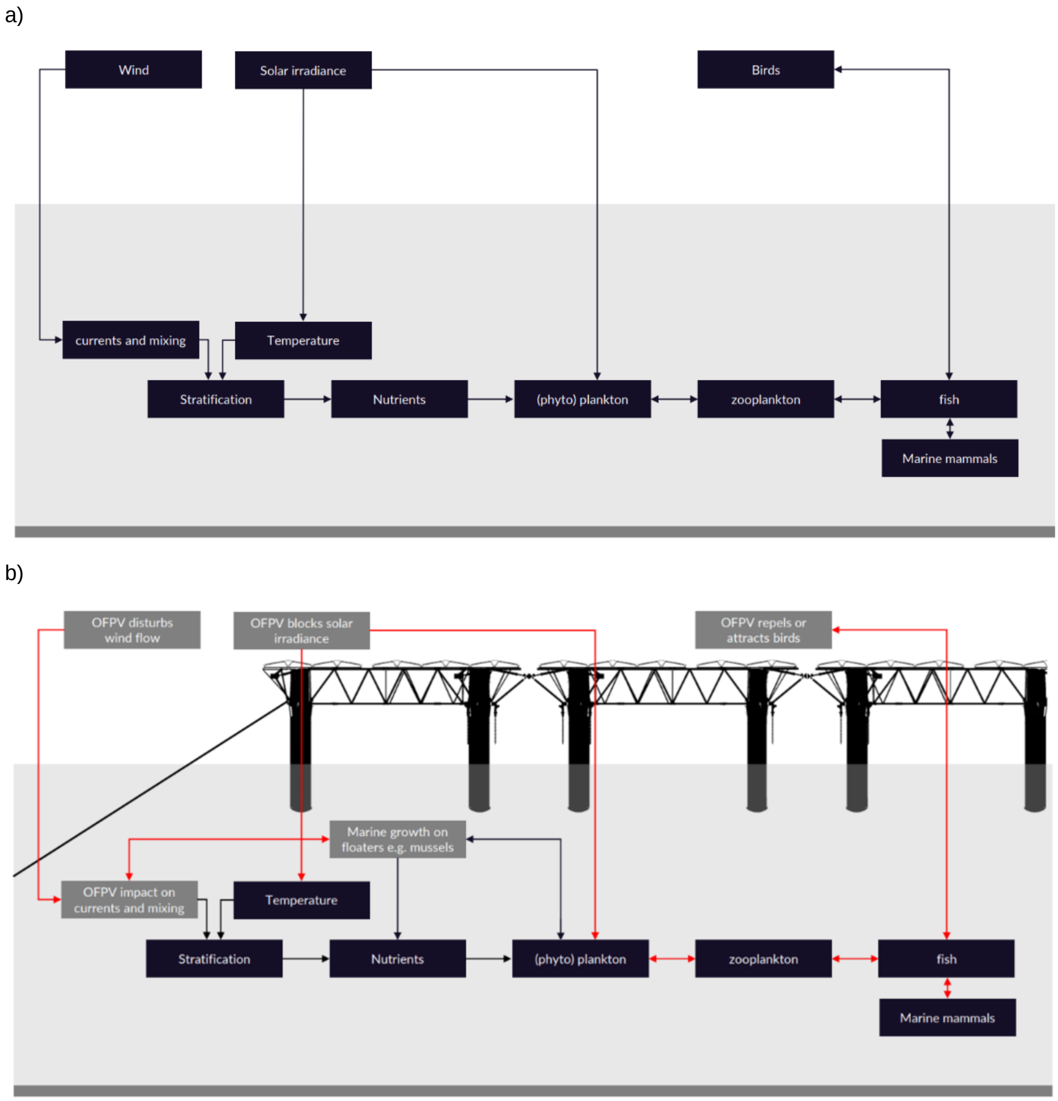

Figure 2: A simplified overview of the environmental and ecological interactions that influence the functioning of marine ecosystems, once without OFPV (a) and once with a OFPV installation (b). In (b), the red arrows represent the primary knowledge gaps of the impact of an OFPV installation on the marine environment.

In a natural marine ecosystem (Figure 2a), solar radiation and wind directly influence the sea surface temperature, the surface currents and mixing, and thus impact the development of stratification. Stratification in turn influences the availability of nutrients in the photic zone of the marine system and the mixing depth of the algae. Nutrients along with sunlight drive the growth of primary producers, phytoplankton, which are grazed on by primary consumers, zooplankton. This forms the base of the marine food web, which in turn provides direct or indirect nutrition for higher trophic levels, including fish, birds and marine mammals.

When OFPV is installed in a marine ecosystem (Figure 2b), two main changes occur. Firstly, OFPV blocks the air-sea interactions, such as solar radiation and wind, and secondly, the floaters and anchor lines of the OFPV introduce substrate into a previously unobstructed environment. These changes potentially influence currents, mixing and stratification as well as the growth of primary producers, while also providing a settling surface for benthic organisms. As OFPV is a new concept, not much research has been done on its impact on the marine system and many knowledge gaps exist, marked with red arrows in Figure 3. These knowledge gaps can be grouped into three categories, namely 1) the hydrodynamics, 2) the base of the marine food web and 3) the higher trophic levels. Figure 3 depicts the processes of these first two categories in more detail, i.e., the impact of OFPV on the hydrodynamics and on base of the marine food web. Only once the knowledge gaps of these two categories are resolved, can the full impact of OFPV on higher trophic levels be determined.

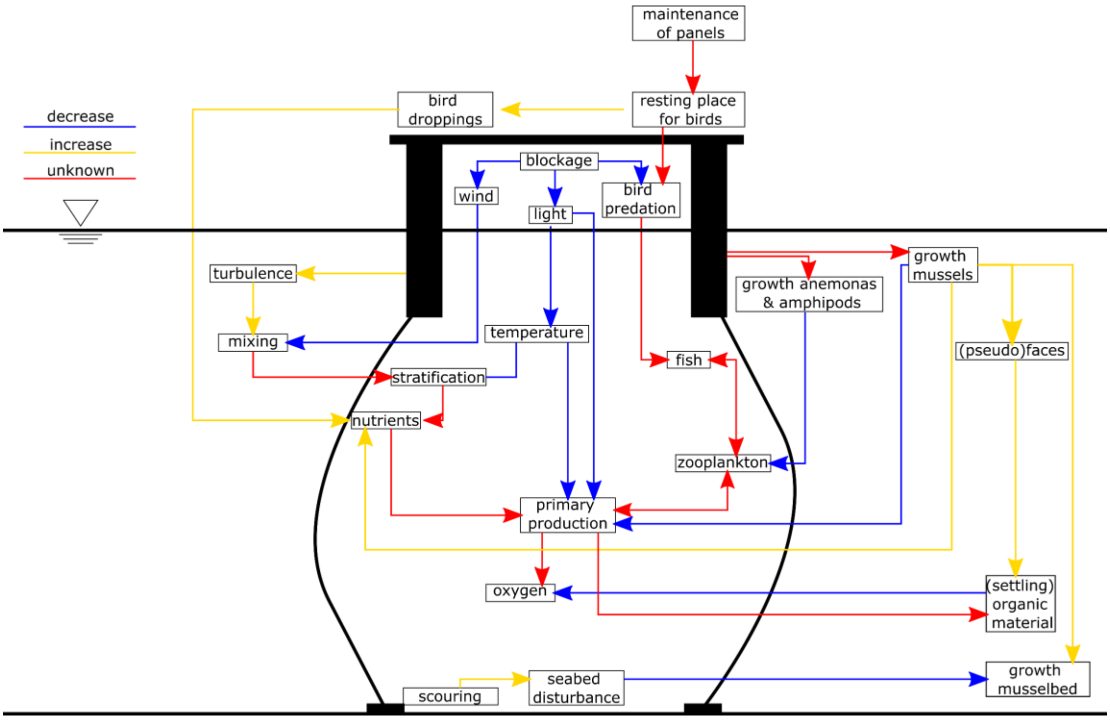

Figure 3: Detailed overview of how OFPV could impact the ambient hydrodynamics and the base of the marine food web. The blue arrows represent expected decreased effects of OFPV, while the yellow arrows illustrate an expected increase. Red arrows highlight unknown effects, due to primary knowledge gaps.

Building upon Figure 2 and Figure 3, the following sections will provide a more detailed description of how OFPV could potentially influence the different components of a marine ecosystem. Because of limited previous research on OFPV and on its impact on the marine environment, research on inland floating PV as well as offshore fixed wind will be used to draw comparisons.

2.1 Hydrodynamics and heat exchange

In a natural marine ecosystem, temperature and salinity gradients can create a stratified marine environment. This means that a two-layered system develops: a euphotic surface layer and an aphotic bottom layer. Due to the abundance of light, nutrients usually limit phytoplankton growth in the euphotic layer, particularly during summer (e.g. Obata *et al*., 1996), while the aphotic layer is (relatively) nutrient-rich but light-limited. This stratification is the primary productivity driver in many marine systems (e.g. Dave and Lozier, 2013).

OFPV has the potential to impact three primary mechanisms that govern temperature stratification, namely the turbulent kinetic energy (TKE), the wind stress (i.e. momentum exchange from atmosphere to water) and the heat exchange between the atmosphere and the ocean. In the first case, OFPV structures such as floaters and anchor lines obstruct the currents which will most likely lead to additional shear stress and TKE near the surface (Karpouzoglou 2020) and near submerged anchor lines. Large OFPV structures may however also reduce turbulence, by preventing wave generation and by reducing the vertical air-water exchange of momentum though impact on the wind speed profile. Monopiles have been shown to increase the TKE in offshore wind farms (Carpenter *et al*., 2016). A modelling study on the North Sea showed that in turbulent, shallow environments, the additional TKE of monopiles could increase the resuspension of sediments, which would decrease the light availability within the water column and result in reduced primary production (Zijl 2021). However, when the environment is stratified and deeper, additional mixing may increase the nutrient availability and thus the primary production, although these effects may be very patchy (Zijl 2021). In some areas, however, additional mixing could potentially also *reduce* primary production when primary producers are being mixed below the euphotic zone, which enhances their light limitation. Although anchor lines are different from (and notably smaller than) monopiles, their effects are expected to show overlap, especially since multiple anchor lines are needed per OFPV. More research is needed to find out and quantify their specific differences, but the impacts are expected to be proportional to the summed diameters of the anchor lines, and as such their relevance can be compared to e.g. those of the co-located monopiles. Overall, the net impact of additional TKE introduced by OFPV on primary production may either be positive or negative, and depends on the OFPV design, size, local bathymetry and stratification situation.

Secondly, the OFPV structures could decrease the wind friction at the sea surface, and (if implemented at a large scale) lead to altered surface circulation and wave patterns (Karpouzoglou 2020). Depending on the OFPV design the surface friction could also increase, especially in a tidal environment, due to the floaters creating drag on the water surface. In addition, wind also acts as a transport medium for suspended particles. Particularly in low-nutrient and low-chlorophyll regions, such as the Mediterranean Sea, iron is introduced to the marine system with the wind in the form of land-based Sahara Desert dust and it has a great influence on the local productivity (Pulido-Villena *et al*., 2010). By reducing wind friction, large scale OFPV could potentially alter the timing or spatial distribution of dust deposition and the associated primary production, although the dust will be washed off during cleaning; the actual impact will thus depend on the extent of the upscaling and the cleaning frequency.

Thirdly, OFPV creates a barrier between the oceanic and atmospheric longwave and shortwave radiation exchange. Solar radiation is blocked, reducing the light availability in the water column and heat from the ocean is trapped at the sea surface. Additionally, the solar panels may give off heat when they are warmed by the sun, warming the sea surface temperature. Should the OFPV float directly on the water surface, then the panels could transmit extra heat into the water column (Kjeldstad *et al*., 2021), increasing the sea surface temperature and the stability of the stratification. However, should the panels be mounted on floaters, then no additional heat would be transmitted via the panels, but a blockage of radiation and heat exchange would still occur (Karpouzoglou 2020). This blockage could decrease sea surface temperatures and thus discourage stratification (Jones 2018). Due to the complexity of the surface water heat balance, and its dependency on the design of the OFPV as well as on the local environment, the overall direction of impact from the OFPV on sea surface temperature and stratification is not always clear. While it might be plausible that on average the presence of solar panels will lead to lower water temperatures, this might thus not always (in time and space) be the case. Also, it must be noted that only the local surface waters are affected, which could change the vertical gradient or mixing patterns and/or enhance phenological mismatches with dependent species in the surrounding (warmer) waters.

2.2 Substances of special interest

2.2.1 Suspended sediments

Suspended sediments are an important factor determining the light availability within a marine system. They can be divided into coarse sediments, which have a high sinking velocity, and fine sediments, which can be suspended in the water column and are transported with the currents (Gayer *et al*., 2006). Anthropogenic activities within marine systems often lead to the disruption of the sediment balance (Gill, 2005) due to construction, scour of anchor lines or decommissioning. This resuspension and transport of fine sediment could result in the burial of sensitive habitats, such as seagrass meadows, even if the source of resuspension is not in direct vicinity of such habitats (Benham *et al*., 2016). A modelling study on offshore wind farms (OWF) in the North Sea by Zijl *et al*. (2021) showed that changes in bed shear stress and vertical mixing due to monopiles may change the vertical distribution of the suspended sediments over the water column. Net effects differ per scenario and area, but may be of the same order of magnitude as some present large-scale interventions such as MV2, sand mining and the release of dredged material. Also, they may be visible beyond the scale of individual wind farms. For example, model results show that upscaling OWF could reduce the longshore sea surface concentrations of suspended matter up to 10% near Texel, which may influence fine sediment transport towards the Wadden Sea (Zijl 2021). OWF in the Rhine ROFI were also analysed by Brandao *et al*. (2023) with satellite images, where no impact on the suspended sediment concentrations was detected. As mentioned above (section 2.1), anchor lines differ from monopiles, and more research is needed to find out and quantify their specific impacts. For resuspension, especially the 'touchdown area' of the mooring line will be of relevance. This area will depend strongly on design, with catenary systems affecting a much larger sea floor area than taut systems.

2.2.2 Oxygen

Since oxygen is a by-product of primary production, any effect on primary producers (see section 2.3) may also impact the oxygen levels. Furthermore, panels that are in direct contact with the water may prevent oxygen exchange with the air and/or may increase the oxygen demand due to epifauna growth. In inland locations, solar panels have indeed been reported to decrease the oxygen production (Chateau *et al*. 2019; Andini *et al*. 2021; Al-Widyan *et al*. 2021).

However, the impact of OFPVs on oxygen levels is expected to be smaller than for inland installations, because of their smaller solar panel coverage ratios, but also because the oxygen demand of the marine waters is typically smaller than that of (often eutrophic) inland waters, and the currents in offshore locations lead to smaller or intermittent residence times under the OFPVs allowing oxygen to be replenished from adjacent areas. Of course, when the OFPVs are scaled up to cover large areas, larger impacts cannot be ruled out.

Another potential impact of OFPVs on oxygen would be driven by changes in stratification. Under stratified conditions, fresh oxygen from the air cannot reach the deeper (aphotic) water layers. As a result, the decay of organic matter may deplete the available oxygen and lead to local anoxia. Depending on the net impact OFPVs on stratification and the local (water and seabed) oxygen demand, the frequency and duration of anoxia events may thus be increased or reduced.

2.2.3 Contaminants

During cleaning and maintenance of the OFPV systems, contaminants that are being used can be introduced into the water (Pimentel Da Silva and Castelo Branco 2018).The ecosystem impact will strongly depend on which and how many chemicals are used. To mitigate these impacts, some companies may choose to clean their systems without chemicals.

Damaged solar panels may also introduce toxic substances and/or heavy metals into the marine environment (Espinosa et al, 2016). To avoid oil-leaks from the transformers, dry (i.e. oil-free) transformers may be used instead. The risk and impact of leaching from the solar panels will strongly depend on its material, as well as on the OFPV design which determines the exposed surface area. For instance, galvanized steel or certain antifouling coatings may leach zinc, nickel, and chrome into the water, which are known to affect the marine organisms (Nijs et al., 2008; Robinson & Meindl, 2019; Hossain & Rakkibu, 1999). In contrast, aluminum will not leach but form an aluminum oxide layer which will stay attached to the floater surface. Leaching of toxic chemicals from plastics will vary with plastic type (Zimmermann *et al.,* 2021).

2.3 Primary Producers

Primary production within marine systems is driven by the availability of light and nutrients, temperature and grazing pressure by primary consumers. The primary producers can be either planktonic, i.e. phytoplankton floating within and transported through the water column, or sessile, e.g. macroalgae or seagrass. Sessile primary producers can reside on a substrate anywhere within the water column if they have sufficient access to light and nutrients. Depending on their lifestyle, each primary producer type is impacted differently by anthropogenic activities.

2.3.1 Phytoplankton

Phytoplankton form the base of the marine food web. They have a low biomass, but a high rate of turnover and production (Falkowski *et al*., 1998). During the winter months, light availability usually limits their growth, as nutrients tend to be introduced into the surface with increased vertical mixing. Towards summer and with the onset of stratification, phytoplankton then often become nutrient limited instead. Being the base of the marine food web, phytoplankton are also subjected to high grazing pressures from primary consumers (e.g. Baars and Fransz, 1984). As already stated in the above sections, the light as well as nutrient availability might be impacted through OPFV installations, which would impact the phytoplankton communities.

Light availability determines the amount of energy that is available for phytoplankton to convert inorganic carbon (CO_2) into organic forms of carbon (Field *et al*., 1998). In a modelling study on three locations of the North Sea, Karpouzoglou (2020) showed that the light availability has a direct correlation with the OFPV coverage. Because phytoplankton can be transported with tides and currents, the study also takes the tidal excursion area into account. In their analysis, they determine that a coverage of OFPV exceeding 40% of the tidal excursion area will lead to significant decreases in primary production. For inland floating PV similar impacts of light availability on primary production have been observed (Jones, 2018; Andini *et al*., 2022). In addition to the direct blockage of light, OFPV may affect light availability also indirectly via its effect on suspended sediments (see section 2.2.1). A modelling study on the North Sea showed that in turbulent, shallow environments, wind farms could increase the resuspension of sediments resulting in reduced primary production (Zijl 2021).

Nutrient availability also drives the growth of phytoplankton. Phytoplankton require a specific nutrient ratio and if any of these nutrients becomes limiting, this will impact phytoplankton growth. As mentioned in previous sections, OFPV has the potential to impact stratification of the water column and thus also the availability of nutrients (Zijl 2021). If OFPV enhances stratification by blocking air-sea exchange, specifically solar radiation and wind friction, nutrients would be limited sooner and primary production would decrease. However, if OPFV results in an earlier breakdown of stratification through additional TKE, this could enhance primary production, unless the algal mixing depth is increased to result in light limitation. Thus, the direction in which OFPV will influence stratification and therefore nutrient availability will depend on if the dominant process is the blockage of air-sea exchange or the additional TKE, and to which extent TKE occurs. Zijl *et al*. (2021) showed that for stratified and deeper areas in the North Sea, increased mixing and ditto nutrient availability may increase primary production (Zijl 2021).

Furthermore, OFPV provides additional substrate for marine growth (Hooper *et al*., 2021), which can increase the grazing pressure on the primary producers. These species can either graze directly on the primary producers or they can graze on primary consumers. Therefore, primary producers will either be alleviated by the grazing pressure of zooplankton, which will be consumed by new taxa growing as biofouling on the structures (Maar *et al*., 2014), or the grazing pressure can be intensified should the new taxa graze on phytoplankton as well (Prins *et al*., 1995).

Clearly, OFPVs may have many different, opposite, and interactive implications for phytoplankton. As explained above, these implications largely depend on the OFPV design and the local situation, which may also be subject to changes over time. This makes it currently very difficult to predict the net effect of OFPV. However, whereas OWF in some areas may still lead to an increase in primary production, note that the net effect of OFPV on primary production is (more) likely to be either neutral or negative, because of their additional direct blocking of sunlight and providing habitat for sessile growth.

Another complication is that, in addition to their local effects on phytoplankton, OFPV installations may also have consequences downstream. Whether these consequences add to the local effect, or whether they compensate it, will again largely depend on the local (or downstream) conditions. For example, when nutrients are locally not used, they may travel downstream, where their increased availability may cause an increase in primary production which may (partially or fully) compensate the original loss. However, this line of reasoning does not apply to light: a local blockage of light will not cause more light to be available downstream. For the downstream impacts it thus makes a difference whether the phytoplankton are dominantly light- or nutrient limited, and how the OFPV affects each of these resources.

Finally, the net impacts, positive or negative will also very likely be strongly scale dependent. Effects of a small (pilot) OFPV may seem insignificant and too small to measure, but when scaled up these effects could potentially become more dominant. This emphasizes the need for mathematical models, which may be used to predict the direction and quantity of the net effects.

2.3.2 Macroalgae

Macroalgae (or seaweeds) are primary producers that range in shape and form, but which can all be seen by the human eye. In principle, they are attached to rocks or other types of hard substrate, but some may occur in a drifting/floating form. Like phytoplankton, macroalgae use light and nutrients for their growth, and produce oxygen as a subproduct. The fact that they are sessile, however, will make them even more sensitive to the blocking of light by OFPVs than phytoplankton are (because they cannot drift away from the OFPV where they may compensate their OFPV-induced losses). Installing OFPVs above (fields of) macroalgae is thus expected to have a negative effect on their occurrence and/or condition.

Due to their requirement of hard substrate, macroalgae usually do not occur in open marine systems. However, with the construction of OFPV, suitable substrate becomes available for the colonization of macroalgae (Kerckhof *et al*., 2010). However, they do not provide nutrition to the same consumers as phytoplankton. Therefore, intensive growth of macroalgae on OFPV structures could shift the functioning of the ecosystem, as they compete with phytoplankton for the same resources, but encourage the growth of different consumers.

When OFPV is installed and new habitat for sessile species such as macroalgae is created, another important factor to consider is the potential of the OFPV structures to act as steppingstones between marine systems, increasing their connectivity. The OFPV area may create new pathways between adjacent marine systems by allowing the sessile species and their associates to survive the migration journey. This could increase the risk for exotic species, viruses or parasites to reach surrounding habitats or hosts.

2.3.3 Seagrass

Seagrass is a marine flowering plant occurring in shallow (subtidal or intertidal) areas close to the shore. Seagrass meadows provide an important nursery habitat for many fish species. They also improve coastal water clarity and they stabilize soft sediments (Collier and Waycott, 2009). Seagrass meadows are sensitive to light deficits and burial under fine sediments (Benham *et al*., 2016). OFPV may thus reduce seagrass growth through the increased resuspension and transport of suspended sediments (see section 2.2.1), which can reduce water clarity and promote burial even beyond the direct vicinity of offshore infrastructure (Benham *et al*., 2016). However, in the North Sea, the semi-local impacts of individual OFPVs are expected to be insignificant, since (or: as long as) OFPVs are not installed anywhere in the vicinity of seagrass meadows. Potentially, however, upscaling of OFPV may lead to large-scale effects that may be of influence, such as the fine sediment transport towards the Wadden Sea (Zijl 2021).

Additionally, such as with macroalgae, the connectivity of adjacent seagrass meadows may be strengthened with the OFPV installations, which could increase the vulnerability of these populations.

2.4 Primary Consumers

Primary consumers form the next level of the marine food web, feeding on primary producers. As a result, their population sizes are dependent on the availability of primary producers. Like the producers, primary consumers can also either be planktonic, or sessile. Therefore, each taxon will experience varying impacts from different anthropogenic forces.

2.4.1 Zooplankton

Zooplankton are planktonic consumers. They include a wide range of taxa, such as crustaceans, rotifers and free-floating larvae of e.g. fish, clams, mussels or oysters. Zooplankton can be divided into primary consumers, which feed on primary producers, and secondary consumers, which feed on other zooplankton (Fransz *et al*., 1991). The bulk of the marine zooplankton consists of copepods, small crustaceans that spend their whole life cycle in the water column.

Since zooplankton are free-floating, the additional substrate provided by the OFPV will not influence their populations directly. However, as discussed above, the installation of OFPV will likely have a negative influence on the primary producers, which would in turn negatively influence the zooplankton too.

2.4.2 (Benthic) Filter Feeders

Filter feeders are marine animals that feed by trapping suspended particles from the water column with a specialised filtering structure. Benthic filter feeders are sessile and include shellfish, anemones, gorgonians, barnacles, tube worms, tunicates, etc. which feed on any suitably sized particle, such as free-floating primary producers or other free-floating primary consumers (e.g. zooplankton). The installation of OFPV is likely to increase the abundance of benthic filter feeders, as the OFPV floaters provide a suitable substrate for their settlement. However, like the zooplankton, their abundance is dependent on the availability of their food which, as mentioned, may be negatively impacted by the OFPV installations. As was mentioned for the sessile primary producers, the OFPV structures may increase the connectivity between adjacent filter feeder populations too. Similarly, this may again increase their vulnerability.

Filter feeding bivalve molluscs (e.g. mussels, clams or oysters) have a specialised method of particle expulsion, known as pseudofaeces, which they use to get rid of unwanted materials that they have trapped and accumulated. The settlement of these species in the surface waters on the OFPV installations, would increase faeces as well as pseudofaeces, which sinks to the seabed and may thus enrich the local seabeds.

2.4.3 Corals

Coral organisms, known as polyps, often form well-known hard substrate communities and are another group of primary consumers. They are slow-growing animals that have a complex feeding strategy, as some species form a symbiosis with the primary producers known as zooxanthellae. This symbiosis is particularly common in shallow, tropical waters, where the zooxanthellae photosynthesize during the day and the corals get most of their nutrients from the photosynthetic by-products. However, all corals also have their own filter feeding structures, which allows them to live in a wider range of habitats. It should be noted that, although corals have been placed in the section on ‘primary consumers’, some (especially the cold water) species do not feed on algae and would be better categorized as ‘secondary consumers’, while the symbiontic species could also be regarded as ‘primary producers’.

Their symbiosis with zooxanthellae makes corals sensitive to the blocking of light by OFPVs, because it will reduce their primary production. Even in shallow and tropical areas (in which corals typically experience a high irradiance and possibly photoinhibition), a small reduction in light may still have an impact on the coral community. This is because light intensity is an important factor in the competitive ability of coral species (Kaniewska *et al*., 2008), with some species being able to optimise their morphology for maximum light acquisition and minimum light damage (Kaniewska *et al*., 2014). The large range of light intensities (including the high-light extremes) under which corals occur, may thus be essential for maintaining their species diversity. During bleaching events, however, a reduction of light has been observed to have a positive effect on coral health (Mumby *et al.*, 2001). Building on this and similar findings, it has been suggested that turbid zones (due to the reduction in light) may serve as a refuge to hard coral populations (Morgan *et al.*, 2016; Sully and van Woesik, 2020). The reduction in light due to solar panels may have a similar (positive) effect on coral health or survival during bleaching events, but it will be difficult to weigh it against the above mentioned (negative) effects on primary production and biodiversity.

Also, corals may be sensitive to OFPV-induced changes in water temperature. Since they cannot tolerate very high temperatures (Shoepf *et al*., 2015), in tropical areas with temperatures at the high end of their tolerance range, some may argue that corals may possibly benefit from the cooling of the surface waters by OFPV. However, as is explained in section 2.1, OFPV structures may also lead to a local or temporal increase of the water temperature. In combination with the above-mentioned negative effect of blocking light, OFPVs are thus expected to have a negative impact on tropical corals.

The North Sea hosts cold water corals known as *Lophelia pertusa* (Scleractinia), which tend to colonise oil and gas rigs (Gass and Roberts, 2006). These are hard corals and do not have symbiotic zooxanthellae and are therefore not dependent on light. The installation of OFPV, particularly the anchoring devices in deeper water, could provide additional habitat for these species. This is also applicable to other corals in the North Sea, which are mostly soft corals such as the Dead Man's Finger (*Alcyonium digitatum*). These corals live in shallow waters up to 50m depth, also do not photosynthesise and colonise hard substrate easily (Budd, 2008). Aside from providing habitat for coral settlement, the installation of OFPV may decrease primary production, as discussed above, and therefore limit food for the corals. Additionally, the OFPV installations may increase sediment suspension, which may block the corals' feeding appendages with inorganic materials.

2.5 Higher Trophic Levels

In this context, higher trophic levels include any marine species that feed on animals. They tend to have a higher biomass, a lower turnover and a lower production than the species that make up the base of the food web.

2.5.1 Fish

Fish usually start their life in a planktonic stage, where they mostly feed on primary consumers (zooplankton). Therefore, most marine fish start their life in sheltered regions that usually have elevated plankton concentrations to feed the larvae. OWF has been found to provide such conditions, benefiting not only the local fish stocks, but also those in surrounding areas (Leonhard *et al*., 2013). OFPV structures may also provide extra shelter but are likely to reduce primary production due to the shading that they create. The resulting decrease in zooplankton makes a positive effect on the local fish stock unlikely. In contrast, the additional perching place for seabirds could increase local fish predation, which rather would decrease the local fish stock.

In addition, subsea power cables associated to the OFPVs are expected to generate electromagnetic fields (EMFs) that are in the range that can be detected by marine organisms. Although there is a general lack of effect studies on effects of EMFs specifically on North Sea species, it is known that several taxonomic groups inhabiting European seas (especially sharks and rays, but potentially also bony fish, invertebrates and marine mammals) are sensitive to EMFs (Snoek *et al*, 2016). The four main effects identified in literature by Snoek *et al*. (2016) are disturbance of 1) behavioural responses and movement (attraction, avoidance); 2) navigation and migratory behaviour; 3) predator/prey interactions and distribution of prey; 4) physiology, embryonic and cellular development.

2.5.2 Birds and Bats

Seabirds are avian species of which a large proportion of the population relies on the marine environment for at least part of the year. Several engineering articles provide indirect evidence for the presence of birds at solar farms, birds using airspace above the panels, and possibly birds using the arrays to perch (Harrison *et al*., 2017). Bats, in contrast, are primarily associated with terrestrial environments, yet some species are known to forage or migrate offshore. In Europe, field observations and recaptures of marked bats have shown that some species migrate seasonally across the Baltic and North Seas between the European continent and either Sweden or the United Kingdom, and some nonmigratory species forage over water far from shore (Solick and Newman, 2021). Activities related to construction and maintenance of OFPV installations may thus disturb the foraging and/or migration behaviour of both birds and bats. On the other hand, the additional perching places could attract seabirds and increase their local presence. Also, the navigational lights on the OFPVs may be of influence. Lights can attract birds, as well as concentrate their prey, which seabirds then take advantage of (Marangoni *et al*., 2022), and bats may be affected even by low light pollution levels (Mariton *et al*., 2022). The net impacts of OFPV installations on the population level should thus be assessed by taxon or guild, with different behavioural traits taken into consideration (Harrison *et al*, 2016). Also, the interaction with other anthropogenic activities may be of relevance. For instance, if the OFPV attracts more birds, there will be a higher likelihood in a hybrid farm that those birds will collide with the wind turbine blades. But then again, a local change in individuals will not translate automatically into a (proportional) change at the population level.

Seabirds feed on fish and their increased presence around the OFPV installations could have a negative effect on the local fish stocks. On the other hand, their droppings/faeces would introduce nutrients into the water column, which could benefit the primary producers. However, in combination with the extra shading introduced by the OFPV, this is unlikely to enhance the local primary production. Again, pilot studies and data are required to determine the net effect.

2.5.3 Marine mammals

Marine mammals have very different lifestyles, depending on their taxon and ecological guild. Many undergo large-scale migrations to follow their food sources or find suitable breeding locations. The main food sources for marine mammals include both primary consumers (e.g. for filter feeding whales) and secondary consumers (e.g. fish).

OFPV may have an impact on marine mammals via their food sources. The impact on the population level depends on the impact on the specific food source as well as on behavioural traits of the marine mammals and should thus be assessed by taxon or guild.

In addition, OFPVs, as well as activities related to their construction and maintenance could result in attraction, repelling, disturbance, disorientation, entanglement or movement hindrance of these animals. Whether this will occur, or to what extent, will again largely depend on the marine mammal behaviour as well as on the design of the OFPV. It is known that seals and walruses can rest on ships and pontoons in harbors, which brings a risk of short-circuit and electrocution of the mammals. Also, they may destroy some of the OFPV construction by biting the floating membranes or electrical cables. Some whales may use hard structures (like boulders) to remove barnacles or dead skin (Fortune *et al*. 2018), so they potentially can interact with the OFPV construction too. Furthermore, some marine mammals may be sensitive to electromagnetic fields (also see section 2.5.1).

3 OFPV and other users

3.1 OFPV and Offshore Wind

In the Netherlands, the current policy regarding offshore activities is to co-locate them as much as possible with offshore wind farms (OWFs), mainly due to the scarcity of marine space. For example, OWF regions cannot be used for bottom trawling and therefore co-locating OFPV and OWF would not further infringe on the available space for fishing. An additional co-location benefit for the OFPV industry is that the grid connections are already in place for the OWF installations, and their capacity is more evenly used. Hence, the Dutch policy is to limit the size of the OFPV to the current OWF export capacity, which is prescribed in the current Dutch licensing regulations (e.g. RVO 2023). Under this policy, the OFPV would cover 37% of the total OWF (see calculation in box 1), which would leave room for other users to be co-located within the same wind farm.

Offshore wind and offshore photovoltaic will both have impacts on the marine ecosystem (Van Duren *et al*., 2021). Their cumulative effects will depend strongly on the OFPV design and local environment. While OWF mainly impacts the local primary productivity via its effects on TKE and resuspended matter, OFPV is expected to do so mainly by causing an additional direct blocking of sunlight and by providing settlement habitat for sessile biota. The exact hydrodynamics, sediment dynamics, light blocking and sessile growth interactive effects will require further investigation. Yet, the added impact of OFPV and the interaction effects with OWF will depend on its area relative to that of the OWF which, under the current Dutch policy, would result in sun-blocking OFPV components covering less than 5% of the OWF area (see box 1); the surface area available for sessile growth would be similar or less, depending on the surface area that is in contact with the water. The added impact is thus expected to be small relative to the already existing effects of OWF. The absolute impacts of the OFPV, however, may still be significant, especially when large areas are covered due to upscaling.

Box 1. Comparison of the required areas for OWF and co-located OFPV under the current Dutch policy

A (rigid) solar panel currently has an efficiency of 23% (e.g. HUASUN 2023; Das Solar 2023; LONGi 2023), which is 230 MWp/km^2. Apart from solar panels, the platform may consist of up to 20% of other components (such as walkways) that may (partially) block sunlight. A typical solar plant (of say 9.1 MW) will thus have of a (sun blocking) platform area of maximally 0.05 km^2.

Areas for mooring lines and safety zones do not block light, but do take up space. Assuming that it is squarely shaped and has 150m mooring and 50m safety zones on all sides, a typical (9.1MW) solar plant will thus require a total area of 0.39 km^2.

In comparison, an offshore wind farm has an energy density of 8,6 MWp/km2 (e.g. Enevoldsen and Jacobson 2021). Hence, a hypothetical (but typical Dutch) OWF of 1GW would require an area of 116 km2. When assuming that the size of a co-located OFPV is limited to the OWF export capacity (as is the current Dutch policy), the co-located OFPV would also be 1GW, and would consist of 110 typical (9.1WM) plants. Its sun blocking area would thus cover 5.5km2, which is 4.7% of the area of the hosting OWF. When including the non sun-blocking mooring and safety zones, the OFPV farm would cover 43km2, which is 37% of the area of the OWF. These percentages are expected to decrease in the future due to the faster increase in efficiency of the solar panels relative to that of wind turbines. They may increase when the policy changes, allowing the export capacity of OFPV to become larger than that of the OWF.

3.2 OFPV and Marine Aquaculture

Due to a range of benefits, most of the offshore aquaculture will also be co-located in either offshore wind farms, or OFPVs. For the Dutch wind farms, the areas within the farms designated for other types of energy generation, such as OFPV, and areas designated for aquaculture are separated in the so-called "area passports" (e.g. for the Borssele wind farm: https://www.noordzeeloket.nl/publish/pages/188385/handreiking-gebiedspaspoort-borssele.pdf). However, such policies may differ in other countries.

The main types of offshore aquaculture currently under development in the North Sea are seaweed and shellfish. Current pilots are also in the final stages of permitting for actual cultivation sites within wind farms. Developments on fish cultivation are restricted to a few test locations (e.g. Norway and Scotland), but they may be applied in other parts of the North Sea in the future.

Direct co-location of OFPV and seaweed is complicated because seaweed needs light to grow and therefore cannot be cultivated underneath OFPV structures. Also, to harvest seaweed, vessels need manoeuvring space, which may be limited, depending on the OFPV set-up. However, it would be possible to cultivate shellfish, such as mussels, underneath OFPVs, since they do not require sunlight to grow. Such a set-up would still require significant technical innovations to gain access to the mussel cultures for deployment and harvest if the shellfish are located underneath solar panels. Therefore, if space is not seriously limited, then OFPV and shellfish cultivation should ideally be separated. It would be sensible to carry out scenario studies to assess under what levels of upscaling, interactive effects can be expected. It is important to note that the impact may occur not directly at the location of the OFPVs, but further downstream (Vilmin and Van Duren, 2021).

Finfish aquaculture is mostly linked to nearshore locations, but there are currently tests ongoing for offshore cultivation (Watson *et al* 2022). To what extent this will develop into a viable industry is not clear. Direct co-location (fish farms interspersed with OFPV) will require some careful planning.

As offshore aquaculture (of any kind) will require a certain level of remote monitoring, having power supplies in the vicinity for measurement devices and communication can be beneficial for aquaculture.

3.3 OFPV and Fisheries

As mentioned in previous sections, the installation of OFPV could affect the local fish populations positively by providing shelter or negatively via the (likely negative) changes in food availability. In case the net local effects on fish populations are positive, spill-over effects may occur. This means that not only the local, but also the surrounding regions would benefit from locally higher fish stocks, potentially replenishing the populations and lowering the fishing effort (and costs) for fisheries. The spill-over effect is also used in the context of Marine Protected Areas (MPAs), which aim to enhance adjacent fisheries by protecting nursery and spawning grounds, and in the context of offshore wind (Brander *et al*. 2020, Stelzenmüller *et al*. 2021). Similar effects can be expected for offshore solar farms. However, OFPVs will be co-located in offshore wind farms in the Netherlands (and possibly also other countries), which are already de-facto areas with no bottom trawling. Therefore, the impact of additional OFPV in the wind farm would be limited.

Within wind farms, bottom trawling will not occur, but other passive fisheries, such as creels, cages, passive nets and possibly fly-shoot might be feasible (Röckmann *et al* 2015, Steenbergen *et al*. 2020). It will require careful marine spatial planning, as well as logistical planning to coordinate these uses within the dedicated offshore wind farm regions.

3.4 OFPV and Tourism

Another important aspect to consider with the installation of OFPV is its impact on sports and recreation. The OFPV structures could obstruct water sports such as sailing, by reducing the space available for such activities, particularly in the nearshore region. The structures may also be visually disturbing to beachgoers and could therefore have an overall negative effect on tourism. The latter is clearly not an issue for locations further offshore; it is safe to assume that floating PV systems (if they are less than 1.75 m in height) cannot be seen from distances larger than 10 km (Soppe *et al*., 2022).

Again, when OFPVs are co-located within wind farms, as is the planning in the Netherlands, the interaction with tourism will be limited, as offshore wind farms have limited tourism-value. The newer farms will have passages for sailing ships, but to access the wind farm itself, vessels need to be fitted with DGPS, which is not common on recreational vessels.

4 Conclusions and recommendations

Offshore floating Photovoltaic (OFPV) has the potential to be a key component to help reach the EU's GHG-reduction goals. The main advantage of installing PV offshore compared to on land is the scalability due to less space limitations. Even though it is more expensive to build PV offshore, the costs could be reduced by co-locating them with offshore wind farms. This would also save space to be allocated to other offshore users, such as the fishing industry, offshore aquaculture or tourism.

To weigh the benefits of OFPV against the costs, it is important to also consider the environmental impacts of the OFPV installations. This literature review provides an overview of the many environmental processes that are potentially impacted by OFPV. The review focuses primarily on the southern North Sea marine system, but similar challenges and considerations would apply to any marine system. These include the blocking of wind and solar radiation, which would have implications for the primary producers. Since these form the base of the food web, this could affect the food availability for all organisms at higher trophic levels. In addition, the structures may affect turbulence and mixing within the water column, for which it will strongly depend on location, design, and scale whether this is a positive or a negative effect. In deeper, stratified waters, more mixing could bring more nutrients to the surface layers thus promoting primary production. At the same time, an increase of vertical mixing may also negatively impact the light-dependent primary producers, which rely on stratification to remain within the euphotic zone. In shallow waters, increased sediment suspension could increase the turbidity of the water, which would decrease the productivity of the primary producers. Also, it could also result in the blockage of feeding appendages or burial of some marine species.

The structures may also provide new habitat for sessile species including primary or secondary consumers, which could shift the competition within the food web and thus the functioning of the entire ecosystem. Furthermore, the new habitats may result in increased connectivity between different populations, which could increase their vulnerability to parasites, viruses or exotic species. For species at higher trophic levels the construction and maintenance of the OFPV installations may disturb their foraging and migration behaviour. It may however also provide additional resting spaces for birds or shelter for fish, which may locally attract individuals, but in turn may also have consequences for the local lower food web.

As this review makes clear, OFPVs may have many different, opposite, and interactive implications. At the same time, only little literature is available on the environmental impacts of OFPV. This makes it currently very difficult to draw general conclusions even about the net direction of the impacts. For the primary producers, the various implications largely depend on the OFPV design as well as on the local situation and upscaling. Overall, the net effect of OFPV on primary production is likely to be either neutral or negative. For primary consumers a likewise (neutral or negative) effect is expected, since they depend on primary producers as their food source. For higher trophic species, the impacts will largely depend on their taxon or guild and the associated foraging or migration behaviors.

In addition to their local effects, OFPV installations may also have consequences for downstream areas. Whether these consequences add to the local effect, or whether they compensate it, will again largely depend on the local (or downstream) conditions. Similarly, for higher trophic levels, a local change in individuals will not translate automatically into a (proportional) change at the population level.

Moreover, the net impacts, positive or negative will also very likely be strongly scale dependent. Effects of a small (pilot) OFPV may be too small to measure, but when scaled up these effects could potentially become more dominant. Also, interactions or accumulation with other anthropogenic activities may occur. In comparison to inland PV, the relative impacts of OFPV are expected to be smaller, as long as their coverage ratios stay smaller too (which is not guaranteed given the technological developments). However, the total area potentially available for OFPV is much larger than that for inland areas PV, so that upscaling of OFPV may still lead to a significant impact that is (in absolute terms) much larger than that of inland PV. In comparison to OWF, which in some areas may still lead to an increase in primary production, the net effect of OFPV on primary production is (more) likely to be either neutral or negative, because of its additional blocking of sunlight and providing habitat for sessile growth. However, under the current Dutch policy, the expected added impact by OFPV is small relative to that of the OWF, but this may change along with future changes in legislation and/or technology. And again, when expressed in absolute terms, its impact may still be large.

With respect to the interactions with other users, it should be noted that OFPV installations are not suitable for direct co-location with all types of users, like aquaculture, water sports, and some types of fisheries. OFPV could affect fisheries also indirectly via their (potentially both positive and negative) influences on fish populations. Furthermore, OFPV structures located near shore may be visually disturbing to beachgoers and could therefore have an overall negative effect on tourism. However, when OFPVs are co-located within wind farms, as is the planning in the Netherlands, the interaction with tourism will be limited, as offshore wind farms have limited tourism-value.

4.1 Recommendation and guidance notes

Although the literature review shows that it is currently very difficult to draw general conclusions even about the net direction of the impacts, it does serve as a basis for providing recommendations and guidance notes on mitigation.

First, it is vital that more data are collected on the environmental impacts of OFPV. OFPV is a new technological field and not much research has been done on its local implications, resulting in many knowledge gaps. Apart from data collection aimed at system understanding, also (long-term) monitoring should be carried out in order to adhere to policy directives ensuring a good ecosystem functioning. Hereby, special attention should go to primary production, which is an essential and potentially much affected process, but which does not play a large role in the current implementation of the Marine and Water Framework Directives (MFD and WFD), nor in the Habitats Directive.

Second, the (net) implications of large-scale implementation of OFPV should be assessed, as well as the interactions or accumulation with other anthropogenic activities. Hereby, it should be noted that some impacts are very small and/or are very difficult to measure in the field, yet very fundamental for the ecosystem (e.g. a reduction in primary production). It is likely that, when the impact is large enough to measure, the impact on the ecosystem is already unacceptably high. Well validated mathematical models may provide a solution for this. By considering multiple (smaller and larger) effects simultaneously, they can be used predict the direction and quantity of their total net impact (with a certain margin of uncertainty) both under conditions of upscaling and co-location.

Third, the location of the OFPV should be selected as to mitigate its environmental impacts. Fragile habitats that are already under threat, such as coral reefs, sea grass beds and kelp forests, should be avoided altogether.

Fourth, the design of the OFPV is an important factor in mitigating its environmental impacts. Environmental aspects should thus be taken into account in selection of the OFPV design, as well as in the development of relevant new technologies. As soon as best practices are known, these should be stimulated by providing guidelines, and once proven, be enforced through (licensing) regulations. Some examples of design considerations are the following:

- The OFPV area blocking the sunlight should be minimized in order to mitigate the impact on primary production. This may be achieved by using more efficient solar panels, minimizing walkways and other areas, making these walkways and other areas translucent or by optimizing the OFPV structure to minimize light blocking
- The OFPV coverage ratio should be small enough to ensure that impacts can be diluted and/or compensated by surrounding waters, even under upscaling conditions. Sun-blocking areas should thus be interrupted with sufficiently large areas that do not block sunlight.
- The contact area of the OFPV with the water should be kept to a minimum to mitigate (1) leaching; (2) fouling (and its associated issues regarding oxygen demand, food web changes and connectivity); and (3) reduction of the air-water exchange. Minimizing the contact area may for instance be achieved by using an elevated solution.
- The 'touchdown area' of the mooring lines should be minimized in order to mitigate disturbance of the sea bottom and resuspension of (in)organic matter. The touchdown area will depend strongly on design, with catenary systems affecting a larger sea floor area than taut systems.
- The OFPV should be built from materials that are selected to minimize the risk of introducing (leaching or leaking) toxic substances (chemicals, metals, oil, plastics, etc.) into the marine environment. The same goes for the selection of cleaning materials and methods, which should avoid chemicals where possible.

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