BayWa r.e.

r.e.think energy

The environmental impacts of floating solar

Authors: Meri Khvedelidze | Michele Tagliapietra | Nora Adam
Christoph Kutter | Anne Sophie Freunek | Elena Garnich | Gayathri Mohan

Table of contents

Growing evidence for floating solar technology

The International Energy Agency (IEA) maintains that the global energy sector can still reach net zero CO_2 emissions by 2050.[1] To combat climate change and satisfy rising demand for renewable energy, we need solutions that maximize efficiency and reduce land use.

Floating photovoltaic (FPV) systems, which deploy solar panels on water bodies, are a promising part of the solution.[2] A 2007 pilot was realized in Japan, with the first commercial system built in 2008 in California[3]. According to S&P global, FPV reached an estimated installed capacity of 4.3GWp by 2022. Of that, Asia accounted for an 87% market share.[4]

Various studies have estimated FPV's potential.[5][6] According to the World Bank, it could generate 400GWp using 1% of global surface water.[5] If ~10% of Europe's freshwater reservoirs accommodated FPV, estimated capacity would near 200GWp.[5] Another study[6] calculated FPV systems could generate ~10% of US electricity consumption using 27% of available water bodies.

Why invest in the future of FPV?

Floating-PV can provide several advantages and opportunities for **unlocking more surface** for development of renewable energy projects, especially in regions with scarce land resources where land is expensive, or where land is unsuitable for traditional PV[6].

Installation is simplified, with less site preparation and faster construction[3].

Several studies suggest a beneficial effect on energy yield, due to water's **cooling effect** lowering modules' operating temperature and increasing efficiency.[7][8] More monitoring from operational experience will accurately quantify the exact difference in energy yield across different climatic conditions[8][9].

Depending on system design, FPV has been shown to **reduce evaporation losses**, potentially saving water in arid areas. Shading from panels can **improve water quality** by reducing algae[10].

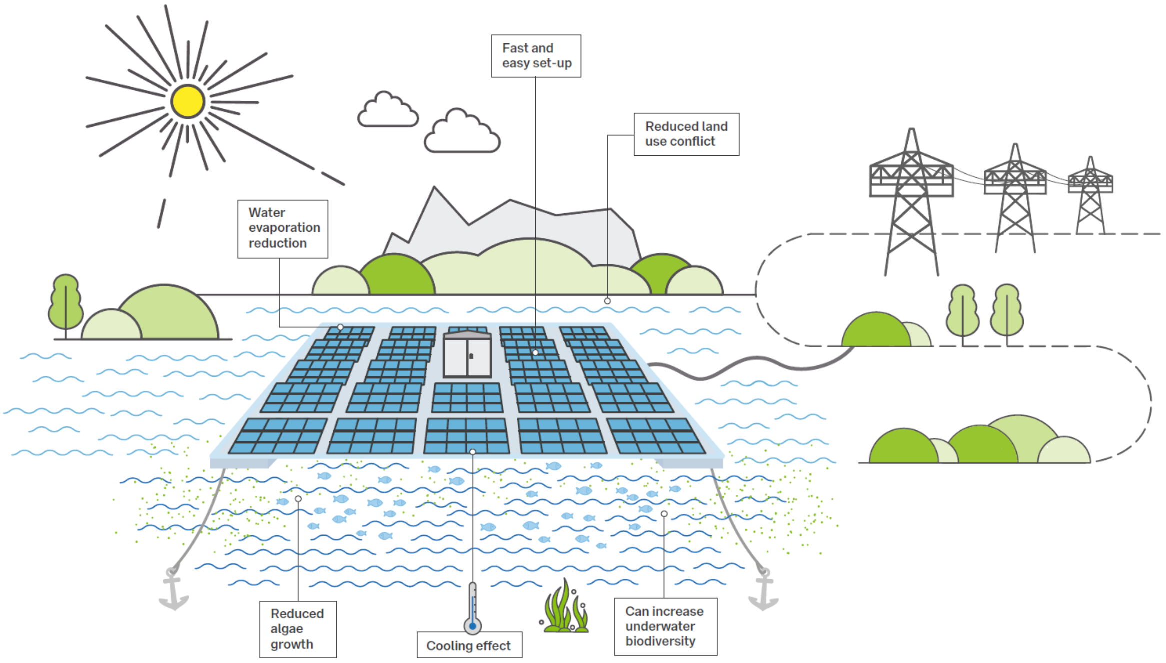


Figure 1. Overview of the benefits of Floating PV

However, uncertainty about consequences for water quality and overall ecology hampers the spread of FPV projects, especially in Europe. Social acceptance also plays an important role. Greater public knowledge of FPV's positive environmental impact is key to expansion.

This whitepaper synthesizes findings from various studies. It provides both a review of results from literature, as well as from studies on BayWa r.e.'s operational plants during the past five years. These include lessons learnt on design, compensation and enhancement measures, operational practices, and monitoring.

We'll include a summary of this impact, and examine case studies on projects of varying scales around the world:

Table 1.BayWa r.e. projects used for conducting environmental impact studies of FPV and their relevant characteristics

Project:	**Weperpolder**	**Bomhofsplas**	**Nij Beets**	**Beilen**	**Sellingen**	**Lippe**	**Sekdoorn**
Capacity [MWp]	2.1	27.4	13.5	15.9	41.1	13.7	14.5
FPV coverage of the lake (%)	7%	26%	29%	48%	40%	35%	29%
Lake surface [ha]	1.5	18.3	10	10	23.8	8	10

Impact on water quality

During the development and operation of FPV projects, it's essential to maintain water quality. Measuring this is a question of monitoring parameters like:

- Water stratification
- Water temperature

- Dissolved oxygen (DO)
- Electrical conductivity (EC)
- Turbidity

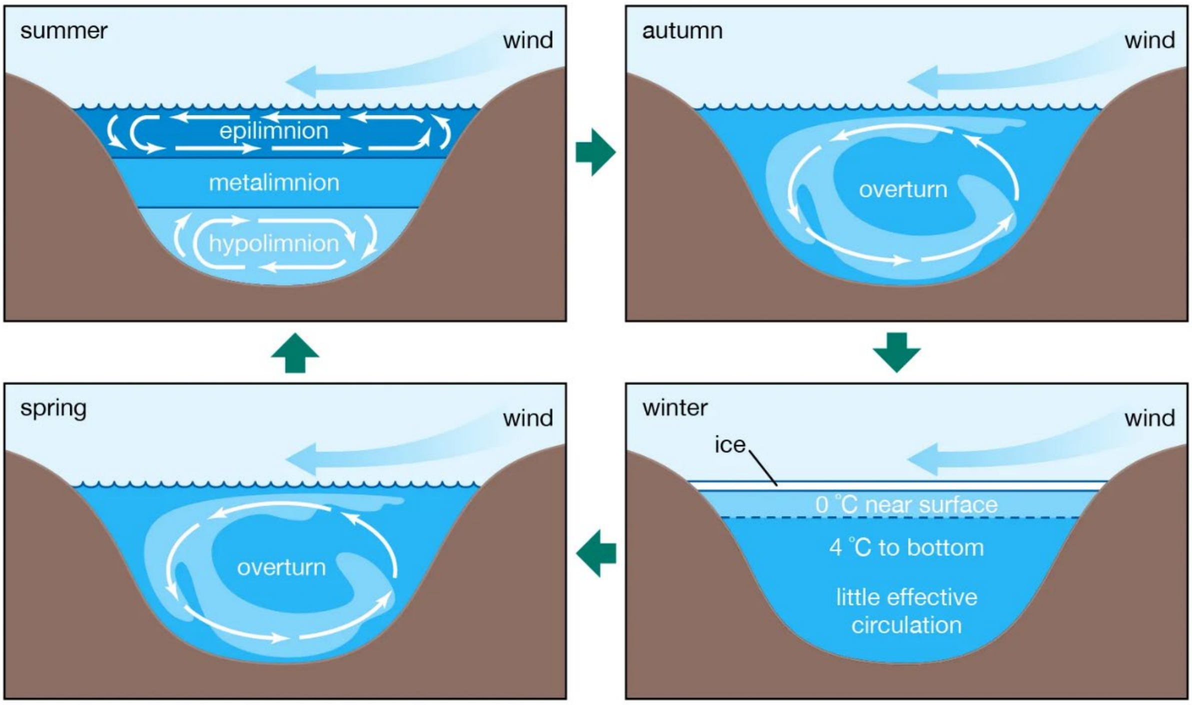
Water stratification

Lakes exhibit vertical stratification over time. Thermal stratification occurs during the warm season in lakes with sufficient depth. This is due to the large differences in density (weight) between warm and cold water.[12]

In summer, the water surface is warmer. Temperature differences increase between surface and deeper water.[13] This creates a cycle in which warm water at the surface floats above the cool water below, while surface water heats as it receives energy from the sun and becomes even less dense compared to the cool water below, creating different layers of water in the lake:[13]

- The upper layer of well-mixed water zone is called the epilimnion
- The second layer, the metalimnion, functions as a barrier that hinders mixing and the transfer of heat between epilimnion and the deeper strate
- This deeper layer, the hypolimnion, is composed of cold water that isn't mixed with the above layers and has poor circulation[14]

Climate change is extending the stratification period in lakes,[15] increasing the duration between spring and fall mixing. As the time between mixing is getting longer, oxygen concentrations in the deep waters of lakes are declining. This has potential harmful consequences for habitats in deep water.[16]



© Encyclopædia Britannica, Inc.

When FPV covers a water body, it reduces the amount of solar radiation reaching the surface. This shields it from the effects of wind mixing,[10] altering water temperature and stratification.[17]

Wind speed and solar radiation typically have opposite effects on the thermal structure of water bodies. Decreases in wind speed tend to increase stratification and surface heating. Decreases in solar radiation tend to increase the mixing and cooling of surface waters.[18]

Stratification determines a variety of biological, chemical, and physical processes within lakes. These involve population dynamics and interactions between species. This in turn affects the exchange of oxygen, nutrients, and carbon between the lake's surface and bottom.[19]

A study by Exley *et al*[20] investigated the potential impact of FPV on an English lake, using a modelling approach. The lake has a surface area of 670ha, a maximum depth of 42m, and an average depth of 16.8m. This makes it significantly larger than the sand pit lakes widely used in Europe for FPV projects. The effects on lake water quality were investigated at cover levels ranging from 0 to 100%.

The study argues that plant-induced changes in the main meteorological parameters of global radiation and wind speed have opposite effects on temperature balance and circulation behavior. For example, increasing the area of a FPV plant reduces global radiation, resulting in a decrease in water temperature.

At the same time, decreasing wind speed causes an increase in temperature, resulting in at least partial compensation. The results showed reduction in water temperature, shorter stratification period, and shallower mixed depth. However, in low FPV cover scenarios, stratification duration was prolonged.

Another study by Ilgen *et al*[21] investigates how FPV systems affect a lake's thermal dynamics. Specifically, thermal stratification, energy budget, and water temperature were examined.

The research is being conducted on a FPV facility with a 749Wp capacity, on lake Maiwald in Germany, which is 70m deep. Wind speed and irradiance beneath the FPV facility significantly decreased, by 23% and 73% respectively vs baseline measurements.

Researchers used the General Lake Model to mimic different FPV occupancies and changing climate conditions using a three-month dataset. Results suggest that, during the summer, FPV coverage results in shorter and less stable thermal stratification. This may have a mitigating influence on the expected heating effect from climate change.

Water temperature

One of the key physical characteristics of lakes is their water temperature. Water temperature is critical for fish population development, reproduction, and immune system maintenance.[22] Variation of water temperature impacts the rates of biological and chemical processes, as well as the level of lake eutrophication.[23]

When water temperature increases, many aquatic organisms' metabolic rates increase rapidly. High water temperatures hinder the process of vertical mixing in lakes. This impacts the dissolved oxygen and essential nutrient levels in the lake, as well as the food chain.[25]

As temperature rises, oxygen and other gases become less soluble, warmer water may not contain enough oxygen to support life.[26] Low temperatures, meanwhile, may restrict metabolic performance by disrupting the equilibrium between oxygen supply and demand.[24]

Dissolved oxygen

Dissolved oxygen (DO) refers to the amount of oxygen in aquatic environments available to fish, invertebrates, and other organisms in the water.[27] Most aquatic plants and animals rely on oxygen.[27] For example, fish can't endure extended periods in water with less than 4 mg/L of DO.[28]

Low dissolved oxygen concentration in water may be an indication of pollution. It's a key factor in the assessment of water quality, pollution control, and treatment processes.[29] DO concentration can be impacted by seasonal changes of water temperature.[30] Throughout summer stratification, the top layer of the lake warms. DO levels increase due to oxygen transfer from the air and algal photosynthesis. Water temperature and DO decrease the deeper you go.[30]

Electrical conductivity

Electrical conductivity in lakes is a valuable parameter for assessing water quality, understanding ecological dynamics, and managing freshwater resources.[31] It indicates both salinity and pollutants directly, as well as the number of contaminants in the water.

Water conductivity ranges between water types; lakes and streams usually have a conductivity range of 0-200µS/cm.[26] Large variations in conductivity may indicate a pollution source in the aquatic environment.[33]

Turbidity

The turbidity of a lake describes water clarity, or whether sunlight can penetrate deeper parts of the lake. Turbidity often varies seasonally, both with the discharge of rivers and growth of phytoplankton (algae and cyanobacteria).[34]

Dredging often leads to high turbidity due to high amounts of dissolved sediments. The sunlight that plants require to produce oxygen for fish and other aquatic life may be blocked.[34] Furthermore, an excessive amount of silt or other particles suspended in the water absorb solar heat. This causes the water to warm and further reduces the amount of dissolved oxygen.

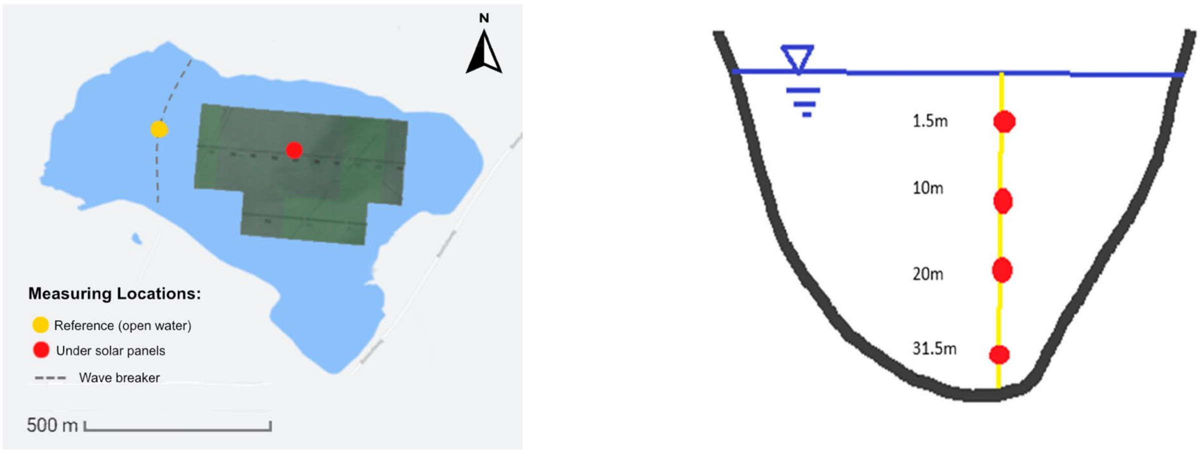
Live studies of FPV projects

These studies look at the impact of FPV on the kind of parameters we've explored so far.

De Lima *et al*, 2021: Underwater exploration at Bomhofsplas

- Location: Bomhofsplas Lake, a sand extraction pit in Zwolle, Netherlands
- Size: 70ha
- FPV lake coverage: 26%
- Installed capacity: 27.4MWp

This 10-month study[35] took measurements using underwater drones and sensors. This happened at varying depths and two locations; under the FPV plant and in open water.



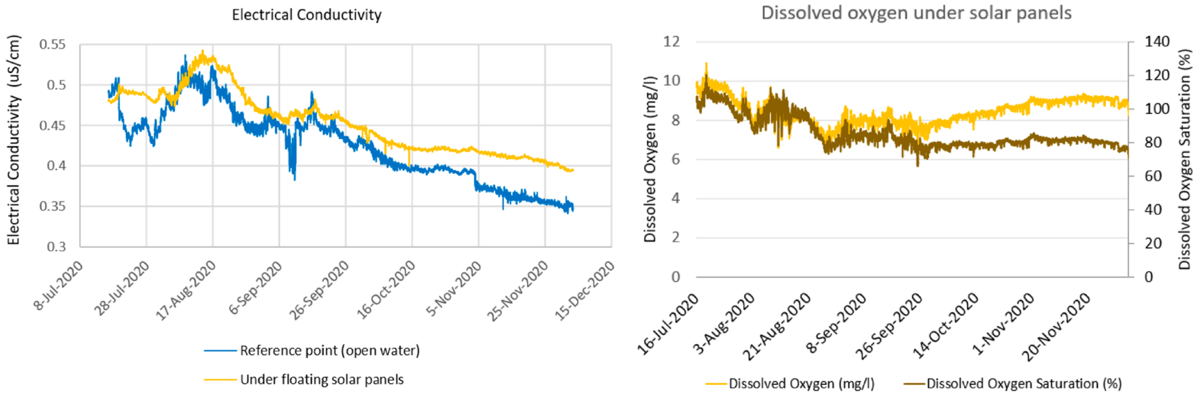
(**a**) (**b**)

Figure 2. (a) Map points indicate the position of sensors and underwater drone dives; at the center of the solar park (red point) and the open water/reference location (yellow point). (b) Vertical schematization of the different sensors positioned at different water depths.

Investigation found negligible differences in temperature balance and stratification behavior between water underneath the solar park and the open water body. Electrical conductivity was similar at both sites, but on average 6.6% higher in open water.

A sudden drop in electrical conductivity at the reference in early September took place, but not under the floating solar panels. The cover of the panels may act as a buffer for sudden weather changes.

Despite fluctuations, DO levels remained healthy throughout monitoring. They stayed above a minimum concentration of 6.48mg/L and a saturation of 65.87%. The minimum DO in water should be between 3-4mg/L for living organisms.[36]



(**a**) (**b**)

Figure 3.Water quality data between July and December 2020: (a) comparison between electrical conductivity at the reference point and under the solar park and (b) DO levels (concentration and saturation) under floating solar panels.

The temperature and conductivity values show very small differences, on average temperature was 3.3% higher beneath FPV. Electrical conductivity was 0.03mS/cm lower at open water. FPV has a minor effect on temperature balance, conductivity, and stratification behavior.[35]

Deltares, 2022: Testing water quality at Beilen

- Location: Beilen, Netherlands
- FPV lake coverage: 48% (lake size 20ha)
- Installed capacity: 15.9MWp

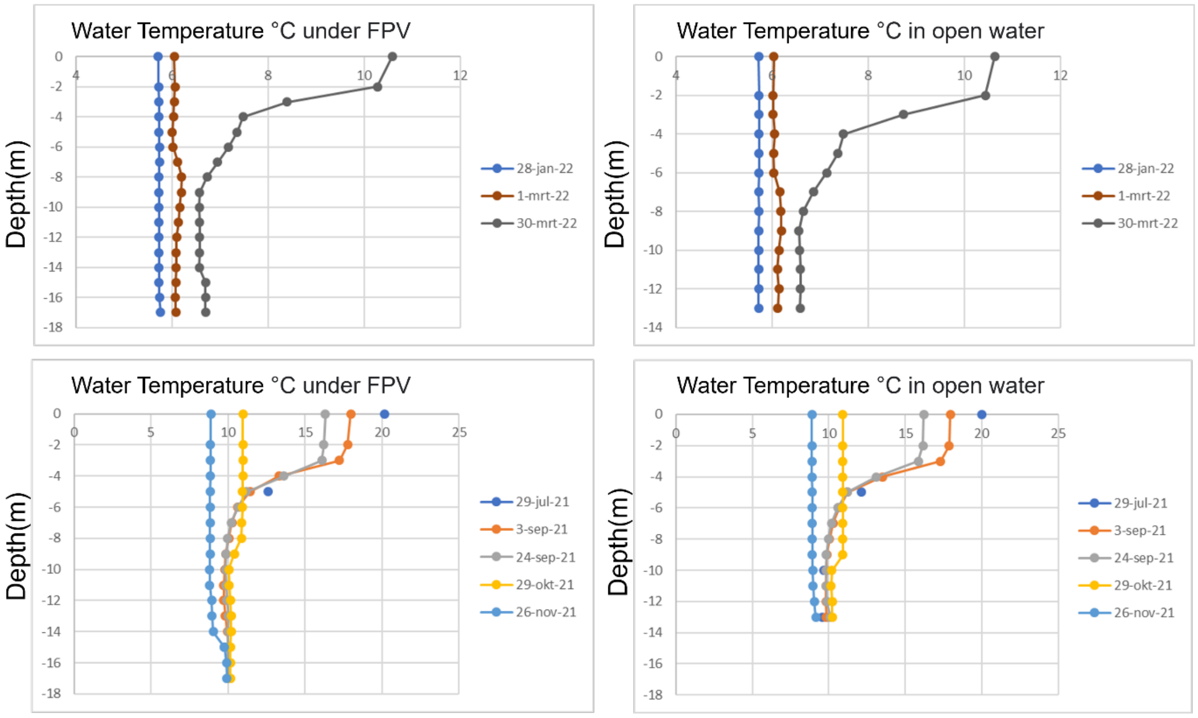
Deltares is an independent knowledge institute for water and the subsurface. Between 2021-2022, they monitored this project for oxygen levels, water temperature, and water transparency at different depths and locations.

Results showed the water quality did not differ between open water and underneath the solar park. In July, initial measurements at four depths prompted the decision to shift to measurements per meter to capture the jump layer.

In September, a perceptible jump layer was observed, from approximately 3m to 7/8m. As autumn unfolded, this jump layer vanished, with no detectable difference in temperature between the open water and water beneath FPV.

In January and March, the water exhibited complete mixing, resulting in minimal temperature differences over depth. On March 30, 2022, the jump layer re-emerged, extending from about 2-4m. Again, there was no temperature disparity between FPV and open water.

Findings suggest that despite the seasonal fluctuations in the jump layer, water temperature stayed consistent beneath the solar farm and in open water.



Water Temperature °C under FPV

Water Temperature °C in open water

Water Temperature °C under FPV

Water Temperature °C in open water

Figure 4. Water temperature at different depth in open water and under solar park.

Enviso, 2023: Continuous monitoring at Lippe Gabrielsplas

- Location: Lippe Gabrielsplas, Netherlands
- FPV lake coverage: 35% (lake size: 23 ha)
- Installed capacity: 13.7MWp

Engineering firm Enviso assessed this site between 2022-2023, again comparing open water to water beneath FPV modules. During warm months, a slight temperature difference of 0.5-

1°C was observed in the upper water layer. This was potentially linked to shading from the solar farm.

However, no significant differences in DO levels were noted in the upper layer, or at a depth of 8-9m. Results showed no noticeable difference between measurements of open water and those under solar panels.

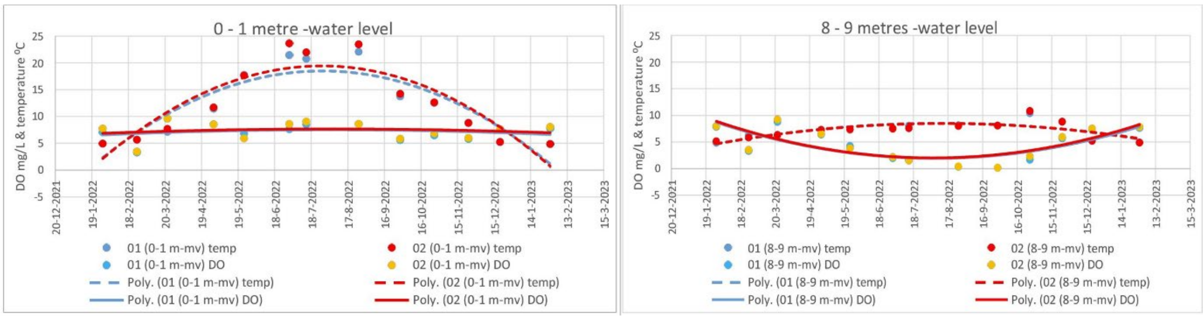


Figure 5.Measured water temperature and oxygen at different depth under solar park (01) and in open water (02)

Yang *et al*, 2022: Theoretical modelling in Singapore

- Location: Tengeh Reservoir, Singapore
- Size: 42ha
- FPV lake coverage: 30%

Outside of the borders of the EU, this study[37] analyzed how a hypothetical installation would affect water temperature and water quality parameters in a shallow tropical reservoir.

A three-dimensional hydrodynamic-ecological lake model was used, alongside field measurements to examine the effects on water quality. A 1ha demonstration and 6m^2 mockup FPV system were installed in Tengeh Reservoir to analyze changes in water quality under the panel compared to open water conditions.

The findings showed lower DO levels under the solar panels (7.97mg/L) than in the open water (8.48mg/L), but still within the acceptable range for living organisms. A slight increase in pH by 0.5 and surface water temperature by 0.5 °C was observed under the demonstration panels.

Impact on algae growth and chlorophyll-a

Algae are a natural part of all aquatic ecosystems; their proliferation can make both positive and negative impacts on the water.

Excess algae can lead to the formation of algal blooms.[38] Most of the bloom is composed of potentially toxic cyanobacteria, a significant threat to aquatic ecology, biota, and even humans.[38] Cyanobacterial blooms can also affect water turbidity, pH, chlorophyll-a, the trophic state of water, and stratification.[39]

Sunlight is essential for algae growth; it's required for photosynthesis. Shading provided by FPV can reduce the proliferation of algae and improve water quality.[38]

Chlorophyll-a (chl-a) indicates phytoplankton biomass, reflecting its production in marine waters in response to nutrient and light availability.[40] Eutrophication results from over-enrichment of waters with nutrients, either from natural or man-made sources.

This can lead to hazardous algal blooms, ecosystem deterioration, biodiversity loss, and oxygen deprivation in bottom waters.[40] Several studies predict increased FPV coverage can lead to the reduction of algal growth and chl-a concentration. 41, 42]

Haas *et al*, 2020: Predicting impacts in Chile

This study[42] investigated FPV's impact on the Rapel hydropower reservoir in Chile, using algal bloom development as an indicator of water quality and overall oxygen budget.

Using a numerical-hydrodynamic model (ELCOM-CAEDYM), the study compared the current condition of a lake without FPV to scenarios with varying levels of FPV cover. Results showed:

- Small FPV installations have limited success in preventing algal blooms
- Moderate-sized installations can effectively avoid blooms while supporting healthy algal concentrations
- Very large FPV with >60% coverage may eliminate algae entirely, posing a potential threat to the lake's ecology (whereas depending on the algae species, algae bloom is considered a negative or a positive effect)

FPV coverages of 40%-100% would reduce chlorophyll-a concentrations below 10 µg/L. According to the World Health Organization,[43] chl-a concentration between 0-10µg/L is safe recreational water.

According to this study, the recommended optimum cover % of FPV for the Rapel hydropower reservoir is between 40 to 60%, to maintain acceptable levels of algal concentration.

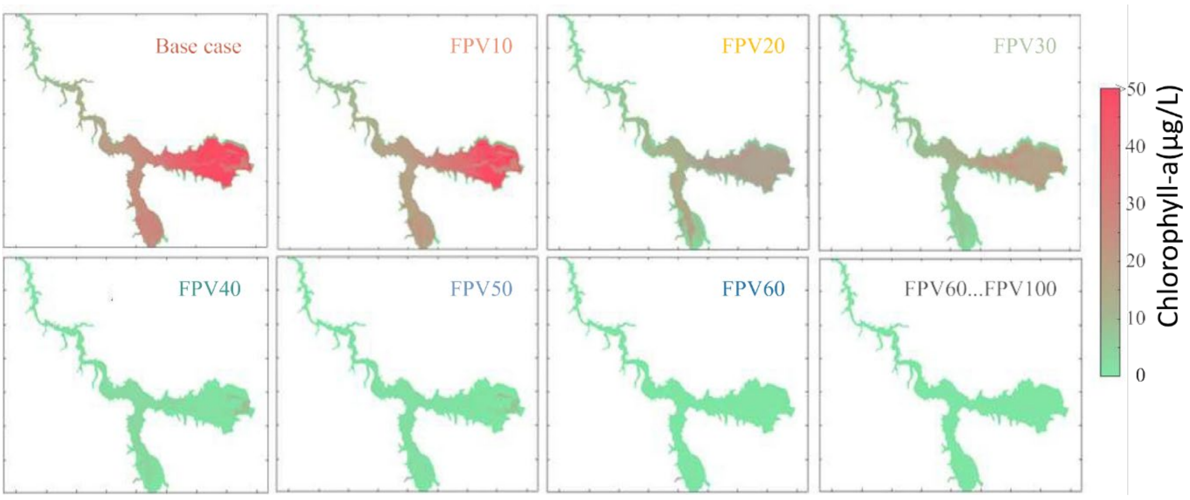


Figure 6:Chlorophyll-a concentrations on a hydropower reservoir in Chile after simulations with varying Floating-PV coverages (Floating-PV10 = 10% Floating-PV coverage, etc.)

Buro Bakker and AKTB, 2021: Drawing comparisons across the Netherlands

Two BayWa r.e. FPV plants were studied by independent ecology advisors, Buro Bakker and AKTB in 2021. Both were in the Netherlands; one at Bomhofsplas with 26% water coverage, the other in Nijbeets with 29%.

Two different locations underneath the FPV Park and open water were compared, and water quality parameters were measured. Results showed average chl-a concentrations in summer of 4.4µg/L in open water, and 6.5µg/L under FPV. Both values are considered "very good" by the Water Framework Directive.

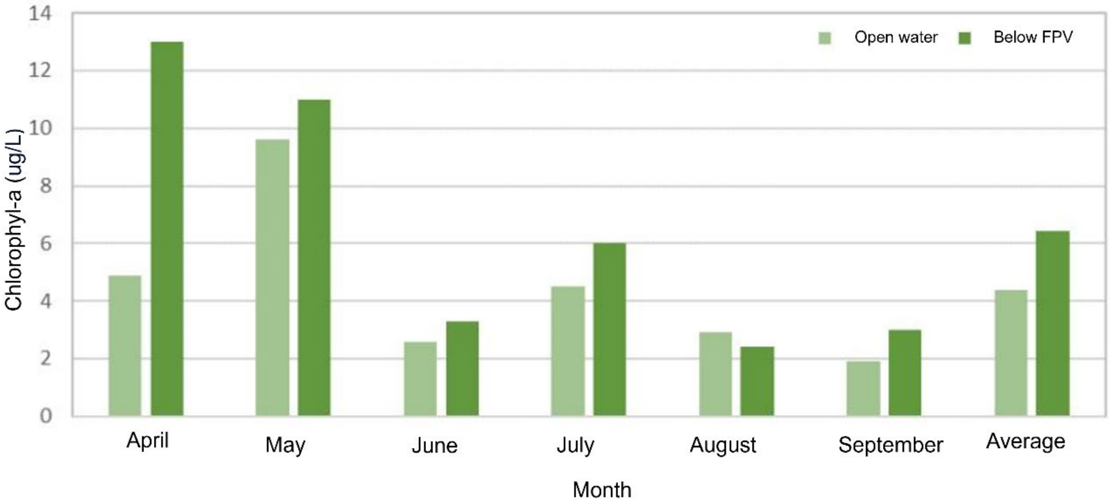


Figure 7.Chlorophyll-a concentrations measured at Bomhofsplas in open water and below solar park

Surface warming throughout spring creates a thermal layer. This may be seen in the lake from June to at least September. The thermal layer, which typically occurs at depths of 6-8m, causes temperatures above it to exceed 20°C while temperatures below stabilize around 8°C.

Oxygen content was generally lower beneath the solar farm, with average saturation levels at 90% compared to 97% at the reference location at Bomhofsplas.

Results at Nijbeets showed oxygen concentration at the water's surface ranges from 7.8-11.2mg/L with a saturation of 81-105%. Oxygen level decreases near the bottom, ranging from 1.8-7.9mg/L with saturation 16–66%. The water's pH ranges from 7.6-8.7 at the surface and 7.6-8.0 at the bottom.

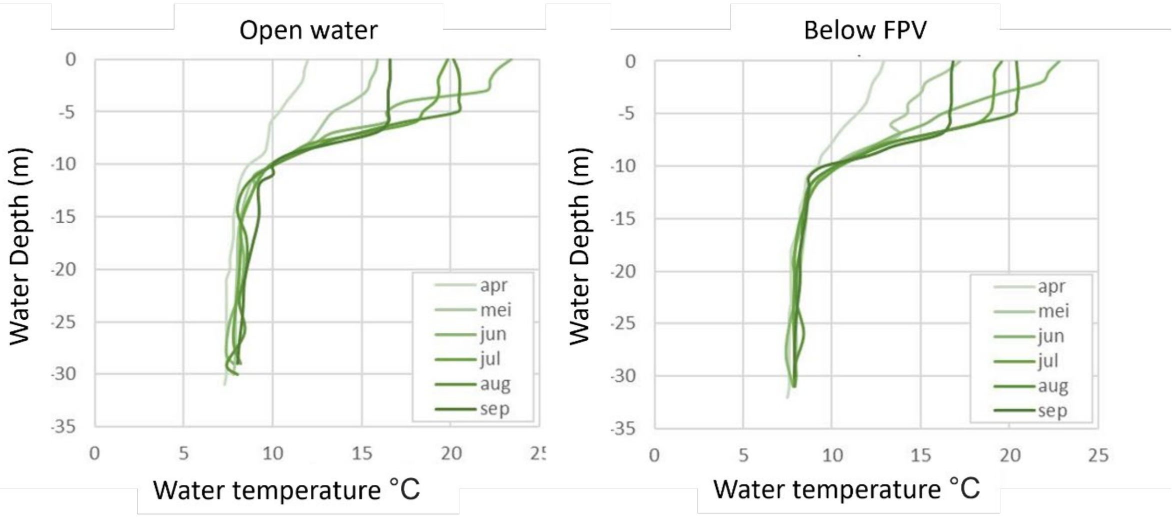


Figure 8.Water temperature in relation with water depth at Bomhofsplas

Impact on water evaporation

One of FPV's economic benefits is its potential to reduce water evaporation.[30] Solar panels reduce the amount of sunlight reaching the water and block wind from sweeping the water surface.[44]

This double effect reduces the amount of evaporated water, important for warmer climates with water availability issues, potentially worsening because of climate change[30].

Several methods used to calculate evaporation reduction due to shading and coverage are also used to measure evaporation reduction due to floating coverage. These include evaporation pan, the water budget method, and empirical formulas like the Penman method.[46][47][48]

Studies on evaporation reduction

A study by Abd-Elhamid *et al*[45] examines strategies to mitigate evaporation from Lake Nasser, a crucial water source in Egypt fed by the Nile. The study used annual evaporation rates calculated by the bulk aerodynamic approach using meteorological data from 2009 to 2020.

Results showed considerable loss of water, averaging 12.00 billion m^3/year, or 22% of Egypt's share of the Nile. This was compounded by the Great Renaissance Dam's impact from Ethiopia. The study suggested using FPV to cover shallow portions of the lake, saving a significant amount of water and producing renewable electricity.

The best water savings are achieved by covering shallow depths up to 1.0m, saving 1.9 billion m^3 annually. FPV is in line with Egypt's environmental objectives, offering sustainable initiatives and renewable energy.

In Jordan, Abdelal *et al*[46] installed an experimental FPV system with 100% coverage in a semi-arid region. They found FPV reduced evapotranspiration by about 60% compared to an uncovered setup in the same location. Improvements in nitrate and chlorophyll concentrations were also observed.

Bontempo Scavo *et al*[47] developed numerical evaporative models (EVMfree and EVMFPV) to analyze the impact of FPV plants on water basin evaporation. Comparison with existing literature models and experimental measurements showed FPV covering 30% of the basin area resulted in a 49% reduction of evaporation.

And in Brazil, Lopes *et al*[49] examined regions with semi-arid climates. They concluded that FPV coverage scenarios of 21.2%, 50%, and 70% could reduce evaporation from reservoirs by 15.3%, 37%, and 55.2% respectively. This is important for increasing cities’ resilience in this type of climate, especially during periods of drought.

Impact on birds

Bird behavioral patterns are diverse, reflecting the complex interactions between them and their environments. Birds have been shown to consider FPV a safe, convenient place to land and rest.

To understand the impact of FPV on birds (and vice versa), it’s necessary to monitor their population and behavior. Strategic placement of vegetation or artificial structures around

FPV arrays could provide additional nesting or shelter. This contributes to habitat diversity and conservation efforts.

Royal Haskoning DHV monitors geese at Weperpolder

Between 2018 and 2019, two years of bird monitoring was done by Royal Haskoning DHV at the Weperpolder FPV plant. This sand mining lake was known as a roosting site for waterbirds.

The study compared tundra goose population data before and after plant construction. Counting was performed at the site over a period of three months.

Before plant construction in 2018, 200 geese were counted. After completion in 2019, that figure was 370. Findings showed no negative influence in areas like birds choosing resting places.

Figure 9. Bird monitoring at Weperpolder in 2019

Another campaign is ongoing at Sellingen, investigating bird behavior around FPV over five years. The first year saw a baseline study completed before construction in 2020/2021. Intermediate results show no impact from FPV on birds. 28,000 Tundra geese were counted during baseline monitoring. 27,000 visited the lake after the solar park installation.

Buro Bakker and AKTB examine migratory bird behavior

Bird monitoring was also conducted at Bomhofsplas and Nijbeets, FPV projects with lake coverage of 26% and 29% respectively. Burro Bakker and AKTB surveyed breeding birds using the BMP-A protocol across sand mining lakes

Between 2020-2021, eight visits were made to Bomhofsplas and five to Nijbeets. Observations were recorded using handheld field computers and processed using the Avimap entry program and Sovon auto-cluster program.

Visits typically occurred in the late afternoon to dusk, with sectors designated for waterbird counts. Sector divisions accounted for the presence of solar farms in both locations. Results of evaluating birds showed that migratory birds use FPV as a sanctuary for resting.

Impact on biodiversity

Biodiversity's crucial role in maintaining ecosystem health, resilience, and functionality can be supported by FPV systems to preserve habitats. Biodiversity considerations during development and management of FPV installations are essential for maximizing environmental benefits and ensuring sustainable energy transition.

Case study: Bomhofsplas explored by Ecocean

The BayWa r.e. Bomhofsplas project is used extensively to research the effects of FPV installations on the lake’s water quality and ecosystem. In 2020, French biodiversity experts Ecocean conducted an in-depth study on the lake’s aquatic environment.

Figure 10. Bomhofsplas FPV (source BayWa)

20 biohuts were installed at the edge of the floating plant. These function as nurseries for small fish and act as habitats and spawning sites for fish, microorganisms, and invertebrates.

Fish were monitored between 2020 and 2023; mainly post-larvae, juveniles, and vagile fauna like cryptic fish and invertebrates. Findings revealed a favorable trend in the colonization and development of species over time under FPV.

Compared to the first full year of observation, there was a rapid growth in the abundance and number of mobile fauna species in 2022, which stabilized in 2023. This highlights the ability of the ecosystem to adjust to the introduction of novel species and the establishment of their populations.

Three fish species (common perch, cyprinids, and tube-nosed goby) and two invertebrate species (Limnae sp and gammarid shrimp) were recorded. The total population recorded was 2382; 1951 invertebrates and 431 fish.

The number of species at the bottom of the food chain, like daphnia and gammarids, demonstrates that the biohut environment is balanced to support aquatic life. These species are important, serving as prey for other fish species and larger animals in the food chain. Their abundance suggests a favorable environment for diverse fauna, critical for the ecosystem's overall health and stability.

Incorporating biohuts into FPV installations facilitated the proliferation and maturation of aquatic life. This had a favorable effect on the ecological equilibrium of the artificial body of water.

Figure 11.Juvenile common perch (Perca fluviaitlis) sampled in one of the biohuts in Bomhofsplas in 2023 – Source: Ecocean

Figure 12.Installed Biohuts in Bomhofsplas

Impact on light permeability

Light influences multiple biological and chemical processes within a body of water, like primary production, photosynthetic oxygen dynamics, and temperature regulation.[50] Light permeability of FPV systems depends on the type of floating structure used, its layout, spacing, and module orientation. Various studies are addressing concerns about reduced light availability under FPV modules.[20][10][2]

BayWa r.e. internal study

We studied light permeability under the type of floating structure implemented as our technical standard. The study was performed with the Python-based ray-tracing software, bifacial_radiance.[51] This uses a backward ray-tracing method to trace individual rays of light in a 3D scene.

Within this scene, the floating structure is modeled in 1:1 scale with non-transparent modules. To avoid edge effects of incoming light from the sides, virtual sensors were placed in the center boat of a 3x3 block. More than 600 virtual sensors in a grid of 0.3cm^2 were placed below the structure to compare irradiance intensity with annual weather data for Germany.

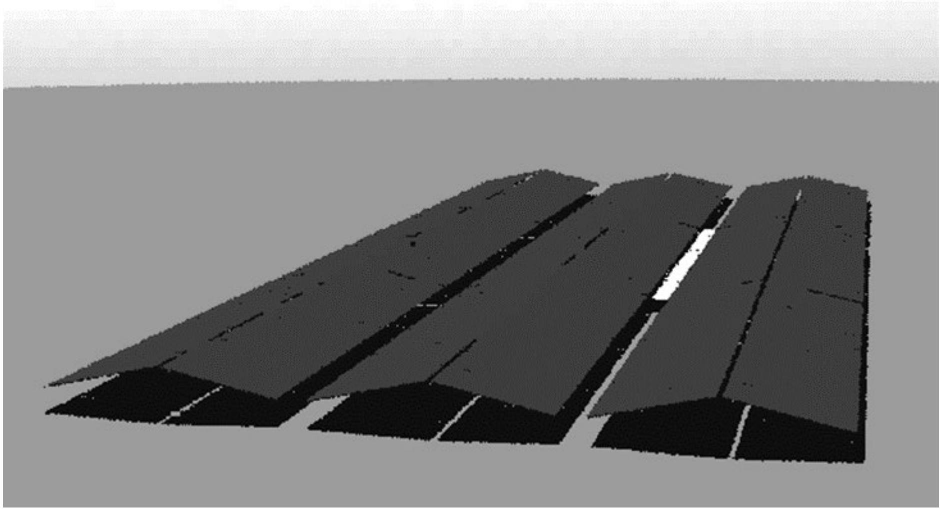


Figure 13.Rendering picture of the modelled floating block

Annual light permeability was calculated as a percentage of incoming solar irradiance reaching the water underneath the floating structure. For a boat with a nontransparent walkway, the yearly average is 5.5%. For a boat with a semitransparent walkway, the result is 5.93%.

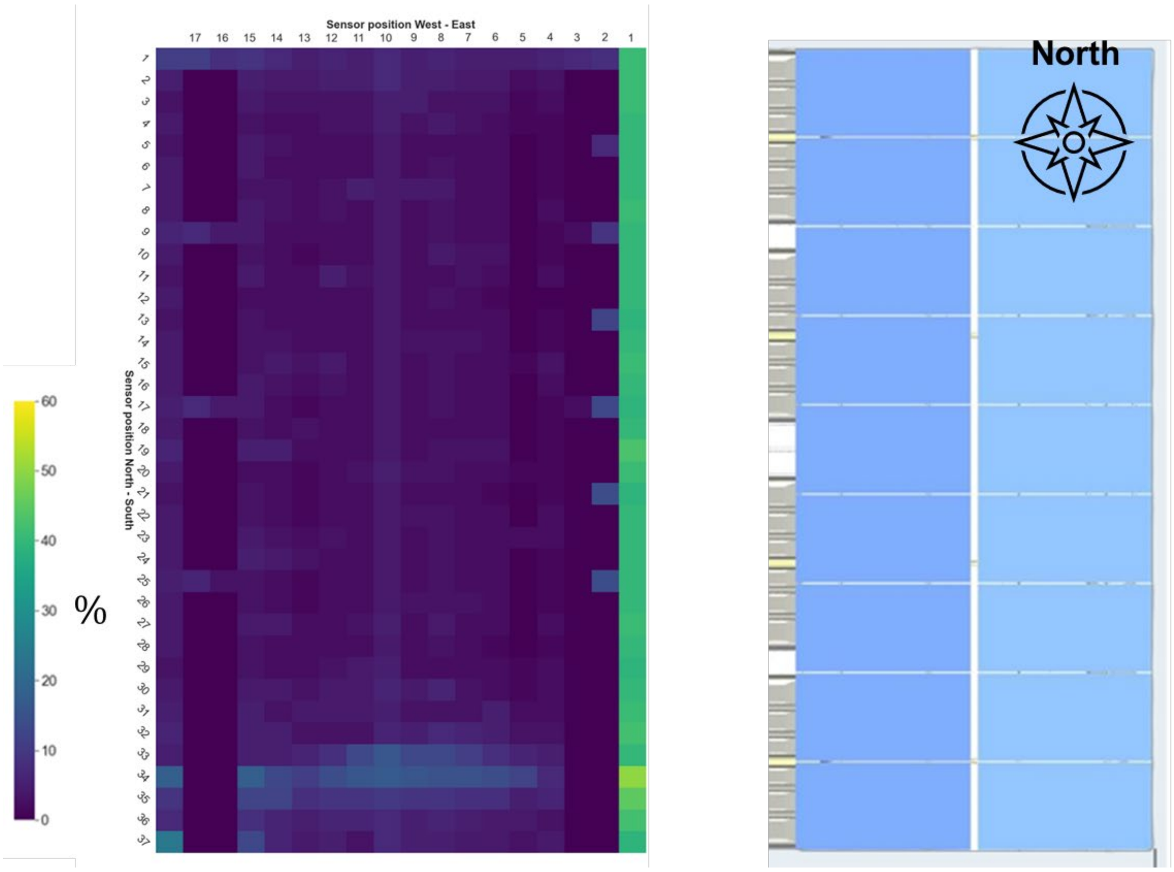


Figure 14.Left: XY-Plot of light permeability below center boat; right: top view of the center boat structure

Results showed the floating structure features a light permeability of ~5.9% in southern Germany. This was simulated by selecting the GHI of one representative day per each month of the year, and averaging results for a full year. The actual transmittance is lower than the top view transparency due to lower sun angles, and therefore incidence angles.

It’s relevant to mention that floating structures are usually placed in open water zones, at a certain distance from the shore. We suggest at least 20-30m, if not otherwise specified by local and national regulations. There, light doesn’t reach the bottom of the water body. Impact on water fauna and flora from decreased irradiance is more limited than in riparian areas.

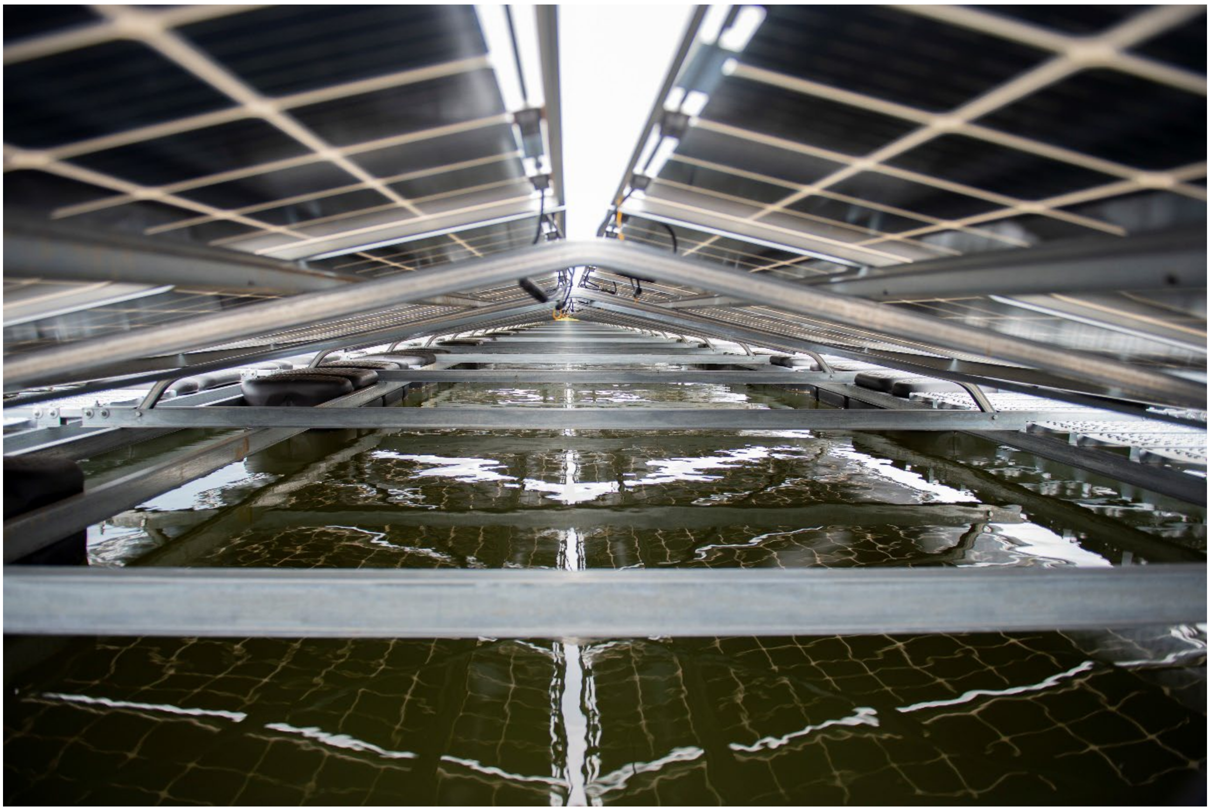


Figure 15.Light going through the PV modules

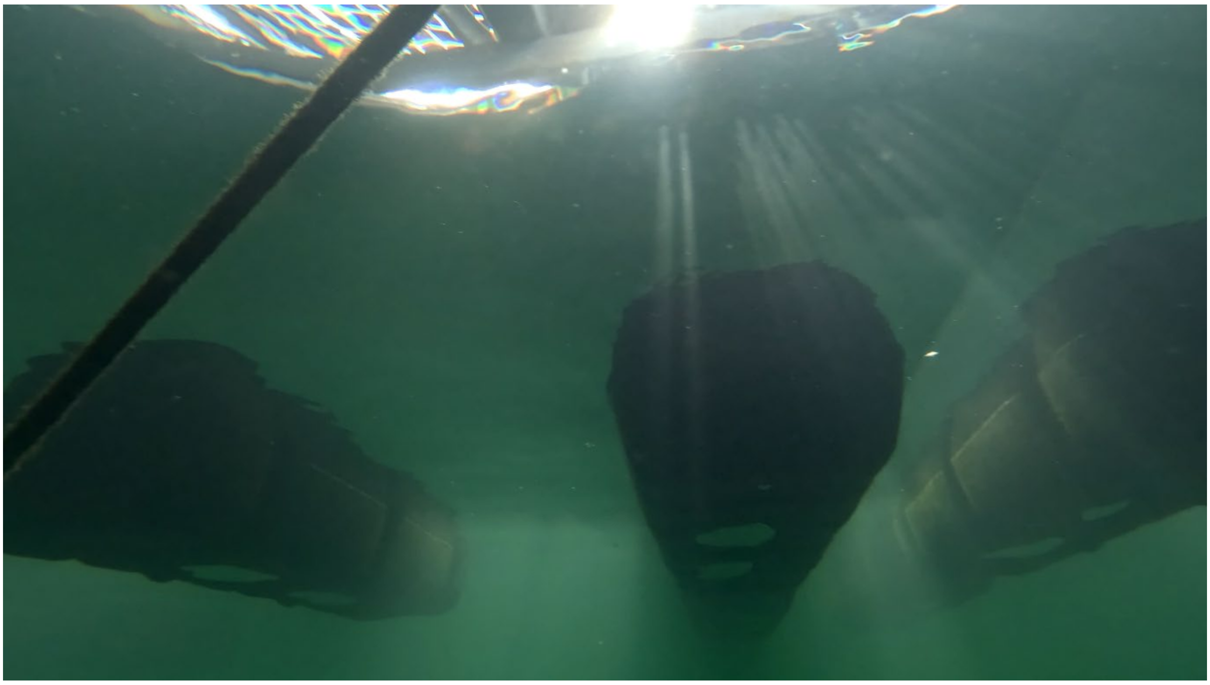


Figure 16. Underwater picture of FPV installation

Drinking water compatibility

Especially when installing FPV systems on reservoirs intended for drinking water, contamination risk is a highly sensitive topic. Structural materials could potentially leak harmful substances, posing a risk to human health. Careful selection of materials, additives, and coatings is required to avoid this, as we did in our very first project on a drinking water reservoir, called Beerenplaat in the Netherlands. (8,804 solar modules on 1.5 hectares produce 4,876 MWh of electricity, referring to the equivalence of the electricity consumption of around 2,000 average Dutch households)

In BayWa r.e FPV projects, a special biodegradable FR3 fluid is used for transformers instead of traditional synthetic oil. The transformer is surrounded by a collecting tank, sealed to prevent oil discharge into water, even in the unlikely event of a spill.

As for steel coating materials, internal calculations observed zinc loss rates for complete standard FPV units of 1.4ha with Magnelis coating, resulting in ~65kg over 30 years. Even at high coverage ratios (~50% lake coverage at 20m depth), this results in a gain of only 0.1mg/l concentration after 30 years. The maximum allowable limit of zinc concentration in Germany is 800mg/l[52], four orders of magnitude larger than the maximum calculated zinc loss.

When certain plastics are exposed to UV radiation, they can deteriorate, embrittle, and release particles into water.[53] Plastics used in FPV systems, like in the floaters providing buoyancy, need to be UV-stable. In case of fire, materials shouldn’t ignite and melt, with additional risk of substances leaking into the water.

The UV stability of HDPE floaters used in BayWa r.e. projects was tested in accordance with ASTM G154. Samples were subjected to 42 cycles of 8 hours of UVA-340 exposure at 60°C, followed by 4 hours of H_2O condensation (dew) at 50°C. One month of these laboratory test settings represents a year of operation in the Arizona climate.

After 26 months of laboratory testing, no wear on the surface of the material samples was detected. The flammability classification was carried out in accordance with DIN 75200.

Floater samples were brought into contact with a flame, but could not be ignited. The flame went out quickly once the ignition source was removed.

Mathijssen *et al*[54] looked at the effect of partial solar panel coverage on a drinking water reservoir in Kralingen, Netherlands. The study looked at the microbial load and pollutant release from solar modules, specifically the mortality rates of cryptosporidia, giardia, and campylobacter.

Results revealed low germ elimination rates and low heavy metal leaching from floats, components, sealing material, and solar modules. The study also investigated organic compounds, but no adverse effects were found. A 30% project-related cover of the lake area is unlikely to impair drinking water use.

Product carbon footprint and reduced CO_2 emissions

It's important to calculate the CO_2 emissions of a FPV project itself. These should be compared to the savings in emissions vs fossil fuel systems.

CO_2 calculations should consider the total lifecycle emissions of FPV systems, including manufacturing, transportation, installation, and decommissioning. Continuous improvements to manufacturing processes and materials improve overall environmental performance.

The BayWa r.e. model focuses on the main steps of the lifecycle and evaluates emissions at each step:

1. **Upstream process** includes the entire backpack; raw material extraction, component manufacturing, transports, etc.
2. **Supplier** considers the product carbon footprint (PCF) of PV modules, mounting structures, inverters, transformers, battery and battery rack housing, HVAC, and cable weights.
3. **Transport** includes shipping from China to Europe and truck transport to the project site.
4. **Construction** looks at construction vehicles' diesel usage (FPV consumes less than ground-mounted PV.
5. **Product use** examines inverters and transformer efficiency by calculating load amounts and PV self-consumption.
6. **Deconstruction** uses a simplified calculation depending on construction's emissions (%)

A 12.3MWp FPV project with an average lifetime of 30 years saves 5,194 tonnes of CO_2 per year, compared to a modern gas plant.[55]

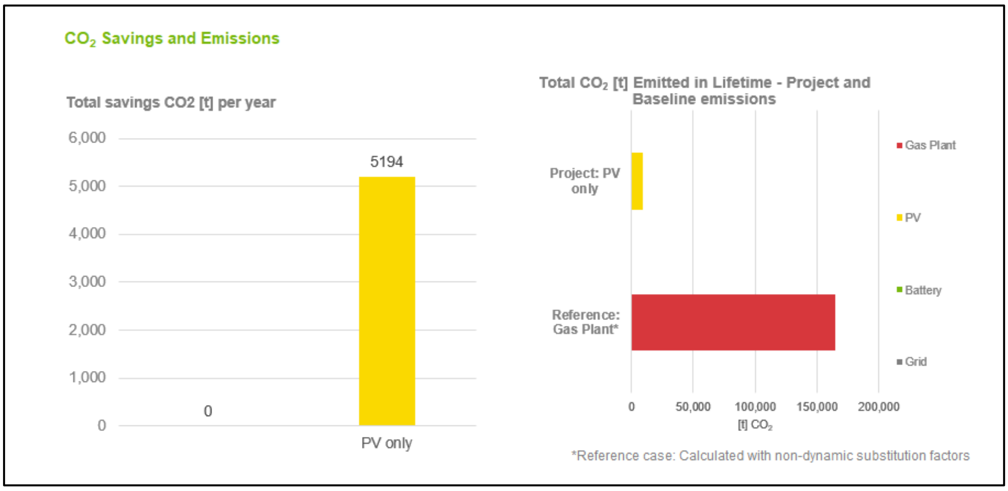
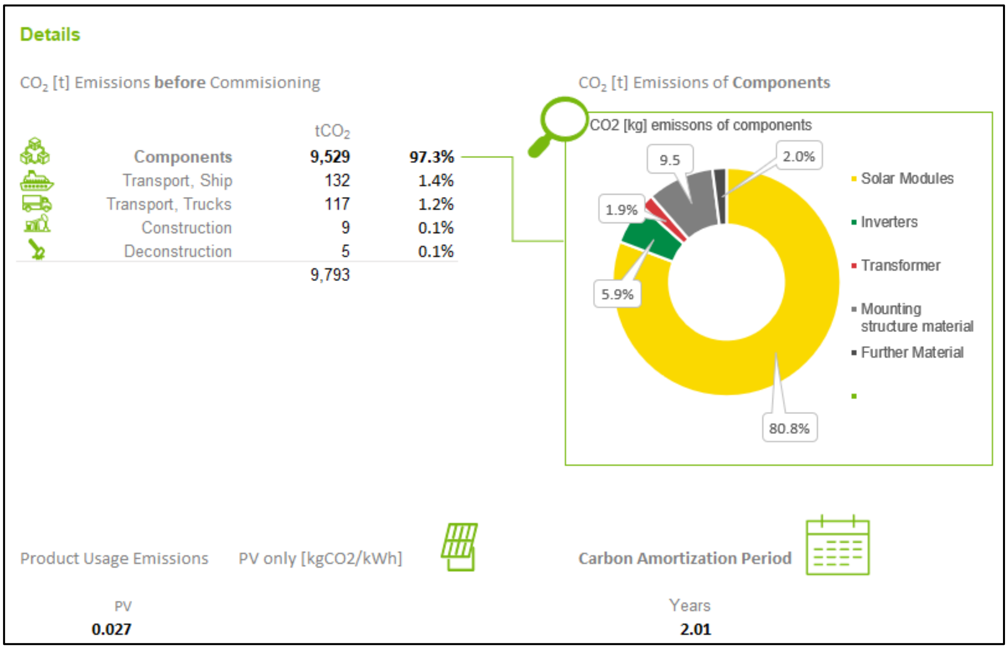


Figure 17: CO_2 savings calculations for a 12.3 MWp FPV project

The CO_{2eq} backpack of the project is amortized after 2.01 years.



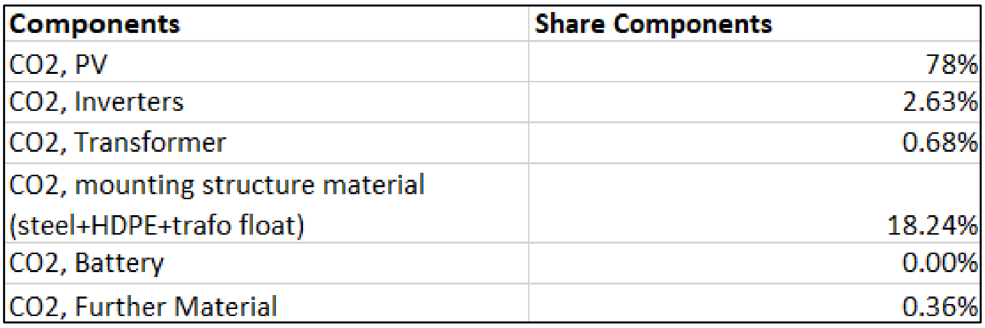
	tCO_2	
Components	**9,529**	**97.3%**
Transport, Ship	132	1.4%
Transport, Trucks	117	1.2%
Construction	9	0.1%
Deconstruction	5	0.1%
	9,793	

PV	Years
0.027	**2.01**

Figure 18: The carbon footprint (in tCO_2) of the various processes within the BayWa r.e. system boundary for the 12.3MWp FPV project

The emission intensity varies according to the underlying sources and scope defined for the assessment. Carbon footprint can range between 500-1041kgCO_2/kWp, with a carbon amortization period between 1.23-2.69 years.

The 97.3% footprint contribution from components includes PV modules, inverters, transformers, mounting structure materials, batteries (if present), and cables.



Components	Share Components
CO2, PV	78%
CO2, Inverters	2.63%
CO2, Transformer	0.68%
CO2, mounting structure material (steel+HDPE+trafo float)	18.24%
CO2, Battery	0.00%
CO2, Further Material	0.36%

Figure 19: The % contribution to the carbon footprint by the various components

These calculations are based on primary data where available and accessible. Results have limitations in assessing all components across the entire system. This can lead to slight deviations compared to other studies.

End-of-life processing is not included in the CO_2 backpack. Results of our internal calculations primarily show CO_2 savings from lifecycle emissions.

To summarize, FPV represents a tangible and effective strategy for lowering CO_2 emissions. It helps shift the energy landscape towards a more sustainable and low-carbon future.

Conclusion: Real potential as a powerful force for energy transition

Various studies show potential positive effects of FPV systems:

- Water evaporation reduction: FPV enhances water conservation in a variety of settings, contributing to overall water resource management
- Preventing algal blooms: Shading could play a crucial role in mitigating algae growth, improving water aesthetics and enhancing water quality
- Mitigating climate change with shorter summer water stratification periods

Operational studies indicate FPV causes n**o noticeable negative impact on water quality**, even at high water coverage ratio up to 50%. On the contrary, it can accommodate aquatic life and drive biodiversity enhancement.

This was evident at Bomhofsplas, Beilen and Lippe Gabrielsplas. We saw **minimal differences in temperature balance, DO levels, conductivity, and stratification behavior** between open water and areas under FPV coverage.

Furthermore, the study emphasizes the importance of assessing water quality parameters, including water temperature, dissolved oxygen, electrical conductivity, and turbidity, during the development and operation of FPV projects. These parameters play a vital role in supporting aquatic life, and careful monitoring is necessary to minimize potential negative impacts and maintain or improve water quality.

The case studies, including those in the Netherlands and Singapore, demonstrate that FPV installations can have positive effects on water quality by reducing algal growth and chlorophyll-a concentration. The studies also highlight the need for a balanced approach, considering factors like FPV coverage percentage, water depth, and the specific ecology of the water body.

Studies in Jordan, Egypt, and Brazil show FPV coverage reduces evaporation by 15.3-60%. FPV systems can **improve water resilience** in semi-arid regions, especially useful during droughts. Despite differences in methodology, data underlines FPV's water-saving benefits.

Light permeability studies indicate FPV structures have a light permeability of around 5.9%. **Impact on aquatic ecosystems is limited**, especially in open water zones where light penetration to the bottom is already restricted.

Materials and coatings used in FPV construction must be carefully chosen to prevent water contamination. Studies show **biodegradable fluids in transformers ensure compatibility with drinking water reservoirs**. Rigorous testing, adherence to industry standards, and ongoing monitoring contribute to the safety of FPV systems in drinking water environments.

Monitoring studies on birds consistently indicate that FPV installations are seen as safe havens by birds, with **no negative effects on bird behavior or population**.

The reduction of CO_2 emissions through FPV systems contributes significantly to environmental sustainability. Lifecycle studies considering manufacturing, transportation, installation, and decommissioning point to **substantial carbon savings**.

Compelling case studies, like Ecocean’s at Bomhofsplas, show a **positive impact on biodiversity**. Three years of monitoring biohuts reveal a favorable trend in the colonization and development of species under FPV. Projects can actively contribute to enhancing aquatic ecosystems, supporting biodiversity, and establishing a dynamic equilibrium.

Careful planning, consideration for local conditions, and monitoring are essential to optimize FPV’s positive outcomes and minimize adverse effects. However, it *can* fulfill rising demand for clean energy while lowering the environmental effect of power generation. These systems are set to play a significant role in the shift to a more sustainable energy future.

References

[1] IEA (2023), Global Energy and Climate Model, IEA, Paris iea.org/reports/global-energy-and-climate-model, License: CC BY 4.0

[2] Bax, V., van de Lageweg, W. I., van den Berg, B., Hoosemans, R., & Terpstra, T. (2022). Will it float? Exploring the social feasibility of floating solar energy infrastructure in the Netherlands. Energy Research & Social Science, 89(102569), 102569. doi.org/10.1016/j.erss.2022.102569

[3] Ranjbaran, P., Yousefi, H., Gharehpetian, G. B., & Astaraei, F. R. (2019). A review on floating photovoltaic (FPV) power generation units. Renewable and Sustainable Energy Reviews, 110, 332–347. doi.org/10.1016/j.rser.2019.05.015

[4] Contact us. (n.d.). Spglobal.com. Retrieved February 4, 2024, from spglobal.com/commodityinsights/en

[5] World Bank Group, Energy Sector Management Assistance Program, & Solar Energy Research Institute of Singapore. (2019). Where sun meets water. World Bank, Washington, DC. https://openknowledge

[6] Spencer, R. S., Macknick, J., Aznar, A., Warren, A., & Reese, M. O. (2019). Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States. Environmental Science & Technology, 53(3), 1680–1689. doi.org/10.1021/acs.est.8b04735

[7] Sahu, A., Yadav, N., & Sudhakar, K. (2016). Floating photovoltaic power plant: A review. Renewable and Sustainable Energy Reviews, 66, 815–824. doi.org/10.1016/j.rser.2016.08.051

[8] Lee, Y.-G., Joo, H.-J., & Yoon, S.-J. (2014). Design and installation of floating type photovoltaic energy generation system using FRP members. Solar Energy (Phoenix, Ariz.), 108, 13–27. doi.org/10.1016/j.solener.2014.06.033

[9] Suh, J., Jang, Y., & Choi, Y. (2019). Comparison of electric power output observed and estimated from floating photovoltaic systems: A case study on the Hapcheon Dam, Korea. *Sustainability*, *12*(1), 276. doi.org/10.3390/su12010276

[10] Sahu, A., Yadav, N., & Sudhakar, K. (2016). Floating photovoltaic power plant: A review. Renewable and Sustainable Energy Reviews, 66, 815–824. doi.org/10.1016/j.rser.2016.08.051

[11] Zhou, Y., Chang, F.-J., Chang, L.-C., Lee, W.-D., Huang, A., Xu, C.-Y., & Guo, S. (2020). An advanced complementary scheme of floating photovoltaic and hydropower generation flourishing water-food-energy nexus synergies. Applied Energy, 275(115389), 115389. doi.org/10.1016/j.apenergy.2020.115389

[12] Boehrer, B., & Schultze, M. (2008). Stratification of lakes. Reviews of Geophysics (Washington, D.C.: 1985), 46(2). doi.org/10.1029/2006rg000210

[13] (N.d.). Illinois.gov. Retrieved February 4, 2024, from epa.illinois.gov/content/dam/soi/en/web/epa/documents/water/conservation/lake-notes/lake-stratification.pdf

[14] Chapter 9 stratification in deep lakes. (1975). In Physiological Limnology - An Approach to the Physiology of Lake Ecosystems (pp. 145–173). Elsevie

[15] Butcher, J.B., Nover, D., Johnson, T.E. *et al.* Sensitivity of lake thermal and mixing dynamics to climate change. *Climatic Change* **129**, 295–305 (2015). doi.org/10.1007/s10584-015-1326-1

[16] Jane, S. F., Mincer, J. L., Lau, M. P., Lewis, A. S. L., Stetler, J. T., & Rose, K. C. (2023). Longer duration of seasonal stratification contributes to widespread increases in lake hypoxia and anoxia. Global Change Biology, 29(4), 1009–1023. doi.org/10.1111/gcb.16525

[17] Armstrong A, Page T, Thackeray SJ, Hernandez RR, Jones ID. Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees. Environ Res Lett 2020; 15:114055. doi.org/10.1088/1748-9326/abbf7b

[18] J. Kalff. Limnology: inland water ecosystems.Prentice Hall, Upper Saddle River, NJ (2002)

[19] Woolway, R.I., Sharma, S., Weyhenmeyer, G.A. et al. Phenological shifts in lake stratification under climate change. Nat Commun 12, 2318 (2021). doi.org/10.1038/s41467-021-22657-4

[20] Exley, G., Armstrong, A., Page, T., & Jones, I. D. (2021). Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. Solar Energy (Phoenix, Ariz.), 219, 24–33. doi.org/10.1016/j.solener.2021.01.076

[21] Ilgen, K., Schindler, D., Wieland, S., & Lange, J. (2023). The impact of floating photovoltaic power plants on lake water temperature and stratification. Scientific Reports, 13(1). doi.org/10.1038/s41598-023-34751-2

[22] Spellman, F. R., & Drinan, J. E. (2012). The drinking water handbook. CRC Press. doi.org/10.1201/b12305

[23] Bhateria, R., & Jain, D. (2016). Water quality assessment of lake water: a review. Sustainable Water Resources Management, 2(2), 161–173. doi.org/10.1007/s40899-015-0014-7

[24] Rubalcaba, J. G. (2024). Metabolic responses to cold and warm extremes in the ocean. *PLoS Biology*, *22*(1), e3002479. doi.org/10.1371/journal.pbio.3002479

[25] Temperature, L. W. (n.d.). Indicators of climate change in California (2022). Oehha.ca.gov. Retrieved February 4, 2024, from oehha.ca.gov/media/epic/downloads/03lakewatertemps.pdf

[26] FAQ: Ocean deoxygenation. (n.d.). Scripps Institution of Oceanography. Retrieved February 4, 2024, from scripps.ucsd.edu/research/climate-change-resources/faq-ocean-deoxygenation

[27] Economical, political, and social issues in water resources. (2021). Elsevier. doi.org/10.1016/c2020-0-03830-2

[28] Characterization and treatment of textile wastewater. (2015). Elsevier. doi.org/10.1016/c2014-0-02395-7

[29] Dębska, K., Rutkowska, B., Szulc, W., & Gozdowski, D. (2021). Changes in selected water quality parameters in the Utrata River as a function of catchment area land use. Water, 13(21), 2989. doi.org/10.3390/w13212989

[30] (N.d.-b). Epa.gov. Retrieved February 4, 2024, from epa.gov/system/files/documents/2021-07/parameter-factsheet_do.pdf

[31] Wu, T., Wang, S., Su, B., Wu, H., & Wang, G. (2021). Understanding the water quality change of the Yilong Lake based on comprehensive assessment methods. Ecological Indicators, 126(107714), 107714. doi.org/10.1016/j.ecolind.2021.107714

[32] What is the typical water conductivity range? (2022, September 27). Atlas Scientific. atlas-scientific.com/blog/water-conductivity-range/

[33] Conductivity. (n.d.). DataStream. Retrieved February 4, 2024, from datastream.org/en-ca/guidebook/conductivity

[34] Angradi, T. R., Ringold, P. L., & Hall, K. (2018). Water clarity measures as indicators of recreational benefits provided by U.S. lakes: Swimming and aesthetics. Ecological Indicators, 93, 1005–1019. doi.org/10.1016/j.ecolind.2018.06.001

[35] de Lima, R. L. P., Paxinou, K., C. Boogaard, F., Akkerman, O., & Lin, F.-Y. (2021). In-situ water quality observations under a large-scale floating solar farm using sensors and underwater drones. Sustainability, 13(11), 6421. doi.org/10.3390/su13116421

[36] Patel, H., & Vashi, R. T. (2015). Characterization and Treatment of Textile Wastewater. Elsevier.

[37] Yang, P., Chua, L. H. C., Irvine, K. N., Nguyen, M. T., & Low, E.-W. (2022). Impacts of a floating photovoltaic system on temperature and water quality in a shallow tropical reservoir. Limnology, 23(3), 441–454. doi.org/10.1007/s10201-022-00698-y

[38] Amorim, C. A., & Moura, A. do N. (2021). Ecological impacts of freshwater algal blooms on water quality, plankton biodiversity, structure, and ecosystem functioning. The Science of the Total Environment, 758(143605), 143605. doi.org/10.1016/j.scitotenv.2020.143605

[39] Anderson, C. R., Moore, S. K., Tomlinson, M. C., Silke, J., & Cusack, C. K. (2015). Living with harmful algal blooms in a changing world. In Coastal and Marine Hazards, Risks, and Disasters (pp. 495–561). Elsevier.

[40] Chlorophyll in transitional, coastal and marine waters in Europe. (n.d.). Europa.Eu. Retrieved February 1, 2024, from eea.europa.eu/en/analysis/indicators/chlorophyll-in-transitional-coastal-and?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8

[41] Château, P.-A., Wunderlich, R. F., Wang, T.-W., Lai, H.-T., Chen, C.-C., & Chang, F.-J. (2019). Mathematical modeling suggests high potential for the deployment of floating photovoltaic on fish ponds. The Science of the Total Environment, 687, 654–666. doi.org/10.1016/j.scitotenv.2019.05.420

[42] Haas, J., Khalighi, J., de la Fuente, A., Gerbersdorf, S. U., Nowak, W., & Chen, P.-J. (2020). Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. Energy Conversion and Management, 206(112414), 112414. doi.org/10.1016/j.enconman.2019.112414

[43] World Health Organization. (2020). Cyanobacterial toxins: cylindrospermopsins (No. WHO/HEP/ECH/WSH/2020.4). World Health Organization.

[44] Farrar, L. W., Bahaj, A. S., James, P., Anwar, A., & Amdar, N. (2022d). Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study Jordan. *Energy Conversion and Management, 260(115598), 115598.* doi.org/10.1016/j.enconman.2022.115598

[45] Abd-Elhamid, H. F., Ahmed, A., Zeleňáková, M., Vranayová, Z., & Fathy, I. (2021). Reservoir management by reducing evaporation using floating photovoltaic system: A case study of Lake Nasser, Egypt. *Water*, *13*(6), 769. doi.org/10.3390/w13060769

[46] Abdelal, Q. (2021). Floating PV; an assessment of water quality and evaporation reduction in semi-arid regions. International Journal of Low-Carbon Technologies, 16(3), 732–739. doi.org/10.1093/ijlct/ctab001

[47] Bontempo Scavo, F., Marco Tina, G., Gagliano, A., & Nizetic, S. (2020). An assessment study of evaporation rate models on a water basin with floating photovoltaic plants. Int. J. Energy Res., n/a, 1–22. doi.org/10.1002/er.5170

[48] Santos, F. R. dos, Wiecheteck, G. K., Virgens Filho, J. S. das, Carranza, G. A., Chambers, T. L., & Fekih, A. (2022). Effects of a floating photovoltaic system on the water evaporation rate in the Passaúna Reservoir, Brazil. Energies, 15(17), 6274. doi.org/10.3390/en15176274

[49] Padilha Campos Lopes, M., de Andrade Neto, S., Alves Castelo Branco, D., Vasconcelos de Freitas, M. A., & da Silva Fidelis, N. (2020). Water-energy nexus:

Floating photovoltaic systems promoting water security and energy generation in the semiarid region of Brazil. Journal of Cleaner Production, 273(122010), 122010. doi.org/10.1016/j.jclepro.2020.122010

[50] Wollschläger, J., Neale, P. J., North, R. L., Striebel, M., & Zielinski, O. (2021). Editorial: Climate change and light in aquatic ecosystems: Variability & ecological consequences. *Frontiers in Marine Science, 8.* doi.org/10.3389/fmars.2021.688712

[51] Ayala Pelaez and Deline, (2020). bifacial_radiance: a python package for modeling bifacial solar photovoltaic systems. Journal of Open Source Software, 5(50), 1865, doi.org/10.21105/joss.01865

[52] German Environment Agency (2017): Waters in Germany: Status and assessment. Dessau-Roßlau.

[53] Sun, J., Zheng, H., Xiang, H., Fan, J., & Jiang, H. (2022). The surface degradation and release of microplastics from plastic films studied by UV radiation and mechanical abrasion. The Science of the Total Environment, 838(156369), 156369. doi.org/10.1016/j.scitotenv.2022.156369

[54] Mathijssen, D., Hofs, B., Spierenburg-Sack, E., van Asperen, R., van der Wal, B., Vreeburg, J., & Ketelaars, H. (2020). Potential impact of floating solar panels on water quality in reservoirs; pathogens and leaching. *Water Practice & Technology*, *15*(3), 807–811. doi.org/10.2166/wpt.2020.062

[55] IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 582 pp.