Deltares

Impact of floating solar on water quality; results of a case study

Kennis van Ecologie voor de Energietransitie (KEEN) – Cluster Water

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Voorwoord KEEN

Het Ministerie van EZK heeft in 2025 opdracht gegeven om het onderzoeksprogramma Kennis van Ecologie voor Energietransitie (KEEN) te starten. Doel van dit programma is te voorkomen dat de energietransitie leidt tot ongewenste ecologische gevolgen en tegelijkertijd te voorkomen dat de energietransitie vertraging ondervindt als gevolg van onzekerheid over de ecologische effecten van hernieuwbare energieopwekking. Het project is begeleid door TKI Urban Energy (Topconsortia voor Kennis & Innovatie) en RVO Rijksdienst voor Ondernemend Nederland.

De energietransitie zal een impact hebben op de kwaliteit en het leven in het water, op het land en in de bodem. Deltares, TNO, WUR en KWR onderzoeken de effecten van het opschalen van hernieuwbare energiebronnen zoals wind, zon, aquathermie en bodemenergie, om ervoor te zorgen dat onze overgang naar een duurzame toekomst zowel effectief als ecologisch verantwoord is. Er is nieuw onderzoek gestart binnen KEEN maar ook lopend onderzoek wordt gebruikt, gebundeld en aangevuld binnen KEEN. In dit rapport worden de eerste onderzoeksresultaten gepresenteerd, de wens is om een langjarige monitoringreeks te kunnen opbouwen. Het onderzoek is georganiseerd in drie clusters:

Cluster Land:

1. Onderzoek naar de verdeling van bodemvocht onder zonnepanelen
2. Onderzoek naar aanvaringsrisico's voor roofvogels bij het combineren van zon- en windenergie, met modellering van de luchtstromen.

Cluster Water:

1. Onderzoek op één locatie naar de effecten van een aquathermie installatie op de ecologie. Er is gekeken naar de effecten van waterfiltering, koudelozing en stroming.
2. Onderzoek naar de relatie tussen bedekking door zonnepanelen op water en de impact op primaire productie van biomassa.

Cluster Bodem:

1. Onderzoek naar de temperatuureffecten van MTO- en HTO-systemen op de grondwaterkwaliteit.

In dit rapport leest u de resultaten van *Cluster water* onderzoek 2: de relatie tussen bedekking door zonnepanelen op water en de impact op primaire productie van biomassa.

Samenvatting

De energietransitie vraagt om nieuwe ruimte voor duurzame energieopwekking. Steeds vaker wordt daarbij gekeken naar drijvende zonneparken op diepe zandwinplassen en andere waterlichamen. Tegelijkertijd staan overheden voor de opgave om te voldoen aan ecologische doelen vanuit de Kaderrichtlijn Water (KRW) en Natura 2000.

Dit leidt tot een bekend en urgent spanningsveld. Hoe faciliteer je duurzame energie, zonder de natuurwaarden te ondermijnen die zijn vastgelegd in wetgeving zoals KRW en Natura 2000? Bij de vergunningverlening voor drijvende zonneparken is dit spanningsveld zeer actueel. Zonder kennis over de impact van een dergelijk park op ecologische doelen is dit een lastige afweging. Nederlandse oppervlaktewateren halen de doelen nog niet. Daarom wordt nu vaak gehandeld vanuit het voorzorgsprincipe, wat regelmatig leidt tot het weigeren van een vergunning.

Eerdere monitoringswerkzaamheden binnen het TKI ZWIMPproject (Van Eck et al., 2024) lieten zien dat het bedekken van oppervlaktewater met drijvende zonnepanelen leidt tot lagere zuurstofconcentraties onder de panelen. Aan het einde van dit project (2022) ontbrak echter nog een duidelijke verklaring voor deze verlaging. De aanname was dat minder licht leidt tot een lagere primaire productie (omzetten van zonne-energie in zuurstof en voedsel voor organismen) naar door algen in de bovenste waterlagen. Door de afname van primaire productie zou de zuurstofconcentratie dalen. Afname van primaire productie kan grote gevolgen hebben voor het meer, omdat algen de basis vormen van het aquatische voedselweb.

Het doel van het hier gepresenteerde KEENonderzoek (Kennis Ecologie voor de Energietransitie) is om deze relatie verder te onderzoeken. Daarbij richten we ons op de relatie tussen verminderd zonlicht, veroorzaakt door bedekking met zonnepanelen, en de effecten op de waterkwaliteit. De nadruk ligt op watertemperatuur en primaire productie. Onze ultieme ambitie is om te bepalen hoeveel lichtreductie een meer kan verdragen zonder dat de primaire productie negatief wordt beïnvloed. We erkennen dat dit een ambitieus doel is. Daarom zien we het KEENonderzoek als een eerste stap in die richting.

Zonneparken op land zijn al langere tijd zichtbaar aanwezig in het landschap. Het is daarom logisch dat er meer onderzoek is gedaan naar effecten op land dan op water. Om natuurwaarden te beschermen is voor zonneparken op land het EcoCertifiedlabel ontwikkeld. Dit label wordt toegekend aan zonneparken die natuurwaarden behouden en soms zelfs versterken. Daarbij ligt de nadruk op vegetatie onder en tussen de panelen.

Onderdeel van deze certificering is de zogenoemde bodemlichttoets. Deze toets beoordeelt of er voldoende licht tussen de panelen door de bodem bereikt voor een gezonde begroeiing. Tegelijk wordt beoordeeld of de hoeveelheid licht die op de panelen valt voldoende is voor een rendabele elektriciteitsopbrengst. Wanneer de lichttoets laat zien dat er onvoldoende licht beschikbaar is, kan het ontwerp worden aangepast. Een mogelijke maatregel is het vergroten van de afstand tussen de panelen. Hierdoor kan meer licht de bodem bereiken. De hoeveelheid licht op de bodem bij een bepaald ontwerp wordt berekend met het TNOmodel BIGEYE. Vegetatiedeskundigen bepalen vervolgens welke hoeveelheid licht nodig is voor een gezonde vegetatie.

Met deze KEENstudie verkennen we of een vergelijkbare lichttoets ook mogelijk is voor drijvende zonneparken. Dit zou een eerste stap kunnen zijn richting

een EcoCertifiedlabel voor zonneparken op water. Het onderzoek naar zonneparken op land is echter niet één op één toepasbaar op water. Daarvoor zijn de verschillen tussen land en water te groot:

- Waterlichamen zijn over het algemeen ecologisch waardevol, in tegenstelling tot veel locaties op (voorheen) intensief beheerde landbouwgronden.
- Water beweegt, waardoor effecten zich op systeemniveau voordoen en niet alleen lokaal. Een minimale lichtdrempel op één vaste plek is daarom niet goed te definiëren.
- In veel watersystemen is licht gedurende een deel van het jaar, maar vaak ook jaarrond, limiterend voor de primaire productie. Een afname van licht leidt dan onvermijdelijk tot een effect.
- De ecologische respons hangt sterk af van andere factoren, zoals waterdiepte, stratificatie, nutriëntenconcentratie, doorstroming en verblijftijd.

Hieronder bespreken we de belangrijkste resultaten. We hebben twee modellen toegepast. Het lichtmodel BIGEYE is gebruikt om de energieopbrengst en de lichtinval te berekenen. Het waterkwaliteitsmodel D3D is gebruikt om veranderingen in watertemperatuur en primaire productie te simuleren. Daarnaast zijn metingen uitgevoerd aan de waterkwaliteit. Het grootste deel van het onderzoek is gebaseerd op een commercieel drijvend zonnepark in een zandwinplas bij Oudehaske (Friesland). Uit de lichtmodellering met BIGEYE komen drie hoofdbevindingen naar voren:

- **Sterke lichtreductie onder drijvende zonneparken.** Drijvende zonneparken verminderen de hoeveelheid licht die het water bereikt zeer sterk. In de lente en zomer loopt de reductie op tot circa 91%. In de winter is het effect iets kleiner.
- **Verschillen tussen zonneparken.** De hoeveelheid licht die het wateroppervlak bereikt hangt af van de geometrie van het systeem.
- **Duidelijke randeffecten.** Aan de randen van de parken is een duidelijke lichtgradiënt zichtbaar. Binnen ongeveer twee meter van de oost en westranden daalt de instraling sterk. Seizoensinvloeden spelen hierbij een rol. In de winter wordt vooral de noordrand extra beschaduwd door lage zonnestanden. De zuidrand ondervindt nauwelijks extra schaduw.

Het waterkwaliteitsmodel D3D is gedraaid met gedetailleerde lichtinvoer vanuit BIGEYE. Daarnaast is een vereenvoudigd scenario doorgerekend waarbij het park als één blok is geschematiseerd. De resultaten laten nauwelijks verschillen zien. Het totale verlies aan licht blijkt bepalend. De fijnmazige ruimtelijke variatie voegt weinig toe.

De modelresultaten laten zien dat scenario's met zonnepanelen gemiddeld lagere watertemperaturen opleveren dan scenario's zonder bedekking. De horizontale temperatuurverschillen binnen het meer zijn klein, ongeveer 0,2 °C. Dit komt door menging van het water. Metingen bevestigen dit beeld. Die laten zelfs een zeer kleine toename zien onder de panelen, van ongeveer 0,26 °C ten opzichte van de onbedekte locatie.

Primaire productie is het proces waarbij planten en plankton zonlicht omzetten in energie. Dit proces vormt de basis van vrijwel al het leven in het water. Zowel modellen als metingen laten een sterke afname zien van de primaire productie onder het drijvende zonnepark. Dit geldt voor zowel het gemiddelde als de variatie in de tijd. De belangrijkste oorzaak is de afname van het beschikbare licht. Veranderingen in temperatuur en stroming spelen hierbij een ondergeschikte rol.

Dit onderzoek laat zien dat vooral de **totale bedekkingsgraad** van een meer bepalend is voor ecologische effecten. Subtiele verschillen binnen het park of randeffecten zijn minder

relevant op schaal van een meer. De bedekking leidt tot een lagere oppervlaktewatertemperatuur in het gehele meer. Daarnaast wordt de primaire productie onder de panelen sterk verminderd door lichtreductie.

De centrale vervolgvraag is hoeveel van een waterlichaam met zonnepanelen bedekt kan worden zonder de ecologische waarde aan te tasten. Anders gezegd: welk percentage bedekking leidt nog tot een acceptabel effect op temperatuur en primaire productie? Dit noemen we de kritische grens.

Op basis van de casus Oudehaske lijkt de kritische grens voor watertemperatuur te liggen tussen 25% en 50% bedekking. Bij 25% is het effect voor temperatuur beperkt. Voor primaire productie ligt de kritische grens lager, namelijk tussen 0% en 25%.

Op dit moment adviseren we om een voorzorgsmaatregel te hanteren. Dit betekent dat de maximale bedekkingsgraad voor drijvende zonneparken onder de gesimuleerde 25% moet blijven. Voor geïsoleerde meren zoals Oudehaske stellen wij een maximale bedekkingsgraad van 15% voor. Dit helpt om grote ecologische effecten te voorkomen.

Deze benadering sluit aan bij het beleid in Duitsland. Daar is het niet toegestaan om meer dan 15% van het wateroppervlak te bedekken. Ook deze waarde is gebaseerd op het voorzorgsprincipe en niet op uitgebreid empirisch onderzoek. Toekomstige modelleringsstudies, in combinatie met monitoring, zijn nodig om ecologische effecten beter te kwantificeren. Daarmee kan voor verschillende typen watersystemen een onderbouwde maximale bedekking worden vastgesteld.

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1 Introduction

Floating photovoltaic (FPV) systems on inland water bodies can potentially contribute to the growth of sustainable energy supply in the Netherlands. When planning the development of these floating photovoltaic (FPV) systems, water managers face important permitting questions and have different, possibly conflicting, considerations. On one hand, authorities want to support the transition to sustainable energy. On the other hand, they are responsible for achieving nature objectives and water quality targets for their water bodies, based on the Natura 2000 Directive and the Water Framework Directive.

Analyses indicate that considerable effort is still required to meet both the ecological objectives and the water quality targets (e.g. advice from the Council for the Environment and the Ecological Authority). Licensing authorities are therefore confronted with a dilemma, which is amplified by the fact that the impacts of floating solar parks are not yet well understood.

Previous monitoring work in the TKI ZWIMP project (van Eck et al., 2024) showed that covering surface waters with floating solar panels leads to reduced oxygen concentrations beneath the panels. However, the extent of this reduction throughout the lake remained unknown. At the end of the TKI ZWIMP project (2022), a clear explanation for the reduced oxygen concentrations was still lacking. We assumed that lower light penetration caused a reduction in primary production by algae in the upper water layers, leading to reduced oxygen release. This assumption may have serious implications for the lake's food web, as algae form the base of aquatic ecosystems.

The aim of the Kennis Ecologie voor de Energiestransitie (KEEN; *Knowledge of Ecology for the Energy Transition*) project is to further investigate the relationship between reduced sunlight - caused by covering water surfaces with solar panels - and its effects on water quality (primarily focussing on water temperature and primary production). This research should provide an initial quantification of this relationship. Our ultimate ambition is to estimate the maximum light reduction of a lake that does not adversely affect primary production. We acknowledge that this is an ambitious goal and we see this research as a step towards this target, rather than aiming to give a definitive answer here.

Answering this question is closely related to developments on land concerning terrestrial solar parks (land-based PV). TNO and Wageningen Research have developed a label called EcoCertified Solar Parks (Krijgsveld et al., 2025) which shows how PV systems on land can be designed to allow sufficient light to reach the ground to support vegetation. For floating systems, such a label does not yet exist, and we therefore explore the possibilities for such an approach.

To answer the research questions, we use both monitoring data and modelling results. There are existing commercially-used floating solar parks in lakes Oudehaske and De Mussels in the Netherlands (Figure 2.1). Extensive water quality monitoring data is available for Oudehaske, and monitoring is underway at De Mussels, making these locations an excellent choice for this research. We will primarily focus on Oudehaske since the available data makes it possible to validate our models. Deltares and TNO are combining their models. TNO uses a model to predict the energy yield and performance of FPV (BIGEYE) and Deltares uses models to predict water quality in waterbodies with FPV (Delft3D4 (Deltares, 2026), hereafter D3D). These models are further explained in the methods section. BIGEYE will be applied to both locations while D3D will just be applied

to Oudehaske. This means that for De Mussels we will investigate the irradiance on the system, while for Oudehaske we will investigate both the irradiance and the water quality. We are aware of related ongoing projects in the Netherlands and will integrate relevant results when appropriate. International literature will also be used. Together, these efforts allow us to take an important next step.

2 Methods

2.1 Study area description

This study focuses on Floating photovoltaic (FPV) systems on two Dutch lakes; Oudehaske and De Mussels (Figure 2.1). Both FPV systems are situated on deep sand-extraction lakes in the northern part of the Netherlands, but differ in hydrological setting, scale, and the degree of lake coverage. Water quality monitoring data from Oudehaske are available and have been thoroughly analysed. In addition, D3D modelling was carried out for lake Oudehaske. Water quality data for the De Mussels is being collected but has not yet been thoroughly analysed and is therefore not presented in this study. However, the results of BIGEYE modelling of the FPV system at De Mussels are presented in this study. No modelling with Delft3D was carried out for De Mussels.

Figure 2.1 Location of the study sites in the Netherlands. The map shows the two solar park installations: De Mussels in Beilen and Oudehaske (built in two phases, I and II).

Oudehaske I and II are located near the village of Oudehaske in the province of Friesland, on an isolated deep sand extraction lake with an area of 32.13 hectares and a maximum depth of 25 meters. Oudehaske I was constructed in 2021, consists of approximately 17,000 solar panels and covers about 15% of the lake's total surface area (calculated using ArcGIS). Oudehaske II was constructed two years later in March 2023 and comprises approximately 38,800 solar panels, covering around 36% of the lake's surface area. Oudehaske I and II together cover slightly more than 50% of the lake with solar panels.

De Mussels is located on a deep sand extraction lake in the municipality of Midden-Drenthe, adjacent to the town of Beilen. Unlike Oudehaske, this lake is not isolated; it receives discharge from a nearby canal. The lake covers 21 hectares, with water depths of up to 20 meters. The FPV system has been operational since 2021 and consists of around

40,000 solar panels, covering approximately 45% of the lake's total surface area (calculated using ArcGIS).

2.2 Water quality field monitoring

To quantify the effects of floating photovoltaic (FPV) systems on lake water quality, two measurement systems are in place for continuous monitoring at Oudehaske. In July 2022, a monitoring buoy was installed in the open water, and an identical sensor was installed beneath the FPV system at Oudehaske I (see Figure 2.2).
The monitoring systems record hourly measurements at a depth of approximately one meter below the water surface. These continuous measurements are taken using an AP7000 Aquaprobe from Aquaread, a multiparameter water-quality probe that measures light, temperature, pH, redox potential, dissolved oxygen, oxygen saturation, salinity, turbidity, conductivity, and chlorophyll-a. The measurement equipment is owned by TNO (TNO | Innovation for life) and maintained by Eijkelkamp (Royal Eijkelkamp | Products for soil and water research).

Figure 2.2 FPV systems at Oudehaske I and II, showing measurement locations beneath FPV panels (orange) and in open water (blue).

Gross primary production (GPP) in the epilimnion was estimated from hourly dissolved oxygen measurements at 1 m depth using the Fourier-based method available in the GPPFourier R package. This method estimates GPP from diurnal variations in oxygen concentrations and expresses production in mg O_2 L^{-1} day^{-1}.

The full data processing workflow, Fourier analysis, and resulting figures are described in detail in Van Veenendaal et al., 2026 (submitted).

2.3 Modelling irradiance (BIGEYE)

2.3.1 BIGEYE model set up

To calculate the total irradiance on the water surface, i.e. under, between and around the FPV, the TNO model BIGEYE (Van Aken et al., 2023; Burgers & Van Aken, 2019) has been applied. The main inputs for the BIGEYE model are solar radiation falling on a horizontal surface (global horizontal irradiance or GHI) and the FPV system's geometry. The system geometry includes the transparency of the FPV module and the orientation of the system relative to the sun. The transparency of the FPV module depends on the spacing of the panel

rows, the tilt angle, the transparency of the panels, and the walkways between floating units, which are a mixture of partially open sections (above the water) and closed sections (above the floats) (Figure 2.3 and Figure 2.4). For the FPV module used at Oudehaske a transparency of 7% is assumed for the area covered by FPV.

Using the BIGEYE model, three geometries have been built based on the technical details of the three FPV systems present at Oudehaske I and II, and De Mussels (Figure 2.1). For each of these geometries, BIGEYE calculates the light that reaches the surface water under the FPV and in the open area around the FPV.

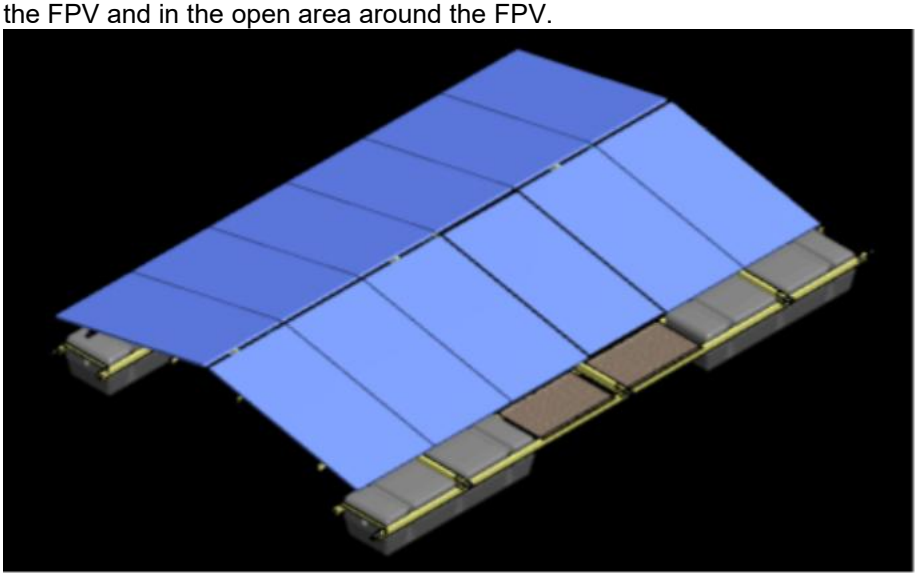

Figure 2.3 Schematic of a floating PV module showing the walkway and floats. Light can reach the water surface through gaps between the PV panels and through parts of the walkway.

Figure 2.4 De Mussels (Beilen) floating PV park. Each floating module has a walkway on one side, with partially transparent segments allowing light through, but also opaque floating segments.(photo: groenleven.nl).

To implement the model in BIGEYE, we used the system geometry parameters shown in Figure 2.5 and Table 2.1, as well as the tilt angle and orientation.

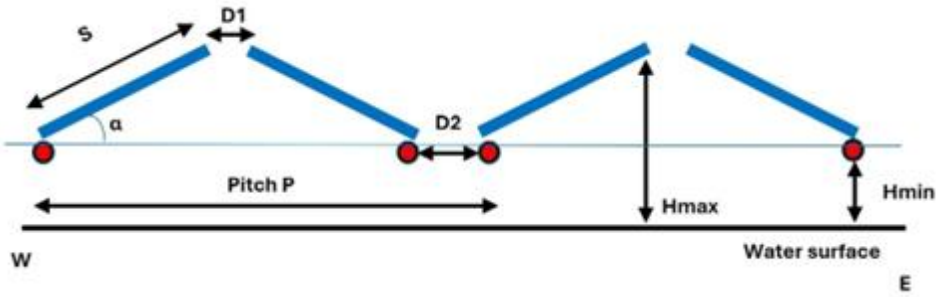

Figure 2.5 Basic geometrical parameters used to construct the systems in BIGEYE, the tilt angle (α), the length (S) of the PV the gap at the top of the east-west configuration (D1) the spacing between each E-W row or the walkway (D2) and the overall Pitch of the system.

Table 2.1 Details of each system, including module sizes, orientation and geometry parameters

Parameter	De Mussels	Oudehaske I	Oudehaske II
Orientation	East West facing	East West facing (11° SE)	East West facing (16° SE)
# PV modules, MWp	40,000, 16 MW	17,000, 6.9MW	38,800, 21.3MW
Module size [m x m]	1.020 x 2.050	1.002 x 2.006	1.154 x 2.285
Modules per floater	9 x 2	6 x 2	8 x 2
Pitch [m]	4.650	4.490	5.060
Tilt [degrees]	12	12	12
Minimum height [m]	0.434	0.443	0.425
Maximum height [m]	0.860	0.860	0.900
Distance D1 [m]	0.100	0.062	0.082
Distance D2 [m]	0.530	0.504	0.510

Global horizontal irradiance data were obtained from measurements provided by the Royal Netherlands Meteorological Institute (KNMI). For both lakes, the nearby KNMI station at Eelde was used (see Figure 2.8), and an hourly time series of irradiance values was generated. Together with the latitude and longitude of the location, this approach enables BIGEYE to accurately determine the sun's position and its angle relative to the system components.

Two BIGEYE outputs were used in this study: the summed values of irradiance over the area of the six representative modules over spring and summer 2021 (see Figure 2.8), and the time series of irradiance across the modules at selected cross-sections. Figure 2.6 and Figure 2.7 show the two cross sections used, these are underneath the floats, where light is partially blocked, and underneath the more open walkway section.

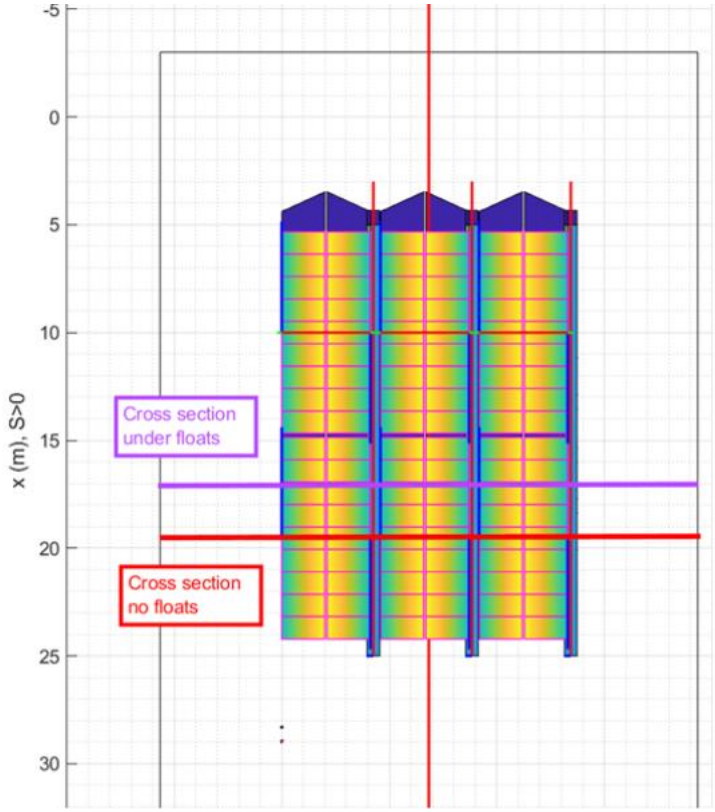

Figure 2.6 Example of geometry set up in BIGEYE.,A representative section of the installation is modelled, including six modules. The horizontal lines show the two main cross-sections that were examined: Under the floats, where less light can get through (purple), and under the more open walkways, where a little more light gets through (red).

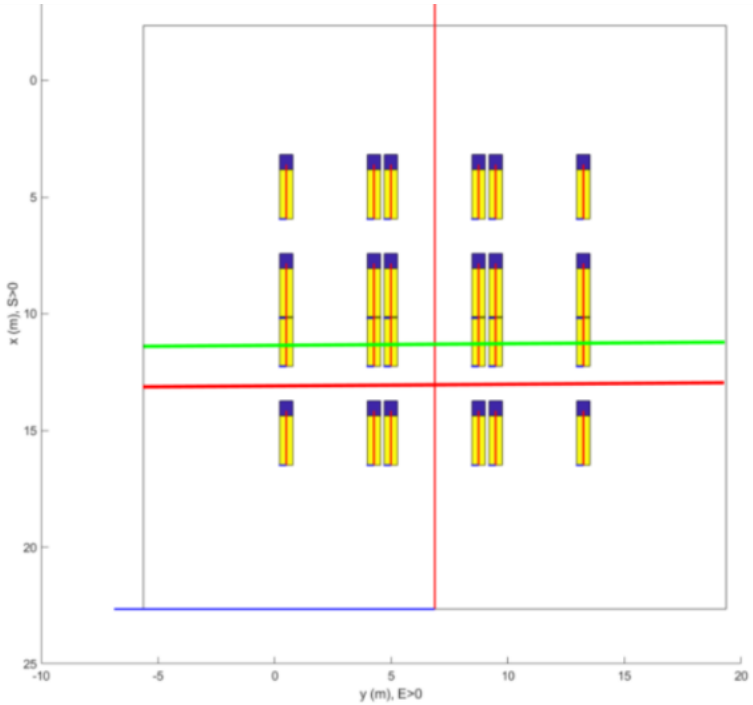

Figure 2.7 As for Figure 3.6, but showing only the floats. The green line shows the cross-section through the floats and the red line shows the cross-section through the open walkway.

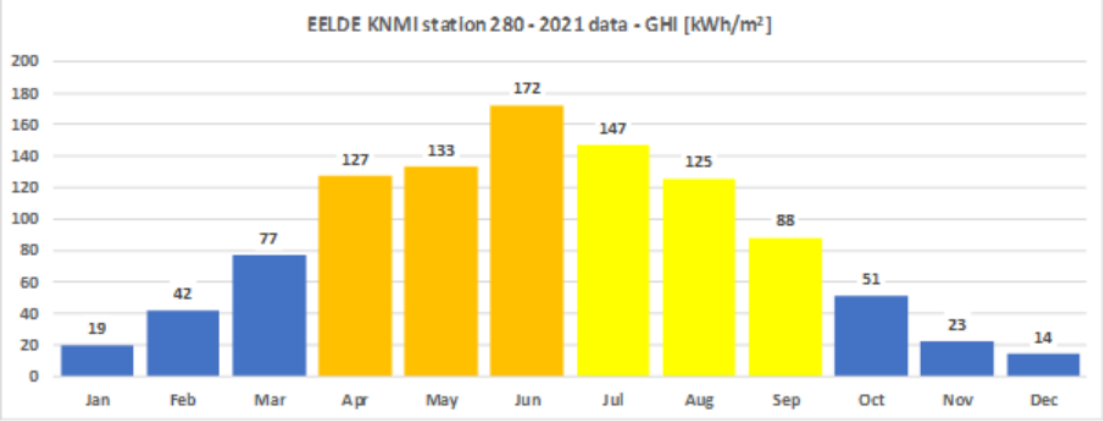

Figure 2.8 Total monthly global horizontal irradiance measured at KNMI station Eelde in 2021. Spring in in orange, summer in yellow, and other periods in blue.

2.3.2 BIGEYE Model runs

For this project two series of model runs have been carried out using BIGEYE. The first series made a seasonal comparison of the three systems using historical meteorological data. The second series provided input to the D3D model in the form of a time series of irradiance data from mid-2022 to mid-2025, matching the time period of the water quality measurement campaign.

2.4 Modelling water quality (D3D)

Delft3D (D3D) is an integrated modelling suite that can be used to simulate the far- and mid-field water and sediment quality due to a variety of transport and water quality processes. In this project, we use the D-FLOW module to simulate three-dimensional flow and temperature in the Oudehaske sandpit, while the D-Water Quality module is used to simulate the local chemical and biological processes related to nutrients, oxygen, and algae growth.

2.4.1 Translation of BIGEYE results to Delft3D input

The irradiance data from BIGEYE was used as an input to the Delft3D model. By using the values from the cross-sections, we could provide D3D with accurate radiation values across the water surface, accounting for the locations of solar panels, floats, etc.

To match the Delft3D model to the resolution at which BIGEYE results were calculated, the lake was represented by a 5x5m grid, which is the smallest practical resolution for Delft3D. At finer resolutions, the model becomes very computationally intensive and small-scale processes come into play which cannot be simulated by the software. The FPV were located on the model grid, distinguishing three types of cells: cells representing the edges of the installations, and cells with or without floats. Although the grid cells are much larger than the actual floats, the total area of float and non-float cells was approximately accurate. The model grid is shown in Figure 2.9.

The irradiance values for each cell type were taken from the BIGEYE results, where values were averaged per cell type. The open water value was averaged across the results for both installations. The so-called float and non-float values (excluding cells near the edges of the FPV) were averaged per installation, to account for the differences as presented in Table 2.1. The edge values were calculated separately for each installation but were averaged across float and non-float gridcells. This provided a daily time series for each cell type.

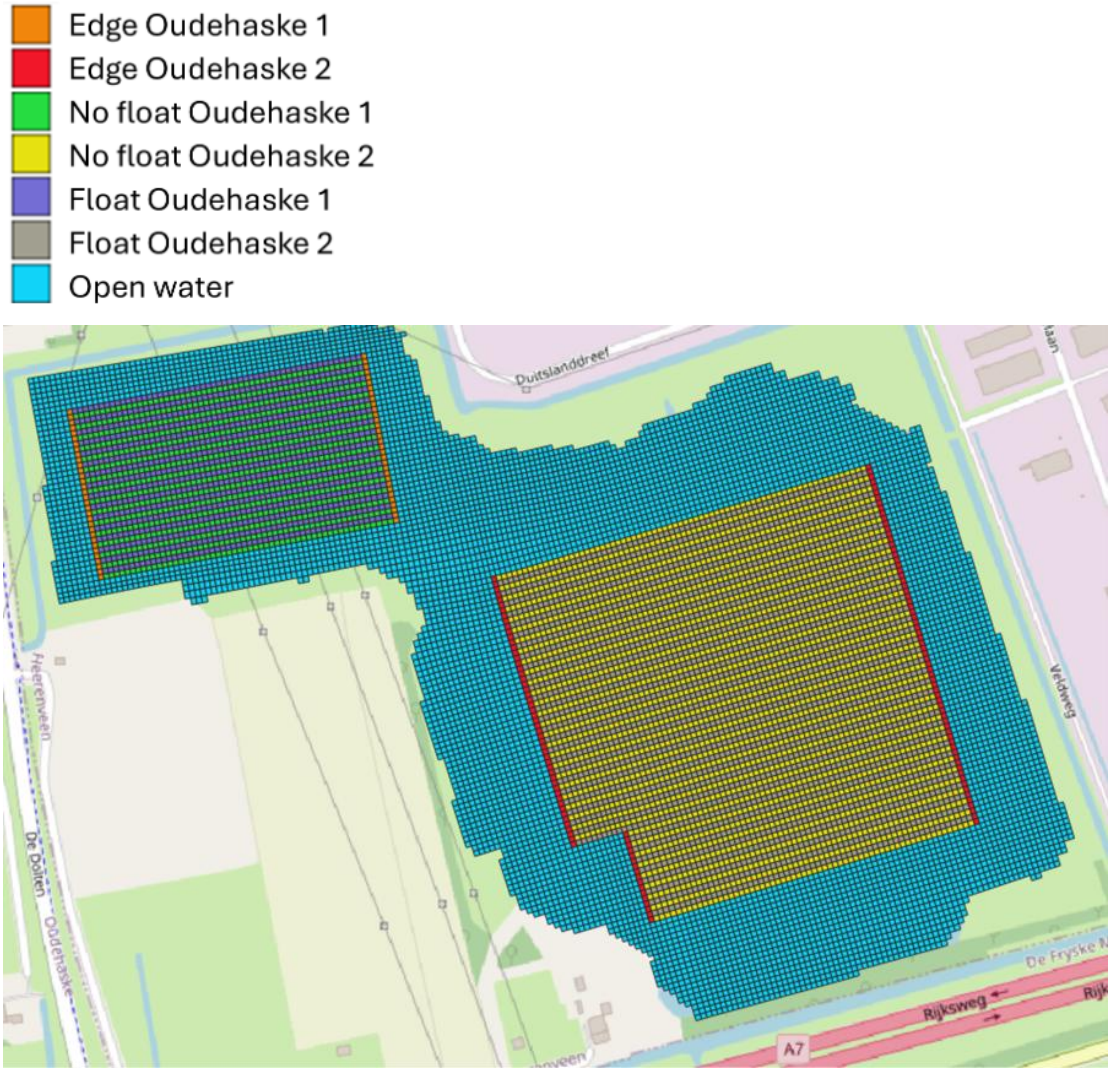

Figure 2.9 Model grid of the FPV systems Oudehaske I and II

2.4.2 D3D model setup

The D3D model for lake Oudehaske was setup as an isolated lake (i.e. no inflows or outflows), using the grid shown in Figure 2.9 and adding 25 vertical layers. Preliminary testing showed that this was sufficient vertical detail to capture the vertical temperature variation and stratification. The vertical layers had depths ranging between 0.5 and 2.5m, with the shallower layers clustered around the depth where stratification occurred, so that this effect could be studied in detail.

Meteorological data for the model (apart from solar radiation) was taken from a local KNMI weather station (Leeuwaarden, since this is the closest station to Oudehaske).
This comprised air temperature, wind speed and direction, air pressure, cloud cover and relative humidity. These parameters were adjusted for FPV grid cells as detailed below. For simplicity, no distinction was made between edge cells, floats, etc.:

- Air temperature under panels = Open water air temperature + open water radiation * 30/900. This is because when exposed to solar radiation, the FPV becomes warmer than the ambient air temperature, and so too does the air below the FPV. This formula is based on the maximum temperature increase of the solar panels (30^{o}C, as based on literature values) reached at a maximum radiation (900 W/m^{2}).
  It provides a smooth diurnal pattern, where there is no increase at night and a large increase during the day, especially in summer.

- Wind speed was reduced by 57%
- Cloud cover was set to 100% under the panels, to include the effect of solar panels on long-wave radiation.
- Air pressure and relative humidity were kept the same as for open water cells.

We also adjusted the Secchi depth in the hydrodynamic model (not in the water quality model) to capture the impact of solar panels on long-wave radiation. Under the panels it was set to 0.3 m, while for open water it was 2 m. These adjustments were mostly based on the adjustments made for modelling a similar solar panel setup in Andijk in the Netherlands (Bijlsma et al., 2021), which is still one of the better informed case studies available. The wind reduction factor was taken from literature (Ilgen et al., 2025).

Since there are no inflows or outflows in this system, nutrients only enter via atmospheric deposition, groundwater seepage, lateral run-off, burial, and bird droppings. In the model, for now we only consider atmospheric deposition and burial.

The coupled hydrodynamic and water quality model was run for a one year simulation (2024, since this was the only full year when both FPVs were present), allowing for comparison with measured data. A three month spin-up period - October to December 2023 - was taken into account to give the model time to reach a certain degree of equilibrium. Initial values were (as much as possible) based on measurements.

2.4.3 Scenario definition

The model was run for five different scenarios which are listed in Table 2.2.

Table 2.2 Overview of model scenarios.

Scenario	Solar panels	Radiation input	Other meteorological parameters
1	None	All cells use 'open water' value	No adjustments
2	Existing coverage (50%)	Simplified 'block' input: all solar panel cells use the average of the float and non-float value for each installation	No adjustments
3	Existing coverage (50%)	Simplified 'block' input: all solar panel cells use the average of the float and non-float value for each installation	Solar panel cells use adjusted air temperature, wind speed and cloud cover values (see 3.4.2)
4	Existing coverage (50%)	Detailed input: includes float, non-float and edge values for each installation	Solar panel cells use adjusted air temperature, wind speed and cloud cover values (see 3.4.2)
5	Halved coverage 25%	Detailed input: includes float, non-float and edge values for each installation	Solar panel cells use adjusted air temperature, wind speed and cloud cover values (see 3.4.2)

The selected scenarios allowed us to investigate:

- the effects of 50% coverage by solar panels vs. no FPV present in the lake (scenario 1 vs. scenarios 3 and 4)
- the effect of taking into account the effect of FPV on other meteorological parameters instead of only those on radiation (scenario 2 vs. scenario 3)
- the effect of detailed radiation input calculated with BIGEYE (scenario 3 vs. scenario 4)
- the effect of varying solar panel coverage (scenario 4 vs. scenario 5).

The setup for all five scenarios is shown in Figure 2.10. For the block radiation input, the average of the float and non-float value was used for all PV cells for each installation. Scenario 5 uses the same values for edge, float and non-float cells as scenario 4. For scenario 5, we expect that the precise distribution of FPV cells would have a significant effect on temperature and primary production in the lake.

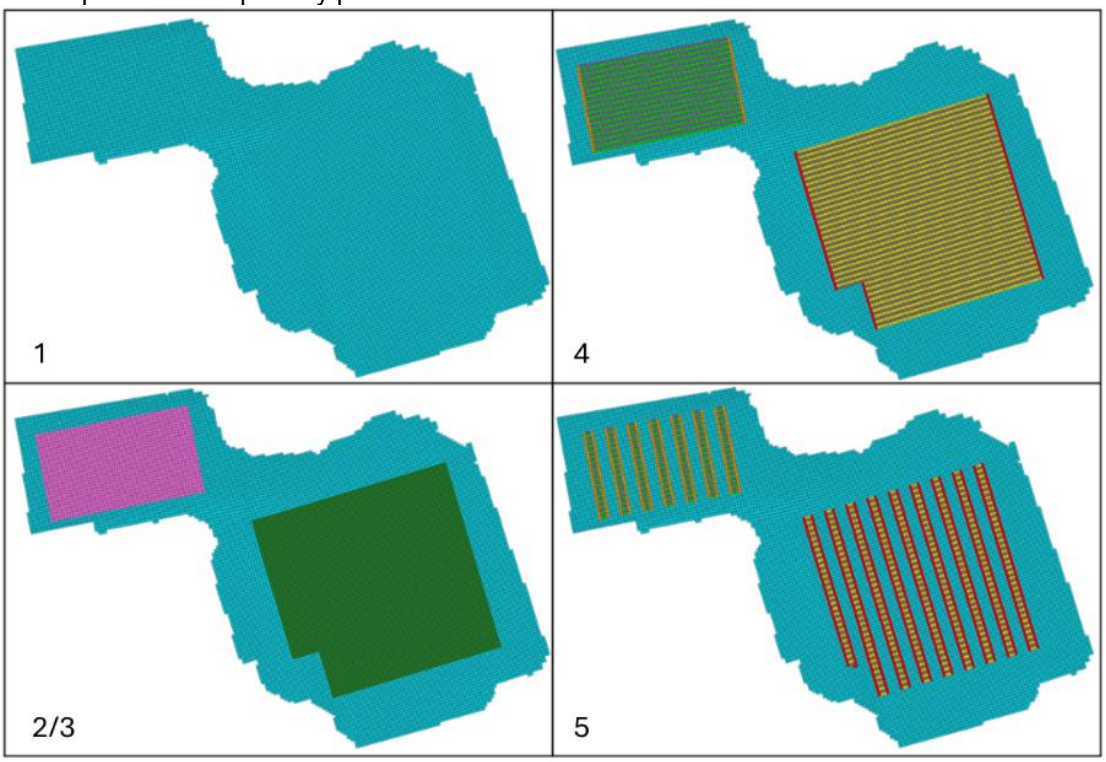

Figure 2.10 Model grid setup for the scenarios. In scenarios 2 and 3, all FPV cells within a block are treated the same, though the values used for Oudehaske I and II are different.

3 Results

3.1 Water quality monitoring results

This section presents the results of the water quality campaign conducted at Oudehaske Floating photovoltaic (FPV) systems since summer of 2022 until summer of 2025, focusing on the key parameters water temperature, dissolved oxygen, and primary production.

3.1.1 Water temperature

A total of 26,598 temperature measurements were collected beneath the FPV and 24,192 in the open water. The difference is due to the measurement buoy in the open water being powered by a small solar panel, which sometimes results in missing data during the winter months with limited sunlight.

Figure 3.1 shows water temperature trends over time (graph a) and weekly mean differences between the sensors (i.e. beneath the FPV and in open water) (graph b) for the period 14 July 2022 to 4 September 2025. On average, water temperatures were generally slightly higher beneath the FPV than in open water at 1 m depth , with the largest differences observed in winter (up to 8.4 % higher under the FPV).

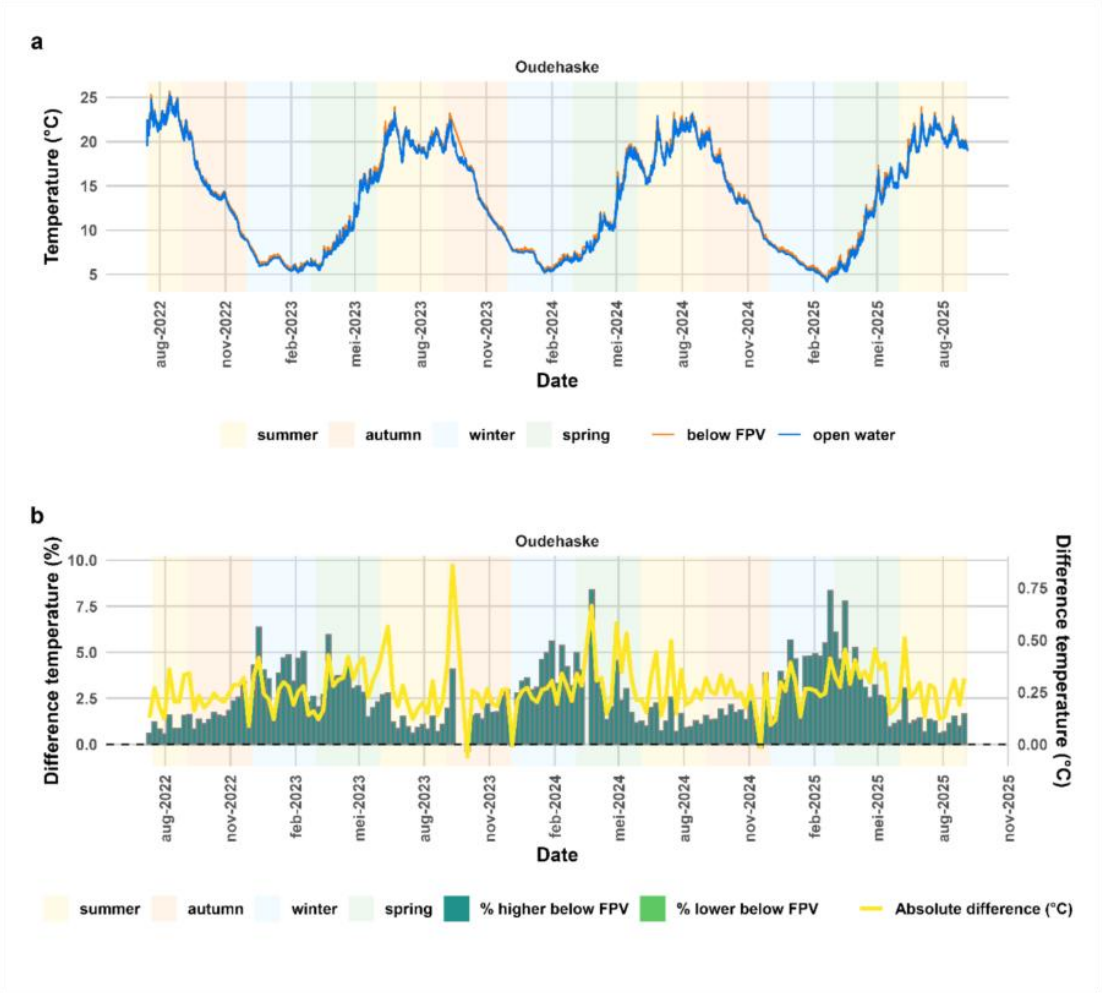

Figure 3.1 (a) Water temperature (°C) beneath the solar park and in the open water at 1 m depth over time at Oudehaske. (b) Relative and absolute differences in weekly mean temperatures between the two locations. Positive values indicate higher water temperatures below the FPV in comparison with the open water, while negative values indicate lower water temperatures.

3.1.2 Dissolved oxygen

A total of 26,598 dissolved oxygen measurements were available beneath the FPV, compared to 24,192 measurements in the open water. Similar to the water temperature monitoring, slightly fewer measurements are available for the sensor placed in open water.

The average dissolved oxygen concentration beneath the solar park was 7.65 mg/L over the whole period, whereas higher values were measured in the open water at 8.73 mg/L. Median values show a similar pattern (8.05 vs. 8.89 mg/L), indicating that oxygen concentrations beneath the FPV are generally lower. The variability is also slightly higher under the FPV (standard deviation = 1.78 mg/L) compared to the open water (standard deviation = 1.25 mg/L), which may reflect greater fluctuations due to factors such as varying light or air temperature conditions. Minimum and maximum values range from 0.72 to 10.79 mg/L beneath the FPV, and from 1.07 to 11.24 mg/L in open water.

Figure 3.2 shows dissolved oxygen beneath the FPV and in the open water of Oudehaske over time (a), the differences in weekly averages between the FPV and open water sensors (b).

A seasonal analysis shows that the largest differences occur in winter (see Figure 3.2b), with oxygen levels under the panels being up to 41% lower.

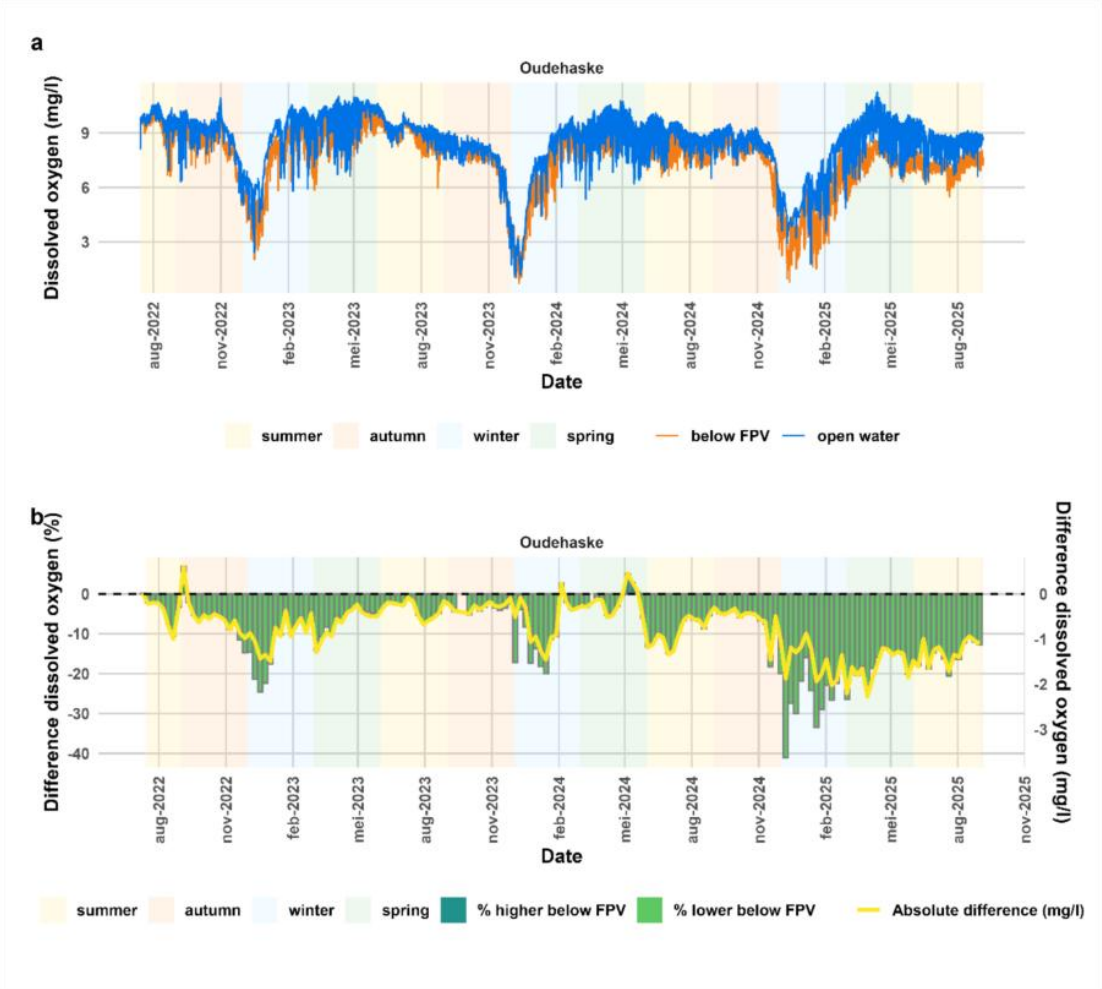

Figure 3.2 (a) Dissolved oxygen concentrations (mg/l) beneath the FPV and in open water at 1 m depth over time at Oudehaske. (b) Relative and absolute differences in weekly mean dissolved oxygen concentrations between the FPV and open water sensors over time. Positive values indicate a higher oxygen concentration below the solar park, while negative values indicate lower oxygen concentrations.

3.1.3 Primary production

Weekly means of the Fourier-based GPP estimates at the FPV location and the open water location in Oudehaske are shown in Figure 3.3. Both locations exhibit clear seasonal patterns in GPP. Primary production was highest during spring and summer and lowest during late autumn and winter. Figure 3.3 also indicates that the open water location generally reached higher GPP values than the FPV location, particularly during the spring and summer of 2024 and 2025. To quantify these differences, only the overlapping days for which both the FPV and open water locations have GPP estimates were considered. On average, GPP at the FPV location was 0.54 mg O_2 L^{-1} day^{-1} lower than at the open water location, corresponding to an approximately 35% reduction in primary production.

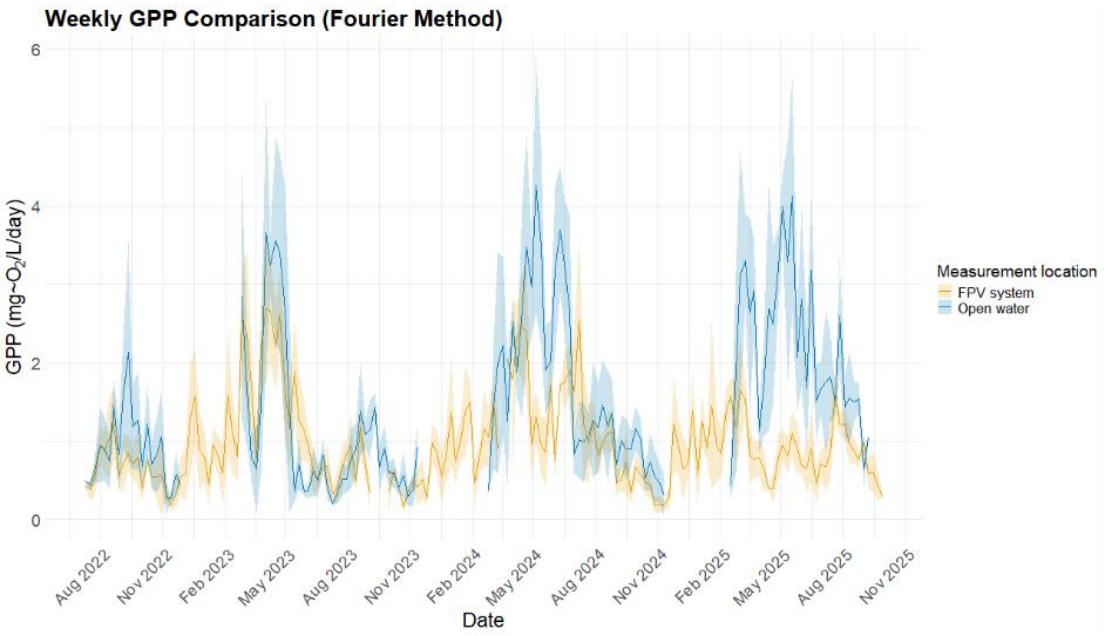

Figure 3.3 Weekly gross primary production (mg O2/L/day) calculated using the Fourier method (Cox et al., 2015) for the open water location (blue) and FPV system (orange) at Oudehaske. The solid lines represents weekly means and the ribbons the 95% confidence intervals of the means. All available GPP estimates for each location are shown. Copied from Van Veenendaal et al. (2026 submitted).

3.2 Modelling results BIGEYE

3.2.1 Seasonal system comparison total irradiance

3.2.1.1 De Mussels

The first BIGEYE model runs allowed us to make a seasonal comparison of the De Mussels system using historical meteorological data. Figure 3.4 shows the calculated irradiance under the cross-section which includes the open walkway. The irradiance distributions are calculated for spring and summer. The total GHI in spring, 432 kWh/m^2, is higher than the 360 kWh/m2 in the summer. The irradiance under the system is significantly reduced. The minimum irradiance under the system is 38 kWh/m^2 for spring and 32 kWh/m^2 in summer. This amounts to a reduction of around 91% for both seasons. Note the sharp transition at the east and west end of the system. The seasonal irradiance drops from 95% to 15% of the open water irradiance over a distance of only 1.5 m.

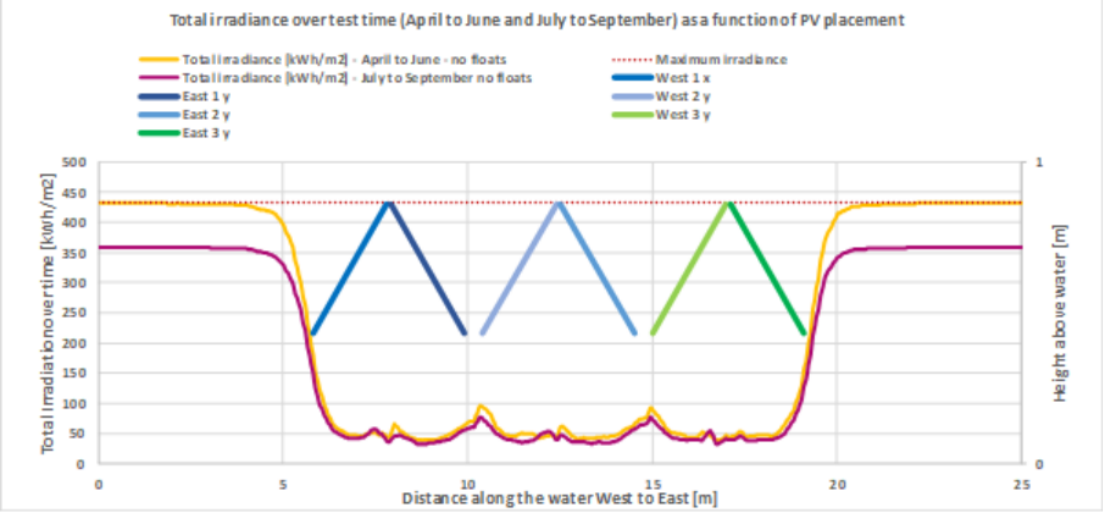

Figure 3.4 De Mussels: total irradiance under and on the sides of the system based on 2021 irradiance data from Eelde for spring and summer and the cross-section under the open walkway. The total irradiance in the open water in spring is 432 kWh/m², and in summer this is 360 kWh/m². The minimum irradiance under the system is 38 kWh/m² in spring and 32 kWh/m²in summer. The chart also shows the placement of the PV elements as a guide.

There are small peaks in irradiance at and around the locations of the walkways. A similar, though smaller, effect can also be seen at the 'top' opening, where there is a small gap between the east- and west-facing solar panels. Figure 3.5 shows De Mussels system results for the cross-section which passes under the floats for the same periods as shown in Figure 3.4. Here, the irradiance under the modules is the same for spring and summer, within the accuracy of the simulations. But under the floats the minimum irradiance is reduced to 10 kWh/m² for spring and 8 kWh/m² for summer, much lower than under the open walkways.

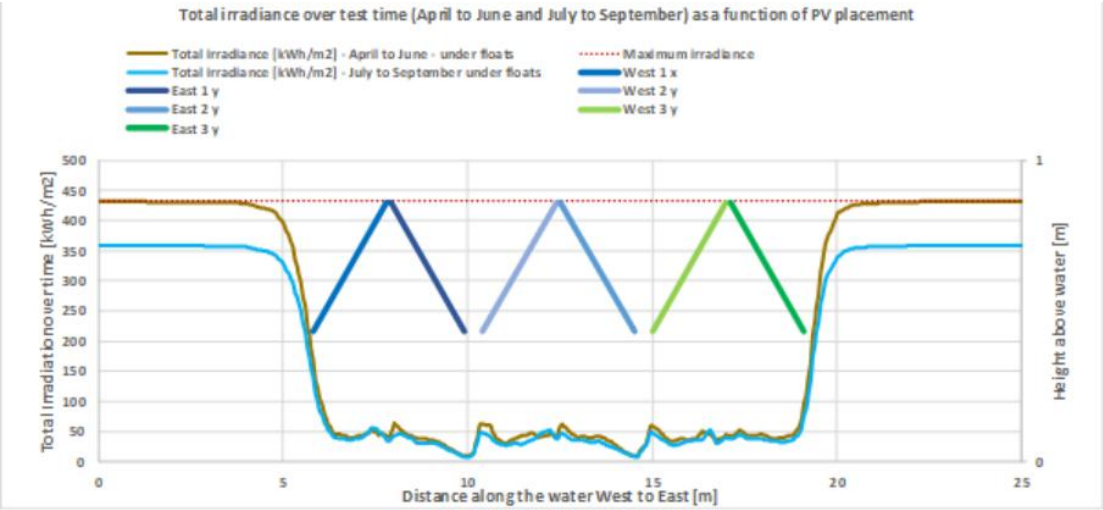

Figure 3.5 De Mussels: total irradiance under and on the sides of the system based on 2021 irradiance data from Eelde for spring and summer and the cross section running under the floats. The total irradiance in the open water in spring is around 430 kWh/m², and in summer this is 360 kWh/m². The minimum irradiance under the system is between 10 and 8 kWh/m² for spring and summer respectively. The chart also shows the placement of the PV elements (each element its own color and legend item) as a guide.

3.2.1.2 Oudehaske

Figure 3.6, the irradiance on the water surface under the FPV system is shown in more detail. We combine results for spring and summer and results under the floats and under the

open walkways. For both the spring (green) and summer (red/orange) results, there is no difference between the float and non-float cross-sections in the centre of the FPV module. This is unsurprising since the floats are on the outer edges of the modules.

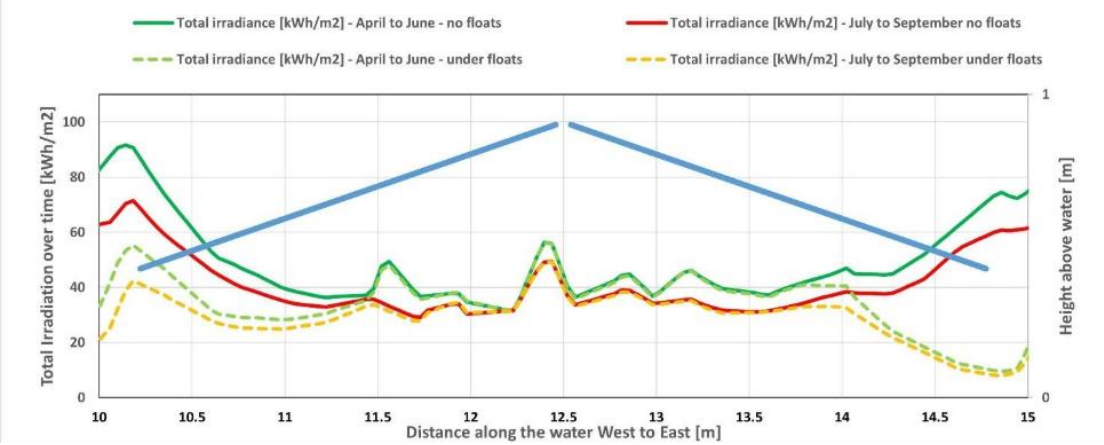

Figure 3.6 Oudehaske II: total irradiance under a single FPV unit based on 2021 irradiance data from Eelde for spring and summer, with cross section running under the floats and under the open walkways ('no floats').

3.2.1.3 Comparison of FPV systems

Full results are presented in Table 3.1. There are some small differences between the FPV systems in terms of average and total irradiance under the FPV. De Mussels lets through the most irradiance and Oudehaske II the least.

Table 3.1 Summary of results for the three systems.

System	Under floats – Spring [kWh/m^2]		Under floats – Summer [kWh/m^2]		No floats – Spring [kWh/m^2]		No floats – Summer [kWh/m^2]	
	min	avg	min	avg	min	avg	min	avg
De Mussels	10	39	8	32	38	54	32	45
Oudehaske I	10	36	9	31	33	51	28	43
Oudehaske II	9	35	8	30	31	46	29	39

De Mussels has the highest open area ratio, and the highest value for minimum irradiance under the PV system. There is a clear relationship, the more open the system, the more light reaches the water surface below the FPV modules and mounting structure.

3.2.2 Time series input for D3D daily irradiance

Here we present the BIGEYE results which will be used as input for the D3D model simulations, i.e. time series of irradiance data for the period July 2022 to December 2024. Results are presented as daily values in a heatmap across the full width of the modelled FPV system.

Figure 3.7and Figure 3.8 show the irradiation as modelled with BIGEYE. The annual pattern of the GHI is clearly visible for the 5m of open water at the western and eastern edges. The position of the floats is shown by the darker vertical color around 10.0m and 15.0m on the x-axis . Compared to the maximum daily GHI of >8 kWh/m^2, the irradiance below the floaters remains close to 0 kWh/m^2 for the whole year.

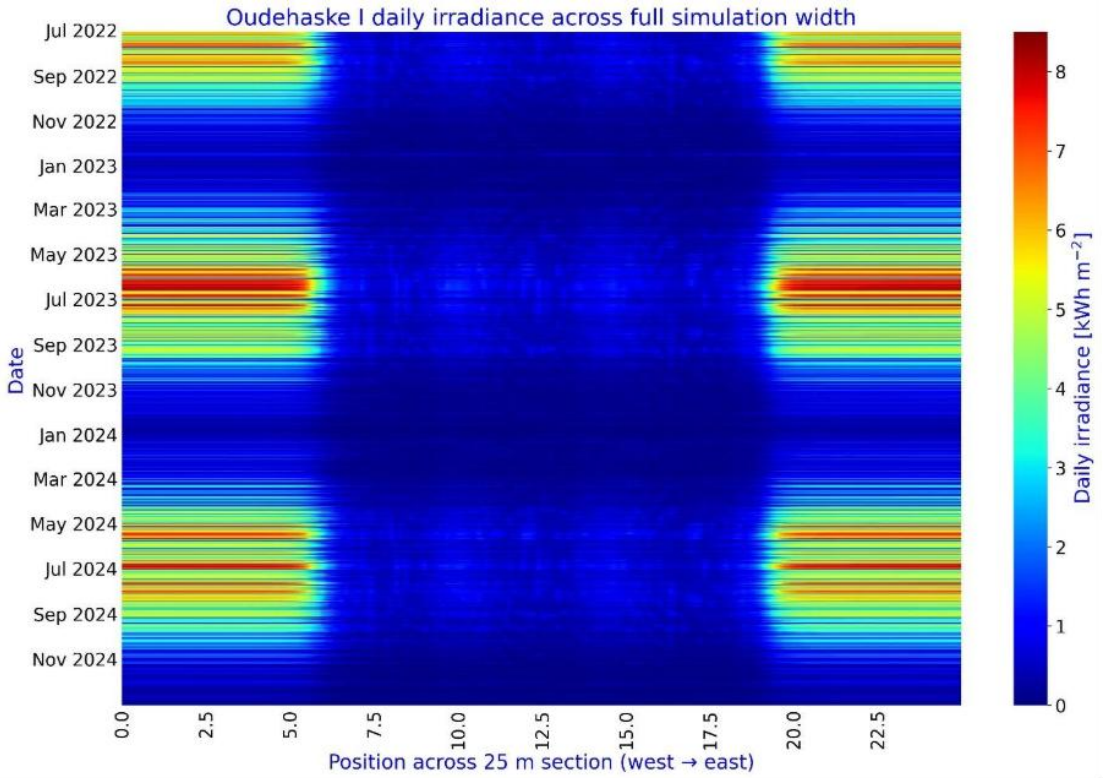

Figure 3.7 Daily total irradiance on the water surface (no floats) for Oudehaske I, July 2022 to December 2024 (y-axis). The position across the system is shown on the x-axis. The color bar indicates the daily irradiance in kWh/m^2.

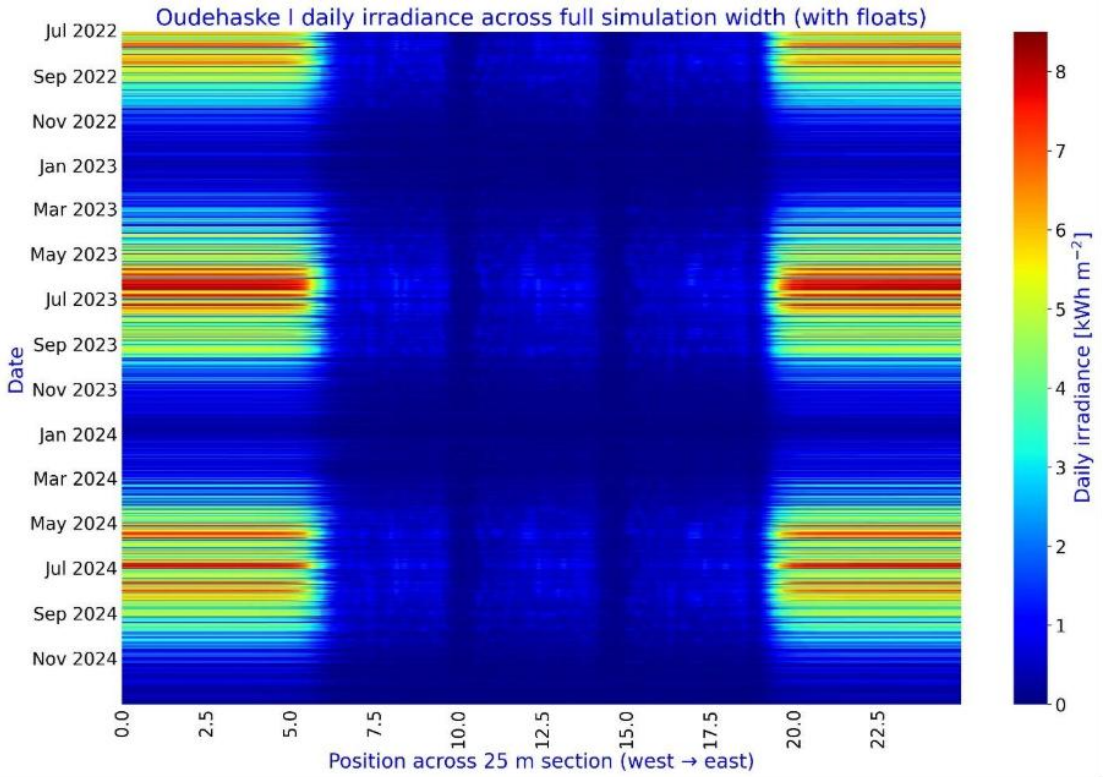

Figure 3.8 Daily total irradiance on the water surface (under floats) for Oudehaske I, July 2022 to December 2024 (y-axis). The position across the system is shown on the x-axis. The color bar indicates the daily irradiance in kWh/m^2.

3.3 Modelling results D3D

3.3.1 Model performance

We only have measurements available for lake Oudehaske since the FPV was installed. No measurements before installation. Hence, for model validation, we used model results from scenario 4 (detailed irradiance from the BIGEYE model and all meteorological adjustments), since this should be most representative of the current setup.

Figure 3.9 shows a comparison between the modelled and measured water temperatures at 1m depth at the two sensor locations (open water and under the FPV). There is a good match between modelled and measured data during summer and autumn, although the model underpredicts winter and spring water temperatures. This is not due to initial values, which are based on measurements; the difference arises already during the spin-up period (not shown in the figures), and re-occurs at the end of the year. Instead, the difference may be partially explained by the impact of FPV on meteorological fluxes and how this is accounted for in the hydrodynamic model.
But the main explanation probably is seepage of (relatively warm) groundwater, that was not yet accounted for in the model. Both issues are however complicated and out of the scope of the current project.

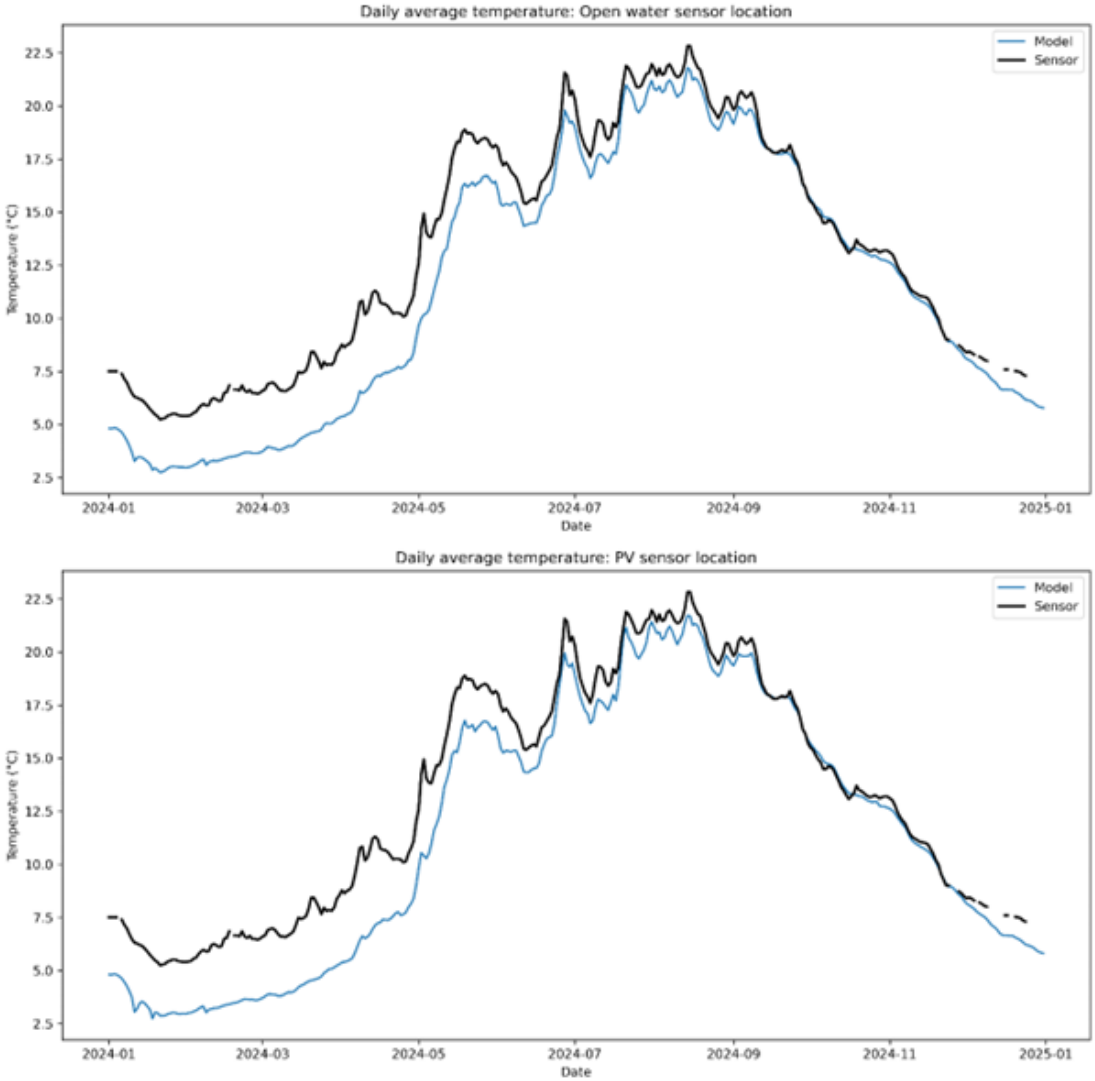

Figure 3.9 Comparison of modelled (blue) vs measured (black) temperatures at 1m depth. THe top plot is for the open water sensor location and the lower plot is for the sensor under the FPV. Spin-up period not shown.

The water quality model was calibrated to match the field concentrations of chlorophyll and oxygen by changing nutrient input and burial rate. Chlorophyll measurements lie below the detection limit (2ug/l), and are considered not to be fully trustworthy , hence we mainly used an average value from literature representative for quarry lakes (which was also consistent with our measurements) to calibrate our model results (1.6 ug/l, Seelen et al 2021). Other parameters were less useful for calibration: phosphorous was below the detection limit (also very low values in our model), nitrogen was non-limiting (in the right range in our model), and the Secchi-depth seemed mainly driven by windspeed.

Figure 3.10 shows that the modelled chlorophyll levels are on average 3.5 ug/l , which is close to the value from literature representative for quarry lakes (1.6 ug/l). The modelled oxygen, however, is clearly too high in winter (Figure 3.11**Error! Reference source not found.**), which is partly explained by the underestimation of modelled water temperatures in that period, unjustly increasing the oxygen saturation levels. But, similar to water temperature, the main deviation is probably explained by seepage of (anoxic) groundwater. Including seepage in the model was however outside the scope of this project. On the other hand, the modelled primary production is quite promising, by showing similar seasonal patterns and a relative difference between the open water location and the FPV location (43%, see Figure 3.12) that matches well the monitored difference of 35% (paragraph 3.1.3 and Van Veenendaal et al., 2026). Note that absolute levels of primary production are difficult to compare due to uncertainties in the required conversion factors (mixing depth and photosynthetic quotient) providing too many degrees of freedom for a useful comparison. Hence, we will not be looking at the absolute changes in primary production but rather focus on their relative changes.

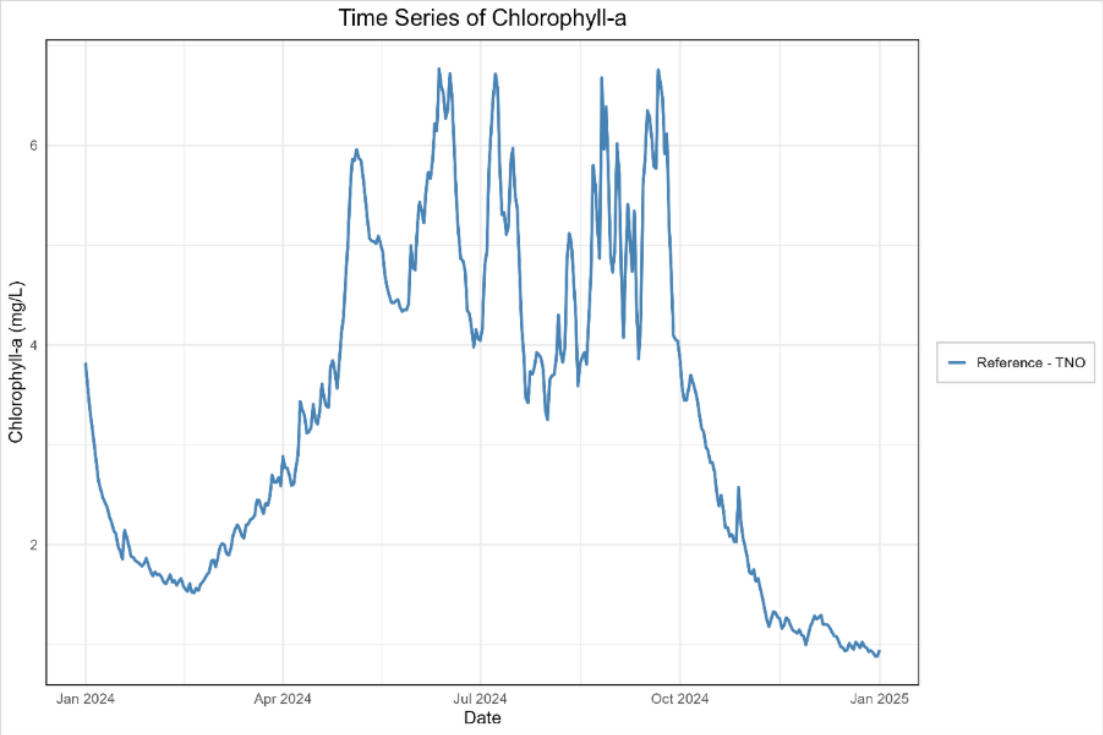

Figure 3.10 Modelled chlorophyll-a concentrations, averaged for the total system (blue line) in Lake Oudehaske. Measurements are not shown because they all lie below the detection limit.

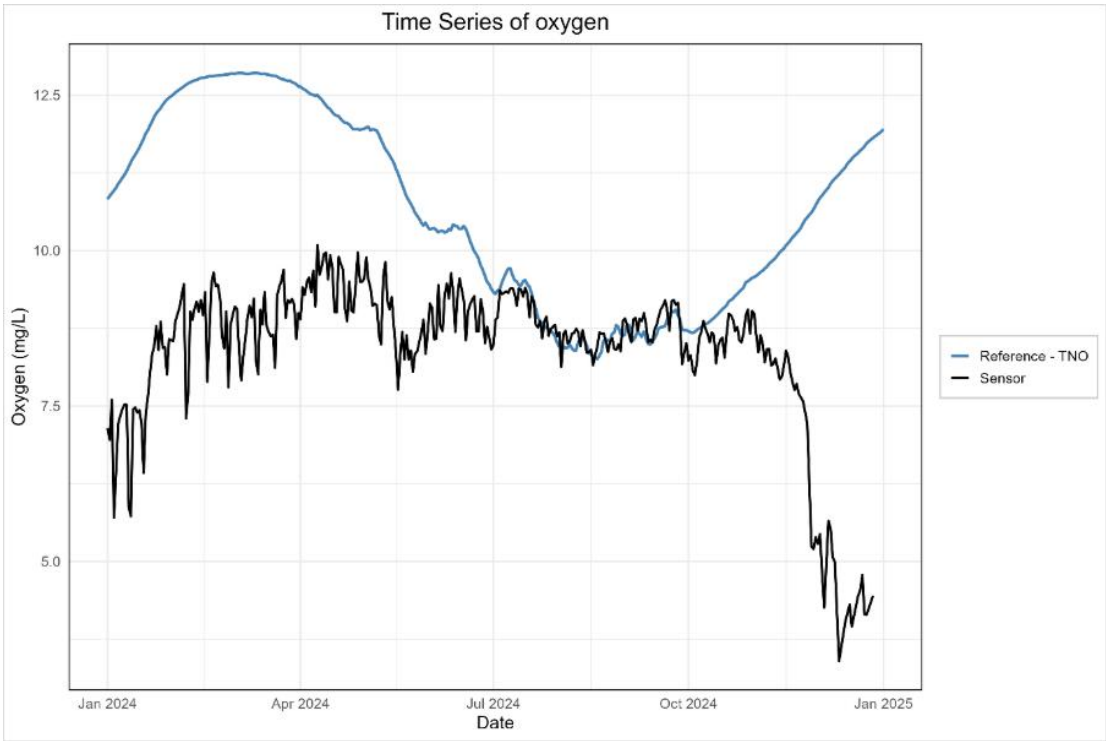

Figure 3.11 Measured (black line) and modelled (blue line) oxygen concentrations in Lake Oudehaske in the open water location.

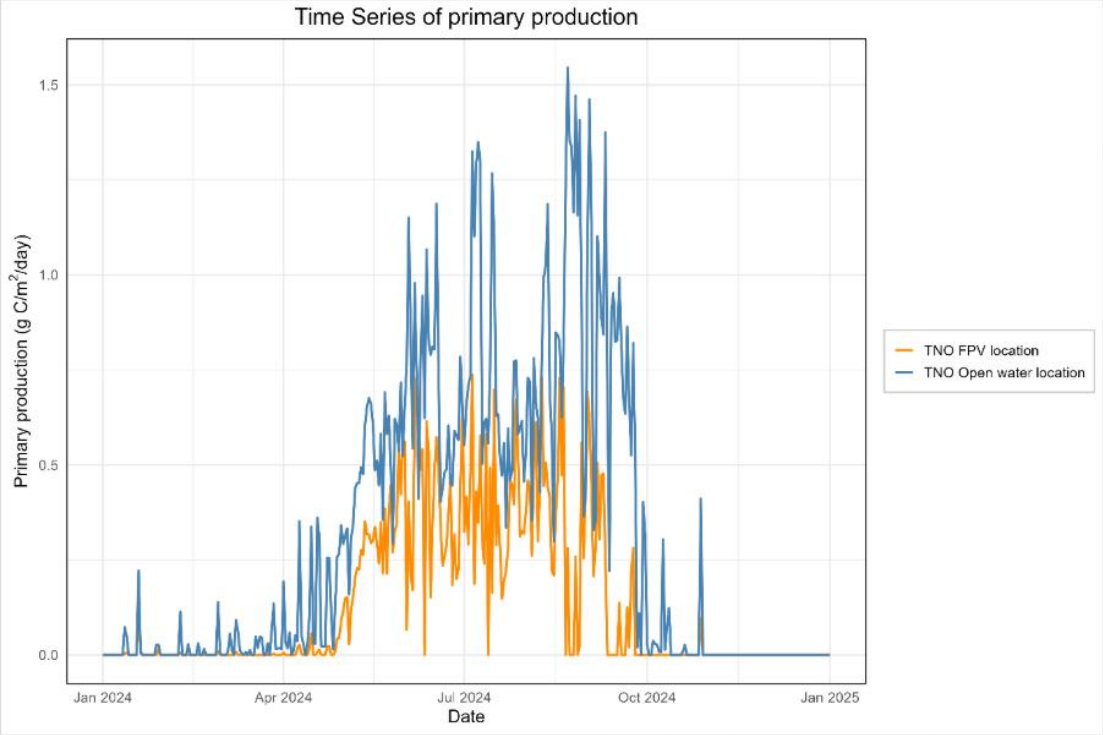

Figure 3.12 Modelled primary production at 1m depth in open water (blue line) and under the FPV in Lake Oudehaske.

3.3.2 Water temperature

What is the general effect of FPV on water temperature?

The modelled seasonal average water temperature values at different depth levels for scenarios 1, 3 and 4 are shown in Figure 3.13. While the water temperature

appears spatially uniform across the lake for all scenarios and depths, there is small local variation (on the order of 0.2°C). The water temperature is higher when there are no solar panels present (scenario 1), while scenarios 3 and 4 (block vs detailed radiation input) show very similar results.

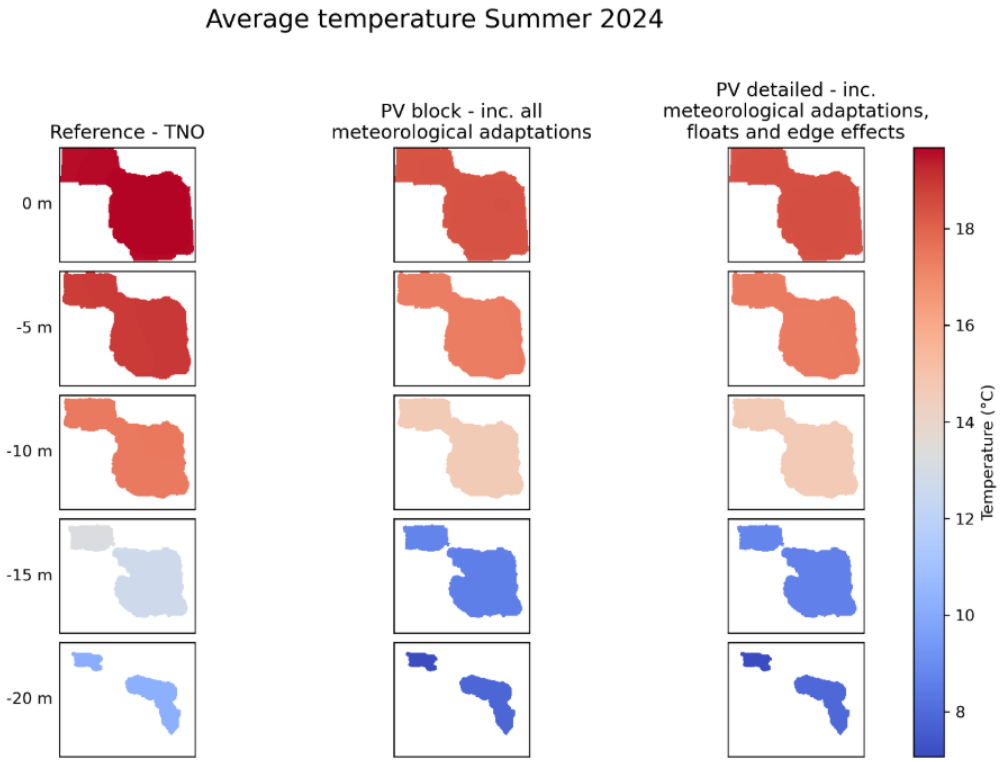

Figure 3.13 Seasonally averaged modelled temperature at different depths for scenarios 1, 3 and 4. Summer is defined as June-August.

We also examined the water temperature depth profile over time. Figure 3.14 shows the modelled temperatures at the locations of the two measuring stations. Stratification occurs at a slightly higher depth when FPV are present, implying less vertical mixing. The length of time over which stratification occurs is about the same with and without FPV.

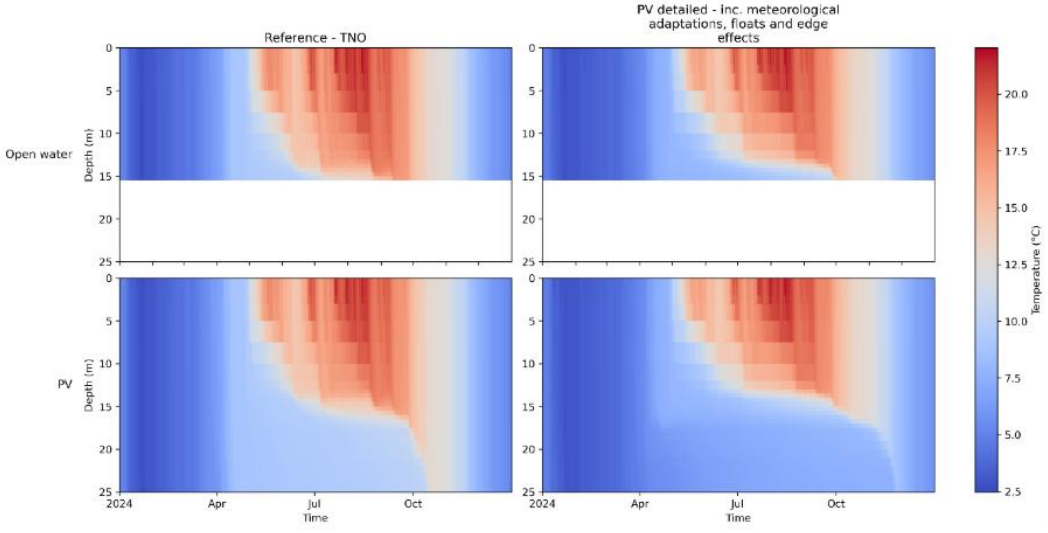

Figure 3.14 Modelled temperature at different depths over time. The plots on the left show the results of scenario 1 (no solar panels) and the plots on the right show the results of scenario 4 (detailed radiation input). The top plots show results for the open water sensor location and the bottom plots show the results at the location of the sensor positioned under the FPV. Note that the lake is shallower at the open water sensor location than at the FPV sensor location.

How important are the (effects of FPV on) other meteorological parameters in comparison to radiation?

Scenarios 2 and 3 are identical except that in scenario 3 also other meteorological parameters than just radiation (air temperature, wind speed and cloud cover) under the FPV have been adjusted. The average surface water temperature for these scenarios plus the reference scenario is shown in Figure 3.15. Water temperatures for scenario 2 (orange) are significantly lower than for scenario 3 (green), highlighting the importance of all meteorological parameters for the resulting hydrodynamics. Therefore we do not consider scenario 2 when looking at the effects on primary production (paragraph 3.3.3).

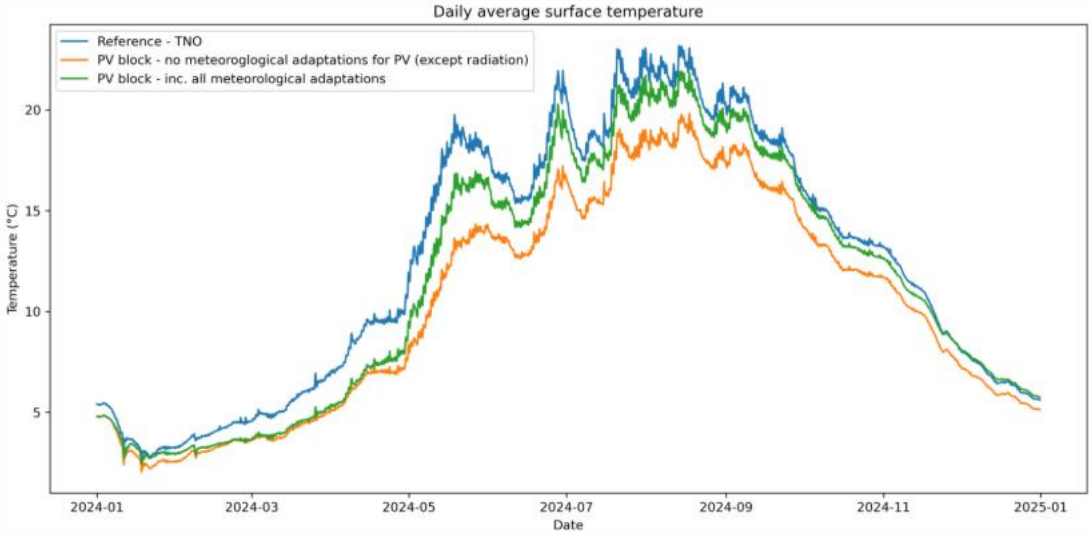

Figure 3.15 Average surface water temperature under scenarios 1 (reference – blue), 2 (block radiation input, no meteorological adjustments – orange) and 3 (block radiation input, all meteorological adjustments – green).

How important is it to use detailed radiation input?

In contrast to scenario 3 that used a single irradiance value for all FPV cells, scenario 4 used different irradiance values for float and non-float cells and also for cells at the eastern and western edges of the FPV installations. All other model settings were kept equal in scenario 3 and scenario 4. Looking at surface water temperatures, the largest difference between these two scenarios was on average only ~0.02°C and occurred at 9am on November 26th (see Figure 3.16). This concludes that using detailed radiation input has a negligible effect compared with the simplified block input.

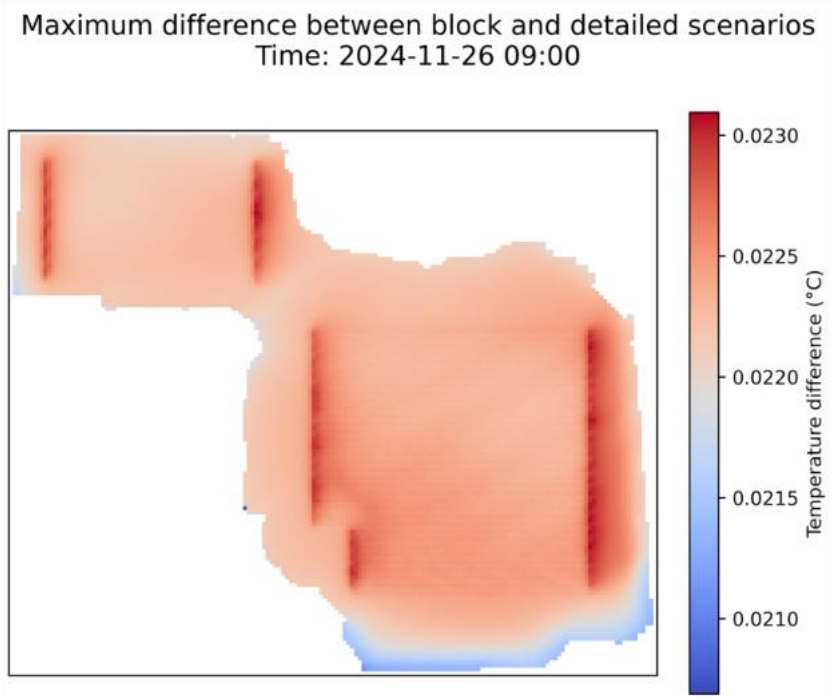

Figure 3.16 Maximum modelled surface temperature difference between scenarios 3 (simple radiation input) and 4 (detailed radiation input).

What is the effect of varying the solar panel coverage?

By comparing the results of scenarios 1 (no FPV), 4 (existing coverage, 50%) and 5 (25% coverage), we can analyse the effect of FPV coverage. The average surface water temperature for each of these scenarios is shown in Figure 3.17. Water temperatures are noticeable cooler under the existing coverage (orange), while the 25% coverage is roughly the same as having no FPV at all (green and blue respectively).

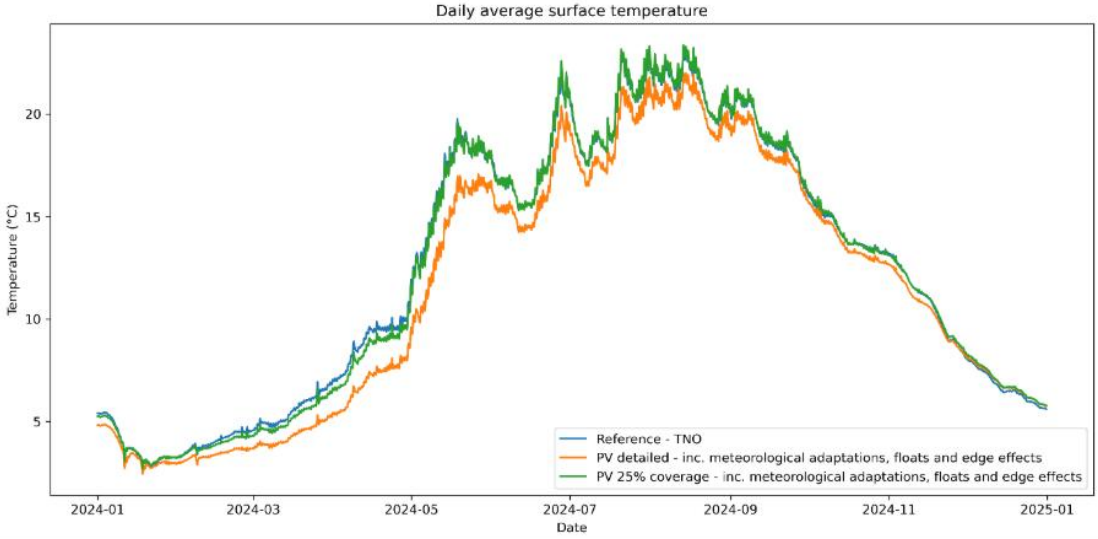

Figure 3.17 Average surface water temperature under scenarios 1 (reference – blue), 4 (detailed radiation input, existing coverage) and 5 (detailed radiation input, 25% coverage – green).

3.3.3 Primary production

Model results show that the primary production can be affected substantially by the FPV system, with large reductions in both the average value and its standard deviation. Interestingly, primary production seems to respond very different to FPV coverage than water temperature does. While the model results showed that halving the FPV coverage

could largely nullify its effects on water temperature, this is not the case for primary production (see Figure 3.18). This suggests that the (direct) effect of FPV on radiation is the main cause of the reduction in primary production, while any (indirect) effects via hydrodynamics (temperature and mixing) are less important.

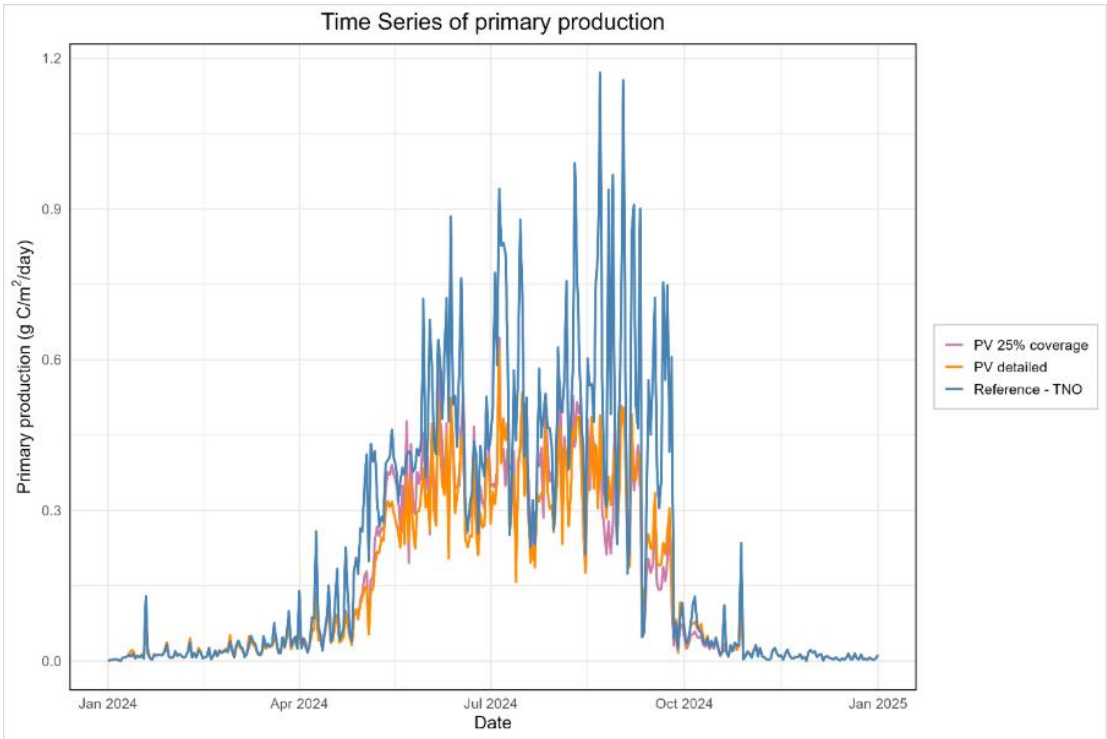

Figure 3.18 Primary production (gC/m²/s) under scenarios 1 (reference – blue), 4 (detailed radiation input, existing coverage - orange) and 5 (detailed radiation input, 25% coverage – purple).

How important is it to use detailed radiation input?

In line with the model results for water temperature, the primary production is hardly affected by using the detailed radiation input (see Figure 3.19).

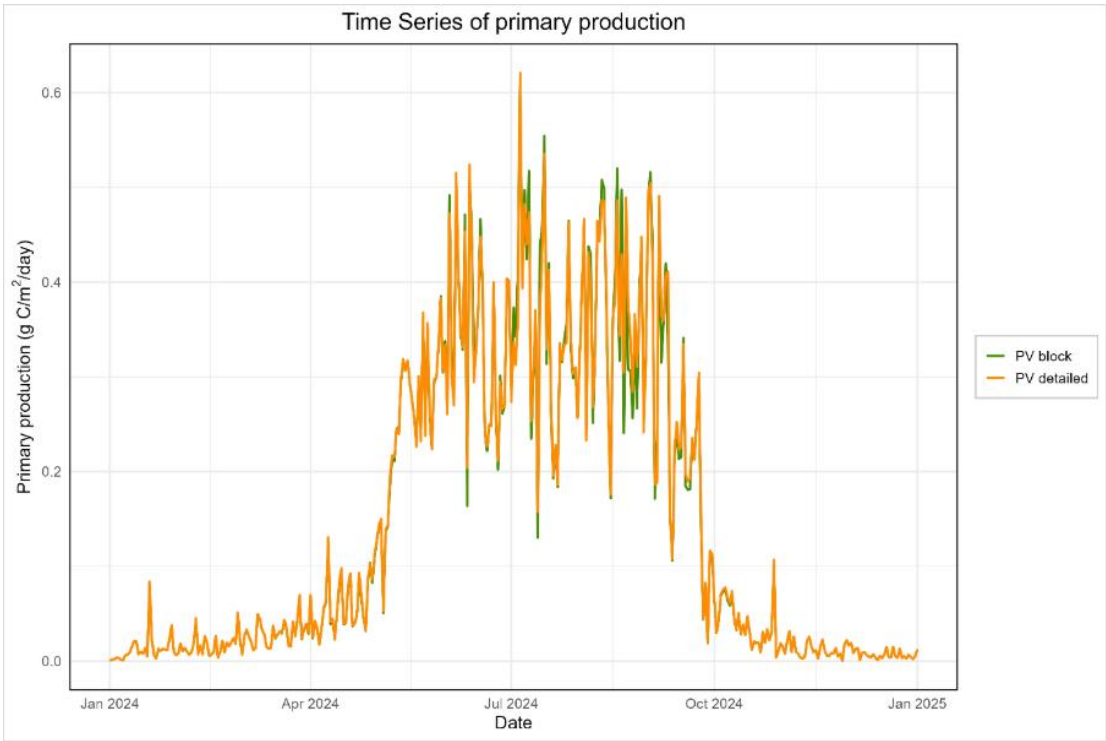

Figure 3.19 Primary production (gC/m2/s) for scenarios 3 (block radiation input, existing coverage - green) and scenario 4 (detailed radiation input, existing coverage – orange).

4 Discussion and conclusions

4.1 The impact of FPV on light, hydrodynamics and water quality

The light modelling with BIGEYE yields three main findings:

- FPV systems substantially reduce the amount of incoming light reaching the water surface. The effect is relatively small in winter, but in summer and spring the reduction can be up to 91% for the modelled systems.

- Differences in light reduction between the three FPV systems are evident. Water below Oudehaske II receives the lowest irradiance because it has the smallest open-area ratio, whereas De Mussels - having more open space between modules - exhibits the least reduced irradiance beneath the system. Floats and walkways further influence light availability.

- Edge effects around the FPV system are clearly present in the radiation reaching the water surface. First, there is a spatial effect: at a distance of approximately two meters from the western and eastern edges and under the FPV system, there is a sharp decrease in irradiance. At two meters from the system, the effect of the FPV system's edges is negligible. Secondly, there is seasonal variation: the northern edges experience significant shading during winter, early spring, and late autumn due to the low position of the sun, while the southern edges remain relatively unaffected.

With the D3D model, we investigated whether these light patterns translate into measurable effects on water quality by examining changes in water temperature and primary productivity. The scenarios with FPV (scenario 2 to 5) revealed consistent lower water temperatures compared to the scenario without FPV (scenario 1), demonstrating that the interception of radiation by FPV modules directly limits solar heating of the water. Interestingly, none of these scenarios leads to spatial variation in temperatures in the lake, suggesting substantial horizontal heat transport and redistribution by advection and dispersion. The monitoring results, however, do show a slight temperature increase under the FPV compared to the open water location, but this difference is rather small (0.26 °C).

Also, modelling results show substantial reduction of primary production due to FPV, both in magnitude and temporal variability. These findings are supported by the monitoring results (described in paragraph 3.1 and in van Veenendaal et al, 2026). The model results suggest that the reduction of light is the main cause of the impact of FPV on primary production, and any changes in hydrodynamics or water temperature only have a minor effect.

The degree of FPV coverage influences both water temperature and primary production, but the effects do not seem to scale linearly with coverage percentage. Critical values, where impacts suddenly or sharply increase with panel coverage, might be used to define safe FPV implementation without significant negative ecological impact. To be on the safe side, FPV implementation should consider FPV coverages that lie well below the critical values. Interestingly, critical values at which temperature and primary production are not or only slightly affected seem to lie at different coverage ratios. Based on the performed simulations for water temperature, the critical FPV coverage seems to lie somewhere between 50% and 25% (i.e. at a coverage of 25% the impact of PV on water temperature is negligible). For

primary production, the critical value seems to lie below the 25% coverage ratio (i.e. at a coverage of 25%, the impact of PV on primary production is similar to that of the existing 50% coverage). It is also likely the distribution and spacing of the FPV will have an effect, and further research is necessary before definitive coverage thresholds can be defined.

Finally, hydrodynamic modelling results suggest that the above-mentioned edge effects do not result in changes in water temperature. A comparison between scenarios shows that the use of detailed radiation inputs (from BIGEYE) has a negligible effect when compared to blocktype (spatially homogeneous) light reduction inputs. Apparently, in the studied scenarios, the total reduction in radiation — rather than fine scale spatial differences — drives the thermal response. It should be noted however, that the spatial extent of the edge effect may not have been optimally captured by the hydrodynamic model. D3D has been developed for large to medium scale applications and therefore does not capture all the fine-scale turbulence processes in full detail. Also, the spatial resolution of the grid that was used in this study (5x5m), while much finer than what is typically used for modelling these kinds of water bodies, is larger than the maximum length of the edge effect (2m). This means that the whole edge effect falls within the width of one grid cell, and the local light gradient is averaged into one edge-value.

Another issue with the D3D (hydrodynamic and water quality) model which may be relevant for assessing the edge effects, is that it does not take into account the angle of the incoming light. This means that below the FPV system no light enters the water column from directions other than purely vertical. However, since the primary production is mostly driven by the total amount of energy received from incoming radiation, these deviations from reality are expected to be of limited impact.

In short, at this stage of our research we conclude that the coverage rate of FPV has a greater impact on the water quality (temperature and primary production) than the (more) subtle variations in light irradiance caused by differences in the geometry of the FPV systems or edge effects.

4.2 EcoCertification

At the start of this research the intention was to find out if an EcoCertified label similar to land-based systems was possible for FPV. Therefore, we used the combination of monitoring data with BIGEYE and water quality modelling. The results presented in this study indicate that a different approach is needed for aquatic systems. This is due to the following differences between land-based PV systems and FPV:

- The starting conditions (i.e. the initial state) of terrestrial and aquatic systems on which solar panels are installed is often very different. In most land-based systems degraded agricultural land was the basis, while in water this is not the case. Lakes may be ecologically valuable and vulnerable systems.

- Water is moving, and algae are moving along with it; a minimum value for the required amount of sunlight for a specific location fixed in space can thus not be defined. In other words: light reduction at a specific location may affect the whole waterbody, and a threshold value should thus be defined at the level of the whole waterbody.

- In aquatic ecosystems, light travels throughout the water where it is being absorbed by all kinds of substances. Depending on lake depth and stratification patterns, light may not reach the bottom even during sunny conditions. This means that light is often limiting in at least part of the system. In these systems, a reduction in light will by definition decrease the primary production. The question for most aquatic

systems is thus not *whether* there will be an effect, but whether the effect is acceptable.

- Aquatic systems are complex. Apart from the depth and stratification patterns, various other factors determine the ecological functioning of the lake, including trophic status (oligo/meso/eutrophic), residence time, fetch length, and background extinction. A safe ecological limit will thus have to be defined per relevant category, but ideally on a case-by-case basis.

Due to the significant complexity and uncertainty in aquatic systems, we will have to take a stepwise approach in defining FPV implementation guidelines that can be used for the EcoCertified label. First, the safe ecological limit should be based on FPV coverage, since this was found to be the dominant driver in the reduction of primary production. Once these maximum coverage thresholds are well established, the FPV geometry (depending on layout and design) may be used for further optimisation. Subtle differences in light availability due to edge effects seemed to be negligible for the studied scenarios, but they might come into play in the finetuning of the safe ecological limits.

Based on the results in this study, it seems that the critical values at which temperature and primary production is not affected by FPV lie at different coverage ratios. For temperature it lies between 25 and 50%, for primary production it lies between 0 and 25%. The simulated scenarios do however not allow for a more precise quantification of the critical values. At this point in time, we therefore recommend working with a precautionary approach, by choosing a maximum coverage rate for FPV that lies in the lower part of the potential range, well below the simulated 25% coverage. For isolated quarry lakes like Oudehaske we therefore propose a maximum coverage ratio of 15% to avoid large ecological impacts. Our approach and proposed maximum coverage rate are in line with the German thresholds. In Germany, it is not permitted to cover more than 15% of the water surface. This value is also based on a precautionary approach rather than through in-depth research. Further modelling studies will help to better quantify the impacts and may contribute to better established maximum coverage rates that -if appropriate- vary for different (categories of) water systems.

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