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Research paper

Floating photovoltaic pilot project at the Oostvoornse lake: Assessment of the water quality effects of three different system designs

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ABSTRACT

Floating photovoltaics (FPV) is emerging as a promising renewable energy technology which enables the production of electricity on surface waters. While this technology could potentially make an important contribution to the energy transition, the current uncertainty about the water quality effects of FPV deployment poses a major barrier to FPV project development and implementation. In this study, we investigated the water quality effects of three distinctive FPV system designs, implemented as part of a 1-year pilot project at the Oostvoornse lake, the Netherlands. A water quality monitoring campaign was set up to monitor on a continuous basis a set of key water quality parameters, including light intensity, water temperature and dissolved oxygen concentration. The measurements were conducted below each of the three FPV systems and contrasted with reference measurements at open water adjacent to the systems. Our monitoring results show that of the water quality parameters considered, the impact of the FPV systems on light intensity was found to be most pronounced, with a light reduction between 73% and 100% relative to the reference measurements. We found limited evidence to corroborate that the FPV systems induced changes to the water temperature and dissolved oxygen concentration. However, it must be noted that this study took place under highly specific conditions due the limited size of the FPV pilot systems and the brackish water of the Oostvoornse lake. This means that the water quality effects reported here may not be representative for a larger scale application of the FPV designs, and may not be one-on-one transferable to other, non-brackish project locations elsewhere.

1. Introduction

In the coming decades, a major expansion in the production capacity of renewable energy will be needed to reduce global carbon emissions and achieve energy security objectives (Holdren, 2006; Owusu and Asumadu-Sarkodie, 2016). Long-term energy projections indicate that solar energy technologies, and in particular solar photovoltaics, will play a predominant role in future energy supplies (Oliveira-Pinto and Stokkermans, 2020). Photovoltaic systems are traditionally being deployed on rooftops and land surfaces using rigid mounting structures. A relatively recent innovation in the solar energy sector is the installation of floating photovoltaic (FPV) infrastructure on inland water bodies. The use of water bodies to produce solar energy alleviates the pressure on land resources, reduces conflict with other land-uses (Gadzanku et al., 2021) and has the potential to increase the electric efficiency of the PV modules due to the cooling effect of the water surface (Dörenkämper et al., 2021). Since the establishment of the first commercial FPV facility in 2007, several major advancements in the design and application of FPV have been made to increase its economic and technical performance (Gorjian et al., 2021). However, FPV technology is still maturing and several aspects of FPV remain poorly investigated. In particular, it is currently not fully understood what effects FPV systems could have on the host aquatic ecosystem (de Lima et al., 2021a; Exley et al., 2021a; Haas et al., 2020).

The uncertainty about possible water quality effects poses a major barrier to the widespread roll-out of FPV technologies (Gadzanku et al., 2021). Waterboards and other government institutions currently lack the knowledge and data required to facilitate licensing and permitting processes (de Lima et al., 2021b), which could lead to the delay or complete abortion of FPV project development. More knowledge on water quality effects is at the same time required to optimize FPV system design solutions and

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define adequate environmental mitigation measures (Cagle et al., 2020). Uncertainty about possible impacts of FPV on the aquatic ecosystem has furthermore been identified as a factor that could trigger public opposition to the deployment of FPV facilities (Bax et al., 2022). Therefore, to accommodate concerns that may exist within the community, it is vital to gain a thorough understanding of the environmental effects of FPV and disseminate scientific knowledge among the public. The water quality effects of FPV could be expected to vary according to system design, location and other project-specific conditions, which calls for studying these effects on a case-by-case basis.

In this study, we examine potential water quality impacts of FPV. We hereby focus on the FPV pilot project at the Oostvoornse Lake, as a specific case study. The pilot project was established in the summer of 2020 with the aim to investigate the mechanical stability, electrical performance and environmental impacts of three distinctive FPV system designs for a period of approximately one year. Here, we describe the results of the water quality study and address the following main research question:

"What is the impact of the three FPV systems on the water quality at the Oostvoornse lake?".

The novelty of the work presented here is twofold. First, this is to the best of our knowledge the first study in which the water quality effects of distinctive FPV system designs are investigated and compared. Second, our study provides insight into the impact of FPV on the availability of light in the water column directly below the systems through the measurement of light intensity – a crucial water quality parameter which thus far has been omitted in FPV-related water quality monitoring studies.

The rest of the paper is structured as follows. The following Section 1.1 provides an overview of the theoretical background and key insights from previous research on water quality effects associated with the deployment of FPV. In Section 2 we present our research methodology, including a description of the study area, the three FPV system designs and our approach to data collection and analysis. The results of the water quality monitoring are provided in Section 3, after which a discussion of these results is provided in Section 4. Finally, in Section 5 we outline the conclusions and reflect on some of the limitations of this study.

1.1. Theoretical background

Recent reviews of the scientific literature and gray documents provide evidence that so far only a handful of studies have evaluated the water quality effects of FPV systems and other artificial floating structures (Dionisio Pires and Loos, 2020a; Exley et al., 2021b). In light of the limited available knowledge on the subject and the lack of a clear water quality monitoring framework, Dionisio Pires and Loos (2020b) developed monitoring guidelines that define which parameters need to be accounted for in the context of FPV-related water quality monitoring activities. These guidelines point to three water quality parameters that are considered to be most important: (1) light availability, (2) water temperature, and (3) dissolved oxygen concentration.

Sunlight is the primary source of energy in aquatic ecosystems and controls for much of all biological and chemical processes, including primary production, photosynthetic oxygen dynamics and the regulation of water temperature. Several studies associate the physical presence of FPV and other artificial floating structures with reduced light availability below the floating infrastructure (de Lima et al., 2022; Sahu et al., 2016) and point to the consequences this could have for a water body at large (Pimentel Da Silva and Branco, 2018; Wang et al., 2021). In general terms, the extent to which FPV causes light suppression will be largely dependent upon FPV system design characteristics — in particular system size and its degree of openness (Exley et al., 2021a). It is reasonable to assume that larger systems, that consist of continuous surfaces of opaque materials and structures, will have the greatest potential to reduce light availability and, as such, to adversely affect the host aquatic ecosystem. However, empirical research aimed at quantifying the availability of light below FPV systems and relating this to FPV design characteristics, such as system size and surface coverage density, is currently not available (Dionisio Pires and Loos, 2020a; Exley et al., 2021b). To the best of our knowledge, only a recent study by Yang et al. (2022) measured the impact of an FPV facility on the amount of solar radiation beneath the panels, but their measurement data reflect ambient air conditions and were not employed to quantify the impact on the availability of light in the water column directly below the facility. The lack of in-situ underwater monitoring data makes it difficult to predict how light suppression impacts will vary according to FPV system design and how this will translate into impacts on ecosystem health and functioning more broadly.

Even though field data on light intensity impacts seem to be largely unavailable, a few previous studies have explored FPV-induced changes to light climate through the use of models. For instance, Delft3D model calculations by Loos and Wortelboer (2018) show that FPV deployment may reduce light availability by 68%–100% (Dionisio Pires and Loos, 2020a). Beyond research oriented to FPV specifically, a few studies have shown how other artificial structures at the water surface reduce solar radiation inputs. For instance, Maestre-Valero et al. (2011) pointed out that a suspended shade cloth, implemented as a measure to counter evaporative losses of irrigation water in Spain, reduces light transmission by almost 100%. In similar manner, Able et al. (2013) found that light abundance below an urban pier located at Hudson River Park in New York was significantly lower compared to a reference location at open water adjacent to the pier.

In addition to reducing light availability, the installation of FPV has been found to shelter the host water body from the influence of wind, leading to a decrease in wind speed and wind-driven water movement (Exley et al., 2021a). Both light suppression and reduced wind speed affect the thermal conditions of a water body, albeit in opposite directions. More specifically, a decrease in wind speed will tend to increase the water temperature at the surface, while a decrease in sunlight penetration will tend to lower the temperature at the surface (Kalff, 2002). Exley et al. (2021a) show through model simulations that temperature effects of reduced wind speed and solar radiation input are highly variable and largely dependent on FPV system design and surface coverage density. Their model results suggest that the percentual decrease in solar radiation input has a larger effect on water temperature than the percentual decrease in wind speed. In other words, when light penetration and wind speed decrease in the same order of magnitude, then it is to be expected that the water temperature at the surface also decreases. In this regard, several studies have associated the installation of FPV with a decrease of the water temperature (e.g. de Lima et al. (2021a), Wang et al. (2021)). The simulations of Exley et al. (2021a) show on the other hand that an increase (up to 2 °C) of the surface water temperature may be possible under the assumption that no more than about 25% of the potential solar radiation input is blocked by the installation of FPV. Yet, current FPV configurations tend to have a limited degree of openness through which sunlight could penetrate the underlying water column, making it improbable that FPV installations could concur with a noticeable increase of the surface water temperature.

However, beyond the effects of wind speed and solar radiation, the study of Yang et al. (2022) shows that the heat energy produced by FPV panels may have a considerable effect on the surface water layer below the panels. More specifically, Yang et al. (2022) show based on in-situ measurements coupled with numerical modeling that the conductive heating of FPV panels warms-up the air layer between the panels and the water surface with about 4 °C on average in the daytime, causing the temperature of the top water layer directly below the panels to increase with about 0.3 °C to 0.5 °C. This suggests that the potential of FPV to reduce water temperature due to the suppression of light may be (partly) offset by the heat transmitted from the FPV panels into the underlying water column — an effect which may be particularly prominent in the case of systems consisting of closed constructions with few openings between the floater modules and PV panels.

Several studies have furthermore associated the suppression of sunlight and wind with changes in the availability of dissolved oxygen in the aquatic system (de Lima et al., 2021a; Wang et al., 2021). Wind tends to oxygenate a water body directly, through wind-driven turbulence at the water surface (Hull et al., 2008), while sunlight alters dissolved oxygen levels indirectly through respiration and photosynthetic production by phytoplankton and macrophytes (Staehr et al., 2010). Hence, a reduction in wind and sunlight induced by FPV is likely to change a water body's oxygen dynamics, but how and to what degree remains still a subject of discussion. For instance, Château et al. (2019) showed through field experiments coupled with model simulations that a 40% solar panel coverage of a fish pond results in a significant reduction in dissolved oxygen levels and water temperature. This could, in turn, translate into negative impacts on fish populations and other animal species and disrupt food chains; a concern which was furthermore expressed by Pimentel Da Silva and Branco (2018).

In contrast to these negative impacts, some studies anticipate that the deployment of FPV may have an overall positive influence on the dissolved oxygen regime of the host aquatic ecosystem. For instance, Haas et al. (2020) argue that FPV-related shading effects could control for excessive algae growth, reduce eutrophication and prevent the depletion of oxygen as a consequence of bacterial decomposition of organic residues. Furthermore, Loos and Wortelboer (2018) point out that the installation of large-scale FPV could increase dissolved oxygen levels, primarily because lessened water movement is considered to improve the conditions for oxygen production by phytoplankton.

As outlined above, a broad range of changes to biochemical and physical processes may be set in motion through the introduction of FPV and it remains highly complex to predict how these changes will play out and what this means in terms of water quality locally as well as for the entire water body. This calls for an expansion of the current body of knowledge, through comprehensive field monitoring of the water quality effects associated with the deployment of FPV systems.

2. Methodology

2.1. Study area

The Oostvoornse lake is a brackish lake located in the province of South-Holland, the Netherlands (Fig. 1). The industrial area and Port of Rotterdam border the lake on the north, while the town of Oostvoorne is located approximately 3 km to the south. The lake has a surface area of about 270 ha, an average water depth of about 20 m and a maximum water depth of about 40 m. The lake was created through the construction of a dam (*the Brielse Gatdam),* after which it came into use as a major sand excavation area for the construction of the Maasvlakte extension of the Port of Rotterdam in the 1960s (Dembski, 2013).

Through the years, the lake's water salinity level has been dropping steadily due to the influx of fresh water from the adjacent dune areas. This has resulted in increasing algae and cyanobacteria growth and, in turn, a reduction of the water transparency and the overall water quality. In an attempt to preserve the lake's unique biodiversity and recreational value, it was decided in 2008 to start supplementing salt water to the lake through the installation of an underground pipeline between the Mississippihaven (one of the Maasvlakte's main channels) and the lake's north bank. Yet, despite this saltwater inlet, excessive algae growth remains a major problem and continues to negatively impact the water quality.

In the months of September and October 2020, three distinctive FPV energy systems were installed at the Oostvoornse lake as part of a 1-year pilot project to evaluate the electrical performance, mechanical stability and ecological impact of the FPV systems. The pilot project also allowed for research into the social acceptability of FPV technology more broadly. The FPV systems were established in the northwest corner of the lake, at about 100 m from the lake banks, see Fig. 1. The research facility further consisted of a floating walkway between the shore and the FPV systems, as well as electrical infrastructure on land.

2.2. FPV system designs

The three FPV systems considered in this study were established by different private developers and varied in size and technical design features, see Fig. 2 and Table 1. The systems will be referred to as "System A", "System B" and "System C". The information below is based on de Jong (2020) and summarizes some of the features of the FPV systems that may be relevant to explain and interpret their water quality effects.

System A has a size of about 350 m^2 and an estimated water surface coverage of 75%. The system is based on a set of High-Density Polyethylene (HDPE) tubes which act as the floating construction upon which the system is build. The tubes are connected by aluminum frames (so called saddles) which are placed on top of the tubes and keep the PV modules in place. The HDPE tubes in the main part of the system are attached to so-called bridle pipes located on the North and South sides of the system. The bridle pipes are in turn moored to the bottom of the lake with 4 anchors.

System B is roughly rectangular, with a size of about 400 m^2 and an estimated water surface coverage of 100%. The system consists of polypropylene floaters upon which the PV panels are mounted at an angle of 5 degrees. The system is moored with multiple anchor lines from all four sides, connected to 8 anchors.

System C is a roughly circular system, with a size of about 600 m^2 and an estimated water surface coverage of 75%. The system consists of PV solar modules mounted to metal frames, which are in turn mounted to polypropylene floaters. The floaters are interconnected and attached to a circular floating HDPE tube, the so-called inner wave breaker. Around the inner wave breaker is the outer wave breaker — an octagonal HDPE floating tube which is moored to the bottom of the lake with 8 anchors.

2.3. Data collection

A monitoring campaign was set up to assess how and to what extent the FPV systems implemented at the Oostvoornse lake affect the water system. This included the continuous measurement of light intensity, as well as a set of physicochemical parameters, including water temperature, dissolved oxygen concentration, pH, turbidity, electrical conductivity and oxygen reduction potential. These parameters could be considered to be straightforwardly measurable, as the measurements require relatively little time and resources and can largely take place in-situ. The monitoring of these parameters aligns closely with previous

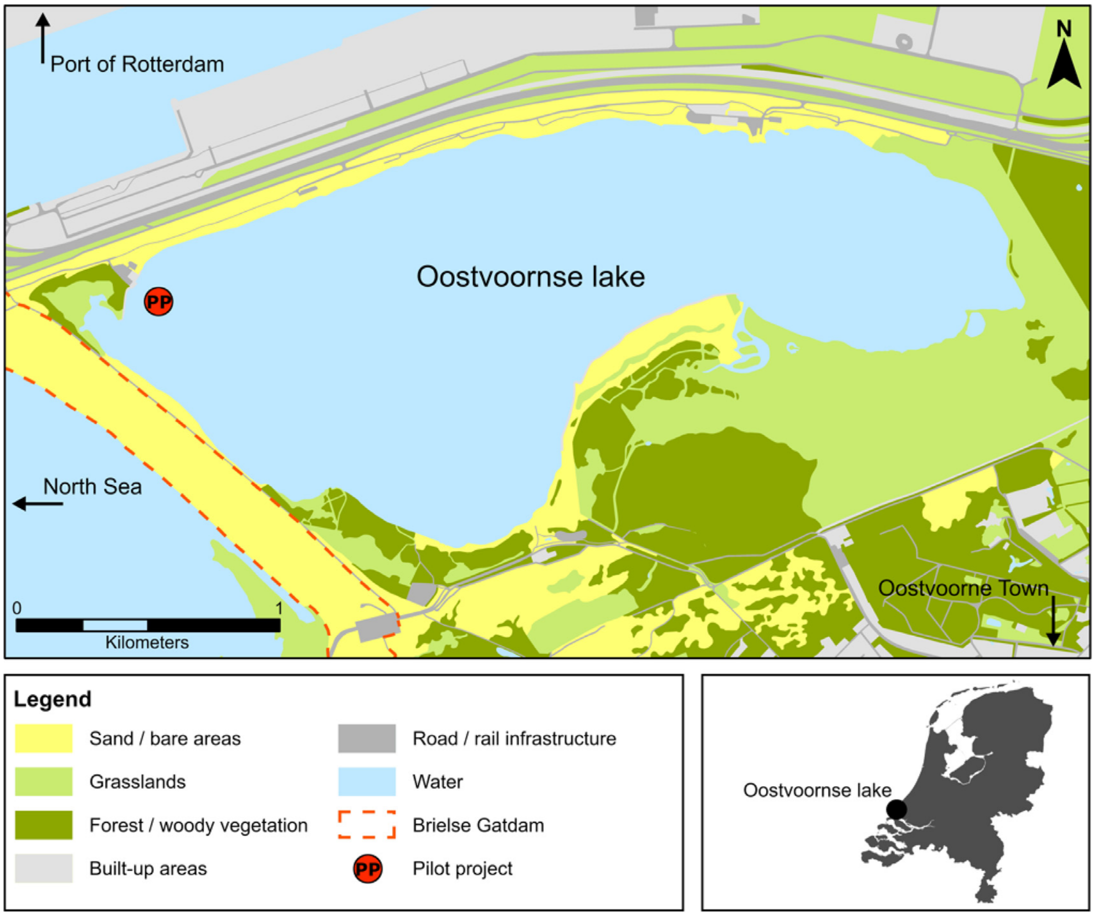

Fig. 1. Study area. The Oostvoornse lake is a brackish lake located in the province of South-Holland, the Netherlands. In the period between September and October 2020, a FPV pilot project was implemented in the northwest corner of the lake, about 100 m from the lake banks. The pilot project allowed for research into technological aspects as well as ecological and societal impacts associated with the project.

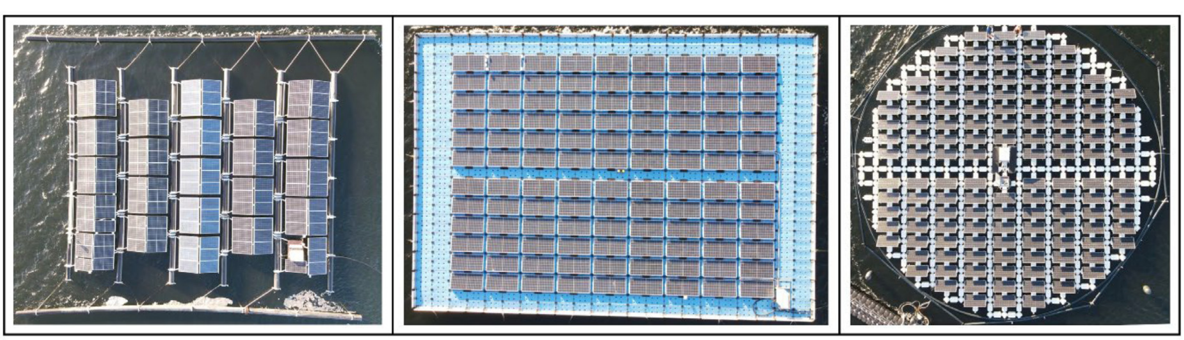

Fig. 2. Top view photos of the three FPV system designs considered in this study, including System A (left), System B (middle), and System C (right). Photos are adapted from de Jong (2020).

Table 1
Overview of the FPV system designs, installed at the Oostvoornse lake as part of a one-year pilot project (de Jong, 2020).

	System A	System B	System C
System size	~350 m^2	~400 m^2	~600 m^2
System shape	Roughly rectangular	Rectangular	Roughly circular
Water surface coverage	~75%	~100%	~75%
Installed capacity	41.93 kWp	39.42 kWp	50.7 kWp
Number of PV modules	136	108	130
PV module angle	18 degrees	5 degrees	25 degrees
Module orientation	East/West	South	Tracking
Floating system	HDPE tubes	Polypropylene floats	Polypropylene floats

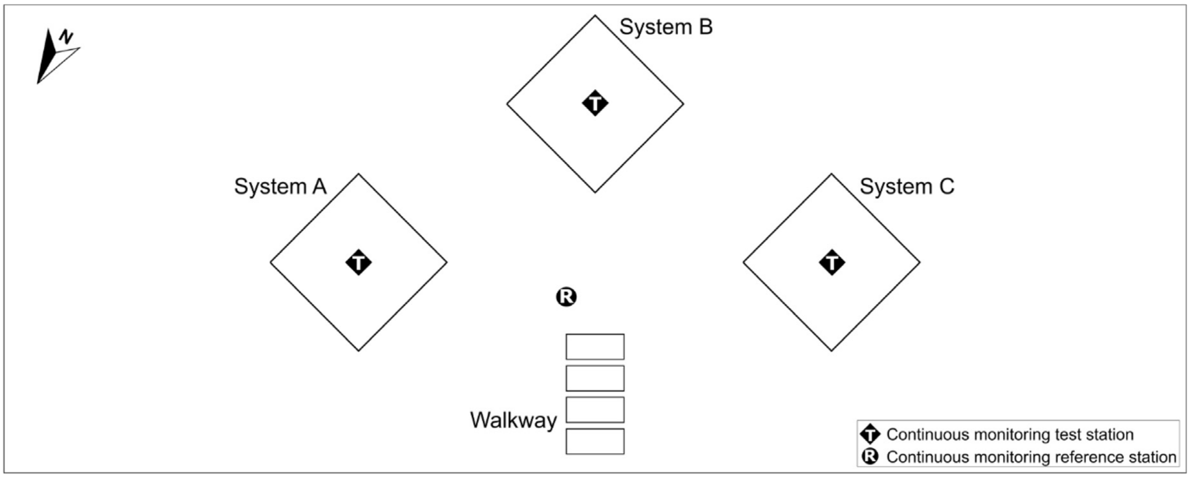

Fig. 3. Schematic overview of the locations of the FPV systems and the reference station, and the locations where the monitoring equipment was installed to collect continuous data on light intensity, water temperature and dissolved oxygen concentration.

research on water quality effects related to the deployment of FPV de Lima et al. (2021a), Wang et al. (2021).

In this paper, we focus our attention on three water quality parameters specifically: 1) light intensity, 2) water temperature and 3) dissolved oxygen concentration. In particular, because the monitoring of these parameters has been recognized to be most important to gain insight into the water quality effects of FPV deployment (Dionisio Pires and Loos, 2020b). The data on the other water quality parameters are available as supplementary materials to this article.

Continuous measurements of light intensity were conducted using HOBO UA-002-64 Pendant Temperature/Light Intensity Loggers, based on measurement intervals of 5 min. Measurements of the water temperature and dissolved oxygen concentration were conducted using Hanna HI9829 portable Multiparameter devices, based on measurement intervals of 30 min. This type of equipment has been regularly used for similar purposes in other water quality studies, see for instance Bouderbala (2021), Long et al. (2012) and Tierno de Figueroa et al. (2019).

The monitoring equipment was placed at the center below each of the three FPV systems, with the sensors submerged at a two-meter water depth. Specifically, we introduced the equipment into the water column through an opening in between the floats and attached the cable to the edge of the floater construction, which positioned the sensors exactly at a depth of two meters below the edge of the floats at the water surface. A reference monitoring station was positioned at open water adjacent to the FPV systems. The specific water depth of two meters was considered to be sufficiently deep to minimize the influence of atmospheric reaeration on the dissolved oxygen measurement, while close enough to the FPV systems to remain in their sphere of influence and measure potential water quality impact. Furthermore, based on preliminary trial-and-error light intensity measurements at a range of water depths, it was found that measurements at a two meter water depth are not under the direct influence of sunlight penetrating through the openings in between the PV panels, but accurately reflect the global shading effect of the FPV systems at large, see also the supplementary materials to this article. Fig. 3 provides a schematic overview of the location of the three FPV systems and corresponding monitoring locations.

Monitoring of light intensity took place in the period between July and November 2021 – a period which stretches from the summer into the end of the fall, covering a broad range of solar radiation intensity. Monitoring of the water temperature and dissolved oxygen concentration took place in the period between March and October 2021 – a period which covers the summer season when primary production is highest, and the fall when die-off and decomposition of organic matter takes place. The length of our monitoring period is similar to the duration of previously reported monitoring activities (de Lima et al., 2021a; Wang et al., 2021). Over the course of the monitoring period, regular field visits (once every two to three weeks) were carried out to read out the collected water quality data and conduct instrument maintenance activities, including cleaning, re-calibration and overall verification of proper functioning of the equipment.

The field monitoring was subject to a number of events and incidents. This hampered to some extent the collection of continuous water quality data and led to missing data in the final database. For instance, strong winds and excessive precipitation events interrupted some of our monitoring activities in the months of March and April 2021. Further, over the course of the study period, some technical issues with the Hanna multiparameter monitoring equipment arose. This required repairment or replacement of the equipment, leading to multiple gaps in the collected data.

2.4. Data analysis

As a first approach to data analysis, the longitudinal measurement data were plotted in charts using graphical software to visualize trends and fluctuations, and to draw comparisons between the different monitoring locations. Outliers in the collected datasets were identified using histograms and subsequently removed before proceeding with further analyses.

Based on previous research (de Lima et al., 2021a; Wang et al., 2021), it may be expected that the water quality effects caused by the FPV systems take place in a largely consistent manner. In other words, a particular FPV system is likely to cause either an increase or decrease in the measurement value of any given water quality parameter over time. In contrast, the observation of incidental increases or decreases in the measured values may be more likely attributable to external factors related to for example abrupt changes in weather conditions or equipment failure. Accordingly, to evaluate the water quality effects of the FPV systems, the measurement data obtained at the location of each of the FPV systems were contrasted with the data obtained at the reference station at open water to identify possible differences in measurement values between these locations and examine to what extent these differences were measured consistently over

Table 2
Average light intensity during daytime (6 a.m.–6 p.m.) in lux. The percentages between brackets reflect the average reduction in light intensity below the FPV systems compared to the reference station.

	System A	System B	System C	Reference
July/August	1012 (−77%)	36 (−99.2%)	1196 (−73%)	4403
September/October	613 (−75%)	11 (−99.6%)	488 (−80%)	2454
November	154 (−85%)	3 (−99.7%)	139 (−87%)	1038

time. For each water quality parameter, average values were calculated and compared to further examine to what extent the data collected at the FPV systems deviate consistently from the reference data.

As pointed out previously, the final database contained multiple gaps with missing data as a result of issues with the monitoring equipment as well as project-related incidents. As a consequence, in order to contrast the different monitoring locations, it was necessary to conduct the analyses based on segments of the monitoring period for which continuous data collected at multiple monitoring locations was available. Meanwhile, to provide insight in seasonal variation, the analyses were as much as possible conducted on a month-by-month basis.

3. Results

This section provides an overview and analysis of the water quality data collected at the location of the three FPV systems and the reference station. Each of the colored datasets in the figures below correspond to a specific monitoring location, with System A displayed in red, System B in blue, System C in green and the reference station in gray. High-resolution figures are available as supplementary materials to this article.

3.1. Light intensity

The light intensity data are presented in three separate graphs, corresponding to the period July/August (Fig. 4a), September/October (Fig. 4b) and November (Fig. 4c). The marked differences in the measured light intensity across the monitoring period, as can be noted in the figures, reflect the large seasonal variation in solar radiation intensity. The data show that over the course of the monitoring period, the measured light intensity at the reference station is considerably higher than below the three FPV systems. In line with expectations based on the estimated surface water coverage (Table 1), we found that System B had the highest impact on light intensity. Yet, also System A and System C appear to cause a substantial reduction in light availability.

Table 2 displays the average light intensity during daytime, measured in the periods July/August, September/October and November 2021. The percentages between brackets reflect the average reduction in light intensity below the FPV systems compared to the reference station. The data show that between July and November, an average light reduction of nearly 100% was observed below System B, whereas the reduction in light intensity below System A and System C ranged on average between 73% and 87%. Light reduction below System A and System C was found to be higher in November (−85% and −87%, respectively) compared to the July/August period (−77% and −73%, respectively).

3.2. Water temperature

Fig. 5 provides an overview of the water temperature at the location of the FPV systems and the reference station in the period between March and October 2021. Over this period, the water temperature ranged from about 5 to 22 °C. The data in Fig. 5 point to a very low variation in water temperature between the FPV systems and the reference station. The dataset of System A overlies much of the data collected at the other three locations, which reduces the visibility of these datasets in the figure.

The water temperature data collected at the location of the FPV systems and the reference station are displayed as monthly averages in Table 3. It can be noted that the average temperature measured below System A is consistently higher than the reference measurements at open water, albeit the differences are small, ranging from 0.12% to 0.47%. In contrast, the average temperature below System B was found to be consistently lower in the months for which temperature data is available, but again with only modest differences of no more than −0.58%. In the case of System C, the water temperature was mostly lower than the reference station, with the only exception being the average water temperature measured in June.

3.3. Dissolved oxygen

The variation in the dissolved oxygen concentration at the FPV systems and the reference station is displayed in Fig. 6. Throughout the monitoring period, the measured concentrations range roughly between 5 and 10 mg l^{-1}. Broadly speaking, the data in Fig. 6 show a slightly downward trend, with relatively high concentrations measured in March (between about 8 to 10 mg l^{-1}) and lower concentrations towards the end of the monitoring period (between about 5 to 8 mg l^{-1}).

Table 4 includes the dissolved oxygen concentration at the location of the FPV systems and the reference station, presented as monthly averages at daytime (between 12:00 and 24:00) and nighttime (between 00:00–12:00). Generally, higher dissolved oxygen concentrations were measured at daytime than nighttime, albeit the differences between day and night were found to be quite modest. In line with Fig. 6, the average dissolved oxygen concentrations seem to be slightly higher at the beginning of the monitoring period than at the end.

The data in Table 4 show that the average dissolved oxygen concentration measured below System B was consistently lower than the reference measurement. The largest differences with the reference station were measured in the period between July–August/September (on average between −4% and -6%).

Less consistent differences were found between the reference station and the systems A and C. In the case of System C, the average dissolved oxygen concentration was incidentally higher (up to 5% in May) and incidentally lower (around -6% in June) than the average dissolved oxygen values measured at the reference station. In the case of System A, the average dissolved oxygen concentration was found to be considerably higher in the months of June and Augustus/September (about 11% to 13%). Differences were less marked in the other months, ranging from 4% higher values to 5% lower values compared to the reference station.

4. Discussion

The FPV pilot project at the Oostvoornse lake has offered the opportunity to investigate technological aspects along with environmental and social impacts associated with the deployment of three distinctive FPV system designs. In this study, we investigated the potential water quality effects of these systems, by monitoring a set of standard water quality parameters on a continuous basis for a prolonged period of time. The data presented in this study demonstrate how key water quality conditions have changed over time and provide insight into the extent to which these changes may be linked to the deployment of the three FPV systems.

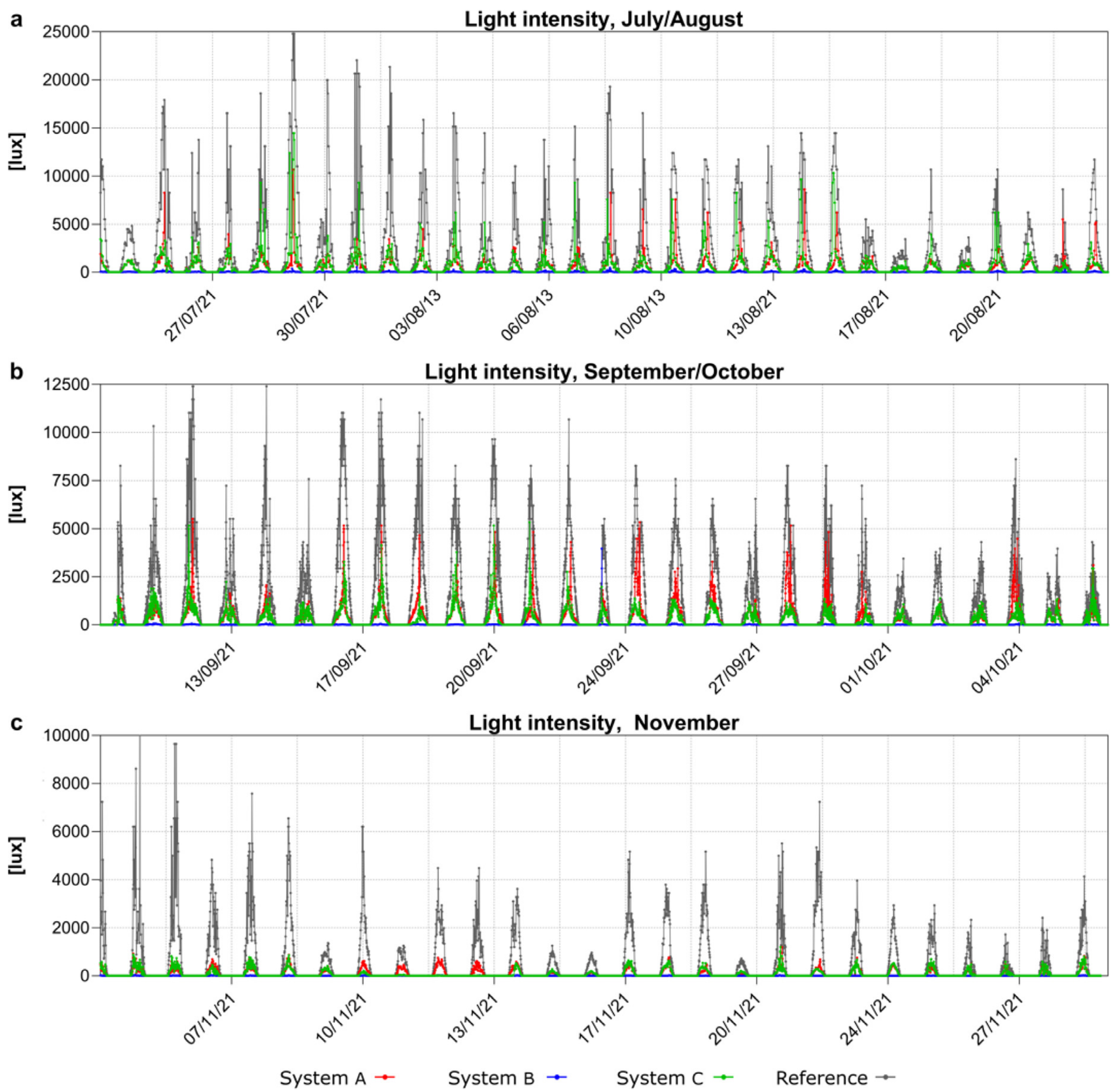

Fig. 4. Overview of the light intensity data collected in July/August 2021 (a), September/October 2021 (b) and November 2021 (c).

Table 3
Monthly average water temperature, in degrees Celsius (°C). The percentages between brackets reflect the average difference in water temperature below the FPV systems compared to the reference station.

	System A	System B	System C	Reference
March	6.30 (0.47%)	–	6.12 (−2.47%)	6.28
April/May	10.36 (0.12%)	10.29 (−0.58%)	10.23 (−1.18%)	10.35
June	20.18 (0.38%)	–	20.12 (0.10%)	20.10
July	18.93 (0.36%)	18.86 (−0.01%)	18.82 (−0.24%)	18.86
August	18.32 (0.35%)	18.23 (−0.10%)	18.21 (−0.23%)	18.25
September/October	17.75 (0.35%)	17.68 (−0.04%)	17.66 (−0.14%)	17.69

In line with expectations and previously reported modeling results (Loos and Wortelboer, 2018), we found that the FPV systems cause a significant reduction of the available light in the water column directly below the systems. The most notable impact on light was found to be associated with System B, reaching a light reduction of nearly 100%. This extensive shading effect can be explained by the closed design of the system, consisting of a continuous surface without openings in between the PV panels and the polypropylene floater construction through which light can penetrate the underlying water column. Both System A and System C have a considerably higher degree of openness, but their impact on light availability was nonetheless substantial, with an average light reduction ranging from 73% to 87%. The light suppression impacts of System A and System C were found to be slightly higher in the autumn/winter period than in the summer period. This suggests that their impact on light availability is generally higher under cloudy weather conditions than under clear skies when sunlight is more likely to penetrate directly into the water column. In a similar manner, this may also indicate

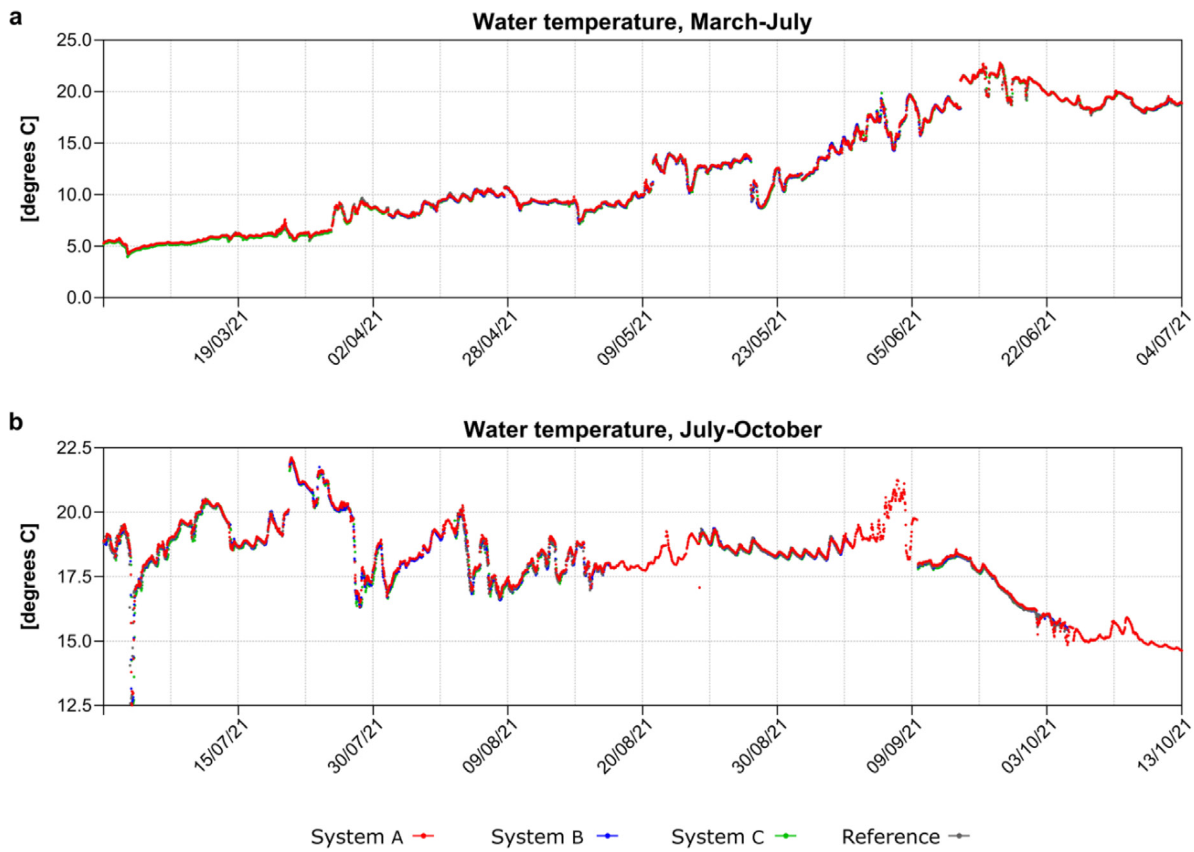

Fig. 5. Overview of the water temperature data collected in the period March–July 2021 (a), and July–October 2021 (b).

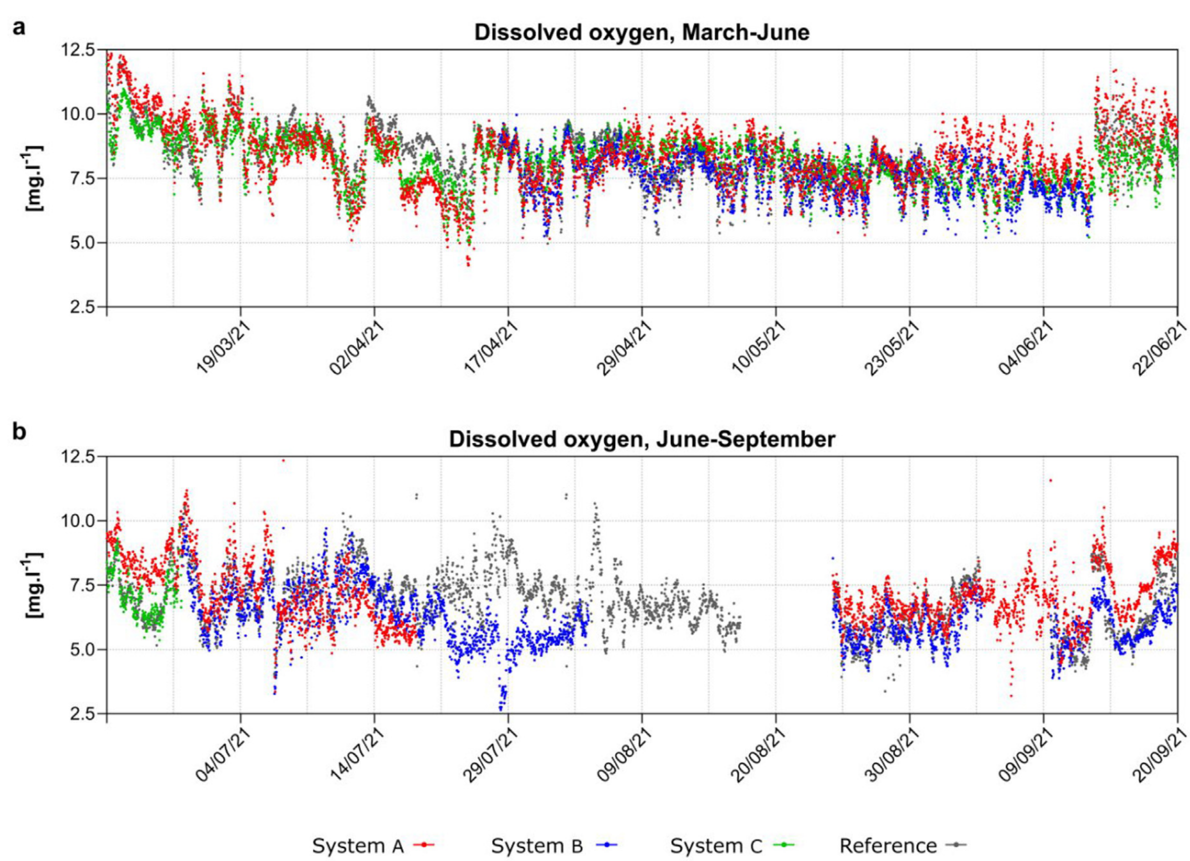

Fig. 6. Overview of the dissolved oxygen data collected in the period March–June 2021 (a), and June–September 2021 (b).

Table 4
Dissolved oxygen concentration in mg l^{-1}, as monthly averages at nighttime (between 00:00–12:00) and daytime (between 12:00 and 24:00). The percentages between brackets reflect the average difference between the dissolved oxygen concentration below the FPV systems and the reference station.

		System A	System B	System C	Reference
March	00:00–12:00	9.04 (0.8%)	–	8.87 (−1.1%)	8.97
	12:00–24:00	9.40 (2.3%)	–	8.96 (−2.5%)	9.19
April	00:00–12:00	7.79 (−1.1%)	7.70 (−2.2%)	8.14 (3.3%)	7.87
	12:00–24:00	8.29 (−2.9%)	8.21 (−3.9%)	8.71 (2.0%)	8.54
May	00:00–12:00	7.97 (4.2%)	7.54 (−1.3%)	7.96 (4.1%)	7.64
	12:00–24:00	7.90 (2.9%)	7.61 (−1.0%)	8.08 (5.2%)	7.69
June	00:00–12:00	8.93 (12.6%)	–	7.49 (−5.6%)	7.93
	12:00–24:00	9.08 (11.6%)	–	7.95 (−2.3%)	8.13
July	00:00–12:00	6.93 (−3.9%)	6.85 (−5.0%)	–	7.21
	12:00–24:00	7.14 (−4.7%)	7.18 (−4.2%)	–	7.49
August/September	00:00–12:00	6.79 (10.6%)	5.80 (−5.5%)	–	6.14
	12:00–24:00	7.24 (13.0%)	6.05 (−5.6%)	–	6.40

that the FPV systems cause a higher blockage of light when the position of the sun is relatively low.

A decrease in the availability of sunlight could in theory lead to reduced photosynthetic oxygen production and adversely affect aquatic organisms, including fish and invertebrate animals (Chislock et al., 2013; Kraemer et al., 2017). These effects are particularly expected when oxygen levels drop below a critical threshold value of about 5 mg l^{-1} (Ficke et al., 2007). Our monitoring results indicate that the dissolved oxygen concentration almost never reached this critical value. On the other hand, we found that the dissolved oxygen concentration gradually decreased over the course of the monitoring period, from about 8–10 mg l^{-1} in the spring period to about 5–8 mg l^{-1} in the summer and fall periods. It appears to be unlikely that this falling trend in dissolved oxygen has been caused by the deployment of the FPV systems specifically, because a similar downward trend also applies to the oxygen conditions measured at the reference station. Instead, the observed decrease in oxygen concentration is more likely to be associated with natural seasonal variation, as oxygen levels in large water bodies are usually higher in the winter season and tend to fall in the summer and autumn periods (Araoye, 2009; Romanescu and Stoleriu, 2014). In addition, the falling trend might also be partly explained by a gradually decreasing capacity of the monitoring equipment to measure the dissolved oxygen level properly. In particular, we noticed over the course of the monitoring period that it became increasingly difficult to calibrate the dissolved oxygen sensors and gain accurate measurement values.

More generally speaking, our monitoring results provide limited evidence to corroborate that the FPV systems caused changes to the oxygen conditions directly below the systems. In the case of System A and System C, we found both higher and lower dissolved oxygen values compared to the reference location, suggesting that the effect these systems may have on the dissolved oxygen concentration is not strictly positive or negative. In the case of System B, we found slightly lower dissolved oxygen values compared to the reference station, which in turn, might be associated with the extensive shading effects caused by the system. Meanwhile, the differences between System B and the reference measurements were quite modest, on average roughly between 1% and 5%, and may have also been caused by other factors. For instance, the Hanna multiparameter monitoring instruments used in our study are associated with a certain level of measurement accuracy. According to the equipment manual, a measurement error of ± 0.10 mg l^{-1} could considered to be acceptable, but in practice we found these measurement errors to be much higher — at least ± 0.30 mg l^{-1} and occasionally even higher.

Our monitoring results furthermore show that the water temperature conditions at the FPV monitoring locations and the reference station were not notably different. This contrasts with temperature effects of FPV reported in previous studies. For example, de Lima et al. (2021a) recorded lower temperature values in the top water layer below a large-scale FPV facility, compared to an adjacent reference location in open water. Their results furthermore showed that FPV-induced shading effects cause the heating of water to take place more slowly (i.e. a delay in water heating) and more uniformly (i.e. a reduction in water temperature peak values). Beyond water temperature dynamics, de Lima et al. (2021a) also found that other water quality conditions varied markedly between the FPV and reference monitoring locations. For instance, the dissolved oxygen concentration below the FPV facility was recorded to be about 1.1 to 1.7 mg l^{-1} lower compared to the nearby reference station.

It is important to note that the work of de Lima et al. (2021a) describes temperature and oxygen effects associated with the implementation of a utility-scale FPV facility of about 18.25 ha, consisting of about 72.000 PV panels. Our study focused on three small-scale FPV systems of about 500 m^2, whose effects on the water quality tend to be much smaller. In particular, the deployment of a large-scale FPV facility suppresses the exchange of water underneath the FPV system and its immediate surroundings (see e.g. Loos and Wortelboer (2018)) — an effect which could be expected to be less pronounced in the case of smaller FPV facilities. Hence, as the degree of mixing of water below and adjacent to small-scale systems is relatively high, it is reasonable to assume that the water quality conditions measured below these systems also partly reflect the conditions adjacent to the systems. This means in practice that the observed water temperature and oxygen effects of the FPV pilot systems may only partly reflect the effect that a particular FPV design could potentially cause when implemented at a larger scale.

As discussed above, the water quality effects of the three small-scale FPV systems considered in this study seem to be less pronounced than the effects of larger FPV facilities as reported in previous studies. This sheds light on the possibilities of implementing FPV without compromising water quality management objectives. More specifically, an opportune implementation solution of FPV that comes to mind is the adoption of small-scale systems. It is increasingly recognized that the development of small-scale renewable energy initiatives will make an important contribution to the energy transition (Ramos et al., 2019). Previous research has furthermore shown that the deployment of small-scale FPV facilities is generally supported by the nearby community (Bax et al., 2022), which could facilitate FPV development and implementation processes. In the specific case of the pilot project considered in this study, the installed capacity of the three FPV systems together adds up to around 130 kWp. By comparison, this roughly corresponds to about 10 to 130 residential rooftop PV installations (Wierling et al., 2021). An expansion of the current scale and installed capacity could be expected to increase the water quality impact of the three FPV systems, but how and to what extent remains subject to further investigation.

In the context of upscaling FPV technologies, it will be important to understand how water quality effects taking place locally (i.e. directly below the FPV systems) translate into impacts on the aquatic ecosystem at large. In this regard, not just the absolute dimensions of the FPV systems play a role, but in particular the lake surface coverage (or the ratio between the area covered by the systems and area of the basin) will shape the degree to which FPV deployment could induce changes to water quality conditions. In the specific case of our study, the combined areal extent of the FPV systems (about 1500 m^2) in proportion to the surface area of the Oostvoornse lake (about 270 ha) translates into a lake surface coverage of less than 0.1%, which is clearly much too low to cause any lake-wide impacts. Model outcomes produced by Loos and Wortelboer (2018) indicate that impacts on the aquatic ecosystem are most likely to take place with lake surface coverages of about 50% or more, depending on the water body in question and FPV-specific design characteristics such as the degree of openness. Our water quality data could be used in conjunction with modeling tools such as the Delft3D application developed by Loos and Wortelboer (2018) to explore how water quality conditions throughout the Oostvoornse lake could respond to an increase in the surface coverage of the three FPV system designs considered in our study.

In retrospect, it has become apparent that the Oostvoornse lake may not have been the most suitable location to establish the pilot project in relation to examining the water quality effects of the FPV systems. On the one hand, the corrosive properties of the brackish lake water seem to have caused the monitoring equipment to become increasingly less reliable over time. This might have led to inaccurate measurement results. For instance, the dissolved oxygen concentration showed a gradually decreasing trend, which might have been caused by a reduced performance of the monitoring instruments over the course of the monitoring period. On the other hand, the aim of the pilot project was to gain insight into the technical and ecological performance of three different FPV system designs and test whether these designs are adequate for a larger-scale application elsewhere. However, the water quality analysis took place under highly specific conditions due to the brackish water of the Oostvoornse lake, and the observed water quality effects reported in this study may therefore not be well-transferable to other non-brackish study locations. Finally, scale matters: the relatively modest scale of the employed FPV systems raises uncertainty about the transferability of the water quality outcomes to utility-scale application.

5. Conclusion

In this study, the water quality effects of three different FPV system designs were examined through the in-situ monitoring of a set of key water quality parameters, including light intensity, dissolved oxygen concentration and water temperature. Data on these parameters were collected below each of the three FPV systems and contrasted with reference data collected at open water adjacent to the systems. Based on the results obtained in this analysis, it can be concluded that the three systems had only a minor impact on the water quality.

Of the water quality parameters considered, the impact of the systems on light availability was found to be most pronounced. More specifically, our light intensity data show a decrease in the availability of light directly below the FPV systems, ranging from about 73% to nearly 100% relative to the reference measurements. A reduction of sunlight may cause shifts in fundamental biological processes such as primary production and change the functioning of the aquatic ecosystem at large. However, the effects of shading caused by the FPV systems could be assumed to be low given the small-scale of the pilot systems and their proportion in relation to size of the Oostvoornse lake.

Beyond the impact on light intensity, we found no specific evidence to suggest that the FPV systems adversely impact the water quality in any other notable way. Generally speaking, our data show that over the course of the monitoring period, water quality conditions such as water temperature, and dissolved oxygen concentration were similar across the FPV and reference monitoring locations. Even though we also recorded differences, they tended to be inconsistent, meaning that the measured value of a given water quality parameter at the location of the FPV systems was not consistently higher or lower than the reference measurement. As previous research has shown that water quality effects caused by the deployment of FPV take place in a largely consistent manner, we may assume that inconsistent variation between the different monitoring locations is associated with other factors, such as abrupt changes in weather conditions or measurement errors.

Although our research shows that the water quality impact of the FPV systems was limited, it must be noted that the results reported here are highly case and context-specific and may not similarly apply to project locations elsewhere. The brackish water of the Oostvoornse lake provide for highly specific water quality conditions, and it is likely that the effects of the FPV systems are different when implemented on freshwater ecosystems. On the other hand, the Oostvoornse lake has a considerable size and water depth, which allows for relatively high water flow velocities, currents and extensive water mixing. This mixing capacity of the Oostvoornse lake may give rise to the situation in which the water quality measurements directly below the FPV systems partly reflect the water quality conditions in the surrounding areas. Hence, to gain further insight into the water quality effects associated with different FPV system designs, it would be required to expand the current scale of the systems or evaluate how they change the water quality conditions of calmer surface waters (e.g. shallow ponds and reservoirs of limited size).

CRediT authorship contribution statement

Vincent Bax: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Wietse I. van de Lageweg:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Rik Hoosemans:** Methodology, Formal analysis, Investigation, Writing – original draft. **Bas van den Berg:** Methodology, Investigation, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vincent Bax reports financial support was provided by the project Pilot Oostvoornse Meer, a collaboration between TNO, SABIC, Equinor and the municipality of Westvoorne.

Data availability

Data have been included as supplementary materials to the article

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2022.12.080.

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