Environmental and technological advantages and disadvantages of Floating Photovoltaics in the Netherlands

Internship and master thesis evaluating the environmental and technological advantages and disadvantages of freshwater and offshore floating photovoltaics in the Netherlands

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List of abbreviations

Acronym	Meaning
AC	Alternating Current
CF	Capacity Factor
DC	Direct Current
DO	Dissolved Oxygen
FPV	Floating Photovoltaic
GHI	Global Horizontal Irradiance
GTI	Global Total Irradiance
KNMI	Koninklijk Nederlands Meteorologisch Instituut
KRW	Kader Richtlijn Water
LBPV	Land-Based Photovoltaic
MPP	Maximum Power Point
PV	Photovoltaic
SDO	Saturated Dissolved Oxygen
STC	Standard Testing Conditions
ZIM	Zimmerman PV-floating

List of parameters

Parameter	Unit	Description
u	m/s	Wind speed
u_r	m/s	Wind speed at reference height
z	m	Height of sensor measuring the wind speed at the KNMI station
z_r	m	Height of sensor measuring the windspeed at FPV system
$Etot$	Kwh	Electricity output
P_{ac}	W	AC Power
CF	-	Capacity Factor
$P_{l,mean}$		Average value of physiochemical parameters
ΔP	%	Relative change of physiochemical parameter by FPV system
P_{dc}	W	DC power
Mi		Number of modules per inverter
A	M^2	Area of one module
η_{inv}	%	Efficiency of inverter
$\eta open$	%	Growth rate phytoplankton open water
$\eta FPV_{d,s}$	%	Growth rate phytoplankton FPV system
$Effect\ FPV$	%	Effect FPV system on growth rate phytoplankton

Abstract

The increasing energy demands, fast depletion of fossil fuels and the need to decarbonise are encouraging the rapid deployment of renewable energy in the Netherlands. A promising new technology to assist in this regard is Floating Photovoltaics (FPV), which can be deployed in both inland waters (freshwater FPV) and at sea (offshore FPV). However, since this is a new technology, there is limited knowledge about its technological performance and environmental impact. Nonetheless, it is important to have more knowledge order to eventually implement these technologies on a large scale. Hence, the objective of this research is to enhance our understanding of the technological performance and environmental impact of FPV systems in the Netherlands.

The technological performance of FPV systems was evaluated by comparing the energy yield, cell temperature and windspeed of a Land Based PV (LBPV), freshwater FPV and offshore FPV system. The environmental performance was assessed by examining the impact of the FPV system on water quality and ecology, specifically on the phytoplankton, macro-invertebrates, and fish. Additionally, the interaction between the FPV system, weather conditions, and environmental impacts was examined.

Previous studies on freshwater FPV were mainly based on assumptions and models. In order to validate or improve these assumptions and models, a case study was conducted for this research, evaluating data on the technological performance and environmental impact of a freshwater FPV system. When data was not available, it was supplemented with literature research. No data was available for offshore FPV. Consequently, a literature review was conducted, supplemented by semi-structured interviews.

From the results becomes clear that the technological performance of freshwater FPV is higher than the performance of a land based system. The main challenge for freshwater FPV is to minimize harmful effects on the environment related to the effects of the decreased light availability under the platform. At a depth of 1 meter, the light intensity beneath the FPV system is reduced by 25%, resulting in decreased algae growth below the system. The reduced light indirectly correlates with lower oxygen levels beneath the panels, creating less favourable conditions for fish and other aquatic life. This issue is particularly pronounced in December when the oxygen concentration in lakes is naturally low.

The main challenge in offshore FPV is to enhance system design to ensure reliability and economic viable system in the future. If successful, offshore FPV is expected to have a higher energy yield than land based systems, can be implemented on a larger scale compared to freshwater FPV and has less risks for the environment.

This study revealed that both freshwater FPV and offshore FPV can contribute to the Netherlands climate objectives. However, to enable their broader implementation, further development of both technologies is necessary.

1. Introduction

The increasing energy demands, fast depletion of fossil fuels and the need to decarbonise are encouraging the rapid deployment of renewable energy in the Netherlands (IEA, 2020). In the Climate Agreement, it has been agreed that by 2030, 70% of the electricity will be generated from sustainable sources in the Netherlands. By 2050, this should be nearly 100% (IEA, 2020). This has led to the fast development of Land-Based PhotoVoltaic (LBPV) systems (Soppe et al., 2022). However, for LBPV installations land surfaces are required. This is especially problematic for densely populated countries like the Netherlands where available land is becoming increasingly expensive and scarce (Golroodbari & van Sark, 2020). Besides, land used for LBPV systems cannot be used for other purposes like agriculture (Cazzaniga & Rosa-Clot, 2020). A manner to mitigate this problem is by installing PV systems on roofs or facades of buildings. However, for the owners of the building this is often still a substantial investment (Spertino et al., 2013). Another solution for this is agricultural PV[1], but the cost of this PV system can be three times as much as regular LBPV (Davey, n.d.). A cheaper alternative is a PV system floating on water, also called Floating Photovoltaic (FPV) (Dörenkämper et al., 2021a).

Within the Netherlands, two type of FPV systems exists. The first type are floating on inland waterbodies also called freshwater FPV system. This technology is suitable for the Netherlands because of the availability of many large fresh water surfaces. The first installations in the Netherlands were installed in 2017 and in 2021 they have cumulative capacity is almost 190 MWp (Jones & Armstrong, 2021). The second type FPV are solar cells floating on the North-sea, also called offshore FPV. In 2019, the first pilot of an offshore solar farm was installed (Jones & Armstrong, 2021). The Netherlands has a promising market for offshore FPV because of its proximity to the North-Sea (Oliveira-Pinto & Stokkermans, 2020).

To analyse the technological performance of FPV, a model comparing the performance of a freshwater FPV system with an LBPV system was developed in (Dörenkämper et al., 2021a). In (Vido, 2022) a model was created to compare the technological performance of offshore FPV with LBPV. Both models indicate that the FPV system generates slightly more electricity than the LBPV system in the Netherlands (3% for freshwater, 8.8% for offshore) (Dörenkämper et al., 2021a; Vido, 2022).

To assess the environmental impact of freshwater FPV multiple literature studies have been conducted such as (Armstrong et al., 2020; DELTARES, 2020). In addition, three case studies have been conducted in the Netherlands to analyze the effect of the system on the water quality (Bax et al., 2023; R. L. P. de Lima et al., 2021; Ziar et al., 2021). Furthermore, in 2018, Deltares, in collaboration with Delft University, developed the Delft 3D model. This model evaluates the effect of installing a freshwater FPV system on water quality for different FPV system designs and various characteristics of the water body.(DELTARES, 2020). Two model studies have been conducted in the Netherlands to evaluate the environmental impact of offshore FPV's (Karpouzoglou et al., 2019; Wezeman, 2022).

The findings from these studies have identified two primary environmental benefits of FPV systems. Firstly, these systems create underwater surfaces that promote the colonization of mussels (Armstrong et al., 2020). Secondly, the studies have revealed that FPV systems effectively reduce the levels of toxic cyanobacteria, leading to an improvement in water quality.

(DELTARES, 2020). The main environmental disadvantage of FPV systems is their light-blocking effect, which hampers photosynthesis, which in turn limits the growth of algae and aquatic plants (Jones & Armstrong, 2021). Another often mentioned disadvantage for freshwater FPV is the decreased oxygen content under the FPV systems (Armstrong et al., 2020; de Rijk et al., 2022). From the literature also

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[1] Agriculture PV is the the simultaneous use of areas of land for both solar photovoltaic power generation and agriculture.[1]

becomes clear that environmental impacts of the FPV systems are context specific and depend i.e. on the dimensions and design of the FPV system in relation to the size of the water body surface, as well as on climatic conditions and the water quality of the lake before installation (Bax et al., 2023; R. L. P. de Lima et al., 2021; Ziar et al., 2021).

Because FPV systems are a newly developed technology, there is currently a significant knowledge gap regarding their technological performance and environmental impacts. Current literature uses models to evaluate the technological performance of freshwater FPV systems. However, for more accurate assessment, analyzing data collected directly from the panel's measurements is needed. Additionally, the mentioned environmental effects of FPV systems are predominantly determined based on expectations and models. Currently, there are still too few studies that analyze the effects of an FPV system on the environment using data (R. L. P. de Lima et al., 2021). Furthermore, little is known about the effect of the aforementioned context-specific factors on the environmental effects of an FPV system. Additionally, all studies done about the technological performance and environmental impact of FPV systems focus on either freshwater or offshore FPV systems. An overview of both technologies is missing.

These literature gaps are translated in the following research question:

What are the technological and environmental advantages and disadvantages of freshwater FPV and offshore FPV in the Netherlands?

In absence of field observations with FPV systems in the offshore environment no data are is available to evaluate their environmental and technological performance (Soppe et al., 2022). Therefore, this thesis primarily focuses on freshwater FPV.

To evaluate the technological and environmental advantages and disadvantages, first a case study is conducted by assessing the impact of the FPV system on a lake. Thereafter, the relationship between weather conditions and the technological performance and environmental impact, as well as the correlation between different environmental effects, were evaluated. This is important to gain a better understanding of how the technological performance and environmental impact changes for different type of system designs and locations in the Netherlands. Besides, it provides a better understanding of the indirect environmental impacts of the FPV system.

This results in the following sub-research questions:

- What are the technological advantages and disadvantages of freshwater and offshore FPV systems for a case study in the Netherlands?
- What are the environmental advantages and disadvantages of freshwater and offshore FPV for a case study in the Netherlands?
- What is the effect of the context specific parameters on the technological and environmental advantages and disadvantages of FPV in the Netherlands?

For offshore FPV, the case study was conducted for the North Sea, which is the only offshore FPV location in the Netherlands. The case study for freshwater FPV focused on a FPV system situated on a lake in Oudehaske. This particular lake was selected due to the available data regarding the system's technological performance and environmental impact.

The data for this research is provided by Deltares, an independent knowledge institute specializing in water and subsurface research (Deltares, n.d.). Deltares initiated the ZWIMP (Zon op water: impact op waterkwaliteit en biodiversiteit) project because there is a need for more knowledge about the environmental effects of the FPV system. Additionally, this project was established to gain more knowledge about how the environmental effects of an FPV system can vary for different designs and locations (Deltares, 2018).

To facilitate the broader implementation of FPV systems, it is crucial to enhance our understanding of their environmental impacts, both positive and negative. With increased knowledge, we can refine the design to amplify the positive environmental effects while minimizing or mitigating the negative ones. This approach lays the foundation for the large-scale implementation of the system. Furthermore, gaining a deeper understanding of FPV systems offers valuable insights into their limitations and highlights key areas for future research.

The models currently used to evaluate the impact of the FPV system on the environment are based on numerous assumptions, which can be improved through the conducted data analysis in this study (DELTARES, 2020). With better models, a more accurate determination can be made by permitting authorities such as researchers, policymakers, private developers regarding the implementation optimum size and layout of the FPV system with little to no impact on the water quality and living environment. Besides, better models make it possible to prevent water quality issues that could lead to, for example, imbalanced oxygen levels and the subsequent loss of aquatic life. Especially when dealing with water bodies that are used for recreation, these negative effects could have high economical and societal relevance (R. L. P. de Lima et al., 2021).

2. Theoretical background

In order to fully understand the environmental and technological advantages and disadvantages of a FPV system, knowledge of certain theoretical concepts is required. These concepts will be explained in the following paragraphs.

2.1 Historical implementation FPV

The first freshwater FPV installation was deployed in 2007 in Japan (Gorjian et al., 2021). Thereafter, freshwater FPV applications expanded globally, with most installation located in Asia (Cazzaniga & Rosa-Clot, 2020). The worldwide capacity is already more than 1 GW (Jones & Armstrong, 2021)

Freshwater FPV is already a commercially deployed system in the Netherlands. The first installations in the Netherlands were installed in 2017 and in 2021 the cumulative capacity is almost 190 MWp (Kroon, 2022). More than 90% of the installations are installed by the company 'Groenleven'. In Figure 1, the cumulative capacity of freshwater FPV in the Netherlands between 2017 and 2021 is shown.

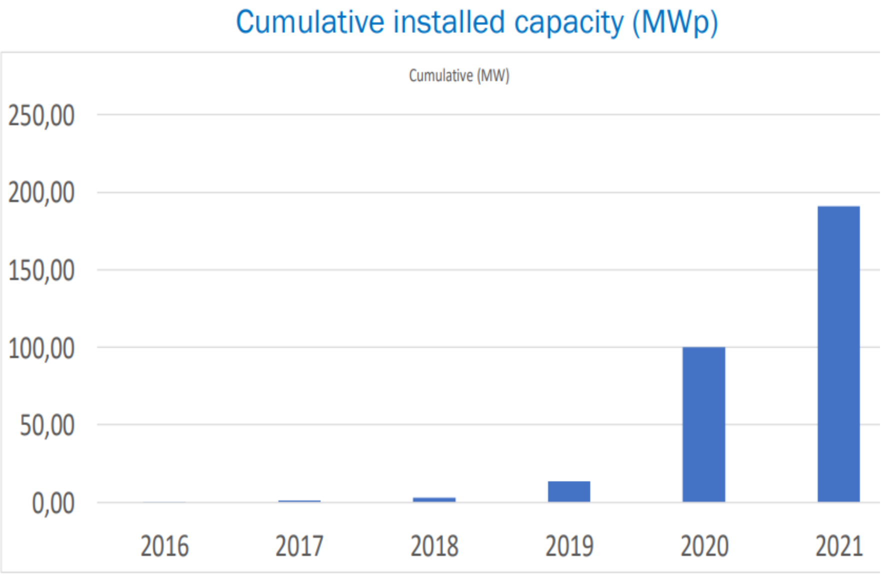

Figure 1: Cumulative capacity freshwater FPV in the Netherlands between 2016 and 2021 (Kroon, 2022)

In Figure 2 the location, capacity and year of installation of all freshwater FPV installations within the Netherlands is shown.

Figure 2: Location, capacity and year of installation of freshwater FPV in the Netherlands (Groenleven, 2022)

Offshore FPV is a newer technology. More than 50% of the entire population lives within 100 km of an oceanic shore and an offshore FPV system can be located to supply energy to these regions (Golroodbari & van Sark, 2020). In 2019, the first pilot of an offshore solar farm was installed on the North Sea by Oceans of Energy (Soppe et al., 2022). The design of offshore FPV is more challenging than the design of freshwater FPV because of stronger winds, higher waves and the presence of tides in the offshore environment (Karpouzoglou et al., 2019). Right now only prototypes and demonstrators have been installed (Soppe et al., 2022).

2.2 Water quality assessment

In the Netherlands, water quality is assessed based on multiple physical and chemical water quality elements (STOWA, 2020). Six important physicochemical parameters are described for this project. **Error! Reference source not found.** provides an overview of these parameters, along with their definition and unit

Table 1: Overview of important physiochemical parameters and their definition and unit

Parameters[2]	Definition	Unit
Light intensity (kJ/(m^2*h))	Light intensity refers to the amount of light energy that is present in a particular area or space. It can vary depending on several factors, including the source of the light, the distance from the source, and any obstructions or filters that may be present (like PV cells) (BIOS, 2022). The light intensity in water is a combination of direct and diffuse light. Direct light refers to light that travels in a straight path from the source to the object without any significant scattering or diffusion. Diffuse light, on the other hand, is light that has been scattered or diffused by interacting with particles, objects, or surfaces (Li et al., 2015).	kJ/(m^2*h)
Chlorophyll	Chlorophyll is a pigment produced by algae and other photosynthetic organisms in water. Its concentration in water is an indicator of the level of primary productivity, which is the rate at which plants and algae are growing and producing organic matter through photosynthesis (EPA, 2022).	µg/l
Turbidity	Turbidity is a measure of water clarity. It describes the amount of light scattered or blocked by particles floating in the water. In rivers and lakes, these particles can come from phytoplankton and other plant material, soils, silt and clay (DataStream, 2023d)	NTU
Corrected electrical conductivity Us/cm	Electrical conductivity is a measure of a material's ability to conduct an electrical current. The conductivity of water is temperature-dependent because temperature affects the mobility of ions in water, therefore, to make meaningful comparisons of water conductivity data across different temperatures, it is necessary to correct for temperature variations. The standard temperature at which water conductivity is typically reported and compared is 25°C. Therefore, the measured conductivity is corrected to this value. In Appendix A, it is shown which formula was used for this temperature correction. (DataStream, 2023a)	Us/cm
Dissolved Oxygen (DO)	DO is the total amount of oxygen dissolved in the water.	Mg/l
Temperature	Water temperature refers to the degree of warmth or coldness of water (Datastream, 2023).	°C

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[2] Next to these parameters the SDO and pH were evaluated as well. However, no relevant changes were seen between open water and the FPV. In Appendix C the SDO and pH are discussed as well.

2.3 Effect ecosystem

To evaluate the impact of the FPV system on the ecosystem, particular attention will be to the phytoplankton, aquatic plants, macro-invertebrates and fish. The reason for focusing on these groups is rooted in the "Kader Richtlijn Water" implemented in the Netherlands, which mandates that European freshwater bodies must meet specific chemical and biological standards (STOWA, 2020). These standards place emphasis on the aforementioned groups.

Phytoplankton form the foundation of the food web, as these microscopic plants provide energy for all other organisms in the ecosystem. Due to this critical role, they are a vital component of a lake's food web, serving as the primary food source for zooplankton and prey fish (STOWA, 2020). There exist two different groups of phytoplankton, algae (wanted) and cyanobacteria (unwanted). Algae are important for the food web and the ecosystem because they serve as food for other organisms. The other type of phytoplankton are the cyanobacteria. Certain varieties of cyanobacteria can produce toxins that are linked to illness in humans and animals (Los, 2009). To produce energy and be able to grow, phytoplankton utilize light through the process of photosynthesis (Los, 2009). The amount of light that phytoplankton needs for its growth varies by species. Cyanobacteria are less dependent on light to grow than algae (Los, 2009).

Aquatic plants form the basis of a healthy lake. They provide shelters for various organisms, including macrofauna and fish (STOWA, 2020).

Macroinvertebrates are invertebrates that reside at the bottom of a lake or on underwater structures that spend at least part of their lives in water. Examples are insects in their nymph and larval stages, snails, worms, crayfish, and mussels. They serve as important indicators of water quality. They feed on plankton and other small organisms by filtering the water that passes through. This process not only extracts nutritious elements from the water but also eliminates potentially harmful particles such as silt and bacteria, thereby they purifying the water (STOWA, 2020).

The fish population is another important indicator of ecological water quality for surface waters. DO and conductivity can have a substantial impact on the fish population in a lake. If the DO concentration of a river or lake is too low, fish may leave the area, suffocate or even die. Every species of fish requires a different amount of DO to survive. When the oxygen concentration is between 0 and 4 mg/l, generally no fish species can survive. Some species can survive at an oxygen concentration between 4 and 6.5 mg/l, while most fish can live at oxygen concentrations between 6.5 and 9.5 mg/l. All fish species can live at oxygen concentrations above 9.5 mg/l (DataStream, 2023b). Lakes that support good populations of freshwater fish have conductivities in the range of 150 to 800 µs/cm. Conductivities outside of this range tend to be unsuitable for some species of fish (DataStream, 2023a).

2.4 Technological advantages and disadvantages

When assessing the technological performance of an FPV system, most of the studies conclude that FPV systems have an improved energy yield compared to LBPV systems (Gorjian et al., 2021; Jones & Armstrong, 2021; Vido, 2022). The main reason given for this is a lower cell temperature since a lower temperature results in an increased output voltage and with that an higher energy yield and CF. Usually, the performance of monocrystalline solar cells increases by ~0.4% for each degree the temperature of the panel decreases (Dörenkämper et al., 2021b), however this value is a function of the cell technology. The cell temperature of a PV panel is determined by several factors, such as incident solar radiation, ambient temperature, wind speed, wind direction and properties of the cell materials and assembly (Dörenkämper et al., 2021b), The cell temperature of an FPV system is lower than the cell temperature of an LBPV system. This is due to two main reasons. Firstly, the air temperature above water is colder than the temperature above land. This is because, for land- or rooftop-based systems, most of the net radiation is used for transferring heat to the surroundings. On water, a significant portion of radiation is used for evaporation. Besides, the specific heat of water is higher than that of land. Secondly, the windspeed over waterbodies is usually higher than the windspeed over land, which is because water has a smoother surface compared to land which leads to less frictional drag on the moving air. As the wind speed increases, heat will be released from the PV cells which decreases the cell temperature (Gökmen et al., 2016).

3. Method

This section discusses the methods used to investigate the environmental advantages and disadvantages of FPV systems. The first paragraph describes the study site of Oudehaske. Afterwards, an overview is provided of the sub-questions and how they will be addressed. Finally, the four research methods used in this study are further explained.

3.1 Study site Oudehaske

The floating solar park in Oudehaske is located in the Dutch province “Friesland” and has a surface area of approximately 31 hectares (Dienst Publiek en Veiligheid, 2018). The lake is equipped with an FPV system consisting of 17,280 solar panels with a total cumulative capacity of 6.65 MWp. Each panel has a surface area of 2.04 m^2, resulting in a total surface area of the FPV park of 3.525 hectares. The FPV park covers 11.4% of the total area of the lake. As the lake is artificial (sandpit) it provides the ideal site for screening and assessing potential impacts before expansion to more sensitive locations. In Figure 3 the lake, the FPV system of Oudehaske and the two measurement locations (the blue points) are shown (Eijkelkamp Soil & Water, 2021).

Figure 3: FPV system and sensors Oudehaske. In the left picture the part of the lake with the panels are shown. The right picture shows the entire lake with the FPV panels (pink rectangle) and the measurement locations (blue dots).

3.2 Overview method

In this section, the approach used to answer all the sub-questions will be explained.

Offshore FPV

As mentioned before, field observations with FPV systems in the offshore environment are missing. Therefore, there is no data available to evaluate their technological and environmental performance. Hence, this thesis primarily focuses on freshwater FPV. To evaluate the technological and environmental advantages and disadvantages of offshore FPV, a brief literature review supplemented with expert interviews was conducted.

Freshwater FPV

The method for freshwater FPV will be briefly explained for each sub-question. First technological advantages and disadvantages of the FPV system have been evaluated. Current literature uses models to evaluate the technological performance of freshwater FPV systems. However, for more accurate assessment, this research has analysed technological data of the windspeed, cell temperature and energy yield directly collected from the panels in Oudehaske.

Afterward, a model of a LBPV system is created for a system in the same location, featuring identical size and solar panels. Using this model, the power output, cell temperature and wind speed were simulated and compared to those of the FPV system. Additionally, a literature review was conducted to explore the technological advantages and disadvantages associated for the freshwater system.

In Figure 4 the method of evaluating the technological advantages and disadvantages of FPV systems in the Netherlands is shown. Grey circles are the input data, orange diamonds are research methods, green squares are results of freshwater FPV, blue squares are results for offshore FPV and purple circles are the sub-research questions.

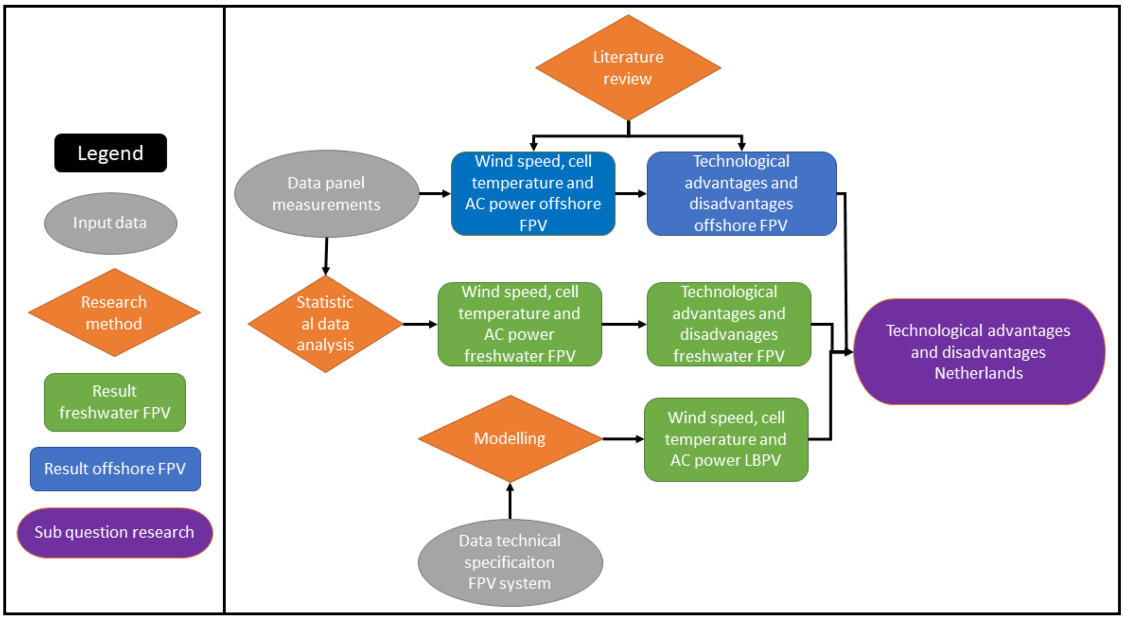

Figure 4z; Method of how the technological advantages and disadvantages of freshwater FPV and offshore FPV are determined in this research. Grey circles are the input data, orange diamonds are research methods, green squares are results of freshwater FPV, blue squares are results for offshore FPV and purple circles are the sub-research questions

Subsequently, the environmental advantages and disadvantages of the FPV system in Oudehaske were determined validating or improving previous assumptions and models about the effects of FPV on the environment in the Netherlands.

The evaluation initially focused on the effects of the FPV system on physiochemical parameters. This is important because these parameters can either improve or worsen the habitat of organisms living in the water body (Landis et al., 2003). Only the species groups that are most important for the KRW have been considered for this project. These include phytoplankton, aquatic plants, macroinvertebrates, and fish (see Section 2.3 for further explanation). When the change in the physiochemical parameter by the FPV system lead to an improvement in the habitat of any of these species, it is considered an environmental advantage of the FPV system. Conversely, when the change in the physiochemical parameter worsens the habitat, it is regarded as an environmental disadvantage of the system.

In the case of the FPV system in Oudehaske, the impact on phytoplankton and fish is the primary concern. Aquatic plants typically don't thrive beyond six meters depth, and since the lake depth beneath the FPV system ranges from 15 to 30 meters, it's unlikely for water plants to grow beneath it. (Wageningen University & Research, 2011). Macroinvertebrates are primarily sensitive to low oxygen levels, but the deep parts of M20 type lakes harbor species that are tolerant to such conditions (STOWA, 2020).

The FPV system can also have effects on the environment that are not related to the measured parameters. To assess these effects, a literature review has been conducted.

In Figure 5 the method of evaluating the environmental advantages and disadvantages for Oudehaske is shown. Grey circles are the input data, orange diamonds are research methods, green squares are results of freshwater FPV, blue squares are results for offshore FPV and purple circles are the sub-research questions.

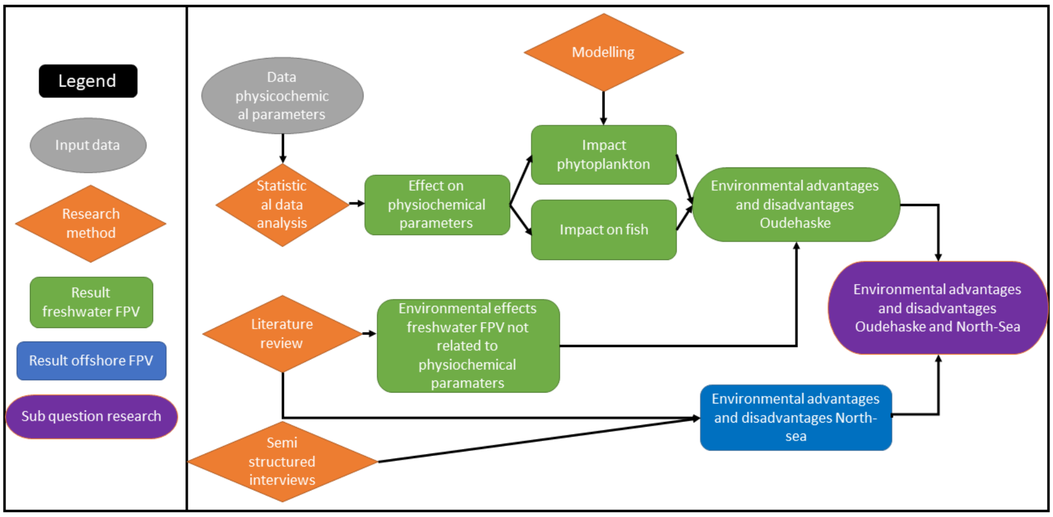

Figure 5: Method of how the environmental advantages and disadvantages of the case studies are determined in this research. Grey circles are the input data, orange diamonds are research methods, green squares are results of freshwater FPV, blue squares are results for offshore FPV and purple circles are the sub-research questions.

The environmental impact of FPV systems depends on a variety of site-specific factors as the size and depth of the lake, the coverage percentage of the FPV system and the water quality before the installation of the FPV system (Armstrong et al., 2020; DELTARES, 2020). To gain a better understanding of how the environmental impact changes under different conditions, the relationship between weather conditions and water quality parameters, as well as the correlation between different water quality parameters, were evaluated. This analysis is based on a literature review and the data of physiochemical parameters collected in Oudehaske. Furthermore, a literature review has been conducted, summarizing the findings of other case studies in the Netherlands that have assessed the environmental impact of FPV systems.

In Figure 6 the method of evaluating the environmental advantages and disadvantages for a case study of a FPV systems in the Netherlands is shown. Grey circles are the input data, orange diamonds are research methods, green squares are results of freshwater FPV, blue squares are results for offshore FPV and purple circles are the sub-research questions.

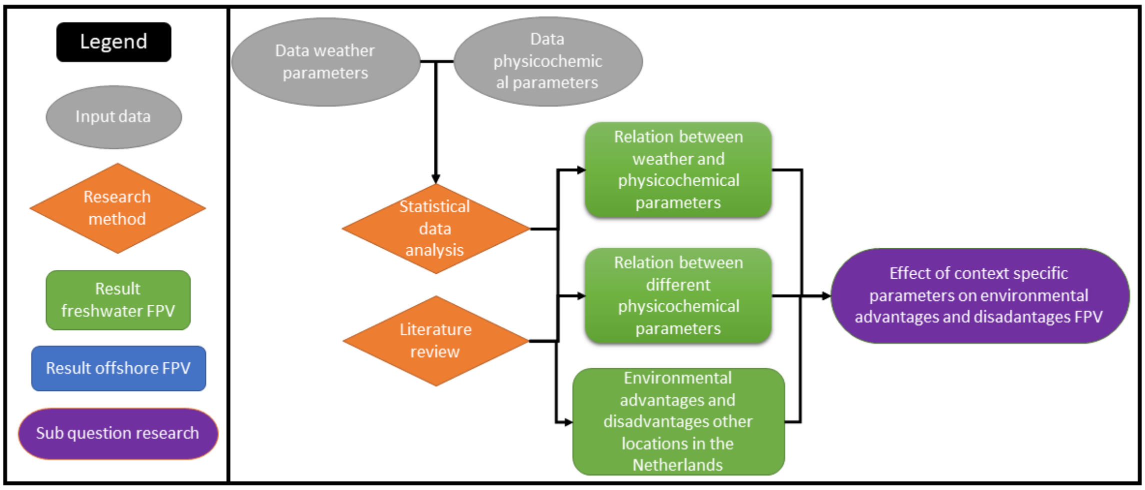

Figure 6: Method of how the environmental advantages and disadvantages of the case studies are determined in this research. Grey circles are the input data, orange diamonds are research methods, green squares are results of freshwater FPV, blue squares are results for offshore FPV and purple circles are the sub-research questions.

Based on the understanding of technological and environmental advantages and disadvantages in Oudehaske and the North-sea, including the influence of contextual factors, a conclusion has been formed regarding the advantages and disadvantages of freshwater and offshore FPV systems in the Netherlands.

Four different research methods were employed for this study. These included semi-structured interviews, literature review . statistical data analysis and modelling. Table 3 provides an overview of which research methods were used for each research objective. In the next chapters each of these methods will be discussed separately.

Table 2: Research objective, technology and used methods for the objective

Research objective	System	Used methods
Evaluate environmental advantages and disadvantages	Freshwater FPV	Literature review + statistical data analysis + modelling
	Offshore FPV	Literature review + 2 semi-structured interviews
Evaluate effect of context specific parameters	Freshwater FPV	Literature review + statistical data analysis
Evaluate technological advantages and disadvantages	Freshwater FPV	5 semi structured interviews + statistical data analysis + modelling
	Offshore FPV	Literature review

3.3 Semi structured interviews

The first research method used are semi-structured interviews. These interviews were used to gather more information about the technological performance of freshwater and offshore FPV, as well as the environmental impact of offshore FPV.

For the technological analysis 5 experts in the field of FPV were interviewed. These interviews are used as an input to decide which of the mentioned differences between an FPV and LBPV system are most relevant for further investigation.

Additionally two semi-structured interviews were conducted about the expected environmental advantages and disadvantages of offshore FPV. The interview questions are presented in Appendix H

All interviewees are presented in Table 4.

Table 3: Interviewed people with corresponding company or university and research topic

Interviewee	Company/University	Technological/environmental
Hesan Ziar	Technological University Delft	Technological
Willem Biesheuvel	Groenleven	Technological
Sara Mirbagheri Golroodbari	Utrecht University	Technological
Paula van Lieshout	Solar Duck	Technological
Marco Huisman	TNO	Technological
Johan van der Molen	NIOZ	Environmental
Luca van Duren	Deltares	Environmental

3.4 Literature review

The second research method used to determine the environmental and technological advantages and disadvantages is a literature review. This literature review was conducted for five different purposes.

Firstly, this literature research was conducted to obtain a comprehensive understanding of all environmental advantages and disadvantages in Oudehaske.

Secondly, a literature review was conducted to assess whether the impact of the FPV system on physiochemical parameters is consistent across all locations in the Netherlands or if there are variations due to context-specific factors. To evaluate this, Dutch data analyzing studies that investigated the effect of FPV systems on physiochemical parameters are review. The studies considered context-specific factors such as the size of the FPV system, the water depth, and the location of the FPV system. The context specific parameters and the effect of the FPV system on the physiochemical parameters are summarized.

Thirdly, a literature review was conducted to analyse the expected relations between the effect of a freshwater FPV system in the Netherlands on the physiochemical parameters, the effect of the weather on the physiochemical parameters and the relation between different physiochemical parameters in Oudehaske. Based on this review, a comprehensive figure was created to illustrate the anticipated relationships between the FPV system, weather conditions, and various physicochemical parameters. This figure provides insights into whether the relationships are positive, negative or can be both.

Fourthly, to evaluate the potential of offshore FPV in the North sea, a mathematical model was developed in (Vido, 2022). The model simulated the technological performance of a 100 MWp system and compared it with a LBPV system in the Netherlands. Among other things the wind speed, operating cell temperature, annual energy yield were evaluated. The results of this study are summarised. This will be complemented by a summary of the report TNO has written in the beginning of 2022 about the challenges and opportunities for offshore solar in the Netherlands (TNO Wim Soppe et al., 2022).

Lastly, a literature review was conducted to gain a comprehensive understanding of the current knowledge regarding the technological performance of freshwater FPV systems in the Netherlands, as well as for the environmental effects of offshore FPV systems in the country.

All research objectives, used search terms, and the ultimately selected literature are presented in Table 5. In Appendix G a summary of the relevant information, the publication year and the references of all revied articles are represented.

Table 4: Research objective, search term and selected literature of all literature reviews done for this project

Research objective	Used keywords google scholar	Selected literature
Find environmental advantages and disadvantages of the FPV system not related to the measured physiochemical parameters in Oudehaske	"FPV" and "environment" or "ecosystem" or "water quality" and "Floating solar" and "environment" or "water quality" or "ecosystem"	(Armstrong et al., 2020; DELTARES, 2020; Gorjian et al., 2021; Jones & Armstrong, 2021; Pimentel Da Silva & Branco, 2018).
Compare physiochemical parameters with results of Oudehaske	"FPV" and "environment" or "ecosystem" or "water quality" and "Floating solar" and "environment" or "water quality" or "ecosystem"	(Bax et al., 2023; de et al., 2021; Ziar et al., 2021).
Evaluate environmental advantages and disadvantages offshore solar	"FPV" and "environment" or "ecosystem" or "water quality" and "Floating solar" and "environment" or "water quality" or "ecosystem"	(Karpouzoglou et al., 2019; Nurmi & Mcdonald, 2022; Wezeman, 2022)
Evaluate technological advantages and disadvantages freshwater and offshore FPV	Freshwater: "FPV" and "technological" or "technology" or "efficiency" and "Floating solar" and "environment" or "water quality" or "ecosystem"	(Kjeldstad et al., 2021)
	Offshore	(Soppe et al., 2022; Vido, 2022)

3.5 Statistical data analysis

The third research method used to determine the environmental and technological advantages and disadvantages in the Netherlands is statistical data analysis. The analysis serves four main purposes. Firstly, it evaluates the data on the technological performance of FPV systems. Secondly, it assesses the average impact and the impact over time on the physiochemical parameters. Thirdly, it quantifies the impact of reduced DO on fish. To conduct this analysis, data on the technological performance and measured physiochemical parameters is first collected. Lastly, the correlation between the weather parameters and the different physiochemical parameters is evaluated.

3.5 1 Data collection

The required data for this analysis has been collected in three different manners.

First, data has been obtained via Deltares for the six physiochemical parameters light intensity, chlorophyll, turbidity, conductivity, DO and water temperature. These parameters were measured by at two locations in the lake. The first location is in the middle of the FPV system, and the second location in open water. The distance between these locations is approximately 340 meter (GPS coordinates, 2023). The data was collected between July 14 and January 31. For the reference measurements outside the FPV park, the probe and has been placed under a buoy at a depth of 1 meter below the water level. The time resolution of the sensors is one hour.

To measure the water temperature, conductivity and DO a AP6000 multiparameter probe from Aquaread was used. On the probe, additional optical sensors have been installed to measure the chlorophyll concentration and turbidity. The sensor for chlorophyll is a fluorometer that emits blue light, which the chlorophyll absorbs and after that emits red light. The turbidity sensor uses a nephelometric technique that utilizes formazin as a reference standard (Eijkelkamp Soil & Water, 2021). The light intensity is measured using a LiCOR radiation sensor (LI-192). The LI-192 uses a silicon photodiode and an optical glass plate filter to create a nearly uniform sensitivity to light between 400 and 700 nm, which corresponds to the light used by most plants and algae.

For the measurements under the floating solar park, an HDPE pipe is attached to the floater of the FPV system. The probe is placed inside this pipe. The light intensity sensor is attached to a metal frame that hangs in the water. Both probes are placed at a depth of 1 meter below the surface water level. All probes are equipped with a brush that cleans the probes. In Table 6 an overview of the measured physiochemical parameters, type of probe/sesnor, period of data analysation and total analysed hours is shown.

Table 5: Overview of physiochemical parameters, type of probe, period of data analysation and total analysed hours

Physiochemical parameters	Probe (time resolution is 1 hour)	Period of data analysation	Total analysed hours
Light intensity	LiCOR radiation sensor[3]	July 14 – January 31	2253
Chlorophyll	AP6000 + optical sensor	July 14 – September 15	1503
Turbidity	AP6000 + optical sensor	July 19 – November 29	3197
Corrected electrical conductivity	AP6000	July 14 – January 31	4831
Dissolved Oxygen	AP6000	July 14 – January 31	4831
Temperature	AP6000	July 14 – January 31	4831

Secondly, to evaluate the relation of weather variables with physiochemical parameters, weather data from the nearest KNMI weather station has been used. This KNMI station is located in Leeuwarden, which is approximately 35 km from the FPV system in Oudehaske. Data on the total Global Horizontal Irradiance (GHI), air temperature, wind speed and precipitation has been downloaded for each hour during the same period as the ecological data from Oudehaske.

Lastly, the technological interviews revealed that the primary focus was on investigating the energy yield during the analyzed period. However, it is also intriguing to compare the cell temperature and wind speed between the FPV and LBPV systems. This can help analyse whether the difference in cell temperature and wind speed is the reason for the difference in energy yield or whether other factors also play a role. Therefore the supplier of FPV systems Groenleven have been asked to provide this data. Groenleven monitors hourly data of the total nominal Alternating Current (AC) power, cell temperature and wind speed with sensors, which are placed on the transformer(s) of the system at an estimated height of 2.5 meters. Active AC power refers to the portion of the total power in an alternating current (AC) circuit that is being used to perform useful work (Kjeldstad et al., 2021).

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[3] : This sensor can only measure light with a wavelength between 400 and 700 nm. For the energy yield calculations irradiation of the closest KNMI station will be used

For the data collection, hourly data were retrieved starting from 14-07-2022 at 17:00 until 31-01-2023 23:00. In total, these comprise 202 days and 4831 hours. Chlorophyll data were only available from July 14 to September 17 (64 days and 1503 hours in total). Turbidity data were only available from July 19 to November 29 (134 days and 3197 hours in total). For the analyses of light intensity and irradiation, only the hours when sunlight was present were selected. This is a total of 2253 hours.

For the data analysis, all data was pre-processed. For a few days during the measurement period, the sensors were either non-functional or undergoing maintenance. For these days, the averages were calculated based on the surrounding days. Subsequently, an outlier check was performed on the dataset, but no outliers were found.

3.5.2 Technological data analysis

The technological data analysis is used to compute the windspeed, cell temperature energy yield and CF of the FPV system of Oudehaske.

As mentioned in section 1.1 the hourly windspeed of the FPV system at a height of 2.5 meter is provided by Groenleven. To compare this wind speed with the wind speed of a LBPV system, data from the nearest KNMI station was used. This station measures this wind speed at a height of 10 meters. To convert this speed to wind speed at a height of 2.5 meters, the wind power law was used. The wind profile power law is a formula that relates the wind speeds at different heights. It can be expressed as:

$$u = u_r(\frac{z}{z_r})^a$$

where u is the wind speed (in m/s) at height z (in m), and u_r is the known wind speed at the reference height. The exponent α is an empirically derived coefficient and depends on how stable the atmosphere is. When the atmosphere is stable, α is roughly equal to 1/7.

As stated in Section 2.4, it is expected that the cell temperature of the FPV system is different from the LBPV system. To evaluate if this is also the case for Oudehaske, the average cell temperature has been calculated. The cell temperature of the FPV system in Oudehaske is measured with three sensors at different locations on the FPV system in Oudehaske. To determine the cell temperature of the FPV system, the average of these three measurements was taken.

Using the AC power output of the FPV system for each hour, the average electricity output per month can be calculated by:

$$Etot_{s,m} = \frac{\sum_{i=0}^{t} P_{ac,final}}{10^3}$$

Where s is the system (in this case the FPV system), m is the month, t is the number of hours for the specific month.

The actual performance of solar panels can be evaluated by different metrices. For this thesis the Capacity Factor (CF) has been computed. The CF is the ratio between the total output and the nominal output of a panel (Marion et al., 2005). It is computed by:

$$CF_{s,m} = \frac{E_{tot,s,m}}{\sum_0^t P_{ac0,s,m}} * 100\%$$

Subsequently the total electricity output and average CF of the LBPV and FPV systems is determined by:

$$Etot_s = \frac{\sum_0^t P_{ac,final}}{10^3}$$

$$C_{F,s} = \frac{Etot_s}{\sum_0^t P_{ac,final,s}}$$

Where $Etot_s$ is equal to the total electricity output between 14 July and 31 January in GWh, $P_{ac,final}$is the obtained hourly AC power, t is the number of hours measurements were taken (4280 hours), and $C_{F,s}$ is equal to the average capacity factor between 14 July and 31 January.

3.5.3 Environmental data analysis

For an overview of the impact of the FPV system on the different physiochemical parameters first the mean of the parameters in open water and underneath the FPV system for the entire measurement period:

$$P_{l,mean} = \frac{\sum_{i=0}^h V_{l,i}}{h}$$

Where l is the location (open water or under the FPV system), P is the mean value of the physiochemical parameter in the measurement period at location l, V is the value of the environmental parameter at location l, and h is the number of hours.

Thereafter the relative change of the physiochemical parameters by the FPV system is determined by:

$$\Delta P = \frac{P_{FPV} - P_{open}}{P_{open}}$$

Where ΔP is the relative change of the physiochemical parameter in %.

The differences in measured value of the physiochemical parameters between open water and the FPV system are not constant throughout the entire period. For a fair data analysis and further discussions, it is essential to investigate the variation of these physiochemical parameters over time. For this analysis, the average value of each parameter is calculated for each day of the measurement period. To determine the average value of the light intensity for each day the hours without sunlight irradiation are excluded. For the other parameters the average of 24 hours measurements is taken. To analyse the impact over time, time plots are made. Besides, the values and day of the minimum and maximum effect of the FPV system in open water and under the FPV system are displayed. To quantify whether the effect of the FPV system remains constant over time or varies significantly, the correlation was determined between the values of the physiochemical parameters in open water and those under the FPV system.

This was done by calculating Pearson's correlation coefficient (r)[4]. The correlation coefficient evaluates the linear relationship between two parameters (in this case the value of the physiochemical parameter in open water and the value of the physiochemical parameters under the FPV system). A positive Pearson's r indicates a positive relationship between the parameters, whereas a negative

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[4] For this report, the Pearson's r has been calculated multiple times to determine the correlation between different parameters. However, the r-squared value is also used here. In Appendix F, the meaning, relevance, and values of the r-squared are provided for all cases where the Pearson's r has been used in this report.

Pearson's indicates a negative relationship. The magnitude of the linear relationship is determined by the absolute value of Pearson's r. An absolute Pearson's r below 0.3 indicates little or no linear relationship, whereas a value between 0.3 and 0.7 suggests a moderate linear relationship. An absolute Pearson's r above 0.7 indicates a strong linear relationship between the variables (Moore et al., 2012). When there is a strong linear relationship between the parameters in open water and under the FPV system, a linear regression equation is established as it can accurately estimate the effect of the FPV system on the parameter (Investopedia, 2023). This equation that can be used to make predictions about the effect of the FPV system on the physiochemical parameters at other locations To determine the Pearson’s r and regression line of the parameters, the scikit-learn Python package was used (Pedregosa FABIANPEDREGOSA et al., 2011).

Correlation physical chemical parameters

Thereafter the relation between the effect of the FPV system, weather variables and the physiochemical parameters and the relation between different physiochemical parameters in Oudehaske is evaluated. This is accomplished by calculating Pearson's r between the weather parameters as well as between the various physiochemical parameters. Again, when Pearson’s r is higher than 0.7 a linear regression equation is established. Also for these relationships a Pearson’s r above 0.7 indicates a strong linear relationship so for these relationships a linear regression equation is established. Besides, time plots and scatterplots of the relevant relationship between the weather parameters and physiochemical parameters and between several physiochemical parameters are created to evaluate the effect they have on each other.

Impact fish

To assess the influence of the FPV system on the fish population, the average DO is determined for open water and under the FPV system. Based on the DO there is determined for how many days during the monitoring period it is sufficient for all fish, most fish, few fish, and no fish to survive. Additionally, it has been determined if and how many of the measured conductivity values are higher than 800 µs/cm or lower than 150 µs/cm.

3.6 Modelling

The fourth research method used to determine the technological and environmental advantages and disadvantages in the Netherlands is modelling. The modelling is used for two main purposes. Firstly, it is used to compare the technological performance of the freshwater FPV system with the performance of a LBPV system. Secondly, a model is created to evaluate the effect of the decreased light on the algae and cyanobacteria separately.

3.6.1 Model LBPV system

In this section, the methodology used to develop the LBPV model, which shares the same technological characteristics and location as the FPV system in Oudehaske is elaborated on. The model was employed to compute various parameters for the LBPV system, including wind speed, cell temperature, annual energy yield, and CF.

To develop this model the supplier of the FPV system Groenleven has provided data about the size, materials, type of modules and type of inverters of the FPV structure. The technological specifications of the modules and inverters have then been taken from the technology sheets of those specific modules/inverters (ENF, 2023; HUAWAI, 2020).

In Oudehaske the float system of Zimmerman PV-floating (ZIM) is used (Biesheuvel of GroenLeven BV, personal communication, 09-03-2023). The pontoons of the system are made from high-quality multilayered HDPE. The system uses a steel mounting structure. This mounting structure has a special magnelis coating to be less corrosive (Zimmerman, 2023). The cables of the FPV system are all located above the water surface and are integrated into the structure in special cable ducts or embedded in the frame. The only cable that goes under water to the land is the medium voltage cable. This cable is already fully insulated and is also integrated in a HDPE pipe that floats on the water. The panels of the system are composed of monocrystalline (Biesheuvel of GroenLeven BV, personal communication, 09-03-2023).

The exact efficiency of the inverter is not known. However, efficiency curves of the inverter is shown in the technology sheet of the inverter. This efficiency curves are shown in Figure 7. The operating voltage of the modules of Oudehaske is 480V, which is slightly lower than the operating voltages shown. Based on the operating voltage of 480V and the efficiency curve an average inverter efficiency of 97% is assumed for this inverter.

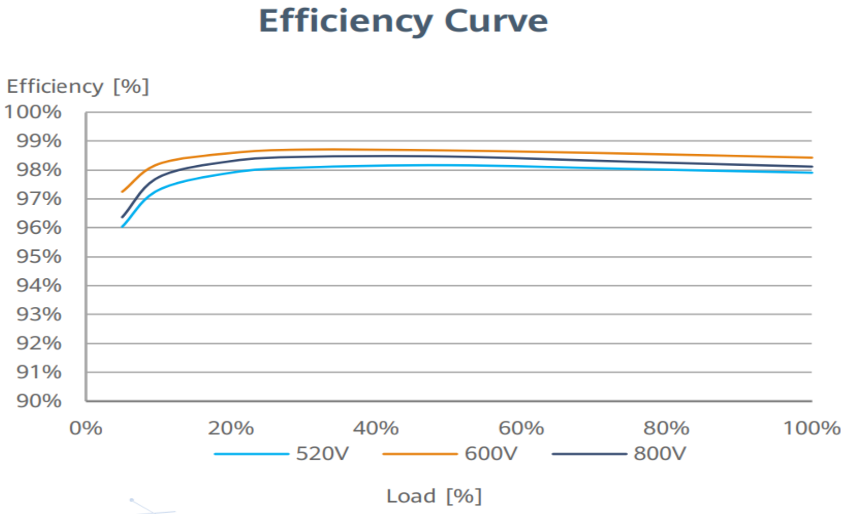

Figure 7: Efficiency curves of the Huawei 60 KTL-MV inverter for three different operating voltages (ENF, 2023)

All gathered information about the design of the FPV system, panels, and inverter is summarized in Table 7

Table 6: All data of the size, the modules and the inverters of the FPV system in Oudehaske

Technical specifications FPV system Oudehaske	
Total number of modules	17280
Capacity per module	385W
Module type	GCL-M3/72GDF
Module technology	Monocrystalline
Efficiency module	18.9%
Temperature coefficient of Voc	-0.3%/C
Tilt	11.1
Azimuth	East/West
Area per module	2.04 m^2
Operating voltage	480 V
Inverter type	Huawei 60 KTL-MV
Total number of inverters	80
Efficiency	97%
Inverter capacity	66000 W
Modules per string	18
String per inverter	12

To determine the cell temperature for the LBPV system, a Python model has been created. The system has been modelled for the same location and with the same technological specifications as the FPV system. The technological data obtained from Table 7 has been used for this purpose.

To determine the cell temperature for the LBPV system, the GTI must first be modelled. De GTI is de solar irradiance on the PV panels adjusted for angle of incidence losses, soiling and spectral mismatch (F. Holmgren et al., 2018). As mentioned in Table 7 the panels are east/west orientated. With different orientations the angle of incidence is different and the GTI will be different as well. So the first step was to generate the GTI for the east and for the west side panels. To determine the GTI, the package PVlib is used in python. This modelling tool is developed by Sandia National Labaratories in python and MATLAB to simulate the performance of PV systems (F. Holmgren et al., 2018). For this method first hourly data of the GHI from the 14th of July until January 31st is obtained from the closest KNMI station. Thereafter PVLIB has functions to compute the Global Total Irradiance (GTI). With the GTI available for both orientations, the cell temperature can be calculated. With PVLIB the cell temperature can be computed as well. For this temperature the effects of the GTI, air temperature, windspeed and the material and location of the panel are considered by PVLIB.

The Direct Current (DC) power of the LBPV model can be determined with the effective irradiance, temperature and the module parameters (F. Holmgren et al., 2018). The DC power output per m^2 of modules is determined by:

$$P_{dc,o} = \eta_{mod} \times \left[1 - C_t \times \left(T_{cell,o} - T_{STC}\right)\right] \times GTI_{a,o}$$

Where T_{STC} is the standard operating temperature of 25 °C. C_t is the temperature coefficient of the module which is equal to -0.03%/C. η_{mod} is the modules efficiency at the operating temperature which is equal to 18.9%.

All modules are connected to inverters which convert the DC power of the module into AC power (Marion et al., 2005). The AC output power of one inverter is then computed by:

$$P_{ac,o} = P_{dc,o} * Mi * A * \eta_{inv}$$

Where Mi is the number of modules per inverter which is equal to 216, A is the area of one module which is equal to 2.04 m^2 and η_{inv} is the efficiency of the inverter equal to 0.97. Subsequently, for each hour, it is verified whether the total output of the panels exceeds the capacity of the inverter. In the case of this system, this never occurs.

Next to the inverter losses, the LBPV system will have other losses such as shading, mismatch, wiring, AC wiring, connections, etc. According to Dobos, (2014), a land-based solar PV system has losses of approximately 14%, without accounting for the inverter losses (Dobos, 2014). In total the system consist of 80 inverters. So for each azimuth angle the number of inverters is 40. So the final AC power output is determined by:

$$P_{ac,final} = \sum_{i=0}^{i=1} n_{inv,o} * P_{ac,o} * 0.86$$

Where $n_{inv,o}$ is the total number of inverters and $P_{ac,o}$ is the AC output.

Once the AC power output is known, the performance can be determined in the same manner as done for the FPV system in Section 3.5.2.

3.6.2 Model phytoplankton

Secondly, a model is created which predicts the growth efficiency of algae and cyanobacteria based on the light intensities at open water and under the FPV system.

The effect of the FPV system on these species of phytoplankton is determined solely based on the light intensity. From the measured physiochemical parameters the light intensity and the temperature could influence the growth of the phytoplankton. However, from the literature becomes clear that the effect of the FPV system on the water temperature is small compared to the effect on the light intensity (Pimentel Da Silva & Branco, 2018).

To understand how phytoplankton grows, which types dominate, and to make future predictions about its quantity and composition of phytoplankton, the mathematical model BLOOM is often used (Los, 2009). This model calculates, among other things, the growth efficiency of the phytoplankton for different light intensities (Los, 2009). The growth efficiency is defined as the percentage of the maximal speed a species can grow. A growth efficiency of 100% indicates that there is sufficient light available for the phytoplankton to grow at its full speed. However, this does not mean that the species is growing at this speed, as other factors such as insufficient available nutrients or low water temperature can also hinder its growth (Reynolds, 2006).

The effects of the FPV system on phytoplankton have been assessed both at the water surface and at a depth of one meter. In order to determine the impact of the FPV system on phytoplankton in these specific areas, the light intensity was initially determined at these four locations. This was done in the following manner:

1. The light intensity at the water surface in open water was assumed to be equal to the hourly irradiance measured at the KNMI station of Leeuwarden.
2. The light intensity under the FPV system at the water surface is assumed to be equal to 10% of these values, because according to Groenleven, the panels allow approximately 10% of the incident light to pass through (Biesheuvel, personal communication, 13-02-2023).
3. The light intensity in open water and under the FPV system at a depth of 1 meter were measured by the LiCoR sensors

The light intensity in the water is measured by the probes in mA. In the BLOOM model, calculations are performed using the unit kJ/m^2/h for light intensity. Therefore the first step is to correct this unit. Please refer to Appendix A for the exact method for this correction.

Subsequently, a relationship was established that links light intensity to the growth efficiency of algae and cyanobacteria. The BLOOM model distinguishes between 3 different types of algae and 3 different types of bacteria. Table D1 in Appendix D provides 10 values for light intensity and corresponding growth efficiency for three types of algae and three types cyanobacteria (Los, 2009).

Given that the growth efficiencies of the three types of algae and the three types of bacteria are quite similar under comparable light intensities, first the average growth efficiency for the algae and an average growth efficiency for the bacteria is calculated for each of the ten light intensities to proceed with the calculations.

After knowing the average growth efficiency for 10 light intensity values, the best fitting function was established in Python for these values with the sklearn package (Pedregosa FABIANPEDREGOSA et al., 2011). With this function the growth efficiency for 1000 different light intensities is estimated. With this relationship and the determined values of light intensity in steps 1, 2, and 3, the average growth efficiency of algae and cyanobacteria was determined for each hour during the measurement period.

To determine the average effect of the FPV system on the growth efficiency of algae and cyanobacteria, the average growth efficiency for the entire measurement period was calculated for all locations. Subsequently, the effect of the FPV system was determined for both phytoplankton species and both depths through the use of:

$$Effect\ FPV_{d,s} = \eta open_{d,s} - \eta FPV_{d,s}$$

Where $\eta open$ is the growth rate of phytoplankton in open water, ηFPV is the growth rate of phytoplankton under the FPV system, d is the depth (0m or 1m) and s is the species of phytoplankton (algae or cyanobacteria)

Then, for each month of the measurement period, the effect of the FPV system on the growth efficiency of algae and cyanobacteria was determined. This was done because it is expected that the effect of the FPV system on the growth of phytoplankton species is not constant over time and because more phytoplankton tends to grow during warmer months ((Edwards et al., 2016)). Therefore, the effect of the FPV system is more important for those months. To calculate this, the average light intensity was calculated for each month at the four locations. Then, the same steps were followed to determine the growth efficiency and the effect of the FPV system on this growth efficiency.

4. Results

This section discusses the results obtained from investigating the technological and environmental advantages and disadvantages of FPV systems in the Netherlands.

4.1 Technological advantages and disadvantages FPV system

First the results obtained from investigating the technological advantages and disadvantages of FPV systems will be discussed. This section is divided into two paragraphs. The first section outlines the performance indicators of an LBPV, freshwater FPV system, and an offshore FPV system. The second section summarizes the technological advantages and disadvantages based on the analysed literature.

4.1.1 Performance indicators

During the measurement period, the total AC output of the FPV system in Oudehaske is 2.287 GWh and the total AC output of the modelled LBPV system is 2.284 GWh. The average AC power output is highest in July and lowest in December. In August, the FPV system and LBPV system produce 1122 kWh/hour and 650 kWh/hour respectively. In December, the AC output is at its lowest with 99 kWh/hour for the FPV system and 166 kWh/hour for the LBPV system.

The FPV system produced approximately 3 MWh more, which is equivalent to a difference of 0.13%. In July and August, the FPV system has a higher AC output than the LBPV system. This difference is greatest in July, where the FPV system generates about 211 kWh/hour more electricity than the LBPV system. In the other months, the LBPV system produces slightly more electricity. In October, this difference is the largest with 99 kWh/hour.

The results indicate that the FPV system generates more electricity during the warmer months of the year (March-September), while the LBPV system produces more electricity during the colder months (October-February). Out of the measured days, there were 68 days in the warmer period and 134 days in the colder period. Therefore, it is expected that if measured over a full year, the difference in electricity yield between the FPV system and the LBPV system will be greater than 0.13%. Figure 8 shows the average AC power for the FPV system and LBPV system for each month.

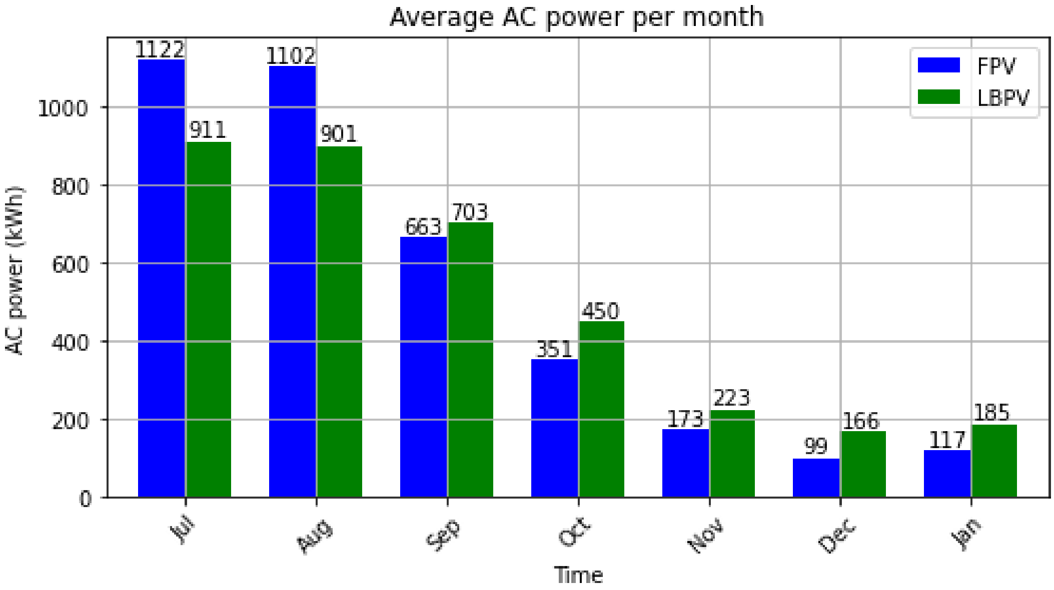

Figure 8: Mean of monthly electricity output and CF of the FPV system in Oudehaske between July 14 and January 31.. Measured FPV values are the blue bars, modelled LBPV values are the green bars. Measurement period between July 14 and January 31.

The CF is calculated in monthly basis in this research. The CF of the FPV system varies between a maximum value of 16.7% in July to only 1.5% in December. The CF of the LBPV system ranges between 13.4% in July and 2.5% in December. The average capacity factor between July 14 and January 31st of the LBPV system is 7.11%, and the average capacity factor of the FPV system is 7.12%. Figure 9 shows the CF for the FPV system and LBPV system for each month

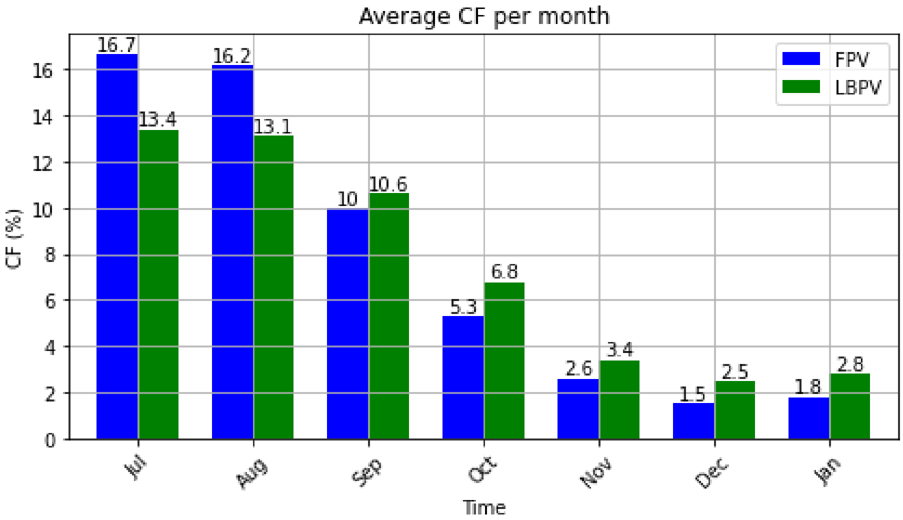

Figure 9: Average CF of the FPV systems for each month. Measured FPV values are the blue bars, modelled LBPV values are the green bars. Measurement period between July 14 and January 31.

The cell temperature on the FPV system is measured at three points on the panel. From the results becomes clear that the temperature of the sensor located in the middle of the panel is lower than the temperature measured at the side of the panels. This is because at the sensor in the middle, the water is deeper, which reduces the effect of the FPV system's heating of the water. In Figure 10 the daily average cell temperature of each sensor located on the FPV system in Oudehaske during the measurement period is shown.

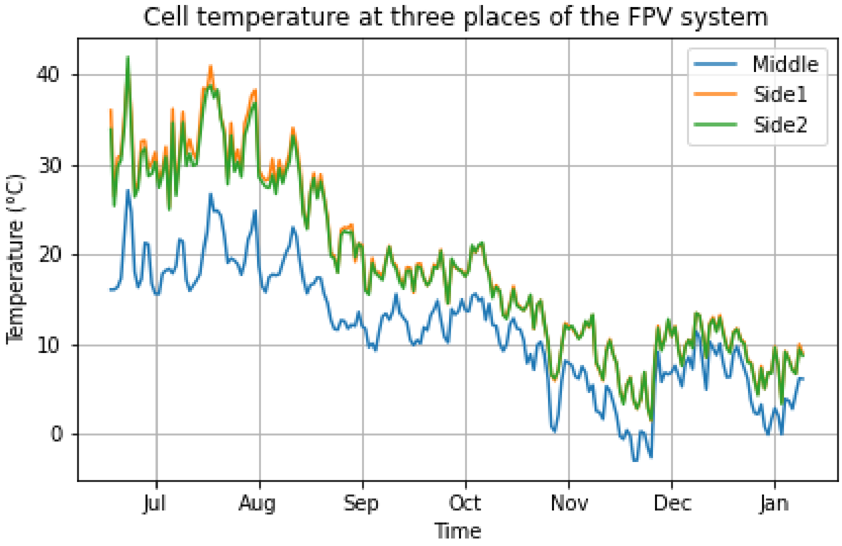

Figure 10: Daily average cell temperature of the three sensors on the FPV system between 14 July and 31 January for hours with sunlight irradiation. The blue line is the sensor in the middle of the FPV system, the green and orange lines are the sensors location at the side of the FPV system.

The FPV system has an average cell temperature of 17.6 °C during the hours with sunlight irradiation. This temperature has a minimum of 6.9 °C in December and a maximum of 29.4 °C in August. The LBPV system has an average cell temperature of 18.2 °C, a minimum cell temperature of 6.2 °C, and a maximum cell temperature of 30.5 °C. On average, the cell temperature of the FPV system is 0.7 °C lower than the cell temperature of the LBPV system. The cell temperature of the LBPV system is higher during the months of July to November, with the greatest difference observed in September, where the LBPV system's temperature is on average 2.1 °C higher. In the months of November, December, and January, the cell temperature of the FPV system is higher than the temperature of the LBPV system. In December, this difference is the largest at 0.62 °C. In the winter months ambient temperature colder makes the system to be cooler. In Figure 11 the cell temperature for the FPV and LBPV system is shown.

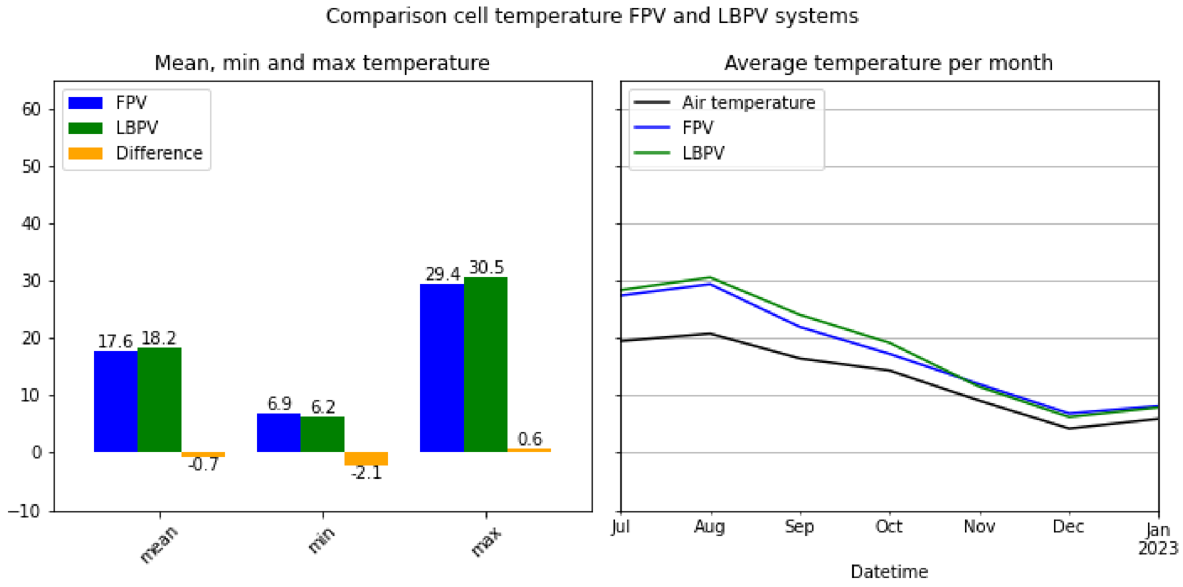

Figure 11: A) The minimum, average, and maximum values of the measured cell temperature on the FPV system (blue bar), the modelled cell temperature of the LBPV system (green bar), and the difference in cell temperature between the FPV and LBPV systems (orange bar). B) Average monthly cell temperature measured on the FPV system (blue line) and modelled cell temperature of the LBPV system. Measurement period between July 14 and January 31.

Although the water is warmer in most of the months, the FPV solar modules have lower temperature in summer time, which is due to water cooling effect which comes from evaporation and the water specific heat coefficient which is higher than air (Dörenkämper et al., 2021a). In Figure 12, the average cell temperature of the FPV and LBPV systems for each month are shown. In addition, the average temperature of the air compared with the average temperature of the water can be seen

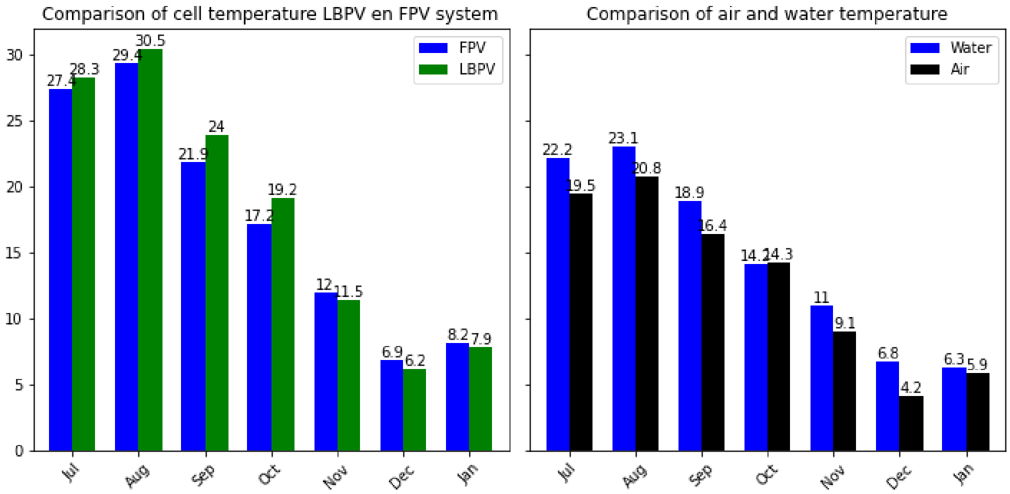

Figure 12: A) Comparison between the cell temperature of the LBPV system (green bar) and the FPV system (blue bar). B) Comparison between the temperature of the water at a depth of one meter (blue bar) and the temperature of the air (black bar) at the KNMI station. Measurement period between July 14 and January 31.

During the months of September and October, both the energy yield of the FPV system and the average cell temperature are higher. This is contrary to expectations, as a higher cell temperature typically results in a less efficient system (Kjeldstad et al., 2021). However, this can be explained when analyzing the cell temperature per hour. The cell temperature of the LBPV system is only higher than that of the FPV system for a small part of the day. In the middle of the day, the cell temperature of the LBPV system suddenly becomes significantly higher. This is because there is high solar radiation during this time of day, which substantially increases the cell temperature of the LBPV system. This effect is smaller for the FPV system due to its cooling effect from the water. As a result, the cell temperature of the LBPV system is a lot higher for that specific period, which causes that the daily average cell temperature of the LBPV system is also higher. However, for the majority of the day, the cell temperature of the LBPV system is lower than that of the FPV system, making it more efficient. This leads to a higher energy yield for the LBPV system compared to the FPV system. Figure 13 depicts the hourly cell temperature of both the LBPV and FPV systems, along with the corresponding solar radiation levels, for six days in mid-September and six days in mid-October.

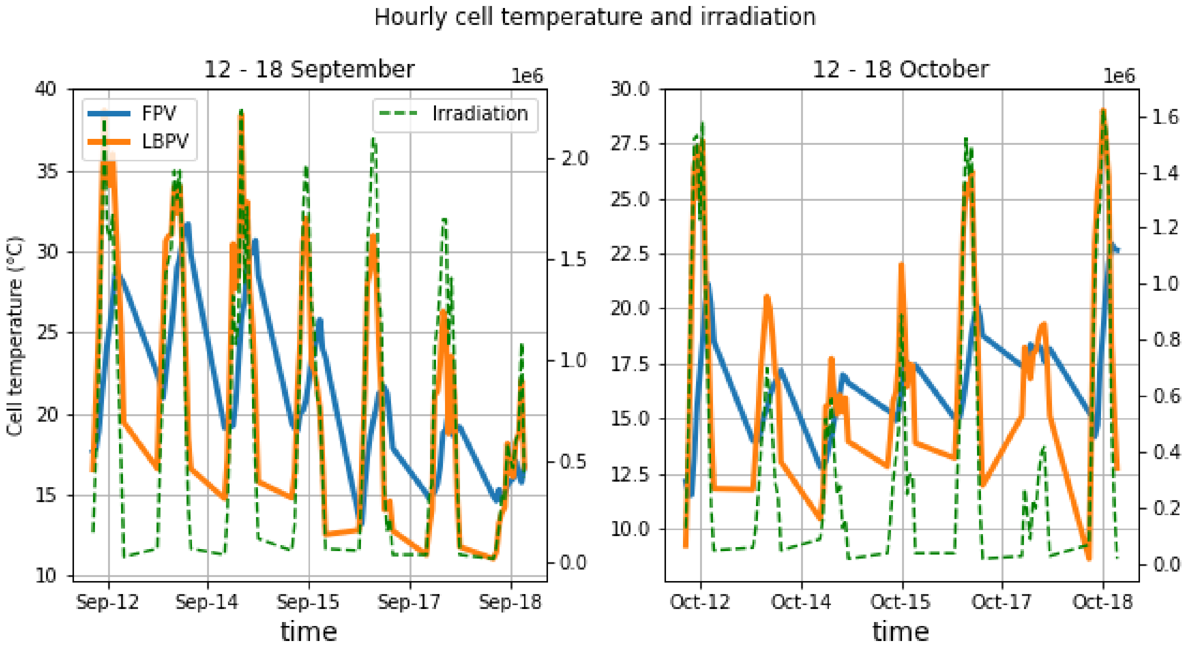

Figure 13: Hourly cell temperature and irradiation for the hours with irradiation. Orange line indicates measurements of the LBPV system, blue lines measurements of the cell temperature of the FPV system and green lines the irradiation at these moments.

The average wind speed measured on the FPV system is 0.7 m/s lower than the average windspeed measured by the nearest KNMII station. This difference ranges from a minimum of 0.4 m/s in November to a maximum of 0.9 m/s in September. Contrary to expectations, the average wind speed over the water is therefore lower than the windspeed over land. The results of the measurements and calculations of the wind speed are shown in Figure 14.

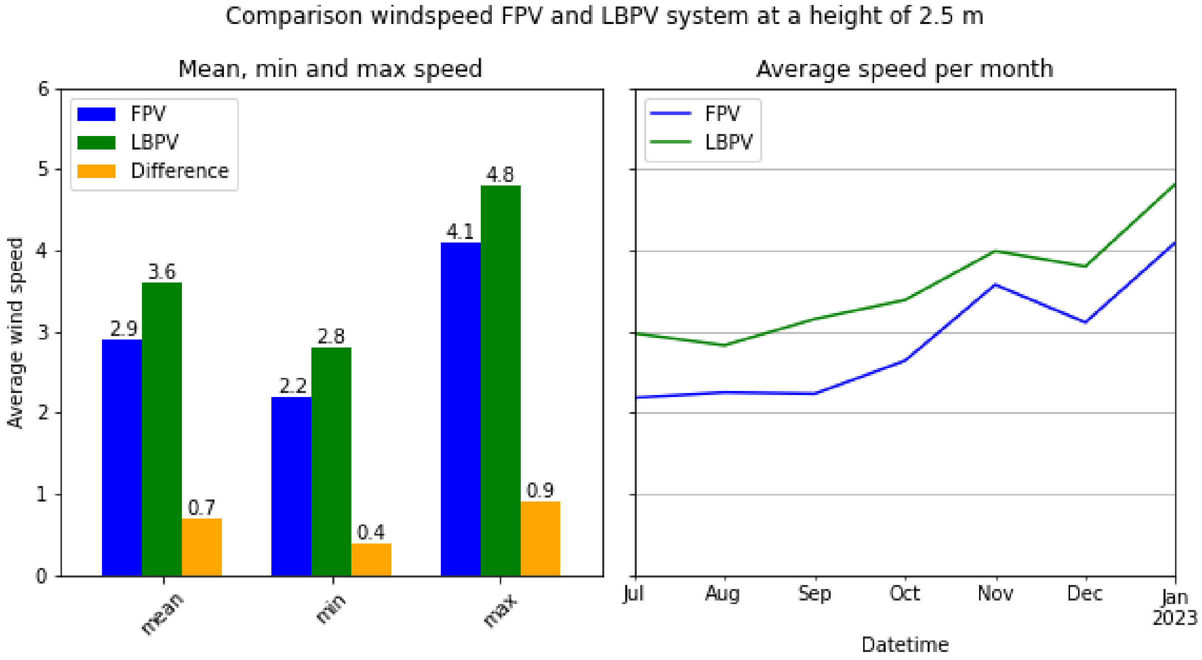

Figure 14: a) Minimum, average, and maximum values of the measured wind speed on the FPV system (blue bar), the calculated wind speed of the LBPV system (green bar), and the difference in wind speed between the FPV and LBPV system (orange bar). b) Average monthly wind speed measured on the FPV system (blue line) and at the nearest KNMI station (green line). Measuring period between July 14 and January 31st.

Offshore FPV

The results of the study by (Vido, 2022) indicate a higher energy yield for the offshore FPV system compared to the LBPV system. The offshore FPV system generates 49 GWh per year, whereas the LBPV system generates 45 GWh. Therefore, the offshore FPV system yields 8.89% more throughout the year. The average cell temperature of the offshore FPV system is 29.2% higher than that of the LBPV system during the winter months from October to February. However, during the summer months, the cell temperature of the FPV system is 12% higher. The difference in the summer months is more significant because there is more sunlight, resulting in more electricity generation. The wind speed at sea is on average 10.8% higher than on land.

The results of the technological performance indicators of the LBPV, freshwater FPV and offshore FPV are summarized in Table 8.

Table 7: Wind speed, cell temperature and (annual) electricity yield model freshwater and offshore FPV

	Land based Oudehaske	FPV Oudehaske	Land based (EW oriented)	Offshore North-sea	Percentage difference freshwater	Percentage difference offshore
Average (annual) wind speed (m/s)	3.6	2.9	6.62	7.34	-19.4%	10,8%
Average cell temperature (October-February)	-	-	7.4	9.56	-	29,2%
Average cell temperature (March – September)	-	-	15.6	13.93	-	12,0%
Average cell temperature (June 14 – January 31)	17.6	18.7			6.25%	-
Average (annual) system yield	2.284 GWh	2.287 GWh	45 GWh	49 GWh	0.13%.	8.89%

4.1.2 Literature review

The difference in energy yield among LBPV, freshwater FPV, and offshore FPV systems is primarily attributed to variations in cell temperatures. However, additional distinctions affecting panel energy yield have been identified in the literature. Two advantages of freshwater and offshore FPV systems, leading to a potentially higher energy yield compared to LBPV systems, are reduced dust accumulation on the panels and minimized shading caused by their surroundings (Golroodbari & van Sark, 2020; World Bank Group et al., 2018).

Three disadvantages are defined which can decrease the efficiency of the panels. First, FPV systems may encounter issues with biomass accumulation, leaves, and bird droppings on panels, which can reduce conversion efficiency (World Bank Group et al., 2018). Secondly, to ensure stability and minimize the risk of damage from wind and waves, FPV systems are designed with a lower than optimal tilt angle than LBPV systems (Gorjian et al., 2021). Thirdly, changes in orientation due to movement of the floating system result in mismatch losses which also cause a lower energy yield (Jones & Armstrong, 2021). If FPV panels are mounted on flexible floaters the wave-induced movement causes the panels to have different orientations. This variance in panel orientations can lead to mismatch losses and reduced power production within a string, as the Maximum Power Point (MPP) of individual panels varies (Soppe et al., 2022).. The last two mentioned disadvantages are both caused by the waves of the water. Since the waves are much less significant for a freshwater FPV system compared to an offshore FPV system, these disadvantages will be greater for offshore FPV systems.

In addition to the electrical factors that impact the performance of FPV systems, there are other technological advantages and disadvantages associated with freshwater and offshore FPV systems. Three notable technological advantages of offshore FPV, as compared to freshwater FPV, include a reduced risk of grid congestion, the potential to integrate solar and wind energy in a hybrid system at the same location, and the feasibility of large-scale implementation (Soppe et al., 2022).

However, currently offshore FPV is not competitive yet with LBPV and freshwater FPV systems in terms of costs and reliability. Three big challenges of offshore FPV are system design, accessibility and fast degradation (Soppe et al., 2022). The design of offshore FPV is particularly challenging and expensive due to additional risks associated with tidal movements, saltwater corrosion, large waves, and high wind speeds (Soppe et al., 2022). The design of offshore FPV is more challenging than the design of freshwater FPV because of stronger winds, higher waves and the presence of tides in the offshore environment (Karpouzoglou et al., 2019).

4.2 Environmental advantages and disadvantages case studies

This section discusses the results obtained from investigating the environmental advantages and disadvantages the FPV system located in Oudehaske. This chapter is divided into three paragraphs. The first paragraph outlines the effect of the FPV system on the physiochemical parameters and the relation between the parameters in open water and the parameters under the FPV system. The second paragraph outlines the effect of the change of the physiochemical parameters on the ecosystem of Oudehaske. The third section discusses potential effects of the FPV system on the water quality and ecology of the lake in Oudehaske that may occur but are not directly linked to the measured physiochemical parameters. Lastly, the expected environmental impacts of offshore FPV systems are discussed.

4.2.1 Impact physiochemical parameters

The turbidity and chlorophyll are most strongly affected by the FPV system. There is also a substantial impact on the light availability, DO and conductivity and there is a small impact on the temperature. The results also indicate that the FPV system has a significant effect on all parameters ($p<0.05$). Table 9 presents the average values of the physiochemical parameters in open water and under the FPV system. It also displays the average effect of the FPV system on the physiochemical parameters in percentages, along with the results of a t-test to determine the significance of the effect. The percentage change for all included physiochemical parameters is visually shown in Figure 15.

Table 8: Mean vales of physical chemical parameters in open water, under the FPV system and the average effect of the FPV system on the physiochemical parameters.

	Light intensity (kJ/(m² \h))	**Chlorophyll (ug/l)**	**Turbidity (NTU)**	**Conductivity (ug/l)**	**Dissolved Oxygen (mg/l)**	**Temperature (°C)**
Mean open water	25120.25	9.24	41.75	433.04	8.66	14.13
Mean FPV system	18964.32	3.01	5.06	477.24	8.03	14.37
Average effect FPV system (%)	-18.2	-59.1	-76.2	10.5	-8.1	2.1
T-test	0.00	0.00	0.00	0.00	0.00	0.00

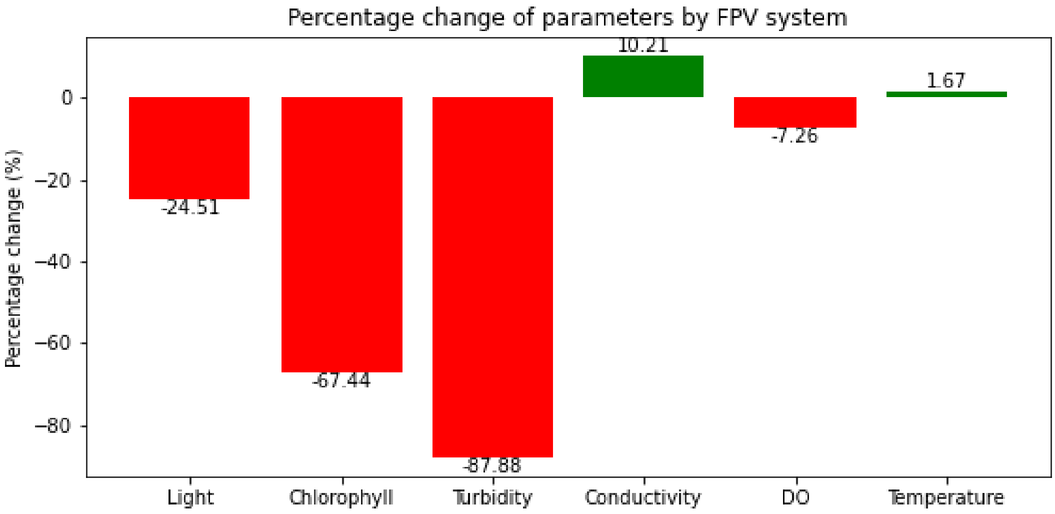

Figure 15: Average percentage change of physiochemical parameters by the FPV system. A green bar indicates an increase of the physiochemical parameter under the FPV system and a red bar indicates a decrease of the physiochemical parameter under the FPV system.

The effect of the FPV system is not constant throughout the monitoring period. The impact of the FPV system is most pronounced in summer in terms of light intensity, chlorophyll, turbidity, and temperature. In autumn, the effect of the FPV system is greatest in terms of conductivity and oxygen levels. Besides, the effect of the FPV system on conductivity, DO, and temperature is more consistent over time than its effect on the light intensity, turbidity, and chlorophyll. This result is also supported by Pearson's r. Pearson's r of these three parameters is higher than 0.7, indicating a strong linear relationship between the parameter in open water and the parameter under the FPV system.

Table 10 presents the minimum and maximum effect of the FPV system, the corresponding days on which this effect occurs and Pearson's r. Figure 16 shows the average light intensity, chlorophyll content, turbidity, conductivity, DO and temperature for each day during the measurement period. The orange lines represent the daily averages values of the 6 parameters that were measured in the centre of the FPV system, while the blue lines represent the averages values measured in the open water. In Figure 17 the scatterplot and regression equation is displayed for DO, temperature and conductivity.

Table 9: minimum and maximum values and days of r squared value between the physiochemical parameters in open water and under the FPV system

	Light intensity (kJ/(m^2 \h))	Chlorophyll (ug/l)	Turbidity (NTU)	Conductivity (ug/l)	Dissolved Oxygen (mg/l)	Temperature (°C)
Minimum effect FPV system (%)	-49.1	-96.9	-99.7	-0.6	-32.4	-0.5
Maximum effect FPV system (%)	-0.8	37.3	54.7	19.5	12.2	5.7
Day of minimum difference	2022-12-23	2022-08-08	2022-08-12	2022-07-26	2022-09-07	2022-07-14
Day of maximum difference	2022-07-17	2022-07-31	2022-09-02	2022-11-01	2022-12-30	2022-08-11
Pearson's r	0.148	0.009	0.032	0.691	0.872	0.999

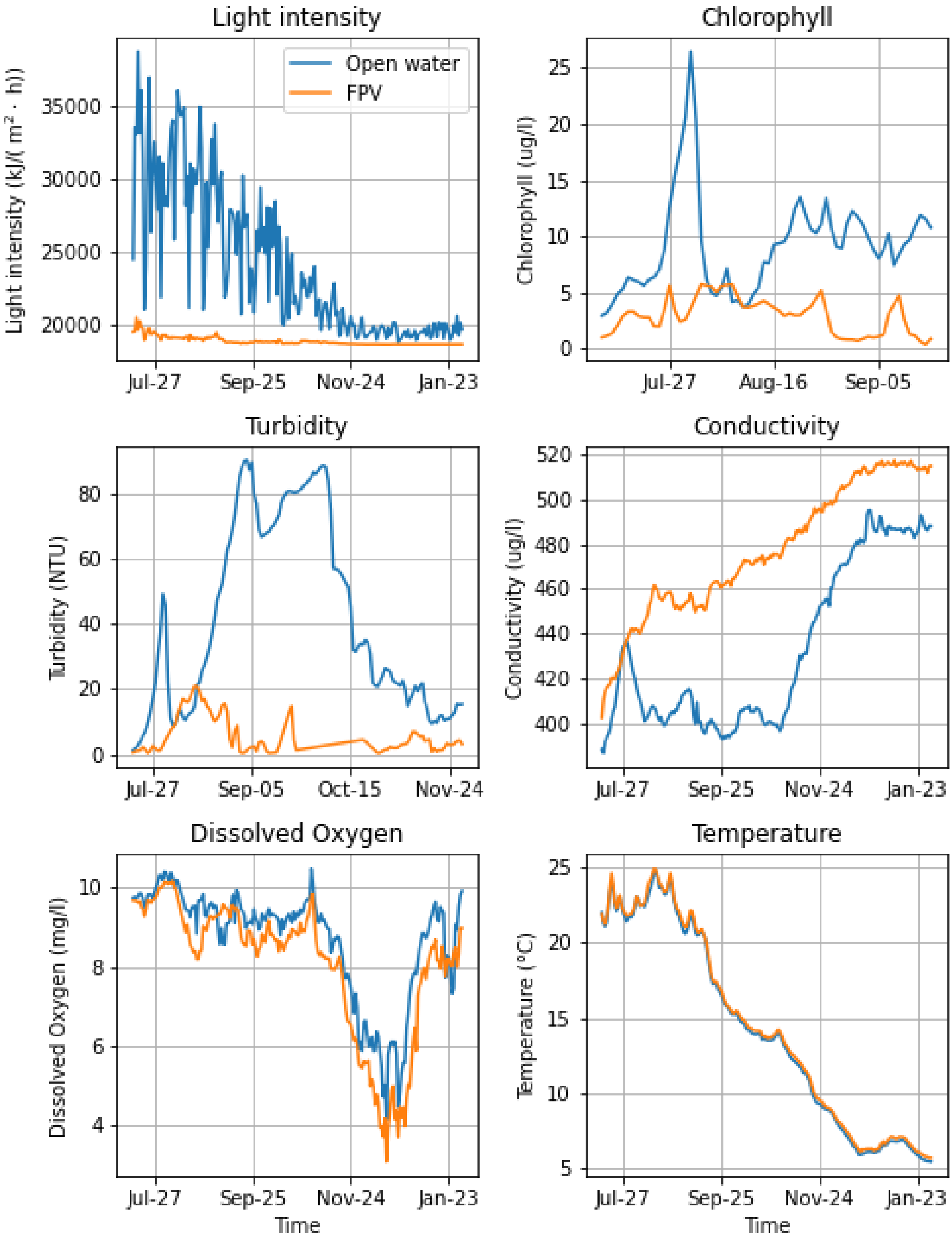

Figure 16 Plot of the daily average values of A) light intensity, B) chlorophyl content C) turbidity, D) Conductivity, E) Dissolved Oxygen, F) Temperature in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system.

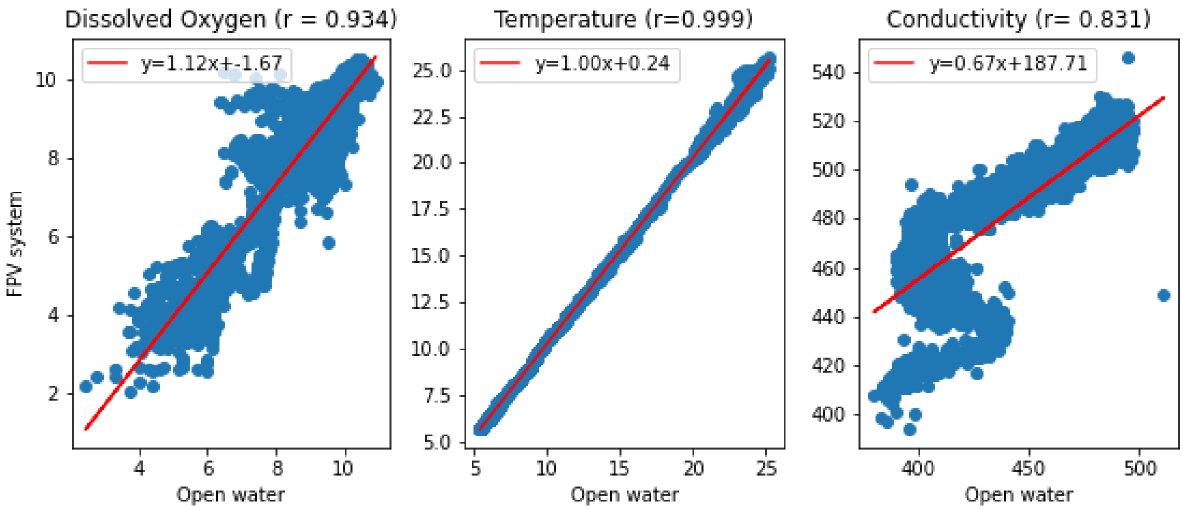

Figure 17: A) Scatterplot, regression line, and regression equation showing the measurements of DO in open water as the independent parameter and measurements of DO under the FPV system as the dependent variable. B) Scatterplot, regression line, and regression equation showing the measurements of temperature in open water as the independent parameter and measurements of temperature under the FPV system as the dependent variable. C) Scatterplot, regression line, and regression equation showing the measurements of conductivity in open water as the independent parameter and measurements of conductivity under the FPV system as the dependent variable.

4.2.2 Impact ecosystem

Next, the anticipated impact of the changes in physiochemical parameters on the phytoplankton and fish will be discussed.

Phytoplankton

In Figure 18, the average growth efficiency of algae and cyanobacteria is plotted against the corresponding light intensity.

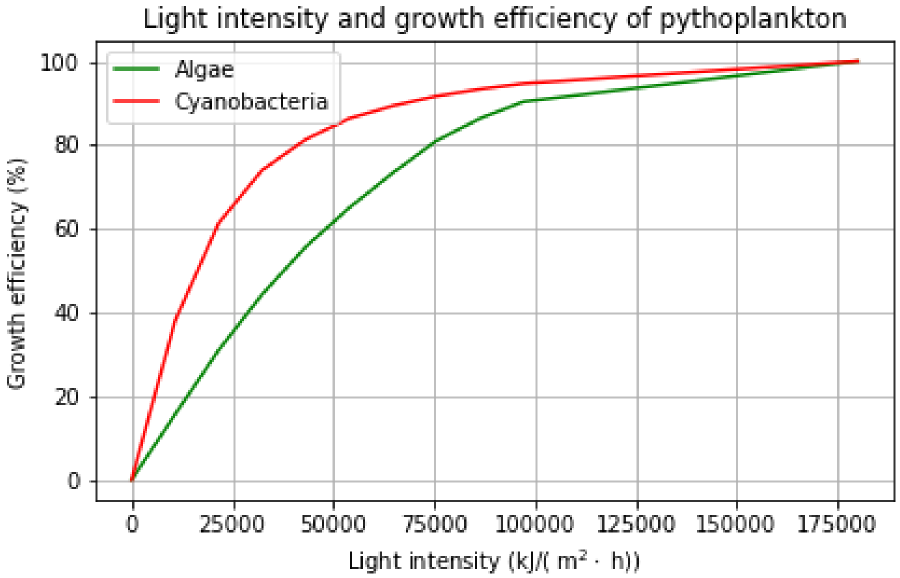

Figure 18: Relationship between light intensity and the growth of different types of phytoplankton. Red line is growth efficiency of cyanobacteria and green line the growth efficiency of algae.

From the results becomes clear that at a depth of one meter in open water, the growth efficiency of algae is 33%, and for cyanobacteria, it is 52%. However, at this depth below the FPV system, the growth efficiency of algae decreases to 27%, and the efficiency of cyanobacteria decreases to 46%. Therefore, the FPV system reduces the growth efficiency of both algae and cyanobacteria by 6% at a depth of one meter.

On the water surface in open water, the growth efficiency of algae is 92%, and for cyanobacteria, it is 100%. However, under the FPV system, the growth efficiency decreases to 44% for algae and to 62% for cyanobacteria. Therefore, the FPV system reduces the growth efficiency of algae by 48% and the growth efficiency of cyanobacteria by 38% on the water surface. On the water surface, the effect of the FPV system is therefore greater on the algae than on the bacteria.

Figure 19 shows the average efficiency of algae and cyanobacteria for the four locations where values of light intensity are known/estimated.

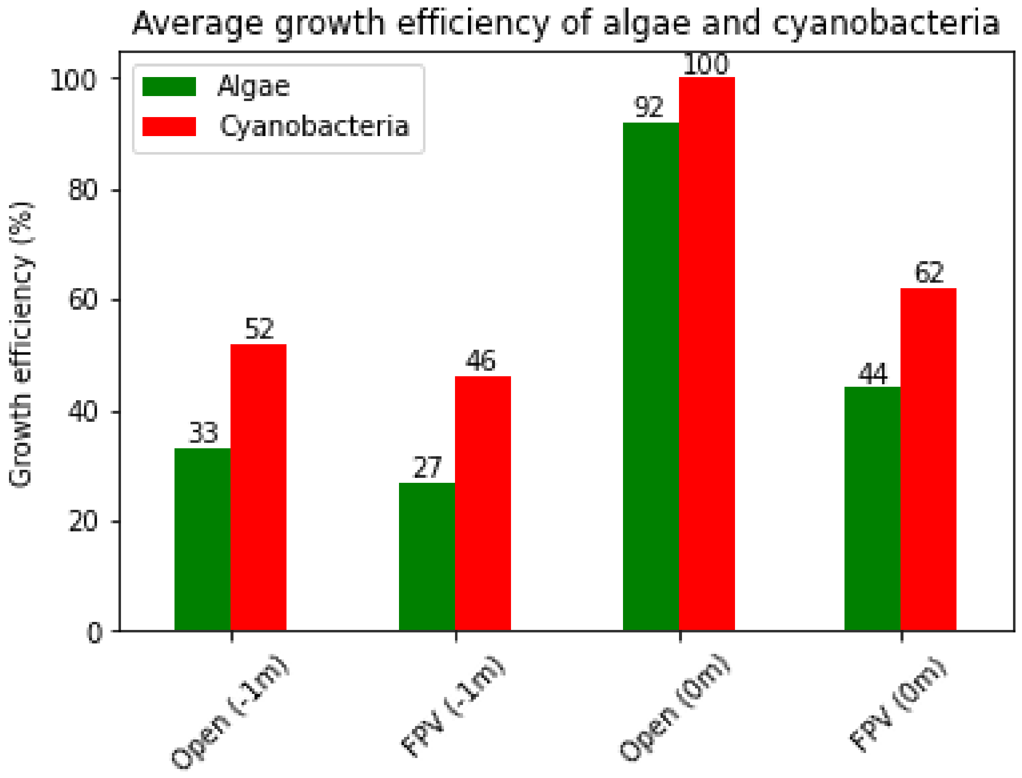

Figure 19: Comparison of the calculated growth efficiency of algae and cyanobacteria in open water and under the FPV system. The green bars are the average growth efficiency

The effect of the FPV system on the growth efficiency of phytoplankton is not constant over time. At the water surface, the effect of the FPV system on reduction of the growth efficiency of phytoplankton is smallest in July and August (the months with the highest irradiation). This is because the irradiation is so high that the growth efficiency under the FPV system is also almost 100% during these months. In November, December, and January (the months with lowest irradiation), the effect of the FPV system is highest. This is because the irradiation in these months is still high enough for phytoplankton in open water to have a growth efficiency of (almost) 100%. However, under the FPV system, the growth efficiency decreases substantially. Therefore, the effect of the FPV system on the growth of phytoplankton is greater in these months. At a depth of one meter, there is only an effect of the FPV system in the months of July and August. This is because for the other months, the difference in the measured light intensity is too small to cause a different growth efficiency. Figure 20 shows the effect of the FPV system on the growth efficiency of algae and cyanobacteria during all months of the measurement period.

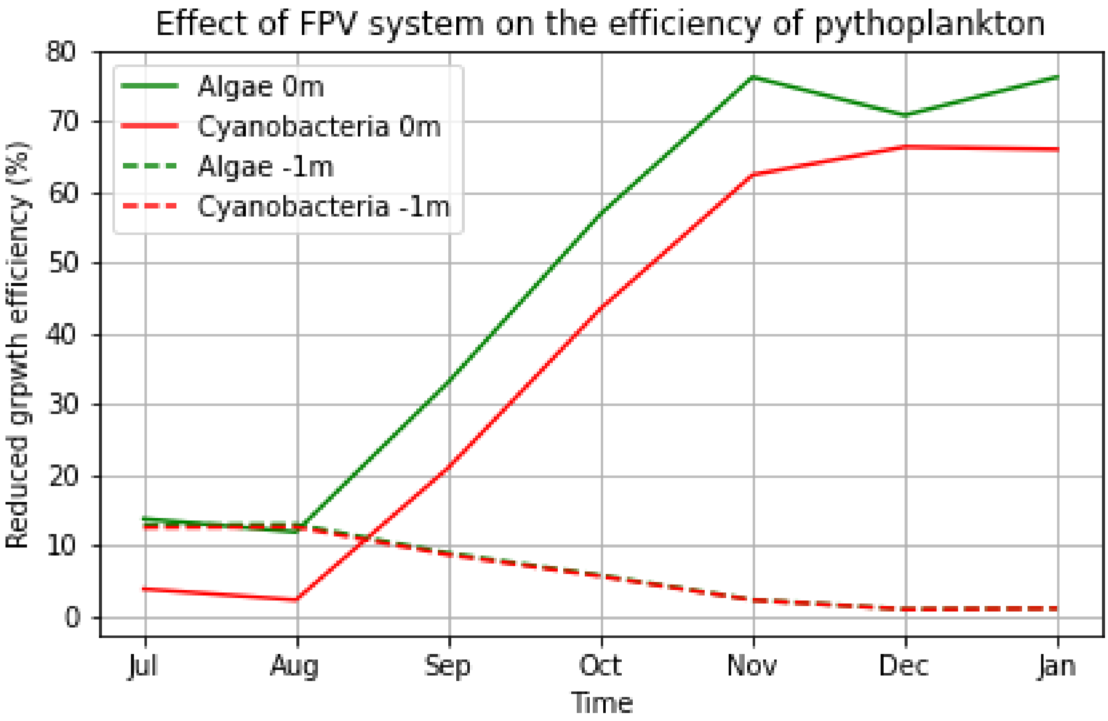

Figure 20: Effect of the FPV system on the growth efficiency of phytoplankton over time. The green lines represent algae, the red lines represent cyanobacteria. Solid lines indicate measurements taken at the water surface, while dotted lines indicate measurements taken one meter below the water surface. The measurements are taken between July 14 and January 31.

Fish

The FPV system can potentially affect the fish population, as there have been instances where the DO falls within a range that is inhospitable for any fish species to survive. This occurs for a duration of seven days under the FPV system. This is from December 12 to December 14, on December 16, December 23 and on December 27. This does not occur in open water. Additionally, under the FPV system, there are 5 more days on which only few fish have enough oxygen to breathe. From November 25 to January 3, few fish can survive under the FPV system. In open water, on most days between November 29 and December 28, few fish can survive at the depth of 1m. Figure 21 shows for how many days the average measured DO concentration is sufficient for all fish species, most fish species, few fish species, or no fish species to breathe.

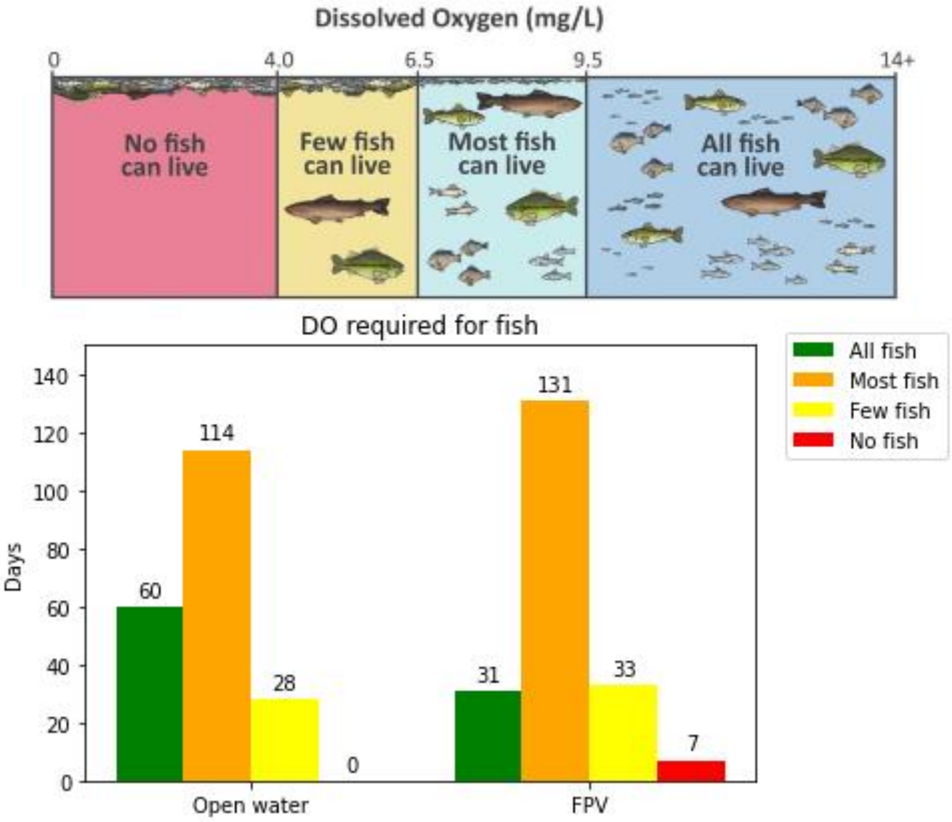

Figure 21: Figure showing the effect of the reduced oxygen on fish for open water and under the FPV system. Green bars indicate that all fish have sufficient oxygen, orange bars indicate that most fish have sufficient oxygen, yellow bars indicate that few fish have sufficient oxygen and red bars indicate that no fish have sufficient oxygen.

The effect of the FPV system on conductivity has no implications for the fish. All measured hourly values of conductivity fall between 380 and 546, which is well within the range of 150 to 800 that is considered suitable for fish.

4.2.3 Other effects on water quality and ecology

Some effects of the FPV system on the environment are not related to the physiochemical parameters that were measured in Oudehaske. To assess these effects as well, a literature study was conducted, and the key findings are summarized in this section.

The FPV system may have further impacts on thermal stratification and ecology of the lake. Thermal stratification (Figure 22) occurs when the sun warms the lake surface in spring and summer and the temperature differences between the surface and deeper water increases. These temperature differences causes that the wind cannot mix the water anymore which makes the lake is stratify in three layers of water (Elçi, 2008). The timing and duration of stratification are influenced by wind patterns over the water surface and water temperature. Since the FPV system can affect these two factors, it has the potential to modify the timing and duration of stratification. It is crucial to examine the impact of the FPV system on stratification because changes in timing and duration can significantly impact the ecosystem, particularly the oxygen and nutrient concentration in a lake. As mentioned earlier, oxygen levels are crucial for fish, while nutrient content influences the growth of phytoplankton communities, which require nutrients to grow. Additionally, an increase in nutrient content can negatively affect fish populations that are sensitive to such changes (Elçi, 2008). More information about how stratification affects the dissolved oxygen (DO), nutrients, and ecology of a lake can be found in (Elçi, 2008).

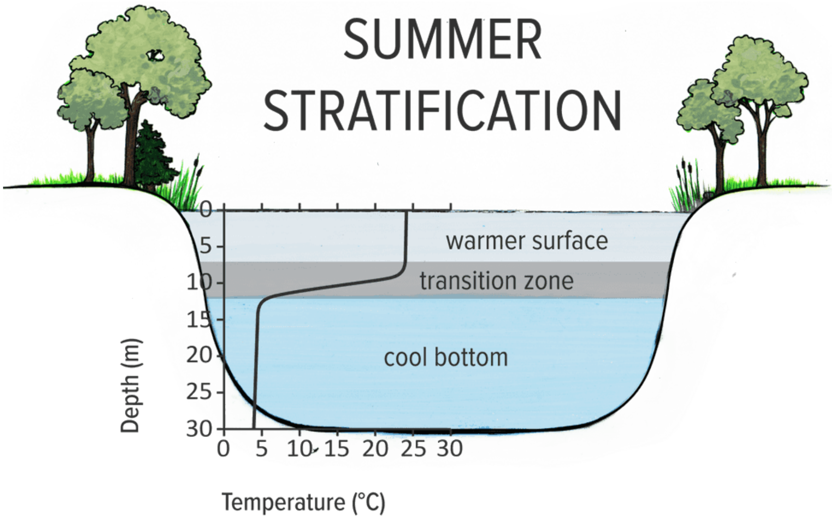

Figure 22: Layers of the water when thermal stratification happens (Elçi, 2008)

The FPV can also have an additional impact on the ecology by impacting macroinvertebrates, fish and birds. The presence of FPV in the waterbody provides an underwater surface which becomes available for biofouling. Often these surfaces are colonised by macroinvertebrates like mussels (Härtwich, n.d.; R. Lima & Cornelis Boogaard, 2015;). Many studies that captured underwater pictures/footage observed macroinvertebrates under the structure (Boogaard et al., 2019; R. L. P. de Lima et al., 2021; Härtwich, n.d.; R. Lima & Cornelis Boogaard, 2015; Pedroso De Lima et al., 2022). This shows that, if designed correctly, floating constructions can stimulate aquatic life and biodiversity in the surroundings of these structures (Boogaard et al., 2019). Besides, these mussels can filter out suspended plankton which results in a decreased turbidity which in turn results in more light availability (Härtwich, n.d.). Secondly, the FPV system has another effect on fish, as it can potentially provide shelter for smaller and juvenile fish. Therefore, the system can increase fish populations (Armstrong et al., 2020). Thirdly, on freshwater FPV platforms a strong presence of birds is often observed. This suggests that they use this platform as a shelter to build, nest and rest (R. L. P. de Lima et al., 2021). However, the bird droppings contain many nutrients which can possibly decrease the water quality (Pedroso De Lima et al., 2022).

4.2.4 Offshore FPV

The main difference in environmental impact between freshwater and offshore FPV lies in the scale of implementation. An offshore FPV system can be deployed on a significantly larger scale compared to a freshwater FPV system, while still maintaining the integrity of water quality and the ecosystem (Karpouzoglou et al., 2019). This is because the impact of an FPV system becomes more noticeable when a larger proportion of the water surface is covered. Considering that the North Sea is approximately 1.9 times larger than the Lake of Oudehaske, it allows for the utilization of a larger system (Karpouzoglou et al., 2019. Besides, in the offshore environment stronger winds, higher waves and the presence of tides results in a constant replacement of the water column underneath the platform. Both interviewed experts also emphasized that noticeable effects of a offshore FPV system on water quality and the ecology will only occur when it is implemented on a large scale. They agree that environmental impacts start to occur when the FPV system spans several to tens of kilometres. In comparison to Oudehaske, this is significant as the surface area of this FPV system is 0.03525 km^2. Below the expected environmental impacts are discussed for a large scale offshore FPV system.

Light availability, chlorophyll and phytoplankton

The literature indicates that due to the diminished light availability beneath offshore FPV systems, there is a decrease in photosynthesis, leading to a reduction in phytoplankton populations. (Karpouzoglou et al., 2019; Wezeman, 2022). Both experts also expect that a large-scale offshore FPV system decreases the volume phytoplankton, which is considered a disadvantage of the FPV system.

Decreased water turbidity

Offshore FPV can reduce water turbidity in two ways. Firstly, the friction between the FPV system and the waves leads to reduced wave action. Wave action is the primary process by which sediment and fine particles are stirred up from the bottom. Secondly, similar to freshwater systems, an offshore FPV system eliminates the effect of wind on the water. This results in lower turbulence and consequently fewer sediments and suspended particles coming from the bottom. As a result of both, the water turbidity decreases.

Macroinvertebrates

Floating objects that cover part of the sea can attract macroinvertebrates. OoE has observed that their structure functions as an artificial reef and provide new substrate for mussels (*Environment - Oceans of Energy*, n.d.). In both interviews, it has also been mentioned that they expect mussels to attach to the FPV systems.

Other marine life

The experts anticipate that younger fish will gather beneath the FPV systems because these systems provide protection for them. Additionally, due to the mussels attached to them, there is also a source of food for the fish. However, if such a system spans several kilometres, it will become very dark underneath, resulting in fewer fish seeking shelter.

No impact

In the offshore environment stronger winds, higher waves and the presence of tides results in a constant replacement of the water column underneath the platform. Therefore, for offshore FPV system the effects on the water conductivity, temperature and DO are expected to be negligible. Besides, there will be no impact on the aquatic plant community since the offshore FPV installations in the Netherlands are located on the North Sea, where no aquatic plants grow.

4.3 Effect context specific parameters

This section discusses the results of the context specific parameters on the environmental effects. First, the results obtained from investigating the change of physiochemical parameters for other locations in the Netherlands are discussed. Secondly, this section discusses the results obtained from investigating the correlation between the effect of the FPV system, weather conditions, and various physiochemical parameters to evaluate the effect of context specific parameters on the environmental advantages and disadvantages. In this case the context parameters are the weather conditions and the values of the physiochemical parameters of the waterbody. This is first done based on the analyzed literature and then based on the data measured by the probes in Oudehaske.

4.3.1 Environmental impact other freshwater locations

Table 11 presents a summary of the results from studies evaluating the impact of the FPV system on physiochemical parameters in water bodies in the Netherlands. The table provides information on the specific effects on the physiochemical parameters, along with relevant contextual details.

Table 10: Location, coverage, surface area, measurement period, and the result of the measured physiochemical parameters of other FPV systems in the Netherlands.

Location	Coverage of the lake surface (%)	Surface area (ha), Water depth (m)	Measurement period	Method	Dissolved oxygen	Temperature	Other physiochemical parameter	Reference
Bomhofplas	30%	60, 31.5	February–June and July–December 2020.	Data logger	- 1.1 mg/l in winter and -1.7 mg/l in summer	3.3% and 0.4 °C higher	Electrical conductivity: 0.03 mS/cm lower at open water (6.6% difference)	(de Lima et al., 2021)
Oostvoorne[5]	Three small systems (less than 1%)	270 , 40	Light intensity: (July-November 2021). Temperature and DO (march and October)	Data logger	Depends on system, some higher some lower	No increase/decrease of more than 1%	Light: System 1: 87% reduction System 2: 100% reduction System 3: 77% reduction	(Bax et al., 2023)
Storm water pond Weurt	-	~2.05, 1.9 m	Temperature (September 2019 to July 2020). Oxygen (September–December 2019, March–July 2020) Chlorophyll (August – september 2019)	Temperature and oxygen: data logger Chlorophyll: weekly sampling	157 hypoxic conditions[6] FPV system and 87 hypoxic conditions in open water	-0.2 °C in winter and -0.8 °C in summer	No significant differences in chlorophyll were found	(Ziar et al., 2021)
Beilen[7]	38%	20 m	From 29-07-2021 to 24-11-2022	17 samples of DO and temperature and 15 samples of water clearity	+1.24 (p-value of 0.433)	+0.51% (p-value of 0.011)	Water clarity (-4.55%, p-value of 0.126)	Appendix D

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[5] For the location of Oostvoorne, the coverage of the FPV system was less than 1%, and apart from removing the light, no effect of the FPV system was observed.

[6] Hypoxic conditions are defined in this article as consecutive periods with more than three measurements of less than 6 mg/l O_2 were found

[7] For the location of Beilen, the data was collected by taking 15-17 samples of the physiochemical parameters in a period of 16 months. Therefore, these results are less reliable compared to the hourly sensor measurements in the other studies.

The effect of the FPV system on the physiochemical parameters are different for different locations. For the water temperature, DO and chlorophyll studies yield different results. For the light intensity, conductivity and water clarity similar results are seen. However, just two studies have analysed these physiochemical parameters. Table 12 summarizes the results of the effect of the FPV system on the various physiochemical parameters where the effect on the physiochemical parameters is tested with data. A total of five studies are included, comprising the three studies conducted in the Netherlands, the data analysis of Beilen, and the data analysis of Oudehaske.

Table 11: Summary of results of effect of FPV system on physiochemical parameters within the Netherlands

Parameter	Number of studies	Increase	Decrease	No effect
Temperature (C)	5	3	1	1
DO (mg/l)	5	1	2	1
Light intensity	2	0	2	0
Chlorophyl	2	0	1	1
Water clarity[8] **((NTU) / (m))**	2	0	2	0
Electric conductivity	2	0	2	0

4.4.1 Literature review

Direct effect FPV system

The FPV system affects the weather parameters irradiation, precipitation and wind speed directly. The amount of sunlight reaching the water surface under the FPV system is reduced by the panels. Groenleven estimates that only about 10% of the incoming light is transmitted between the panels into the water (Groenleven, personal communication, 13-02-2023). Next, it is expected that under the FPV a lower wind speed is present and that the influence of precipitation on the physiochemical parameters is less (Pedroso De Lima et al., 2022).

The FPV system affects the physiochemical parameters light intensity, water temperature and conductivity directly. The water temperature is directly affected by the FPV system in two ways. First of all, the FPV system reduces the temperature by blocking sunlight that would otherwise heat the water. Secondly, the FPV system can raise the water temperature through the heat release from the panels (Armstrong et al., 2020). The conductivity is directly affected by the FPV system because of leaching of the metals of the metallic mounting structure of the FPV system in the water. This is a process where the metals dissolve in water, form ions, and increase the water's electrical conductivity (Mathijssen et al., 2020).

Relation between weather and physiochemical parameters

Sunlight irradiation can impact light intensity and water temperature. The increase in surface irradiation will increase the irradiation at 1 meter depth, the level of the probe. Secondly, increased irradiation leads to higher water temperatures, as more sunlight heats up the water (White et al., 1997).

Air temperature impacts the water temperature. Due to convection and conduction the temperature of the air affects the temperature of the water. Higher temperature in air leads to the convection of

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[8] One study measured the water clarity with a secchi disk, one study measured the turbidity

heat from the air to the water. When the air is warmer than the water, the water will warm up. Conversely, when the air is cooler than the water, the water will cool down (Piccolroaz et al., 2013).

Wind speed can have an impact on the water temperature, turbidity and DO. Firstly, when wind blows across the surface of the water, it creates turbulence and circulation, which can cause a cooling effect on the water due to heat transfer through evaporation (Bever et al., 2018). Secondly, a higher windspeed can increase the turbidity of the water since this turbulence stirs up sediment and suspended particles from the bottom, and brings in organic matter and debris from the surrounding environment . Lastly, a reduction in windspeed over the water can lead to a decrease in oxygen flux into the water, which lowers the DO concentration (Armstrong et al., 2020).

Precipitation can impact the turbidity and conductivity of a lake. During rainfall, turbidity in lakes tends to increase as particles from the soil surface get washed into the river and sediment on the river bed is resuspended. Rainfall can affect conductivity in two ways. Firstly, increased precipitation can result in more infiltration of groundwater. Since Oudehaske is located near the sea, this groundwater has a high salt content and therefore increases the conductivity of the lake (Teurlinx, personal communication, 17-03-2022). Conversely, heavy rainfall can decrease the conductivity of water by diluting the current concentration (Mekong River Commission, 2014).

Effect between physiochemical parameters

The physiochemical parameters are interconnected and affect each other (de Rijk et al., 2022).

The chlorophyll content is influenced by the intensity of light and the water temperature. Since chlorophyll is a pigment produced by photosynthetic organisms and light is required for photosynthesis, increased light intensity results in increased chlorophyll production (Bouterfas & Belkoura, 2006). Besides, an increased temperature of the water increases the growth rate of phytoplankton which in turn increases the amount of chlorophyll present in the water (Bouterfas & Belkoura, 2006).

The turbidity is affected by the chlorophyll content. A lower chlorophyll content leads to a lower water turbidity since a lower chlorophyll content indicates the presence of less suspended particles in the water column, which decreases the turbidity (DataStream, 2023d).

An increase in water turbidity results in a decrease in light intensity in the water. As the amount of suspended particles in water increases, less light can penetrate the water column, and the light intensity decreases (DataStream, 2023d).

The DO is influenced by the chlorophyll content and water temperature. Through photosynthesis, chlorophyll in photosynthetic organisms uses light energy to convert CO_2 and water into organic compounds and releases oxygen as a by-product. As a result, less DO is produced (EPA, 2022).

The temperature of the water affects the DO in two manners. Firstly, there is a negative relationship between temperature and DO since cold water can hold more DO. However, these parameters can be positively related as well. This is because the water temperature affects the stratification of the waterbody which has a substantial effect on the DO (Exley et al., 2021). Thermal stratification as explained in Section 4.3.3, occurs when the sun warms the surface of a lake in spring and summer, leading to an increase in temperature differences between the surface and deeper water. These differences in temperature cause the water to stratify into three layers, with the wind unable to mix the water any further (*Lake Stratification and Mixing*, n.d.). As a result, all the oxygen of the lake remains in the upper water column which is approximately 3 meters deep. This leads to more oxygen at a depth of 1 meter, where the probe is located. As the surface water cools, the stratification reverses resulting in the DO in the upper 3 meters of water mixing with the entire lake. Then the DO at the sensor depth of 1 meter decreases (*Lake Stratification and Mixing*, n.d.).

In Figure 23, the relationships between the FPV system, the weather parameters and the physiochemical parameters are visually represented. A green square represents a weather parameters, blue circles are physiochemical parameters, a green arrow indicates an expected positive relationship, a red arrow indicates an expected negative relationship and an orange arrow indicates that the relationship can be both positive and negative.

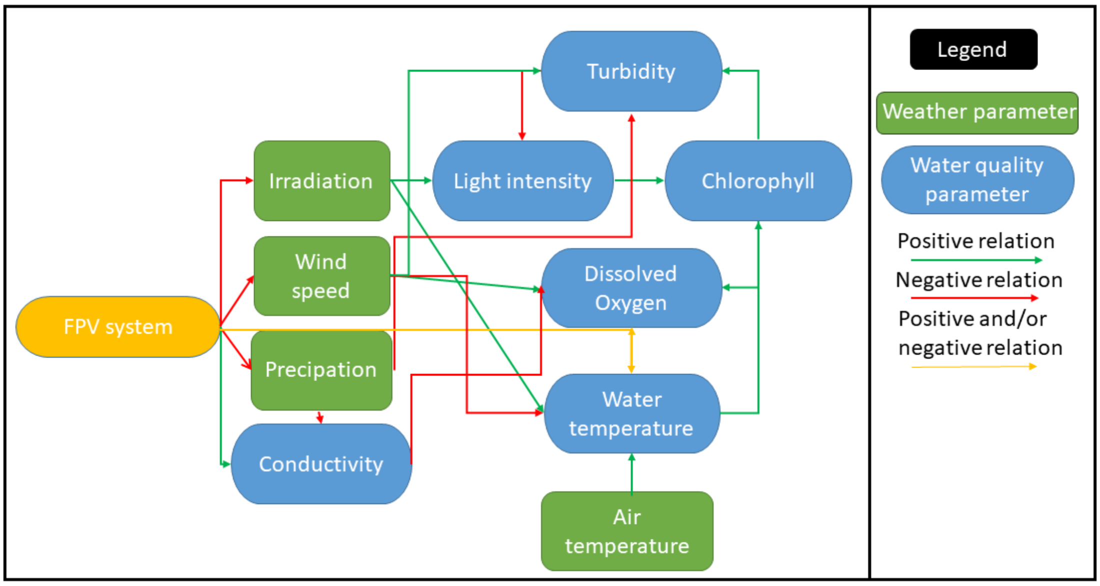

Figure 23: Direct and indirect effects of the FPV system. The weather parameters are presented with a green colour. The physiochemical parameters are presented with a blue colour. A green arrow indicates an expected positive relationship, a red arrow indicates an expected negative relationship. An orange arrow indicates that the relationship can be both positive and negative.

4.3.2 Data analysis

For this data analysis Pearson's r is calculated between the weather and the various physiochemical parameters. The physiochemical parameters light intensity, water temperature and conductivity are directly affected by the FPV system. The effect of the FPV system on these parameters in Oudehaske will be discussed first.

Light intensity

Based on the literature revieuw, it is expected that irradiation and turbidity can have an effect on the measured light intensity. There is no linear relation between turbidity and irradiation. The correlation coefficient between irradiation and light intensity in open water is 0.76 which indicates a strong linear relationship. The correlation coefficient between irradiation and light intensity under the FPV system is 0.27 which indicates no linear relationship. This difference is remarkable, but it can be well explained.

As mentioned before, the measured light intensity is a summation of direct light from the sun and diffuse light from the surrounding. In open water, the measured light intensity is predominantly direct light coming from the sun, resulting in a strong linear relationship with the irradiation. In Figure 25 it is shown how the panels in Oudehaske look like. The sensor underneath the FPV system is positioned in the middle of the panels. There are four solar panels positioned side by side, blocking sunlight. Between the four panels is a gap through which the sunlight falls. As a result, the light that falls on the probe under the FPV system is predominantly diffuse light, and the correlation with the incident light is low.

Figure 24: Floating solar system design of Groenleven (De Reimert Groep, 2021)

For open water at a depth of 1 m, only 3.03% of the incident light is still present. Under the FPV system 25.3% of the light at the water surface under the panels is present at a depth of 1 meter. There are two explanations for this difference. Firstly, the turbidity under the FPV system is lower than in open water. As a result, less light is attenuated between 0 and 1 meter (DataStream, 2023d). Secondly, under the FPV system, there are more objects that can reflect light towards the probe than in open water. As a result, there is more diffuse light falling on the probe under the FPV system compared to the amount of light falling on the probe in open water.

In Figure 26 a correlation plot and a time plot between irradiation and the measured light intensity is displayed.

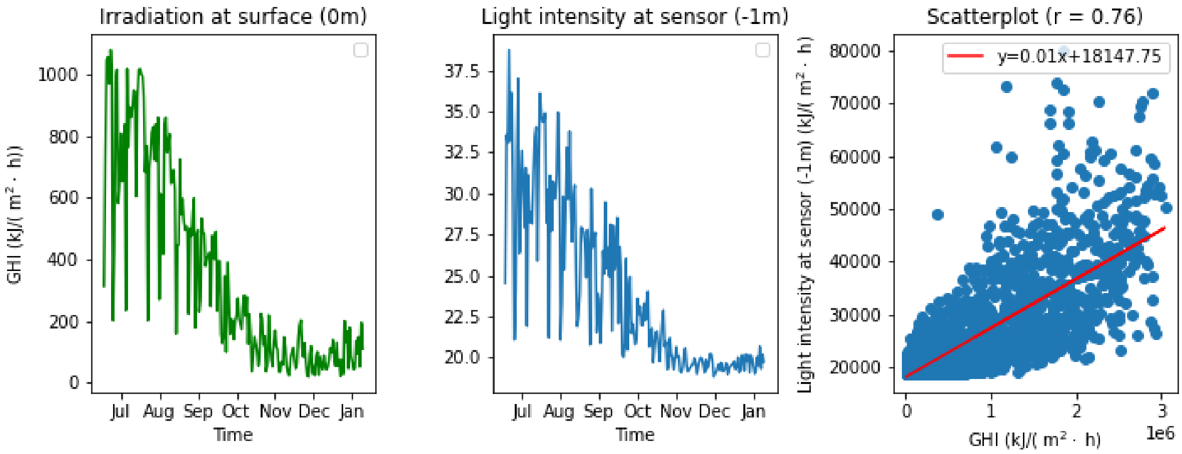

Figure 25: A) Plot of the daily average values of irradiation in open water and under the FPV system. The irradiation is measured at the surface at the closest KNMI station B) Plot of the daily average values of measured light intensity in open water and under the FPV system by the sensors. C) Scatterplot, regression line and regression equation with the irradiation as independent variable and the light intensity as dependent variable in open water. The light intensity is measured at a depth of 1 meter below water. Blue lines/dots indicate values of the sensor located in open water, the orange lines/dots represent measurements/estimations under the FPV system. Measurements were taken between July 14th and January 31th (202 days).

Water temperature

The temperature of the water under the panels increases by 1.67%. Therefore, in Oudehaske, it is likely that the heat released by the FPV system is slightly greater than the cooling effect caused by blocking sunlight.

The Pearson's r between air temperature and water temperature is 0.84 for open water and under the FPV system. Therefore it can be concluded that the air temperature has a strong linear relation with the water temperature. However, the water temperature is consistently a little higher than the air temperature throughout all months. This phenomenon occurs because water has a higher conductivity than air, causing it to cool down the panels. Additionally, the air temperature tends to be colder at night compared to daytime. However, the difference in temperature fluctuations for the water is relatively smaller, resulting in a higher average water temperature overall (Mu et al., n.d.).

In Figure 24 a time plot and a scatter plot are shown depicting the relationship between air temperature and water temperature.

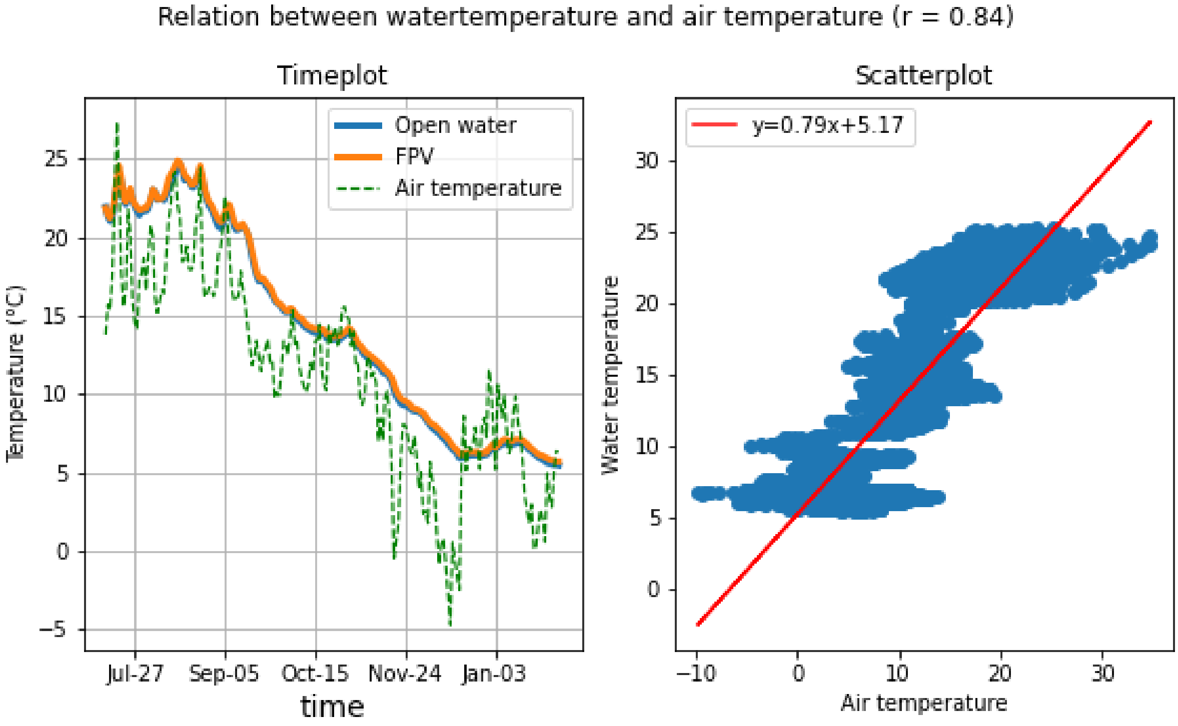

Figure 26: A) Scatterplot showing the relation between air temperature and water temperature in open water B) Plot of the daily average values of temperature in open water, under the FPV system and the air temperature. The water temperature is measured at a depth of 1 meter below water. Blue line indicate measurements of the sensor located in open water, the orange line represents measurements under the FPV system, green lines are measured temperatures at the closest KNMI station. Measurements were taken between July 14th and January 31th (202 days).

The correlation between irradiation and water temperature is 0.42, indicating a moderate linear relationship. Additionally, the correlation between wind speed and water temperature is -0.32, suggesting a moderate negative linear relationship between these parameters.

Conductivity

The conductivity under the FPV system is on average 10.21% higher than the conductivity in open water. Therefore, it is likely that the mounting structure of the FPV system may introduce metals into the water which increases the conductivity of the water. Among the weather and physiochemical parameters considered, only rainfall had the potential to impact conductivity. However, no linear relationship was observed. This could be attributed to the fact that rainfall can have both increasing and decreasing effects on conductivity, and these opposing effects offset each other.

Indirect effects

The FPV system indirectly affects the chlorophyll content, turbidity, and DO. The following sections will discuss how these changes occur due to the FPV system and which parameters have an influence on them.

Chlorophyll

Based on the review literature, the chlorophyll content can be influenced by light intensity and water temperature. The results have shown that both light intensity and chlorophyll decrease below the FPV system. However, the relationship between these two parameters is not linear, as the Pearson's r between light and chlorophyll in open water and below the FPV system are -0.1 and -0.0047, respectively. This is because factors other than the total amount of light also influence the chlorophyll content of the water. These may include the presence of nutrients and the amount of CO_2 in the water (Armstrong et al., 2020). Moreover, the species composition of phytoplankton varies across time and different types of phytoplankton contain varying amounts of chlorophyll (Reynolds, 2006).

Under the FPV system, there is a moderate linear relationship between water temperature and chlorophyll. However, no linear relationship is present in open water.

Turbidity

The turbidity can be affected by the chlorophyll, precipitation and wind. The Pearson's r for the relationship between chlorophyll and turbidity is 0.37 for open water and 0.5 below the FPV system. This indicates a moderate linear relation between these variables. This relationship is particularly clear at the end of July. Both the chlorophyll content and turbidity increase from July 14th to the peak on July 31st. The small peak slightly later on August 7th also corresponds to this. After that, the relation between chlorophyll content and turbidity becomes less clear. After August 21st, turbidity continues to increase while chlorophyll content remains fairly constant. One reason for this may be that there are more cyanobacteria in late summer instead of algae. Cyanobacteria contains less chlorophyll than algae (it is not known how much less). Therefore, it may be that the phytoplankton increases despite the constant chlorophyll. Due to this increase in phytoplankton, turbidity also increases. Between turbidity and windspeed and turbidity and precipitation no linear relation was found. Figure 27 displays the measured values of chlorophyll and turbidity for open water and below the FPV system. It also displays a scatterplot with chlorophyll as independent variable and turbidity as dependent variable.

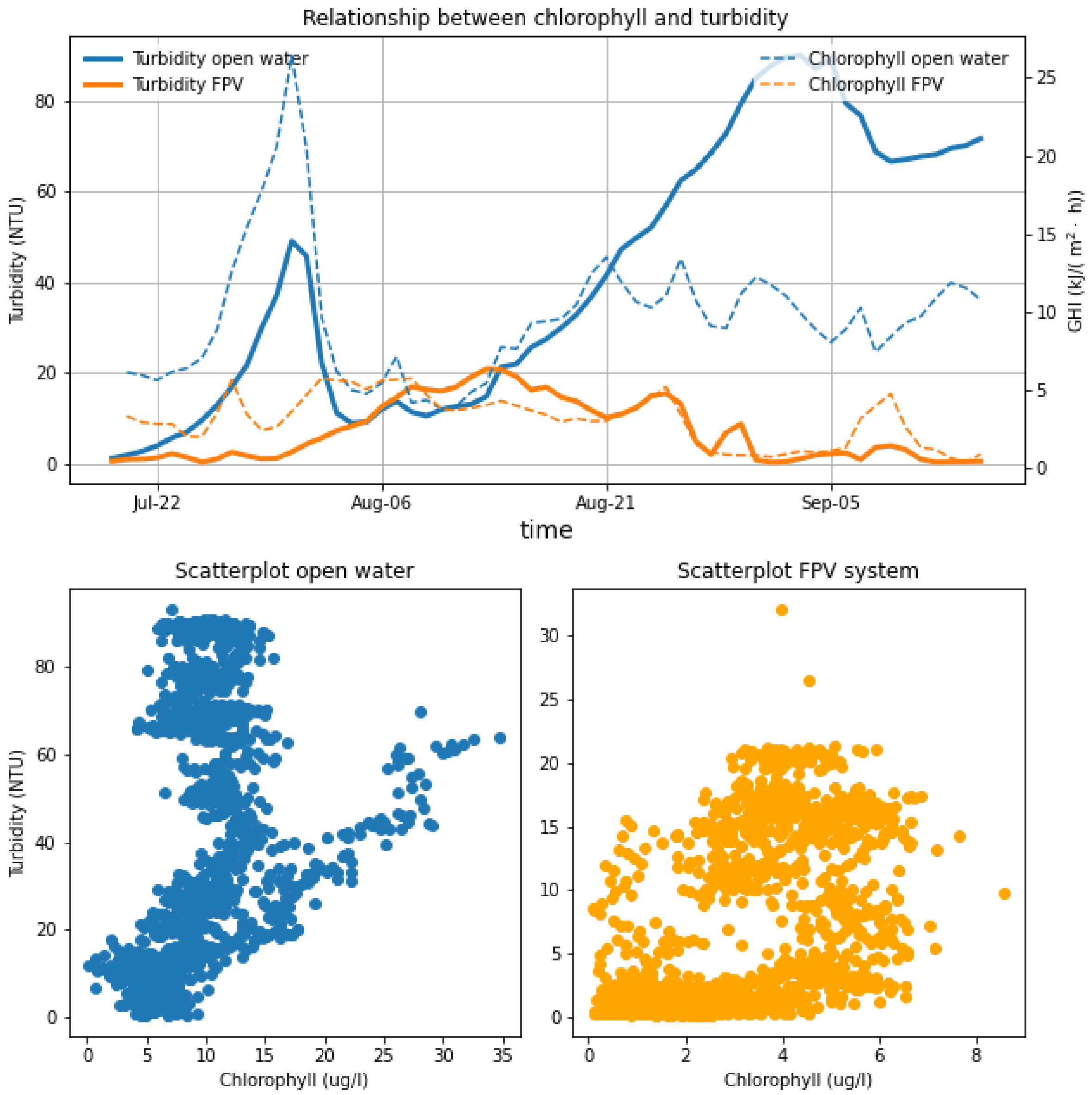

Figure 27: A) Plot of the daily average values of turbidity (bold line) and chlorophyll (dotted line) in open water and under the FPV system. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. Turbidity values are represented on the left y-axis. Chlorophyll values are represented on the right y-axis. B) Scatterplot with chlorophyll as independent variable and turbidity as dependent variable in open water. C) Scatterplot with chlorophyll as independent variable and turbidity as dependent variable under the FPV system. Both parameters are measured at a sensor depth of 1 meter. Measurements were taken between July 19th and September 15th (58 days).

Dissolved Oxygen

The oxygen concentration may be related to water temperature, chlorophyll content, and wind speed. The correlation between temperature and oxygen under the FPV system is 0.71 which indicates a strong positive linear relationship between these parameters. Under the FPV the correlation is 0.65 which indicates a moderate positive relationship. Therefore, the effect of thermal stratification is likely to be greater than the effect of reduced oxygen uptake in warm water.

From October 30 onwards, a remarkable decrease in the oxygen content is noticeable, with the lowest concentration being detected on December 30. Therefore, the expectation is that the thermal stratification reverses around the 30th of October

Figure 28 illustrates a time plot of the DO concentration and the water temperature in open water and under the FPV system.

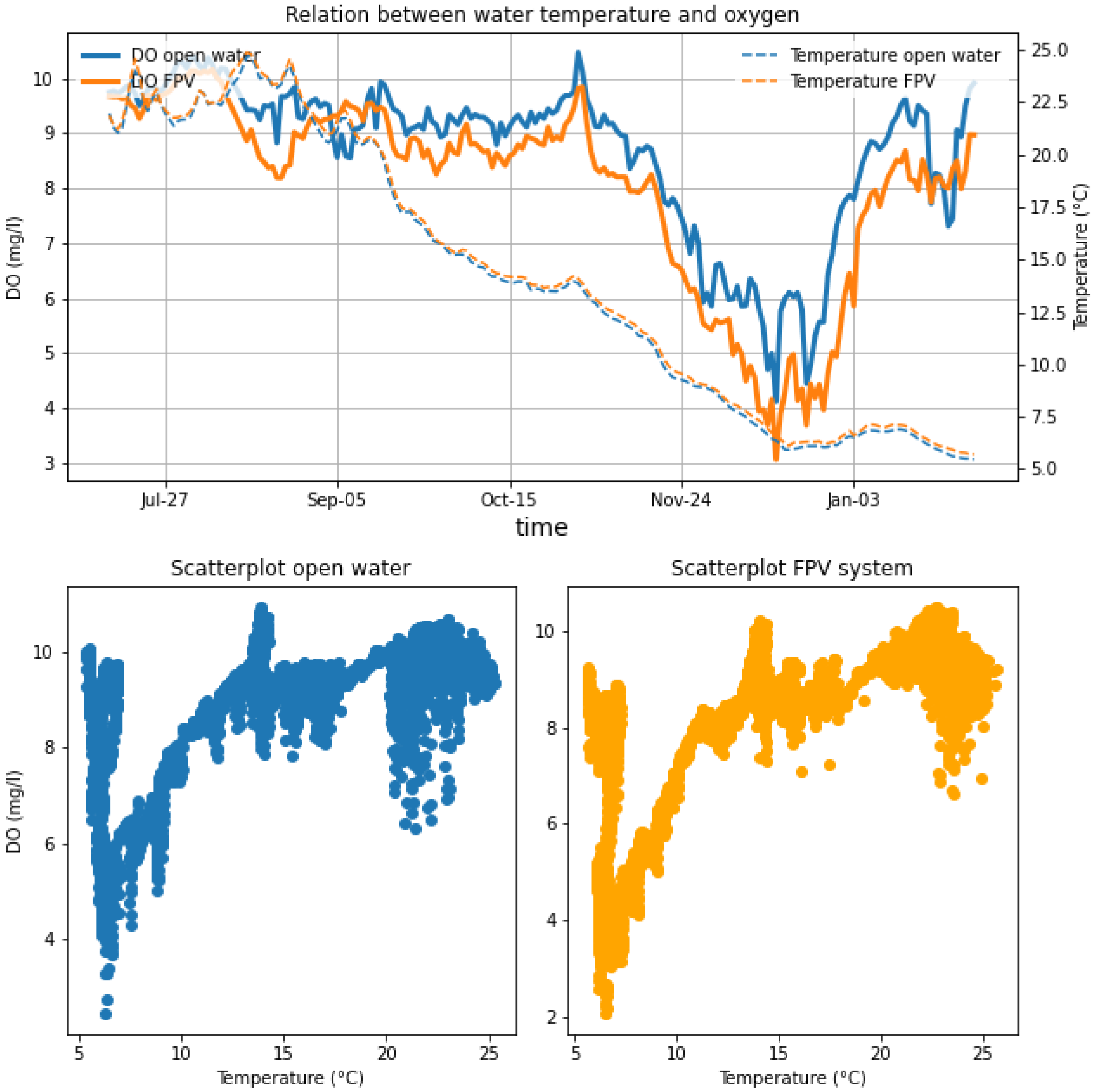

Figure 28: Plot of the daily average values of DO (bold line) and temperature (dotted line) in open water and under the FPV system. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. DO values are represented on the left y-axis temperature values are represented on the right y-axis. B) Scatterplot with temperature as independent variable and DO as dependent variable in open water. C) Scatterplot with temperature as independent variable and DO as dependent variable under the FPV system. Chlorophyll values are represented on the right y-axis. Both parameters are measured at a sensor depth of 1 meter. Measurements were taken between July 14 and January 31 (202 days).

Even though the relation between water temperature, stratification and DO is interesting to consider, it does not explain the decrease in oxygen content caused by the FPV system. This is because the FPV system leads to an increase in water temperature, but to a decrease in oxygen content. Since the correlation between these parameters is positive, the increase in temperature under the FPV system will not explain the decrease in oxygen under the FPV system.

Given that the oxygen concentration in water is influenced by multiple factors, it is challenging to identify the primary cause of the observed decrease in DO levels due to the FPV system in Oudehaske.

Two reasons have been mentioned most in the literature to explain the decrease in DO under the FPV system. First, there is less chlorophyll present under the FPV system which decreases the oxygen produced. From the results becomes clear that both parameters decrease below the FPV system. However no linear relation is identified between these parameters, The correlation in open water is 0.049, and the correlation under the FPV system is 0.2. Secondly, the reduced windspeed could lead to a reduced uptake of oxygen by the waterbody. However, no linear relationship was found between these two parameters, as the correlation for both open water and under the FPV system is less than 0.1.

Correlation coefficients

Figure 29 presents all correlation coefficients between the weather parameters and the physiochemical parameters. In Figure 30, the Pearson's r between the physiochemical parameters are displayed for both open water and under the FPV system. Figure 31 illustrates the Pearson’s r for the physiochemical parameters that exhibit a moderate or strong linear relationship, with Pearson’s r of 0.3 or higher.

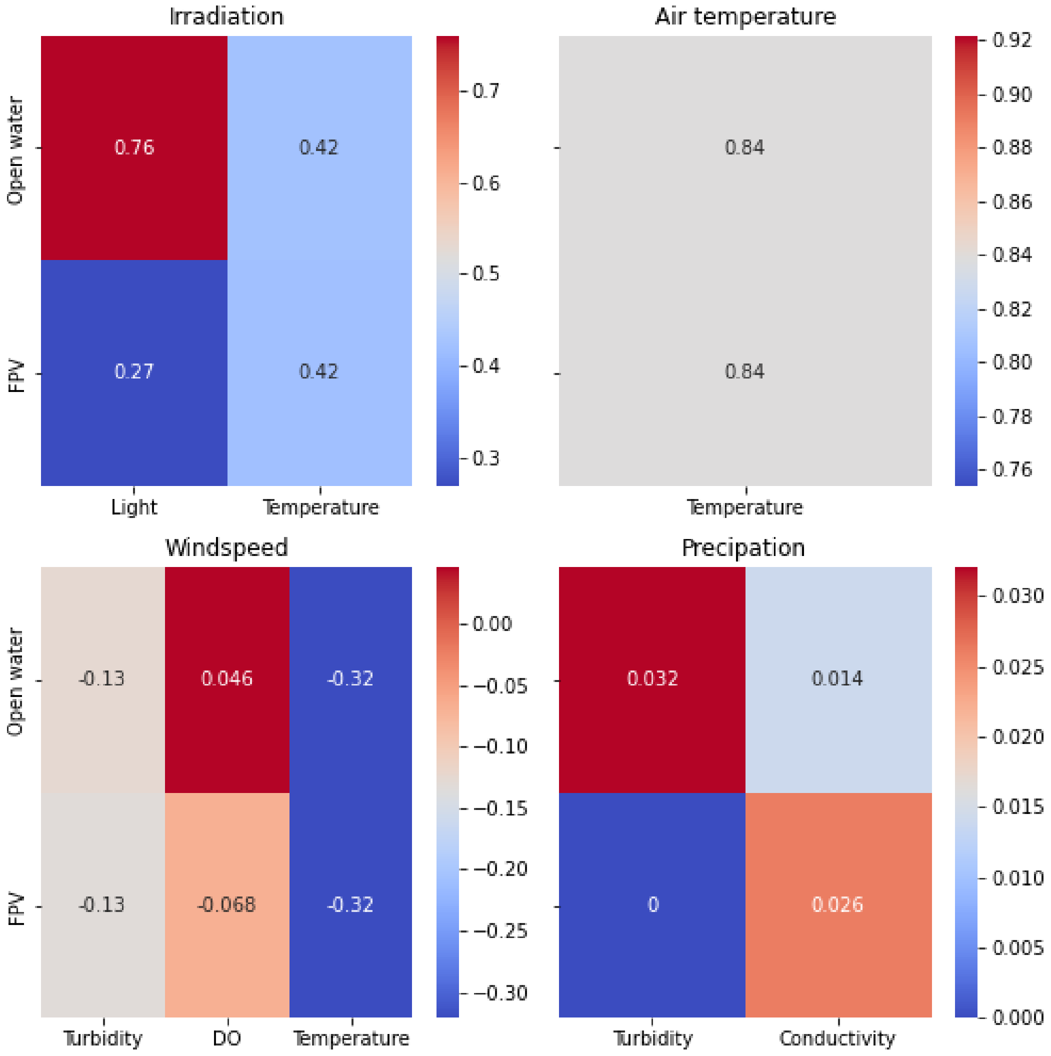

Figure 29: Correlation between GHI and the ecological parameters light and temperature in open water and under the FPV system. B) Correlation between air temperature and water temperature in open water and under the FPV system in open water and under the FPV system. C) Pearson’s r between the weather variable windspeed and ecological parameters turbidity, DO and temperature in open water and under the FPV system D) Pearson’s r between precipitation with turbidity and conductivity

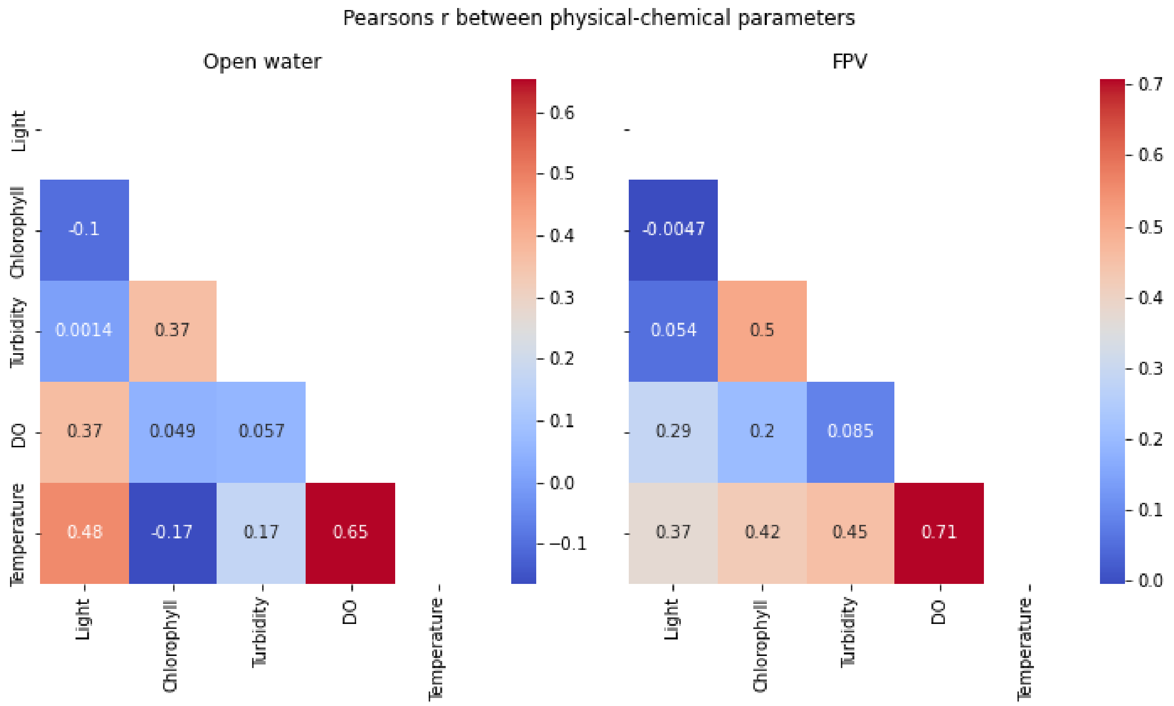

Figure 30: A) Pearson's r for all ecological parameters in open water B) Pearson's r for all physiochemical parameters under the FPV system

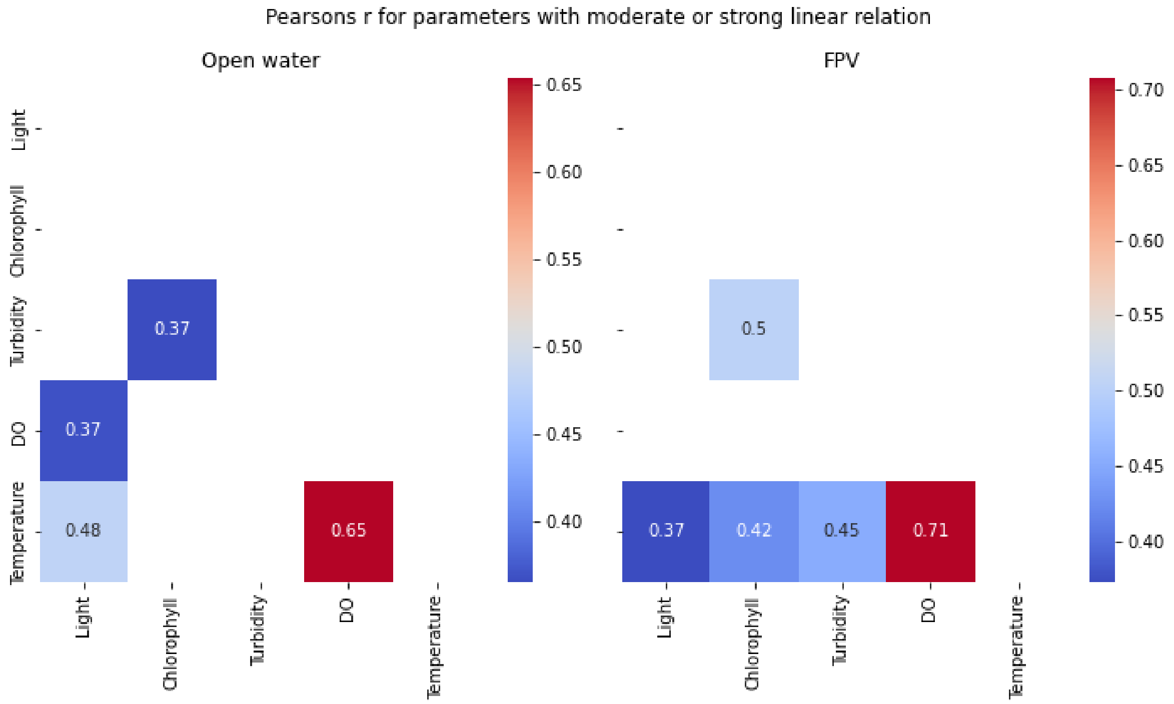

Figure 31: A) Pearson's r for all physiochemical parameters in open water with a Pearson's r of more than 0.3 B) Pearson's r for all physiochemical parameters under the FPV system with a Pearson's r of more than 0.3

In Appendix F more time plots and scatterplots can be observed between weather parameters and the physiochemical parameters, as well as between different physiochemical parameters.

5. Discussion

In this section, the theoretical implications are first discussed, followed by the identified research limitations and possibilities for future research.

Theoretical implications

Scientific relevance

According to freshwater FPV models, it was anticipated that these systems in the Netherlands would generate approximately 3% more electricity compared to land-based systems. This increase can be attributed to the water's ability to lower the cell temperature of the FPV system, thereby enhancing its overall efficiency (Dörenkämper et al., 2021a).

However, it should be noted that models are less precise than data analysis, as they rely on various estimations. This study provides a more precise assessment of the technological performance of a freshwater FPV system by analyzing collected data from the system. The findings confirm that a freshwater FPV system outperforms a LBPV system in terms of electricity generation, particularly during the summer months with higher irradiation levels. The lower cell temperature of the FPV system is identified as the primary factor contributing to this advantage. However, other factors such as reduced dust accumulation on the FPV system and fewer shading objects in the surrounding environment may also play a role in the observed performance differences.

The literature highlights several key environmental advantages of freshwater FPV systems. Firstly, the presence of FPV systems in water bodies creates underwater surfaces that promote the colonization of mussels. Secondly, these systems have been found to decrease the levels of toxic cyanobacteria. Lastly, FPV systems have the potential to improve water clarity (Armstrong et al., 2020; DELTARES, 2020).

This study further validates these advantages, revealing that the impact on water clarity is even more significant than initially anticipated. The turbidity reduced with 88% beneath the FPV system. This reduction in turbidity is advantageous as it enhances underwater light availability, facilitating improved visibility for fish and their ability to locate and capture prey (DataStream, 2023c).

From the literature becomes clear that the main environmental disadvantage of FPV systems is their light-blocking effect, which hampers photosynthesis, which in turn limits the growth of phytoplankton and aquatic plants (Jones & Armstrong, 2021). It is anticipated that the impact on algae will be greater than on bacteria, as bacteria are less reliant on light for growth (Pimentel Da Silva & Branco, 2018). Additionally, a decrease in oxygen content is expected under the FPV system, primarily due to the reduced presence of phytoplankton and aquatic plants, which are significant oxygen producers (DELTARES, 2020).

The effect on light intensity had not been quantified for a large-scale FPV system in the Netherlands until this study. It is the first to provide data showing a significant decrease of 24.5% in light intensity one meter below the water surface due to the FPV system. Additionally, there was a lack of previous research quantifying the impact of the FPV system on phytoplankton volume using probes in the Netherlands. Therefore, this study utilized probes to measure the chlorophyll content, as it serves as an indicator of phytoplankton presence. The findings revealed a 59% reduction in chlorophyll levels during the measurement period, suggesting a corresponding decrease of approximately 59% in phytoplankton under the FPV system.

Furthermore, this study confirms that the reduction of algae is larger than the reduction of phytoplankton by creating a model that estimates that the average impact of the FPV system on the growth efficiency of algae and cyanobacteria. From the model becomes clear that on the water surface the impact on the growth efficiency of algae is 10% higher than the impact on the growth efficiency of cyanobacteria in Oudehaske. However, at one-meter depth, there is no difference, and both types are equally influenced by the FPV system. The decrease in algae caused by the FPV system has indirect effects on macrofauna and fish, as algae serve as a vital food source for these species (STOWA, 2020).

Within the Netherlands, already for two FPV systems a decrease in oxygen content under the panels have been observed (R. L. P. de Lima et al., 2021; Ziar et al., 2021). However, because the effects of an FPV system are context-specific, it is important to evaluate the effect of the FPV system on the oxygen content for more locations. This study confirmed that the oxygen concentration in Oudehaske also decreases under the panels. Previous studies predicted that reduced oxygen levels could impact fish populations. This study further investigated this issue and found that the FPV system creates less favorable living conditions for fish. This is mainly a problem in December when the oxygen concentration in the lake is already naturally low. At the location of the probe under the FPV system, there are seven days in December with such low oxygen that it is insufficient for any fish species to breathe. This does not occur in open water.

Currently, the impact on fish may not be significant as the fish can swim to other locations if there is insufficient oxygen at the probes location. However, this study demonstrates that there is an impact on the fish even with only 11% coverage. The impact on phytoplankton will be greater since they are unable to move themselves within the water.

The existing literature has provided limited insight into the interplay among the effect of the FPV system, weather conditions, and various physiochemical parameters. This study explores these relationships, presenting a flowchart, plots, and insights into the interconnectedness of these factors.

This study has revealed that the FPV system directly influences three of the measured physiochemical parameters: light intensity, conductivity, and water temperature. Among these parameters, the effect on light intensity is by far the most significant for the ecosystem. It is expected that the impact on light intensity results in both lower chlorophyll levels and lower oxygen concentration, which are the primary concerns associated with the FPV system.

As became clear from previous results the effect of the FPV system on the chlorophyll and DO are substantially influencing the ecosystem. The chlorophyll is positively related to the light intensity and the water temperature. The oxygen content is positively related to the chlorophyll, the water temperature and windspeed. Even though these parameters are related, there is no linear relationship found between them. From this research, it becomes clear that only linear regression is a suitable method for predicting the relationship between air temperature and water temperature, as well as between irradiation and light intensity in open water. For the other relationships, linear regression might not be a suitable method. This is not surprising because a lake is a complex system where multiple factors influence each other.

The literature study on the technological performance of offshore FPV systems has revealed that it is expected that offshore FPV can outperform LBPV system, mainly due to the cooler PV panels. However, further technological development of these systems is necessary to ensure this. As highlighted in the literature, this study emphasizes that the main challenge in offshore FPV lies in improving system design to ensure reliability and economic viability.

The literature and experts concur that offshore FPV can be implemented on a larger scale compared to freshwater FPV, while causing fewer environmental impacts (Nurmi & Mcdonald, 2022; Soppe et al., 2022). For a large-scale implementation, the primary expected effects are on phytoplankton due to reduced light availability. Also for offshore systems it has been seen that mussels are attached to the system.

Social relevance

Due to the relatively new nature of FPV systems, the impact of installing an FPV system on water quality and aquatic ecology is still largely unknown. This research has contributed to the knowledge development regarding FPV systems in the Netherlands, which is essential for scaling up these systems. When these systems can be implemented in more locations and on a larger scale, it will aid in achieving the Dutch objectives of the climate agreement, which aims to generate 70% of electricity from sustainable sources by 2030 and nearly 100% by 2050. It is crucial to reach these goals due to the increasing energy demands, fast depletion of fossil fuels and the need to decarbonise in the Netherlands. This research has contributed to this aim in five manners.

Firstly, FPV systems in the Netherlands are primarily installed in water bodies with low ecological value, such as sand pits. With the created knowledge about the ecological impact and the direct and indirect impacts of the FPV system, obtaining permits for installing these systems in water bodies with higher ecological value will become easier.

Secondly, this study has demonstrated that an FPV system significantly reduces water turbidity and decreases the presence of cyanobacteria. For lakes experiencing any of these issues, this can serve as an additional motivation to install FPV systems.

Thirdly, with the new/confirmed knowledge that the FPV system primarily has a negative effect on chlorophyll and oxygen, mainly due to the reduction in light availability, and considering the understanding of the interrelation between weather and various physicochemical parameters, it is possible to enhance existing models that predict the impact of an FPV system on the environment. The development of modelling capabilities to explore the impacts of FPV across water body types and FPV designs is important to better predict the effect of FPV on the water quality. Besides, the impact of the FPV system on the physiochemical parameters across different types of waters will be understood better (Pedroso De Lima et al., 2022). Additionally with improved modelling capabilities more is known about how the negative effects of the FPV system occur. With this knowledge research can help and look at manners to mitigate the negative environmental effects of the FPV system. Besides, the system design can be improved, and the optimal size of the system without any negative impact on the environment can be better determined.

Fourthly, by evaluating the energy yield of the FPV systems in comparison to the LBPV system this research has validated the hypothesis that FPV systems outperform LBPV systems. Besides, knowing the energy yields help determine the optimal size and layout of solar panels. Comparing the energy yield of the FPV systems with a LBPV system gives information which can be useful for decision-makers who need to choose between these two renewable energy options. Besides, by computing the energy yield and CF for each month, opportunities can be identified for optimizing energy production, such as adjusting the orientation of the solar panels or increasing the capacity of energy storage systems.

Lastly, For offshore FPV this study has contributed to the current literature by summarizing the existing literature on the environmental aspects of offshore FPV in the Netherlands, supplemented by interviews with experts. This provides a comprehensive understanding of the current knowledge on offshore FPV and identifies areas for future research to further develop this technology and ultimately enable its large-scale implementation. The next paragraph will delve deeper into the ideas for future research.

Research limitations

This paragraph will first discuss the limitations of the case study done for the freshwater FPV system in Oudehakse. Subsequently, the other limitations of this research will be addressed.

Case study Oudehaske

In the case study of Oudehaske, four primary research limitations have been identified.

First of all, the case study for the freshwater FPV system was conducted over a period of 6.5 months. However, for a better assessment of the technological performance and environmental impact data of at least one year and preferably several years should be evaluated. This is important because the technological performance and environmental impact of the FPV system varies over time. Besides, some ecological impacts of floating solar may take longer to manifest and it is interesting to evaluate if all seen impacts are occurring every year. Also when sensors are broken for a portion of the time (like what happened to the chlorophyll and turbidity sensor) a sufficient amount of data will remain to analyse the impact of the FPV system on these parameters. Additionally, each year exhibits different weather conditions, which can result in varying effects of the FPV system for different weather circumstances. Despite being a study of 6.5 months, the results are still reliable. The time plots show that the FPV system consistently influences the analyzed parameters positively or negatively throughout almost the entire period. While the percentage of the FPV system's effect on the physical chemical parameters may vary slightly if observed over a year, it is expected that the overall impact of the FPV system on the environment will remain comparable.

Secondly, there is no available data of the physiochemical parameters regarding the environmental impact of the FPV system prior to its installation. It is possible that the impact of the FPV system extends beyond the area directly beneath it and also affects the water quality in open water. Consequently, in order to conduct a comprehensive study on the environmental impact of the system, it is necessary to collect data on water quality parameters prior to installation. In addition, a more accurate assessment of the ecological impact can be made if there is more information available on the species of phytoplankton, macro-invertebrates, and fish present prior to the installation of the system. For phytoplankton, it is important to know how much of the phytoplankton are algae or bacteria. To make an estimation nonetheless, a model was developed for this study that examines the effect of light on the algae and bacteria. To assess the impact of the FPV system on macroinvertebrates in Oudehaske, the effect was estimated based on a comparable FPV system at Bomhofplas, which used identical panels and made underwater videos with drones to evaluate if macroinvertebrates were attached to the system. The effect of the FPV system on fish could be better evaluated if information is available about the current fish species present. This would allow to look up how well these fish can thrive in low-oxygen environments. If the fish are well-adapted to low-oxygen conditions, the impact of the FPV system on the fish would be less substantial than if the fish have poor tolerance for low-oxygen environments. To estimate the potential impact on fish, an assessment was made based solely on the survival of fish species under various oxygen concentrations in the lake.

Thirdly, the water quality parameters are only measured at one point underneath the system in the middle of the panels leaving the impact of the FPV system on the environment unknown for other locations and depths. Despite this limitation, this study provides a good understanding of the general impact of a FPV system on the environment.

Fourthly, this study reveals that the impacts on chlorophyll and DO have the most significant effect on the waterbody's ecosystem. However, the study has insufficient available data to explain the decrease in chlorophyll and oxygen caused by the FPV system. Two important parameters are missing in this study. Firstly, there is a lack of data on nutrient concentrations in open water and under the FPV system. It is anticipated that the FPV system has an influence on nutrient levels, which can subsequently impact algae growth as algae rely on nutrients for their growth. Furthermore, it is expected that the FPV system influences water flow as the wind has less grip on the water beneath the panels. This is an important effect because, as observed in this study, wind influences water turbidity, temperature, and DO concentration.

Other limitations

Another limitation of this research is that too little locations within the Netherland, currently there are only 5 location within the Netherlands that have collected data of the physical chemical parameters and quantified the impacts of FPV on these parameters within the Netherlands. These studies are measuring effect of the FPV system on different physiochemical parameters. This makes it challenging to compare findings across different studies and locations. Additionally, out of these 5 locations, 3 locations are deep sand extraction pits which have very similar water body characteristics.

Additionally, for this research five assumptions have been made that could potentially have a minor impact on the results.

First of all, during this study the fact that 10% of the incident light on the FPV panels is reaching the water surface underneath the panels is estimated by the supplier of the panels Groenleven.

Secondly, for the determination of the effect of the light intensity on the phytoplankton composition, the model is created based on the light intensity during the day, however, in some occasions phytoplankton could also grow during the night since little light is available as well. Also the effect the FPV has on the water temperature can have an impact on the phytoplankton, but due to time constraints this is not considered in this study. Due to the substantial difference in light levels between day and night, and the relatively larger impact of the FPV system on light intensity compared to water temperature, it is not anticipated that incorporating these two factors into the model would yield significantly different results. However, future research could consider including these factors to assess their potential influence on the outcomes.

Thirdly, the data used for the air temperature at the KNMI station is measured data from the nearest station. However, the ambient temperature of the FPV site could be lower compared to the temperature of the KNMI station due to the evaporation of water in that area.

Fourthly, the cell temperature on the FPV system has been measured at only three points on the panel, and the average has been taken from those measurements. To determine the cell temperature of the FPV system more accurately it should be measured at more locations on the panel.

Lastly, for the LBPV system it is assumed that there are 14% losses due to losses such as shading, mismatch, wiring. Also for the offshore model which predicted the technological performance indicators of the offshore FPV system some estimations have been made. These estimations are mentioned in (Vido, 2022).

Even though these assumptions could change the results a little, it is not expected that the estimates will deviate significantly from the actual values and impact the results of this study.

Future research

Future research should prioritize the collection of additional data during case studies, comprehensively mapping the variations in technological performance and environmental impact across different conditions, and enhancing the design of freshwater and offshore FPV systems. The following sections delve deeper into these options.

Data case studies

For future case studies about the environmental impact of FPV systems, it is advisable to measure not only the parameters recorded in this study but also the water flow and nutrient concentration in the lake. To measure the water flow, flow meters can be installed to measure both the direction and velocity of water in open water and beneath the FPV system. The nutrients can be measured using the same probes that are used for measuring temperature, conductivity and DO in Oudehaske (Eijkelkamp Soil & Water, 2021). To comprehensively evaluate the FPV system's effect on these parameters, measurements should be taken across the entire water column beneath the system for at least one year at a hourly time resolution. For this type of study, the implementation of cost-effective monitoring methods that utilize intelligent and remote/automated measuring devices can contribute to a better analysis of the environmental advantages and disadvantages of an FPV system in the Netherlands (R. L. P. de Lima et al., 2021).

To gain a better understanding of the environmental impact of the FPV system, data is also needed on the physiochemical parameters, phytoplankton, and fish prior to the implementation of the FPV system. It is recommended to install probes/sensors measuring the physiochemical parameters at least one year before the implementation of the FPV system. For the phytoplankton, regular samples should be taken that provide information on the types of phytoplankton present in both open water and beneath the FPV system. Based on this data, it can be determined whether the FPV system has a greater impact on algae or bacteria. Underwater videos can be obtained using a drone to examine whether and how much macroinvertebrates are present on the FPV system.

Change of impact across different designs and locations

Future research can gain insight into how the effect of an FPV system varies for different designs and locations in the Netherlands in two ways.

Firstly, future research should prioritize conducting a comprehensive comparative study encompassing various waterbodies across the Netherlands, each possessing distinct characteristics (e.g. shallow and deep lakes and sandpits and drinking water reservoirs) and implementing different percentages of solar panel coverage on the lakes. Within this study a standardised measurement method should set up. The results of the different locations should be compared

Secondly, future research should focus on improving models that predict the impact of the FPV system on the environment. With enhanced modeling capabilities, the indirect effects of the FPV system can be better understood. This is important because the results have shown that the indirect consequences of the FPV system, such as reduced chlorophyll and oxygen levels, have adverse effects on the lake's ecology. By improving the models, a better understanding can be gained of the origins of these indirect effects, which is crucial for mitigating them in the future. Additionally, the models can better predict the maximum size and power output of the FPV system with minimal impact, particularly on the oxygen and chlorophyll content of the waterbody. To ultimately predict the effects of the FPV system under these various conditions, the development of modelling capabilities is crucial. Furthermore, alternative regression methods can be utilized to analyze the relationship between weather conditions and physiochemical parameters, providing a more comprehensive understanding of the decrease in chlorophyll and DO caused by the FPV system. Additional information on this topic can be found in Appendix I.

Design improvement

Lastly, future research should focus on improving the design for freshwater and offshore FPV systems to enable their larger-scale implementation and to maximize the electricity output while minimizing the ecological impact.

For freshwater FPV systems, design improvement should focus on achieving more light underneath the FPV system since the adverse effects on the environment primarily arise from reduced light under the panels. This could include alternative panel materials, different size of the FPV system, more space between the panels, panels with increased light transmittance, panels located at a different location on the lake or lamps under the panels.

For offshore FPV, only environmental impacts are expected when implemented on a large scale. Consequently, it is necessary to first install these large-scale offshore installations. Therefore, future research should focus on the technological development of these systems. TNO has identified the most important research topics for the technological development of offshore solar in the Netherlands to make the technology reliable and economically viable (Soppe et al., 2022).

6. Conclusion

This thesis aimed to answer the research question: *“What are the environmental and technological advantages and disadvantages of freshwater FPV and offshore FPV for the systems in the Netherlands?”*

The technological advantages and disadvantages were evaluated by comparing i.e. the energy yield and cell temperature of a LBPV, freshwater FPV and offshore FPV system. To assess the environmental impact first a case study was done for the FPV systems to determine the environmental advantages and disadvantages for that system. Thereafter, the interaction between the effects of the FPV system, the weather conditions, and environmental impacts was examined.

The results indicate that freshwater FPV systems do not exhibit significant technological disadvantages. This mature technology provides higher power output compared to a LBPV system, especially during the summer months with increased irradiation. Freshwater FPV systems also offer several environmental advantages. Firstly, they create underwater surfaces that promote the colonization of mussels. Secondly, these systems have been found to decrease levels of toxic cyanobacteria. Lastly, they have the potential to significantly improve water clarity by reducing water turbidity.

The primary disadvantage of freshwater FPV systems is the adverse impact on the environment caused by reduced light availability beneath the platform. This diminished light availability results in decreased algae growth below the system. Additionally, there is a decrease in oxygen under the FPV system, primarily due to the reduced presence of phytoplankton and aquatic plants, which are significant oxygen producers. This is mainly a problem for fish in December when the oxygen concentration in the lake is already naturally low.

This study highlights that the indirect effects of the FPV system on chlorophyll and DO are the main drawbacks of the freshwater FPV system. Chlorophyll levels are positively correlated with light intensity and water temperature. The oxygen content is positively correlated to the chlorophyll, the water temperature and windspeed. Even though these parameters are related, there is no linear relationship found between them.

The estimate is that a offshore FPV system has a higher efficiency than a LBPV system, mainly due to the cooler PV panels. Besides, offshore FPV can be implemented on a larger scale than freshwater FPV, with fewer environmental impacts. However, currently offshore FPV is not competitive yet with LBPV and freshwater FPV systems in terms of costs and reliability.

Freshwater FPV systems and offshore FPV systems can both assist the Netherlands in achieving its climate objectives. However, further development is required for both technologies to fully realize their potential in this regard. For freshwater FPV, it is recommended to conduct further research to mitigate/minimize the effects of reduced light, enabling its implementation on a larger scale without adverse ecological impacts. Additionally, it is recommended to enhance models that can accurately predict the environmental impact of the freshwater FPV system. With improved models a clearer understanding of the indirect effects on chlorophyll and oxygen levels, which have adverse ecological implications for the lake, can be obtained. Additionally, improved models enable researchers, policymakers, and private developers to make more accurate determinations regarding the optimal size and layout of the FPV system, ensuring minimal impact on water quality and the living environment. For offshore FPV, future research should prioritize the technological advancements of these systems to ensure their reliability and economic viability.

7. Acknowledgements

I would like to express my gratitude to Dr. Sara Z. M. Golroodbari, a researcher at Utrecht University, and Anna Duden, also a researcher, for their invaluable supervision of my thesis. Their insightful feedback and suggestions greatly improved my work. I would also like to thank Miguel Dionisio Perez, an aquatic ecologist at Deltares, for his guidance during my internship and thesis, and for always being available to answer my questions. I am grateful to Deltares employees Sacha de Rijk, an advisor in freshwater ecology and water quality, and Tineke Troost, an expert in ecological modelling, for their helpful discussions and for answering my questions about this research.

Additionally, I would like to thank the individuals who shared their expertise through interviews. Johan van der Molen from NIOZ, Luca van Duren and Lisa Schneider from Deltares provided valuable insights about the ecological impact of FPV in the offshore environment. Hesan Ziar, an Assistant Professor at TU Delft, Willem Biesheuvel, a developer of sustainable energy projects at Groenleven, Dr. Sara Z. M. Golroodbari from the University of Utrecht, Paula van Lieshout, a project manager at Solar Duck, and Marco Huisman, a scientist in maritime and offshore technology at TNO, provided information about the technological advantages and disadvantages of freshwater and offshore FPV. I also would like to thank Ruben van Eldik and Dana Westbeek for helping me with my python code.

8. Appendix

Appendix A – Calculation of light intensity and corrected conductivity

Light intensity

The light intensity of the Eijkelkamp system is measured in mA. To convert this to $kJ/(m^2 * h)$ two conversion values are used. The conversion value of this sensor is 0.0059 microamps per micromole $s^{-1}m^{-2}$. The conversion value of micromole to watt is equal to 0.22. Therefore, to compute the light intensity in the following equation is used.

$$Light_t = Light(\mu A) * 0.0059 * 0.22 * 3600$$

For these days interpolation of the data is used to replace the missing values.

Corrected conductivity

The probes in Oudehaske measured the conductivity. However, because this conductivity is very temperature dependent it is best to evaluate the corrected conductivity for a temperature of 25 °C. To convert the values the temperature coefficient of variation is used. The Temperature Coefficient of Variation is the rate at which a solution's conductivity increases with an increase of temperature and is expressed as the percentage increase in conductivity for a temperature change of 1°C. The Temperature Coefficient of Variation is different for each solvent / solute mixture, but after much research, Aquaread scientists settled that 1.91% / °C at 25°C is a suitable correction factor for environmental water. Aquaprobes measure the electrical conductivity at the sample temperature (Bier, 2018). The Aquaprobes also measure temperature, so using these two values it is possible to refer to the absolute EC measurement at both 25°C using the following formula:

EC(25C) = EC(ABS) / (((Temp - 25) x 0.0191) + 1)

Appendix B – Effect physiochemical parameters

In this appendix, a more extensive analysis has been performed on the time plots of the analyzed physical-chemical parameters. Besides, to better predict the effect of the FPV system on the ecological variables a linear regression is performed to determine the effect of the independent variable (the measured values of the parameters in open water) on the dependent variable (the measured value under the FPV system). The result is an estimated linear equation that can be used to make predictions about data (Investopedia, 2023). Additionally, the R-squared value is calculated for each parameter. R-squared is a goodness-of-fit measure for linear regression models. If the R-squared value of the linear regression line is lower than 0.7, a linear regression is not suitable to determine the effect of the FPV system on an ecological parameter.

Light intensity

The measured light intensity at the sensor under the panels is on average 18.2% lower than the light intensity in open water. The degree to which the light intensity decreases is highly dependent on the total light exposure. In the summer months, when there is more sunlight, the light intensity can decrease up to -19039 kJ/(m^2*h) (49.1%) which was the light intensity difference measured on the 17th of July. On dark days in winter, the difference in light intensity can be just 44 kJ/(m^2*h) (-0.8%), which was the difference in light intensity measured at the 23 of December. Figure B shows the average light intensity under water for each day during the measurement period and shows a scatter plot with light intensity in open water as independent variable and the light intensity under the FPV system as dependent variable.

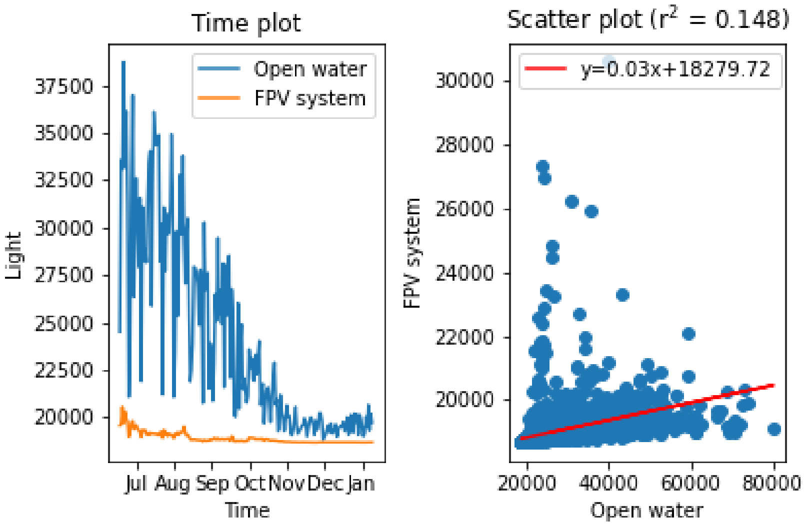

Figure B32: a) Plot of the daily average values of light intensity in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and January 31 (202 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Chlorophyll

On average, chlorophyll decreases by 6.2 µg/L (-59.1%) under the system. This difference reaches its maximum at 22.8 µg/L (-96.9%) on July 31. Shortly thereafter, the chlorophyll content in open water drops. On August 8, the chlorophyll content under the FPV system is even 1.6 µg/L higher. The R-squared value of chlorophyll is equal to 0.009 which is lower than 0.7. Therefore, a linear regression is not a good method to determine the effect of the FPV system on this parameter.

Figure B2 shows the average chlorophyll content for each day during the measurement period and shows a scatter plot with chlorophyll in open water as independent variable and the chlorophyll under the FPV system as dependent variable.

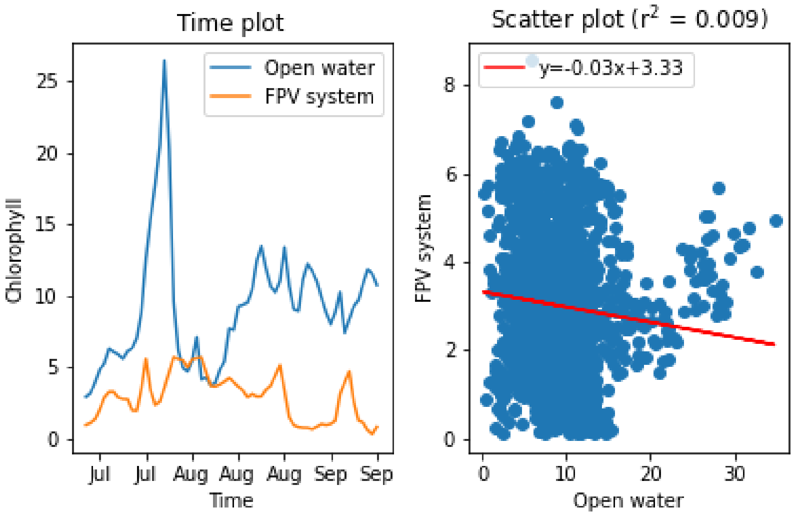

Figure B33: a) Plot of the daily average values of chlorophyll in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and September 15 (63 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Turbidity

The measured values of turbidity under the FPV system are lower than the measured values in open water. The measured values under the FPV system are on average 36.5 NTU (76.2%) lower than the measured values in open water. Especially in September and October, the difference in measured turbidity values is substantial. On September 2, the measured difference is the largest (89.2 NTU, -99.7%)). During almost the entire measurement period, the turbidity of the water under the FPV system is lower, except for mid-August. On August 12, the measured turbidity under the FPV system is 6.1 NTU higher. The R-squared value of turbidity is equal to 0.032 which is lower than 0.7. Therefore, a linear regression is not a good method to determine the effect of the FPV system on this parameter B3 shows the average turbidity for each day during the measurement period and shows a scatter plot with turbidity in open water as independent variable and the turbidity under the FPV system as dependent variable.

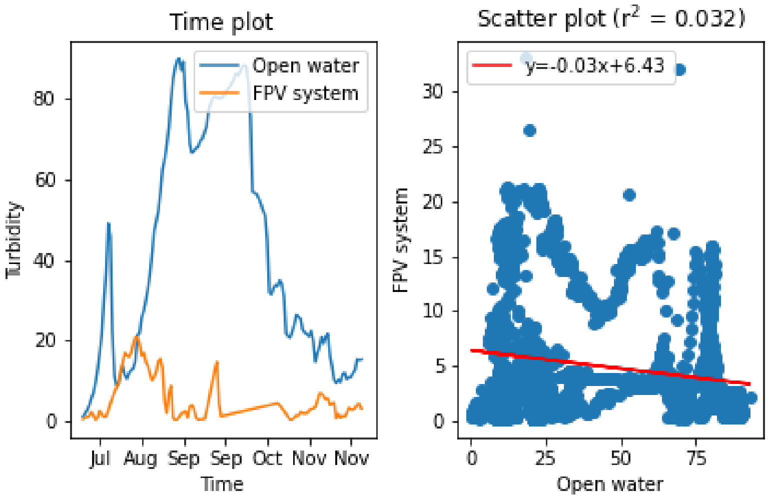

Figure B34: A) Plot of the daily average values of turbidity in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 19 and November 29 (63 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Conductivity

The measured conductivity values are higher at the sensor under the FPV system compared to open water. On average, the conductivity content increases by 37.4 uS/cm (10.5%) under the FPV system. Especially in August, September, and October, the difference between the measured values in open water and under the FPV system is substantial. The difference is maximum at 63.4 µg/L (-96.9%) on October 30. The R-squared value of conductivity is equal to 0.691 which is lower than 0.7. Therefore, a linear regression is not a good method to determine the effect of the FPV system on this parameter. Figure B4 shows the average conductivity for each day during the measurement period snd shows a scatter plot with conductivity in open water as independent variable and the conductivity under the FPV system as dependent variable.

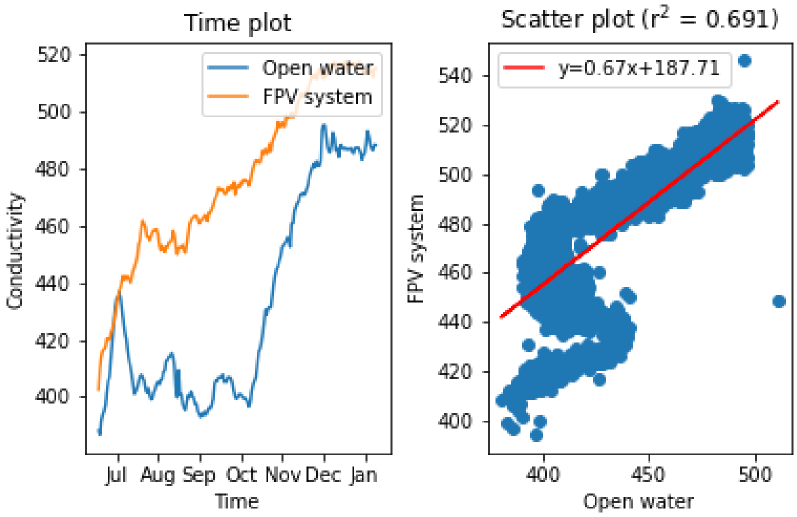

Figure B35: A): Plot of the daily average values of conductivity in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and January 31 (202 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Dissolved Oxygen

The oxygen levels in water follows the same trend in open water and under the FPV system. however the oxygen level under FPV system is slightly lower under the FPV system throughout the measurement period. On average the DO decreases by 0.63 mg/L (-8.1%). This difference can increase to 1 mg/L (32.4%) and on December 30. Figure B5 shows the average DO for each day during the measurement period and shows a scatter plot with DO in open water as independent variable and DO and under the FPV system as dependent variable.

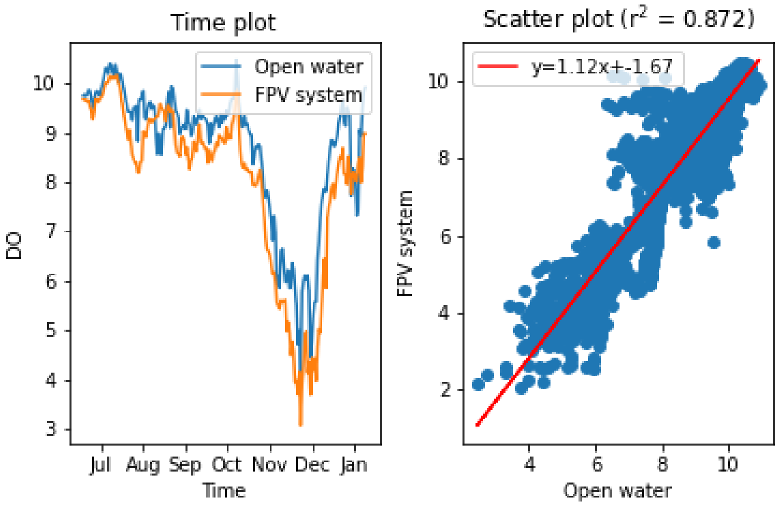

Figure B36: A) Plot of the daily average values of SDO in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and January 31 (202 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Temperature

The temperature under the panels is about 0.3 degrees (2.1%) higher than the temperature in open water throughout the measurement period. This difference is maximum at 0.6 degrees on August 11st. FigureB6 shows the average temperature for each day during the measurement period and shows a scatter plot with temperature in open water as independent variable and the temperature under the FPV system as dependent variable.

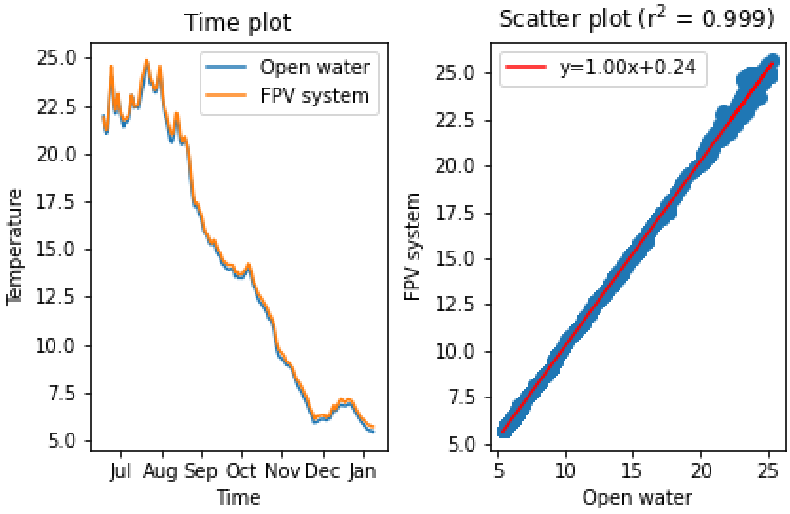

Figure B37: A) Plot of the daily average values of temperature in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and January 31 (202 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Appendix C – Analysis of Saturated Dissolved Oxygen and Ph

Next to the discussed physiochemical parameters in the report, the SDO and pH were measured as well in Oudehaske. In this appendix these results will be discussed.

SDO is calculated as the percentage of DO concentration relative to when completely saturated at that temperature (DataStream, 2023b). The SDO levels in water follows the same trend in open water and under the FPV system. However, the SDO level under FPV system is slightly lower under the FPV system throughout the measurement period. On average the SDO decreases by 5.4% (-7.7%). This difference can increase to 12.1% (32.1%) on December 30. Figure C1 and shows the average SDO for each day during the measurement period and shows a scatter plot with SDO in open water as independent variable and SDO and under the FPV system as dependent variable.

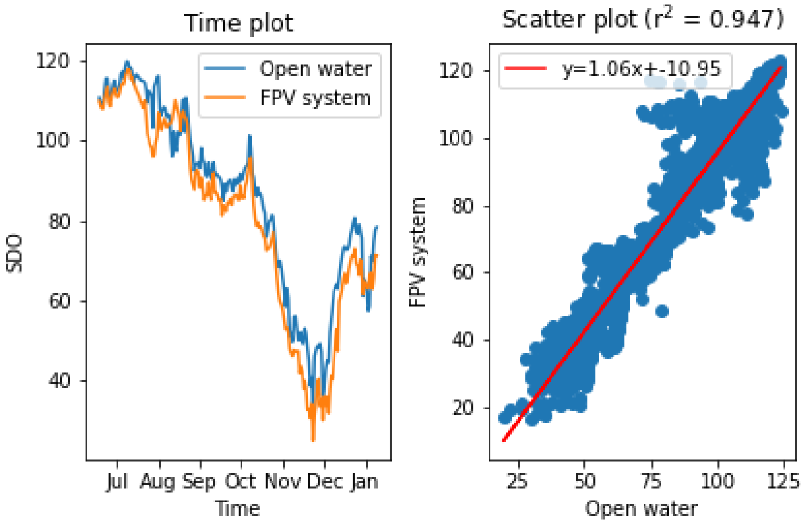

Figure C1: A): Plot of the daily average values of SDO in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and January 31 (202 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

The pH measures the degree to which water is acidic or basic. It is unitless (DataStream, 2023c). In Oudehaske it is measured with the AP6000 probe as well. The measurement period is from July 14 to January 31. The measured pH values have changed the least due to the FPV system. Under the FPV system, the pH is on average only 0.1 lower. This is because Oudehaske is a buffered lake. A buffered lake contains many dissolved calcium compounds, these compounds make the lake capable of preventing fluctuations in acidity, thus maintaining a constant pH value ((Landis et al., 2003). Therefore it is concluded that the FPV system has no substantial influence of pH of the water and this parameter will not be considered for further analysis. Figure C2 shows the average temperature for each day during the measurement period. Figure 10b shows a scatter plot with temperature in open water as independent variable and the temperature under the FPV system as dependent variable.

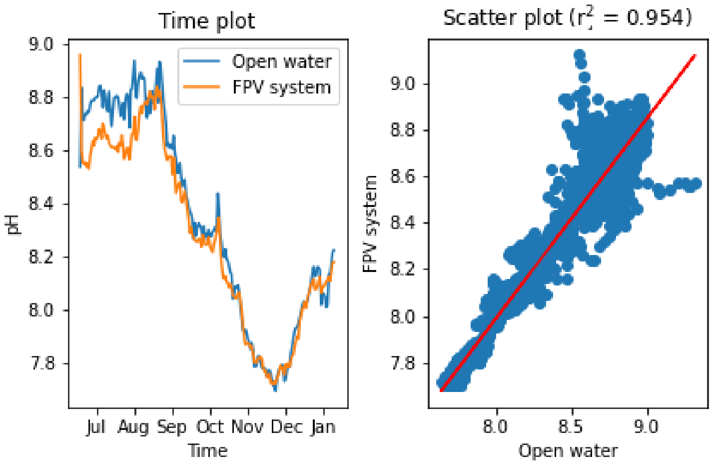

Figure C2: A) Plot of the daily average values of pH in open water and under the FPV system at a sensor depth of 1 meter below water. Blue lines indicate measurements of the sensor located in open water, and the orange line represents measurements under the FPV system. Measurements were taken between July 14 and January 31 (202 days). B) Scatterplot, regression line, and regression equation showing the measurements in open water as the independent parameter and measurements under the FPV system as the dependent variable.

Appendix D – Table phytoplankton

Table D1 displays the light intensity and corresponding efficiency of these six types of phytoplankton according to the BLOOM model (Los, 2009).

Table D12: Light intensity with corresponding growth efficiency of the six species of phytoplankton

Light intensity (kJ/(m²h))	Diatomes (algae)	Flag (algae)	Green (algae)	Apha (cyanobacteria)	Mic (cyanobacteria)	Blue-Green (cyanobacteria)
0.00	0.00	0.00	0.00	0.00	0.00	0.00
10800.00	0.15	0.15	0.16	0.22	0.51	0.41
21600.00	0.30	0.30	0.31	0.40	0.81	0.63
32400.00	0.43	0.43	0.44	0.53	0.94	0.75
43200.00	0.54	0.54	0.56	0.62	0.98	0.84
54000.00	0.63	0.63	0.65	0.69	1.00	0.90
64800.00	0.72	0.71	0.73	0.74	1.00	0.94
75600.00	0.81	0.78	0.81	0.78	1.00	0.97
86400.00	0.87	0.83	0.86	0.81	1.00	0.99
97200.00	0.92	0.87	0.90	0.84	1.00	1.00

Appendix E - Data analysis Beilen

For this project a small data analysis was conducted on the FPV system located on a lake in Beilen as well. In addition to the large dataset from Oudehaske, Deltares provided a smaller dataset for the FPV system located on a lake in Beilen. The lake covers an area of 21 ha and the water depth can get approximately to 20 m. Approximately 38% of the lake is covered by the FPV panels. In Figure E1 the lake of Beilen with the FPV system is shown.

From this FPV system of Beilen 17 samples were collected between 29-07-2021 and 24-11-2022 to measure the Dissolved Oxygen (DO) and temperature. Additionally, 15 measurements were conducted to assess the impact of the FPV system on water clarity. This was done using a Secchi disk, which is a disk used to measure water clarity. The disk is submerged into the water until it is no longer visible, and the depth at which it disappears is recorded. A higher Secchi depth value indicates clearer water, while a lower Secchi depth value indicates lower water clarity (NALMS, 2022). To analyse the effect of the FPV system on the physical-chemical parameters in Beilen, the averages of the measured values of the parameters were calculated for the measurements in open water and under the FPV system. Based on these averages the mean impact of the FPV system on the physical-chemical parameters in Beilen is evaluated.

Figure E1: FPV system located in Beilen (Drents Overrijsselse Delta, 2022)

Results Beilen

In Beilen the average depth where the secchi disk was still visible was lower under the FPV system, indicating a higher water clarity under the FPV system. The water temperature and DO (Dissolved Oxygen) are slightly higher on average under the FPV system. Out of the three parameters, only the effect of the FPV system on temperature is significant (p-value < 0.05). In Table E1, the average depth of the Secchi disk, the average temperature, and the average oxygen content for samples taken in open water and under the FPV system are presented. Additionally, the table displays the differences and corresponding p-values.

Table E1: The mean value in open water and under the FPV system, the difference between open water and the FPV system and the difference in % between de measurements in open water and under the FPV system of the 17 measurements for temperature and oxygen and the 15 measurements for the turbidity.

	Mean open water	Mean under FPV	Difference	Percentage (%)	p-value
Secchi depth (m)	1.32	1.26	-0.06	-4.55	0.126
Temperature (C)	13.71	13.78	+0.07	0.51	0.011
DO (mg/l)	85.33	86.57	+1.24	1.45	0.433

In Figure E2 the results of all samples 15 samples of turbidity and 17 samples of temperature and DO are displayed

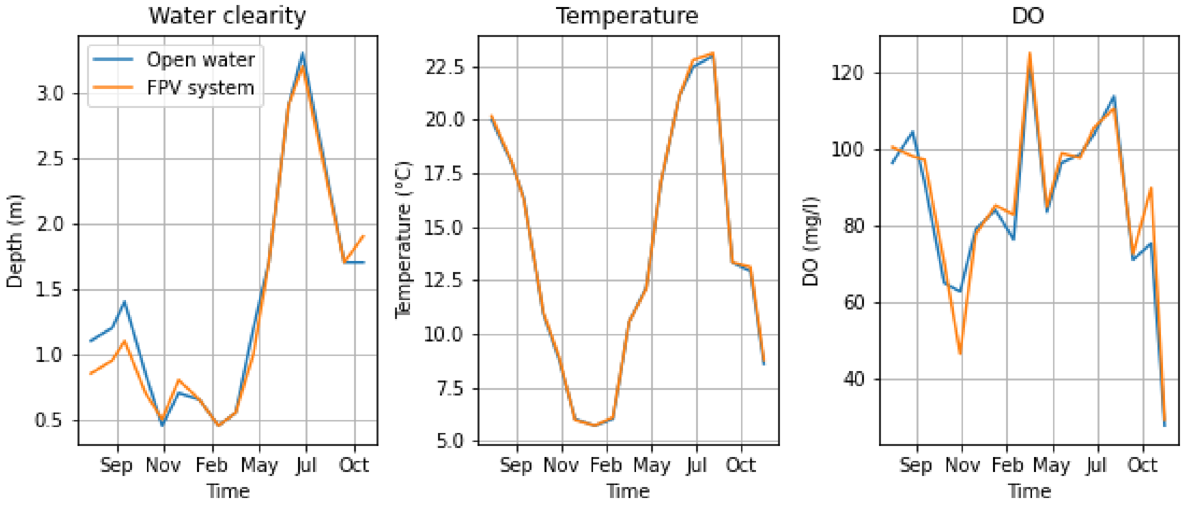

Figure E2: Result of the water clearity, temperature and DO measurements in Beilen. Blue lines indicate measurements in open water, orange lines are measurements under the FPV system. Measurements between July 29 2021 and 24 November 2022.

Appendix F – More information on correlation between parameters

In this Appendix, more information is provided about the relationship between the weather parameters and the physical-chemical parameters. This appendix is divided into two parts, with the first part showing more time and scatter plots, and the second part evaluating the R2

Appendix F1 – Time and scatterplots

In Figures F1-F3, time plots are presented, providing insight into the relationship between the weather parameter windspeed and the physical-chemical parameters temperature, dissolved oxygen (DO), and turbidity.

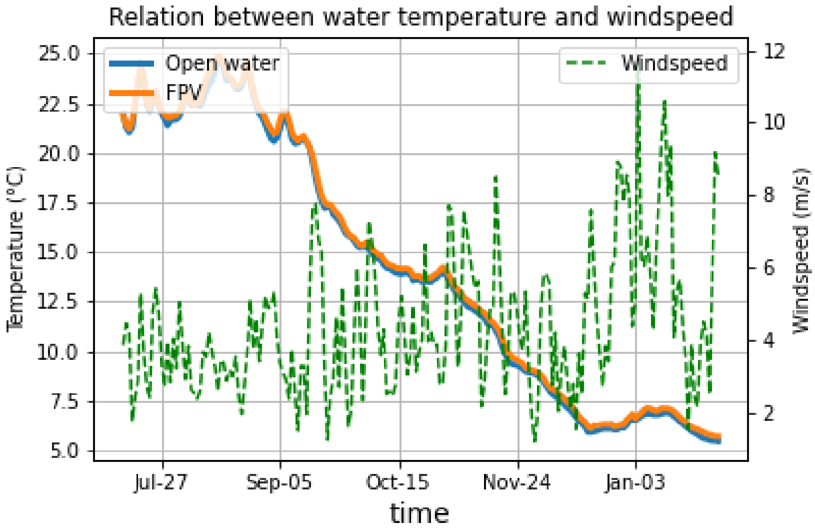

Figure F1: Plot of the daily average values of temperature in open water and under the FPV system on the left y-axis. Temperature is measured at a sensor depth of 1 meter. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. On the right y-axis the windspeed (green line) is displayed measured on the panels. Measurements were taken between July 14 and January 31 (202 days).

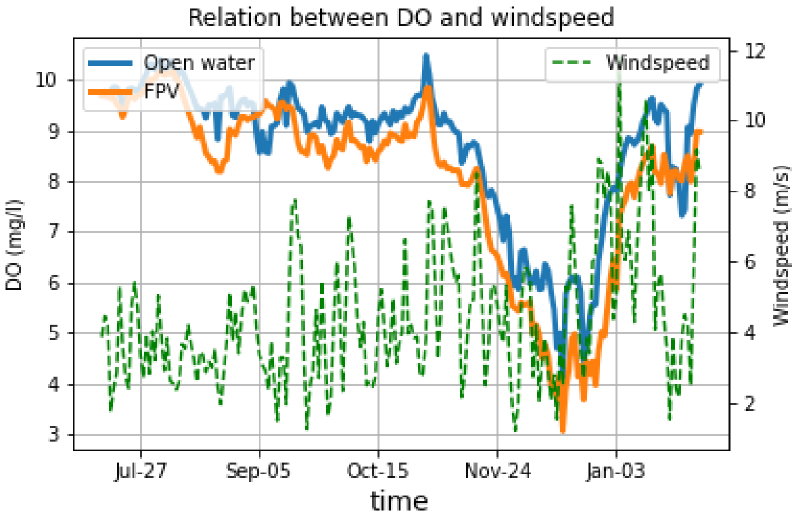

Figure F2: Plot of the daily average values of DO in open water and under the FPV system on the left y-axis. DO is measured at a sensor depth of 1 meter. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. On the right y-axis the windspeed (green line) is displayed measured on the panels. Measurements were taken between July 14 and January 31 (202 days).

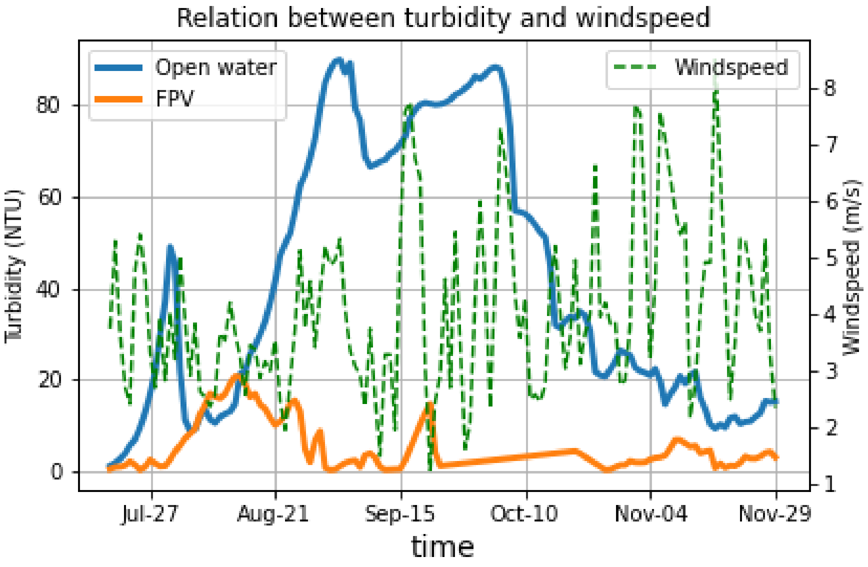

Figure F3: Plot of the daily average values of turbidity in open water and under the FPV system on the left y-axis. Turbidity is measured at a sensor depth of 1 meter. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. On the right y-axis the windspeed (green line) is displayed measured on the panels. Measurements were taken between July 19 and November 29 (134 days).

In Figures F4-F6, time plots are shown, providing insight into the relationship between the parameter precipitation and the physical-chemical parameters chlorophyll, turbidity and conductivity.

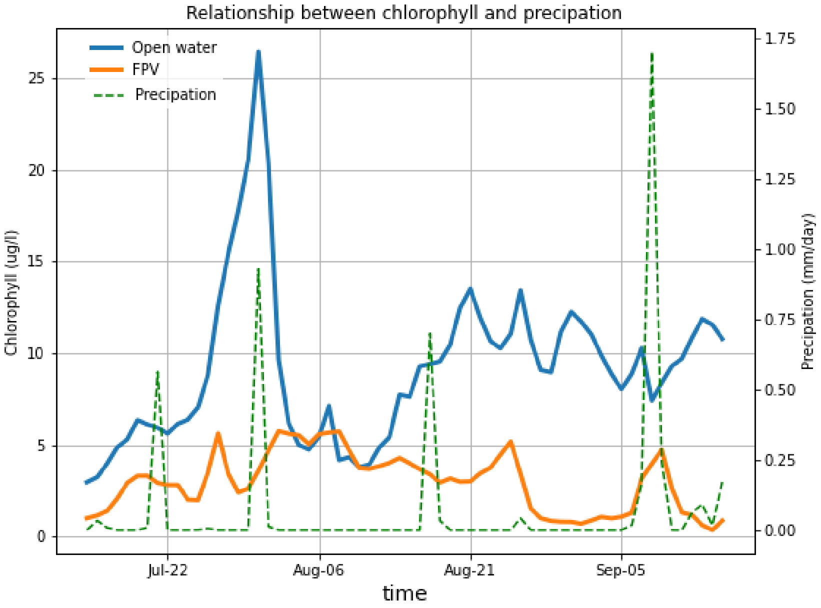

Figure F4: Plot of the daily average values of chlorophyll in open water and under the FPV system on the left y-axis. Chlorophyll is measured at a sensor depth of 1 meter. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. On the right y-axis the precipitation (green line) is displayed measured at the closest KNMI station. Measurements were taken between July 14 and September 15 (63 days)..

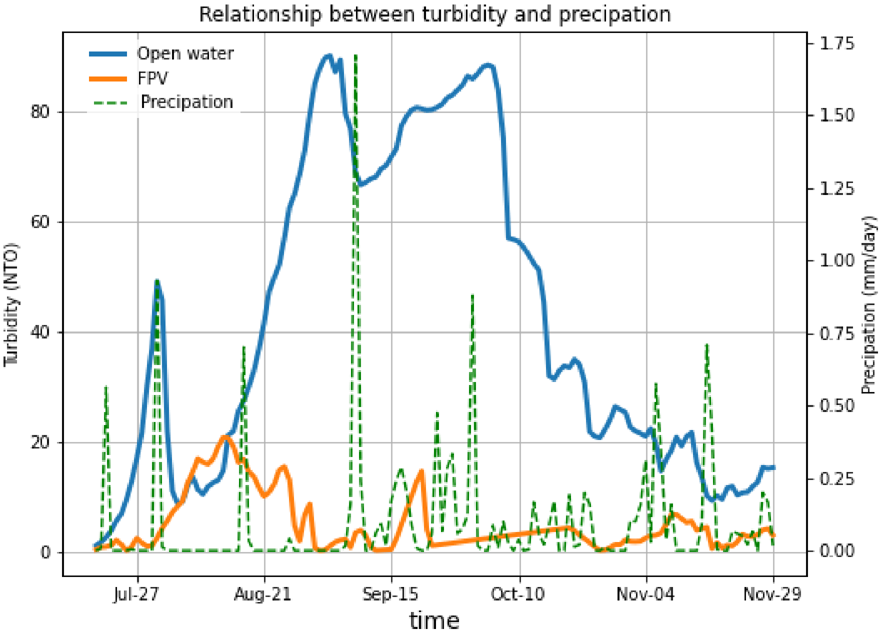

Figure F5: Plot of the daily average values of turbidity in open water and under the FPV system on the left y-axis. Turbidity is measured at a sensor depth of 1 meter. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. On the right y-axis the precipitation (green line) is displayed measured at the closest KNMI station. Measurements were taken between July 19 and November 29 (134 days).

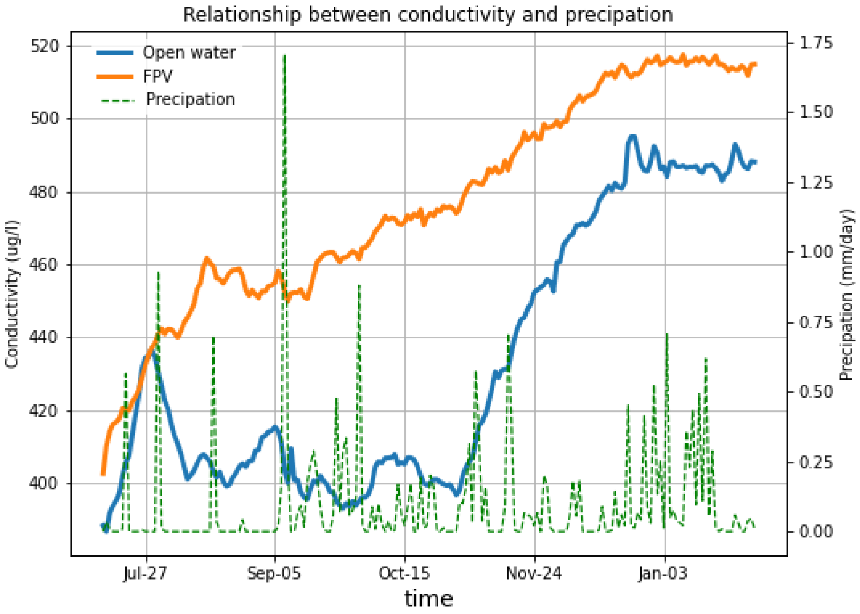

Figure F6: Plot of the daily average values of conductivity in open water and under the FPV system on the left y-axis. Conductivity is measured at a sensor depth of 1 meter. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. On the right y-axis the precipitation (green line) is displayed measured at the closest KNMI station in Leeuwarden. Measurements were taken between July 14th and January 31th (202 days).

Relation between physiochemical parameters

A correlation was expected between light and chlorophyll, and between chlorophyll and DO, but the Pearson's r between these parameters is lower than 0.3 not linear Figure F7 displays a time plot and a scatter plot of the measured values of light and chlorophyll for open water and below the FPV system. In Figure F8, a time plot and a scatterplot of the DO concentration and chlorophyll content are shown for open water and under the FPV system.

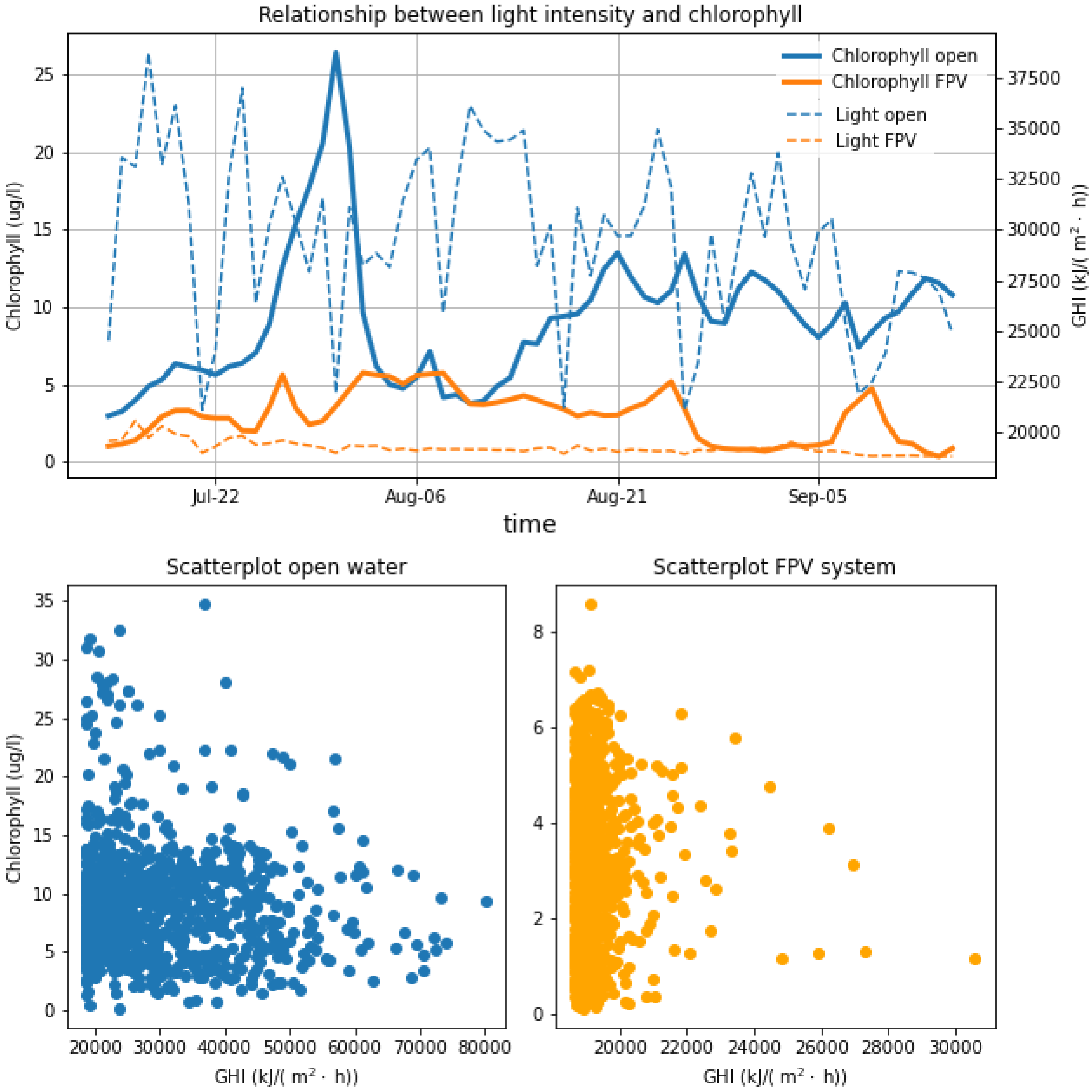

Figure F7: Plot of the daily average values of chlorophyll (bold line) and DO (dotted line) in open water and under the FPV system. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. Chlorophyll values are represented on the left y-axis. B) Scatterplot with light intensity as independent variable and chlorophyll as dependent variable in open water. C) Scatterplot with light intensity as independent variable and chlorophyll as dependent variable under the FPV system. DO values are represented on the right y-axis. Both parameters are measured at a sensor depth of 1 meter. Measurements were taken between July 14th and September 15th (63 days).

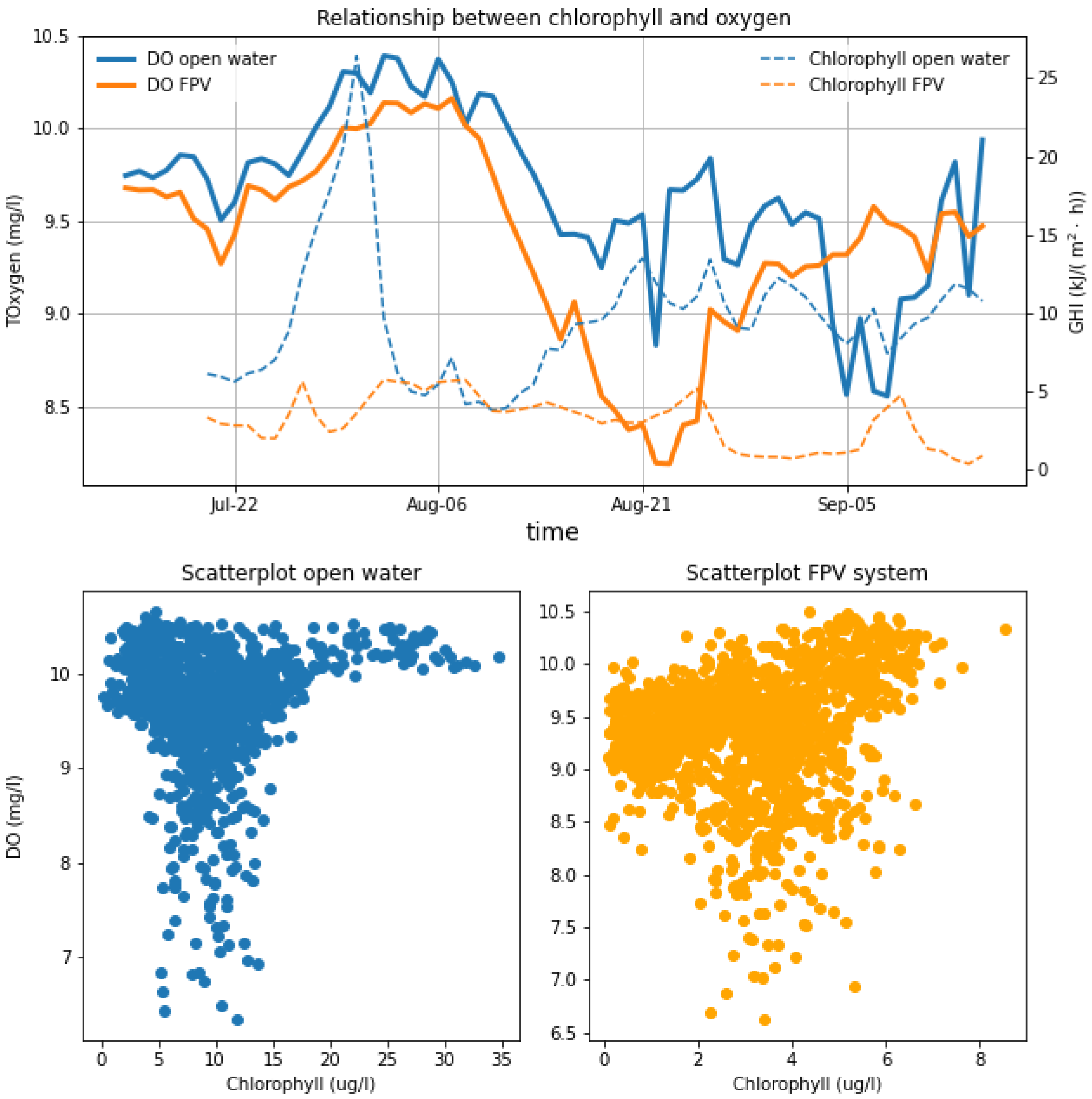

Figure F8: A) Plot of the daily average values of DO (bold line) and chlorophyll (dotted line) in open water and under the FPV system. Blue lines indicate measurements of the sensor located in open water, orange line represents measurements under the FPV system. DO values are represented on the left y-axis. B) Scatterplot with chlorophyll as independent variable and oxygen as dependent variable in open water. C) Scatterplot with chlorophyll as independent variable and oxygen as dependent variable under the FPV system. Chlorophyll values are represented on the right y-axis. Both parameters are measured at a sensor depth of 1 meter. Measurements were taken between July 19th and January 31th (202 days).

Appendix F2 – R-squared values

Between the weather and the physical-chemical parameters, there is only an R^2 of 0.7 for the relationship between air temperature and water temperature. For these parameters, linear regression is therefore a good way to express the relationship. In Figure F9 all R^2values between the weather parameters and the physical-chemical parameters can be seen. Between the different physiochemical parameters in open water and under the FPV system, the R^2 is never higher than 0.7, so linear regression is not a good method to determine the effect of different physiochemical parameters on each other.

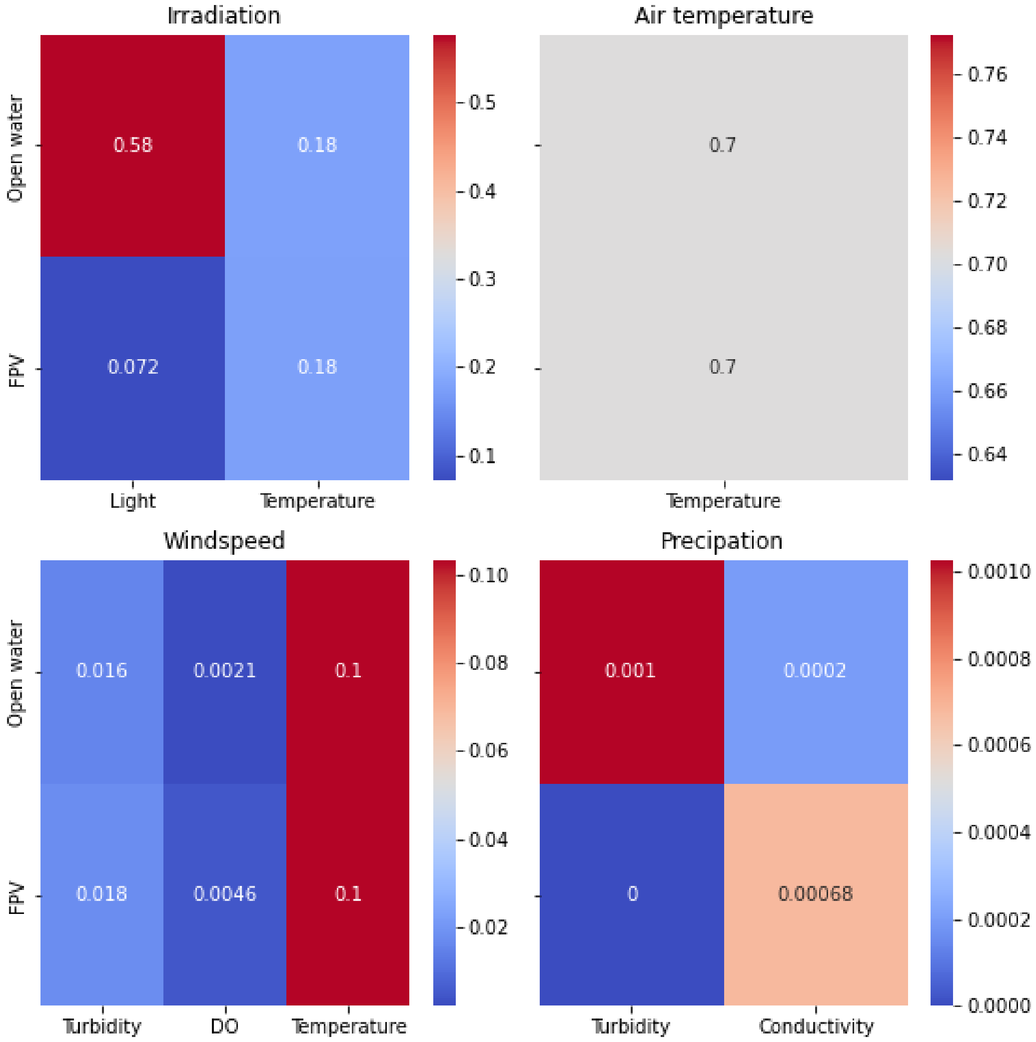

Figure F9: R^2 between GHI and the ecological parameters light and temperature in open water and under the FPV system. B) R^2 between air temperature and water temperature in open water and under the FPV system in open water and under the FPV system. C) R^2 between the weather variable windspeed and ecological parameters turbidity, DO and temperature in open water and under the FPV system D) R^2 between precipitation with turbidity and conductivity

In Figure F10, the R^2 between all physical-chemical parameters can be seen.

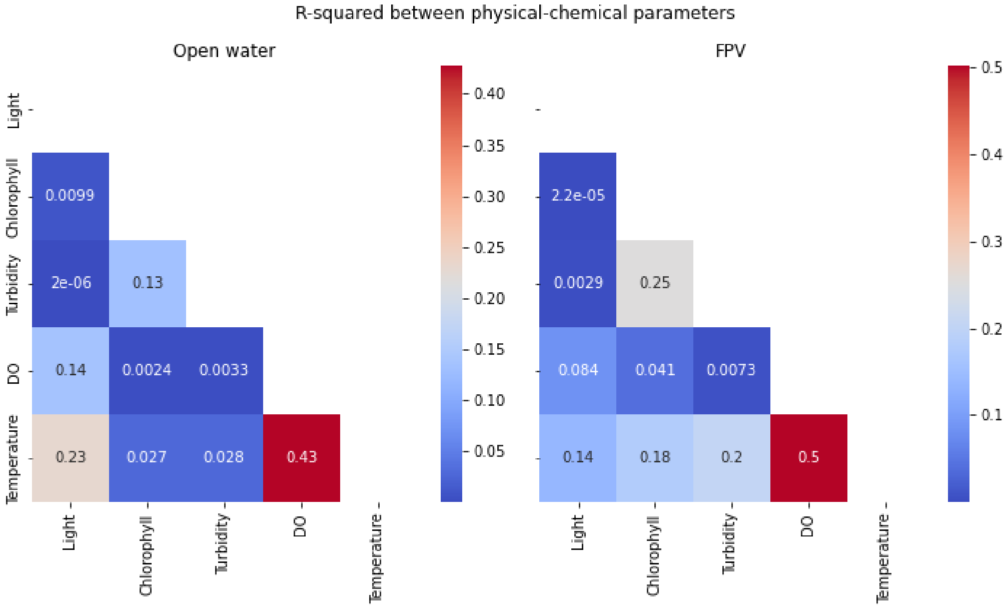

Figure F10: A) R^2 for all ecological parameters in open water B) R^2 for all ecological parameters under the FPV system

Appendix G – Information reviewed articles

In Table G1 more information is provided about the most important articles used for the literature review. For these articles, the year of publication, a brief summary of the article's content, and the authors of the articles are presented.

Table G1: Overview of most important articles used for the literature review with the year it is written, a short summary of the context and the authors

Article name	Year	Short summary	Author
In situ measurements Netherlands			
Floating photovoltaic pilot project at the Oostvoornse lake: Assessment of the water quality effects of three different system designs	2023	Measurements of effect of freshwater FPV on water quality parameters at Oostvoorne	(Bax et al., 2023)
Innovative floating bifacial photovoltaic solutions for inland water areas	2021	Measurements of effect of freshwater FPV on water quality parameters at Wuert	(Ziar et al., 2021)
In-Situ Water Quality Observations under a Large-Scale Floating Solar Farm Using Sensors and Underwater Drones	2021	Measurements of effect of freshwater FPV on water quality parameters at Bomhofsplas lake	(R. L. P. de Lima et al., 2021)
Literature review			
PV tech power report: floating solar	2020	Summary of environmental impacts freshwater FPV	(Jones & Armstrong, 2021)
Is floating photovoltaic better than conventional photovoltaic? Assessing environmental impacts	2018	Environmental impacts freshwater FPV	(Pimentel Da Silva & Branco, 2018)
Zonnesystemen op water	2020	Effect freshwater FPV on water quality and nature and identifying missed knowledge	(DELTARES, 2020)
Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees	2020	Summary environmental impacts freshwater FPV	(Armstrong et al., 2020)
Recent technological advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems	2020	Environmental impacts freshwater FPV	(Gorjian et al., 2021)
Offshore solar			
Effects of Floating Solar Platforms on the Hydrodynamics and the Ecosystem of a Coastal Sea	2019	Effect of decreased light availability offshore FPV	(Karpouzoglou et al., 2019)
Environmental impacts and benefits of marine floating solar	2021	Environmental effects marine FPV based on other offshore structures	(Hooper et al., 2021)
A numerical study of light levels underneath floating solar panel arrays at sea	2022	Effect of decreased light availability offshore FPV	(Wezeman, 2022)
Mapping potential environmental indicators of offshore renewable energy	2022	Environmental effects offshore FPV	(Nurmi & Mcdonald, 2022)

Appendix H - Questions semi structured interviews

All question are for FPV systems in the Netherlands. For all question about offshore FPV a large scale offshore system is considered.

Interview questions technological

Who are you? For how long have you been working in the FPV business and where is your research/company about?

What do you consider as the main technological advantages of FPV compared to ground-mounted or rooftop PV?

What do you consider as the main technological disadvantages of FPV compared to ground-mounted or rooftop PV?

What do you consider as the main technological advantages of offshore FPV compared to freshwater FPV?

What do you consider as the main technological disadvantages of offshore FPV compared to freshwater FPV?

Do you think that the presence of birds on the platform will influence the efficiency of the FPV system and to what extent? Do you expect this to be different for freshwater and offshore FPV and why?

Do you think that the cooling of the water will affect the efficiency of the FPV system. If yes:

- Do you expect an small/big increase/decrease and why?
- Do you expect a difference between freshwater and offshore and why?

If no

- Why?

Do you think that a higher windspeed on freshwater/sea will change the efficiency of the panels?

- Do you expect an small/big increase/decrease and why?
- Do you expect a difference between freshwater and offshore and why?

If no

- Why?

Do you think that the often larger distance between the panels and the convertor will change the efficiency of the system?

- Do you expect an small/big increase/decrease and why?
- Do you expect a difference between freshwater and offshore and why?

If no

- Why?

Are you doing research for a specific type of FPV. If yes can you tell more about:

- The structure of the floater
- The anchoring and cabling system

- Material of the floater
- Size of the system

Is there anything else you want to mention about this topic?

Do you know people that are interesting to interview?

Interview questions environmental

Do you think that the chlorophyll concentration underneath the offshore FPV panel will be different from the chlorophyll concentration in the open sea. If yes:

- Do you expect an small/big increase/decrease
    - Can you quantify it?
- Which environmental impacts do you expect this increase/decrease to have?

If no

- Why?

Do you think that the turbidity levels underneath the offshore FPV panel will be different from the turbidity in open sea. If yes do you expect an small/big increase/decrease and which environmental impacts do you expect this to have?

- Do you expect an small/big increase/decrease
    - Can you quantify it? Based on what data and indicators?
- Which environmental impacts do you expect this increase/decrease to have?

If no

- Why?

Do you think that the seawater temperature underneath the offshore FPV panel will be different from the water temperature in the open sea. If yes:

- Do you expect an small/big increase/decrease
- Which environmental impacts do you expect this increase/decrease to have?

If no

- Why?

Do you think that the light attenuation underneath the offshore FPV panel will be different from the light attenuation in the open sea. If yes:

- Do you expect an small/big increase/decrease
- Which environmental impacts do you expect this increase/decrease to have?

If no

- Why?

Do you think that the oxygen content underneath the offshore FPV panel will be different from the oxygen concentration in the open sea. If yes:

- Do you expect an small/big increase/decrease
- Which environmental impacts do you expect this increase/decrease to have?

If no

- Why?

How do you think that the FPV platform will influence the phytoplankton community and why?

How do you think that the FPV platform will influence the aquatic plants community and why?

How do you think that the FPV system will influence macrofauna and why?

How do you think that the FPV system will influence birds and why?

How do you think that the FPV system influences other marine life and why?

What do you consider as the main environmental advantage(s) of offshore FPV and why?

What do you consider main environmental disadvantage(s) of offshore FPV and why?

What environmental impacts do you expect to be most different between a freshwater and offshore system?

Is there environmental legislation that can possibly hinder the deployment of offshore FPV?

Should environmental legislation be adjusted to encourage the development of FPV?

Is there anything else you want to mention about this topic?

Do you know people that are interesting to interview?

Appendix I – More future research ideas

When there is no linear relationship between the measured parameters, while a relationship is expected, further research can focus on non-linear relationships. Two possible analysis from which other than linear relationships can be deduced are a polynomial regression analysis or a multiple linear regression (MLR) analysis.

As mentioned earlier, a polynomial regression analysis is a machine learning tool that can capture non-linear relationships between variables by fitting a non-linear regression line. It is employed when linear regression models may not sufficiently account for the complexity of the relationship. Based on the scatterplots, a polynomial regression analysis could yield promising results for understanding the relationship between conductivity in open water and under the FPV system, as well as the correlation between chlorophyll and turbidity in both open water and under the FPV system.

Multiple linear regression (MLR) is a statistical technique that utilizes multiple independent variables to predict the outcome of a dependent variable. It is commonly employed when modelling more complex relationships that involve several factors. MLR could be used to explain the decreased oxygen concentration beneath the FPV system. The amount of oxygen in a lake is complex and dependent on multiple ecological parameters. As described earlier, factors such as chlorophyll, temperature, and conductivity can influence the oxygen concentration. Through MLR, it can be determined to what extent these physical-chemical parameters collectively explain the oxygen concentration in the lake.

Once offshore FPV systems have been implemented on a large scale, similar steps to those taken for freshwater systems should be followed to evaluate their environmental impact. In the context of offshore FPV's environmental effects, special attention should be paid to the impact on the phytoplankton community, as this represents the primary environmental concern associated with offshore FPV systems. Just like with freshwater systems, it is essential to develop a reliable model that can assess the maximum feasible size of offshore FPV systems without causing harm to the environment. However, constructing such a model for the offshore environment can be more challenging due to factors such as stronger currents and the presence of tides.

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