# Monitoring of bifacial floating PV systems and validation of a toolbox for its simulation.

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by

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Front page image: Floating solar farm in Huainan, China. NRDC (2017)
https://www.nrdc.org/stories/floating-solar-farms-catch-california

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# Abstract

The development of solar photovoltaic systems has seen a rapid increase in the recent years propelled by mass manufacturing and constantly declining costs of PV modules. In some regions, however, the levelized cost of energy is still rather high, posing some challenges for this technology to take a leading roll in the energy mix. In order to overcome this, two approaches are being taken by the industry. On the one hand, improvements on the PV technology itself are enabling new PV systems to achieve higher yields of energy. One of this novel technologies is bifacial PV modules. On the other hand, some research is being done in the deployment of PV systems in alternative configurations such as floating on water. This allows countries with land limitations, such as the Netherlands, to consider PV energy as a feasible and cost effective way to supply its energy demand.

A pilot system called InnoZoWa is being developed by the water authority Rivierenland in the Netherlands. This system will evaluate the feasibility of floating bifacial PV systems in the country. At the current phase of the project a monitoring system is developed. This system serves as means of data acquisition for research purposes from a PV system that can potentially be deployed in larger areas of inland shallow water.

Delft University of Technology is one of the partners involved in the development of InnoZoWa. The PVMD group from the university is in charge of the electrical specifications and data analysis. The same group has developed in recent years a toolbox for the design and simulation of PV systems. This tool must go through different validation stages. This project is an opportunity to test out the toolbox and establish its accuracy and reliability.

The toolbox presents also an opportunity to simulate the outcome from the InnoZoWa study system . Therefore, the toolbox is used to reproduce the different scenarios and configurations proposed in the pilot. As a result of this simulation, it is concluded that bifacial floating systems with reflectors are the technology with the highest potential in the setup. Other configurations including tracking functionalities show an even larger potential but their self energy consumption is a concern.

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# 1
# Introduction

From the human perspective, energy is an enabler to improve people's quality of life. It enables services that range from warming people's homes to transporting merchandises across continents. It makes it possible for civilizations to organize themselves in complex ways that allow further advancements in social, economical and scientific progress. The control and manipulation of vast amounts of energy also propelled some economies to the highest levels of human development in the world. Historically, the development of nations has been closely related to a reliable and secure access to energy resources. As seen in figure 1.1, the OECD, a group of the most industrialized countries, represent currently around 50% of global energy consumption while their population is barely 17% of the world's total [14]. This is, however, rapidly changing since developing countries account for the largest share in the global energy demand growth. One reason for this is population growth but also the aspirations to higher living standards that are derived from higher incomes in those regions [15].

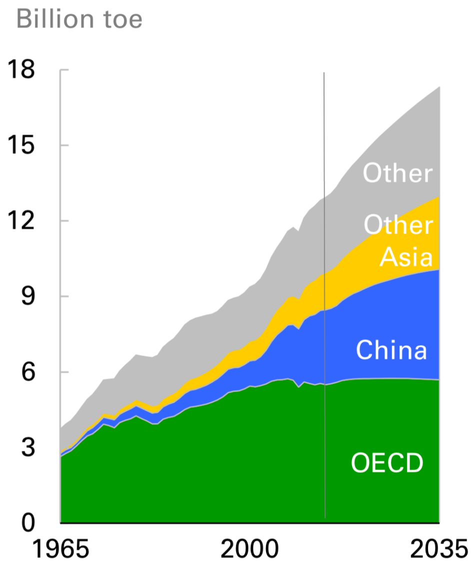



Figure 1.1: Historical and projected energy use among OECD countries and other regions [1]

In parallel to the growing global energy demand, the challenge of coping with climate change makes it crucial to redefine the paths towards economic development. If developing countries were to replicate the same pattern of development that most OECD countries followed, in terms of fossil fuel usage, the resulting environmental impact would potentially make irreversible damage to the natural cycles that support life on Earth [16]. Therefore, it is necessary to solve energy scarcity and in-equal accessibility in a sustainable and economical manner. The principles for this have been defined in the objectives of the Paris Agreement signed in 2015. Until April 2019 185 countries, including the European Union, agreed to transform their economies in order to keep the global increase in temperature well below 2 degrees Celcius in reference to pre-industrial levels [17]. This plan focuses primarily in reducing the emissions of green house gas (GHG) emissions caused by fossil fuel usage and related to global warming. In this context renewable sources become the center of attention for all stakeholders that shape the global energy systems: governments, energy intensive industries and the public opinion.

In its 2018 World Energy Outlook, the International Energy Agency (IEA) investigated three scenarios of development. The business-as-usual scenario, called 'Current Policies', and another one considering the policies announced by governments until this moment, 'New Policies Scenario', will not meet the targets established by the Paris Agreement. The alternative proposed by the IEA is called 'Sustainable Development Scenario', where further actions must be taken in order to achieve the targets that ensure global warming around 1.5 degrees Celsius. In this scenario, energy generation from wind and solar photovoltaic (PV) sources must increase from 1,500 TWh in 2017 to 14,100 TWh in 2040 [18]. This represents an increase of 940% over the next 2 decades in the share of energy supplied from these sources.

As challenging as it seems, increasing the solar PV generation capacity might be one of the must feasible options to respond to the expected global energy demand growth while staying within the internationally agreed limits to GHG emissions. In order to asses the feasibility of renewable energy sources, it is necessary to compare the global energy demand with the amount of energy available from the primary sources. Figure 1.2 shows the potential of solar, hydro, biomass, geothermal and wave-tidal sources in terms of how many times they could satisfy the global energy demand. It is necessary to keep in mind that this theoretical availability does not account for technical and economical limitations. However, as technology improves, it is possible to expand the potential to capture energy and to do it in a financially feasible way.

Global solar energy generation capacity has experienced an exponential growth since year 2000 primarily led by solar PV capacity increments in Germany and China [19]. In the first case it was caused by policies for transitioning into a diversified carbon neutral energy mix, the Energiewende. In the latter case, environmental concerns and increasing health costs generated by a heavily polluting energy system based on coal [20]. These, and growing global demand of solar PV generation capacity influenced the expansion of PV module production. During the last two decades the increase in production of silicon-based PV modules at the mass scale derived in a decrease in cost from USD $5/W in year 2000 to around USD $0.7/W in 2015. As Kavlak explains in [21], the learning curve of the industry and the adaptation of supply of material and manufacturing processes for the specific purpose of PV module fabrication have been responsible for the largest share in the reduction of production cost of this technology. In figure 1.2 a comparison is provided for the reduction of the levelized cost of energy (LCOE) for several renewable sources between 2010 and 2017 where solar PV outpaced all other technologies.

According to the International Technology Roadmap for Photovoltaic, the cost of several solar cell technologies will not experience a significant reduction as a result of further expansion of production capacity [22]. The pressure will be set in the coming years on improving the performance of the cell itself. Higher energy yields per cell are typically achieved through

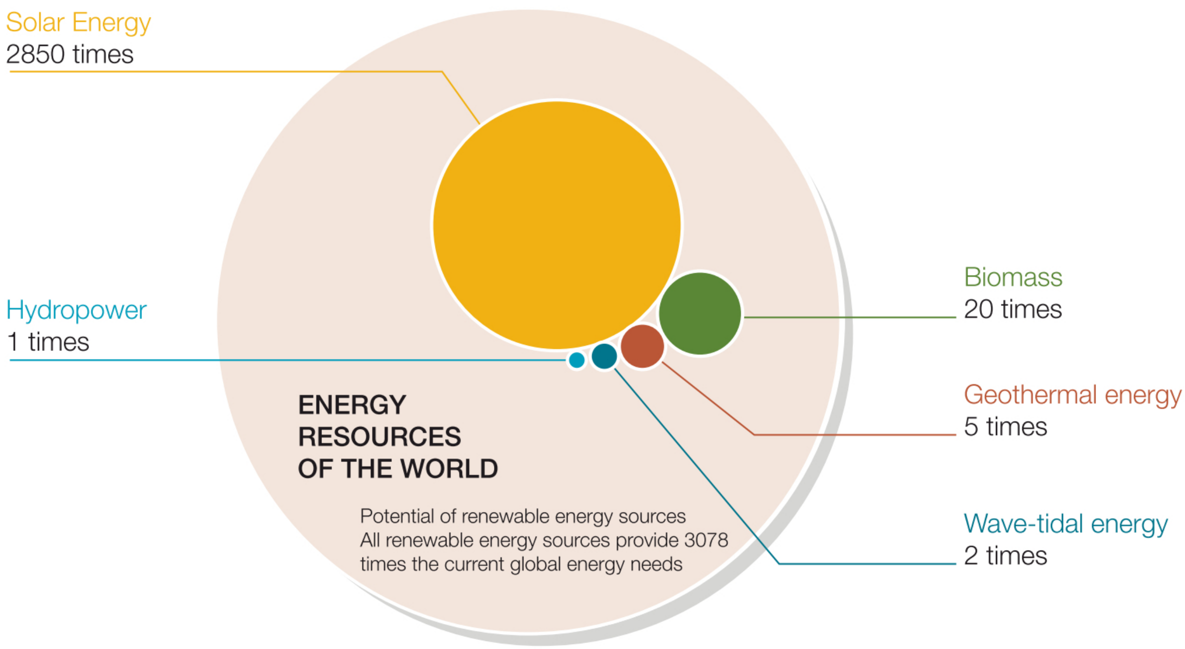



Figure 1.2: Potential of Renewable Energy Sources of the World [2]

improvements of the technology, moving it towards the theoretical limits of crystalline silicon (c-Si), however, this usually makes use of more complex manufacturing processes and thus higher production costs. Furthermore, the balance of system (BOS) costs which include mounting racks, cables, inverters and the installation itself have not decreased at the same pace as PV modules [6]. All in all, the challenge of the solar PV industry is to increase the performance of solar modules without incurring in higher production costs. A promising solution is the use of bifacial modules which, as we will see later on, can respond to the challenges with minimum technological modifications and with additional technical and economical advantages at the system level.

Bifacial modules have been researched for several decades but only recently they have become commercially feasible given the advancements in state of the art solar cell architectures. First generation solar cells used metallic back contacts that covered the back surface completely and blocked any light coming from the rear of the cell. The development of passivated emitter rear contact (PERC) and passivated emitter rear totally diffused (PERT) with grid contacts on both sides of the cell, instead of complete surface contacts, allow transmission of light through both sides of the cell [6]. Some studies argue that the manufacture of bifacial modules incur in costs ranging between 90.3 to 124.7% of the cost of a similar monofacial module [23]. The gain from the implementation of bifacial modules has been proven to range from 4 to up to 25%, where the optimal configuration of the system, depending on the conditions at the location, is crucial to achieve the maximum gain [23]. Given the relatively low cost increase of bifacial modules in comparison with monofacial ones, and the potential gain in energy it is expected that this technology opens the possibility to improve the performance of solar modules according to the expectations of the industry. Some estimations predict a steady increase of the market share for bifacial modules to more than 35% by 2028 [22].

In the midst of these developments some regions face additional challenges in the transition towards renewable energy systems. In this thesis we are concerned with two challenges

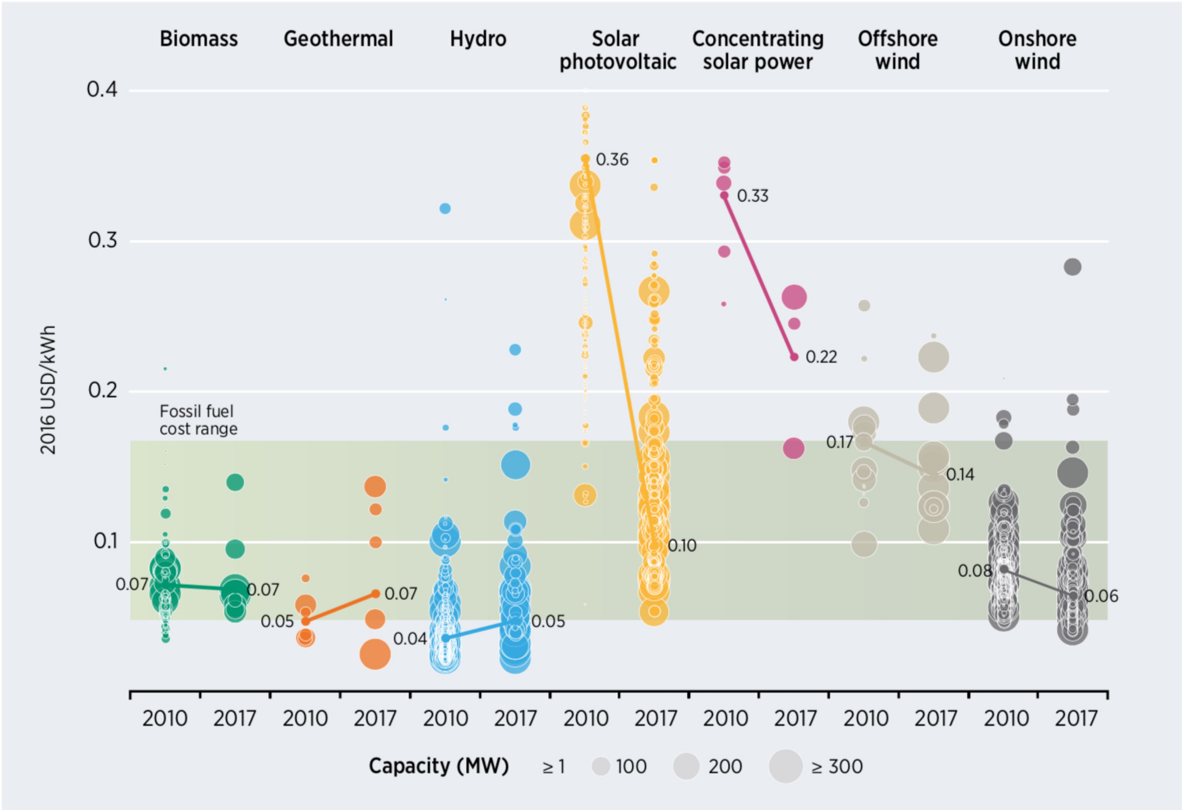



Figure 1.3: Global levelised cost of electricity from utility-scale renewable power generation technologies, 2010-2017 [3]

faced in the Netherlands: land scarcity and relatively low solar irradiance. With a population density of 509 people per square kilometer (the highest in Europe after Monaco and San Marino) [24], the dedication of land for the specific purpose of solar PV generation is controversial in a territory where the allocation of land is strongly disputed between different crucial forms of use such as farming, housing or industry. On the other hand, the amount of solar energy reaching Dutch territory is low, as in most parts of Northern Europe, with 1000 kWh/m$^2$ when compared to lower altitudes closer to the Equator which can reach up to 1,900 kWh/m$^2$ [25].

The following sections will elaborate on two key issues that are dealt with in this thesis. Floating PV systems in the Netherlands are introduced in section 1.1 as an alternative to land use restrictions and the current challenges in the implementation of bifacial solar modules are clarified in section 1.3. Later on, section 1.2 explains how both of these issues stand at the core of the main research project called Innozowa. Finally, the research questions of this thesis are presented in section 1.4.

## 1.1. Floating systems in the Netherlands

To meet the agreements settled in the Paris Agreement, the European Union has established a target of at least an 80% reduction in GHG emissions by 2050 [26]. This goal is later on translated to the goals established by each member state. The Dutch case is particularly interesting given the great reliance of the country on natural gas. Despite the introduction of carbon reducing policies such as the European Emission Trade System (ETS), Dutch companies have not been incentivised initially to transition into renewable sources because of their efficient use of fossil fuels [26]. This resulted in a delay in renewable energy capacity deployment which in 2020 will mean a missed target of 14% [27]. However, the Dutch government has set in motion new policies that aim to accelerate the transition in order to meet future targets [26]. Some estimations argue that meeting the targets for 2050 requires using a surface of land equal to 2,200 square kilometers, 10% of the area currently dedicated to farming [28].

With around 52,000 hectares of shallow inland water, the Netherlands possesses a potential to host a significant amount of floating solar PV capacity [29]. Given that most of the Dutch waterways, infrastructure and water-related services fall into the jurisdiction of public water authorities, these entities are currently the common initiators of research projects in the sector. An example of this initiative is the document generated by the Dutch Foundation for Applied Water Research, knowledge centre of Dutch water authorities, 'Guide for the licensing of floating solar parks on water', which establishes guidelines for the development of floating solar PV projects in order to provide juridical and technical certainty to developers [29]. But not only the public sector is interested in this novel enterprise. In 2020, the largest floating solar PV project is expected to start operating in the Netherlands on the shallow waters of a previously site used for sand extraction. With a capacity of 48 MW, the project owned by Kremer Zand and Grind will provide electricity for around 13,000 households [30].

Solar cells are tested at standard test conditions that establish 25 degrees Celsius as the reference temperature of operation [31]. There is a linear relation between temperature and current and voltage levels of operation. As temperature increases current increases and voltage decreases. However, the magnitude of the change is higher for the voltage than for the current and the overall effect on output power is negative. Figure 1.4 provides a typical current-voltage temperature relationship. Furthermore, the effect of the current on electrical losses from the resistance of the cables is quadratic as the power loss from cables is given by equation 1.1, where $R$ is the resistance of the cables and $I$ is the current at which the system operates.

**(1.1)** $$P_{loss} = RI^2$$

All things considered, it is desirable to maintain low temperatures of operation if possible. In addition to the advantages of space usage, floating PV systems can also benefit from the cooling effects of water and produce higher energy yields than land based systems of the same capacity.

That being said, it is also necessary to consider the challenges that floating PV systems pose to developers. The main concern is commonly the mechanical design of the structures supporting the solar modules. Such elements must be able to withstand conditions of constant movement from the flow of water, wind gusts and changes in the depth of the water. Also, moisture must be treated with caution as it can cause corrosion and damage to the electrical elements. Also, some concerns exist in relation to the services that must be provided for the maintenance of the site such as algae removal and the environmental impacts on species inhabiting the place [32]. Most of these challenges are considered in the research project introduced in the following section.

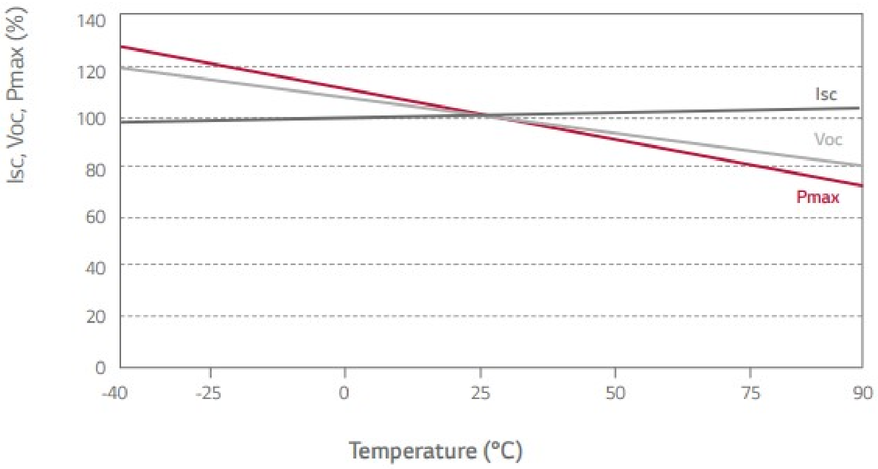



Figure 1.4: Current-voltage temperature characteristics of a bifacial n-type LG 335W solar module [4]

## 1.2. INNOvatieve ZOn-pv op WAter (INNOZOWA)

In the previous section of this chapter, the Dutch water authorities have been introduced as relevant actors in the development of floating solar PV systems in the Netherlands given the role they play on the administration of shallow waterways and water storage locations. One of them, the 'Waterschap Rivierenland' (WSRL), Water Authority Rivierenland, initiated in 2017 a project, 'Innovative Solar-PV On Water'(INNOZOWA), which aims to move forward their learning curve on floating PV systems and explore the possibilities for the water authority to be energy neutral. The partners collaborating in the project are Hakkers BV, a company specialized in construction on water, Blue21 BV, focused on design of innovative structures built on water and TU Delft one of the leading research institutions in the Netherlands in the field of solar photovoltaics [33].

The location of the project lays in the premises of the water authority and is a water basin built for water storage purposes. The site is in the town of Weurt, near the city of Nijmegen in the eastern central part of the Netherlands. Figure 1.5 provides a satellite view from the site, circled in red. The approximate area of the water basin is 15,200 square meters. From figure 1.6 it is possible to observe the surroundings of the water basin which are free of obstacles and will translate in a favorable sky view factor (SVF).

Some of the challenges faced in the development of floating solar PV projects have been previously mentioned. Some specific challenges to overcome in Innozowa are the changing depth of the water, the periodic works performed on the basin to remove algae and dragging at the bottom floor. Although this issues concern mainly the mechanical design of the structures supporting the PV modules, they will impact the configuration of the system, cabling and disposition of additional elements such as reflectors for the better utilization of bifacial solar module capacity.

The initial set-up of the project aims to analyse in a pilot phase two mechanical structures for the support of the PV modules, one of which will include one axis tracking capability. On both of these approaches the performance of monofacial and bifacial modules, with and without reflectors, will be measured. The results from this pilot configuration will provide empirical data to guide the decision towards up-scaling of the system and eventual development of a

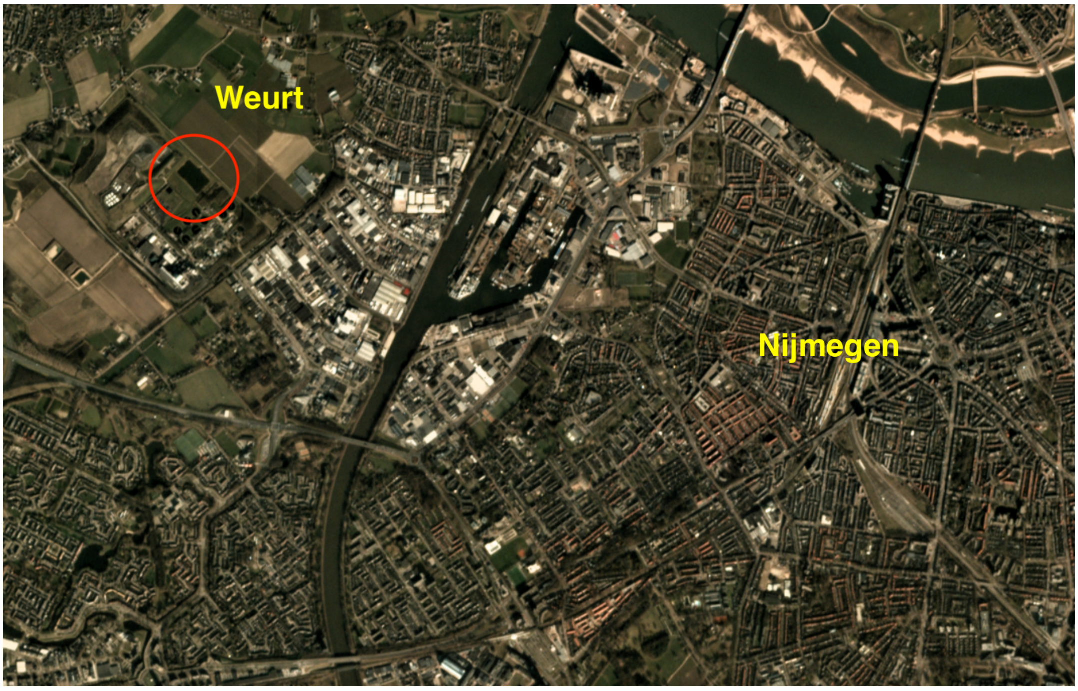



Figure 1.5: Satellite view of Nijmegen and the Water basin at Dutch Authority Rivierenland [5]

commercial product. In chapter 2 further details of the system will be provided.

From the pilot set-up, Innozowa intends to answer to following research question:

***What type of floating PV system configuration performs the best in terms of the energy yield vs capital cost (fixed, tracking, monofacial, bifacial, with or without reflector) in shallow water in the Netherlands?***

In section 1.4 this research question will be related to the research question of this thesis.

## 1.3. Validation of bifacial PV yield models

The efforts towards increasing the performance of PV modules have been presented. A promising solution, bifacial modules, is increasing its market share globally. As its deployment advances, it provides with more and more available data to validate its feasibility. However, contrary to monofacial panels, the models to predict the behaviour of bifacial systems in the long term are not fully developed. The procedure to determine the power rating of bifacial modules has been just recently defined by the International Electrotechnical Commission (IEC) in the IEC TS 60904-1-2:2019 standard [34]. These measuring directives ensure the reliability of the technical information that manufactures will provide about their products. However, the configuration of bifacial PV systems is not standardized and the complexity of their design, in comparison with monofacial PV systems, can deliver significant differences in the power output. Figure 1.7 provides a schematic view of different installation layouts for bifacial modules using tilt angle with North-South orientation, completely horizontal or vertically mounted in East-West orientation. In figure 1.8 a comparison of the output from these three configurations is provided. Comparing a typical Norht-South configuration of monofacial modules with optimized tilted angle, the bifacial module outperforms with up to 30% accord-

Figure 1.6: Water basin at the site of the water authority Rivierenland

ing to Kopecek [6]. However, this estimation varies significantly among several studies and one reason for that was until recently the lack of standardization of the power rating of bifacial modules. Another reason is the value for irradiance reaching the rear side of the module. This value depends at a large extent on the albedo of the ground or the reflective surface located below the bifacial panel but other factors such as row spacing, height from the ground, spacing between modules, module transparency and weather also influence (1.2) [35].

$$\textbf{(1.2)}\ Rear\ Irradiance = f(albedo, tilt, row\ spacing, height, racking, module\ transparency, weather)$$

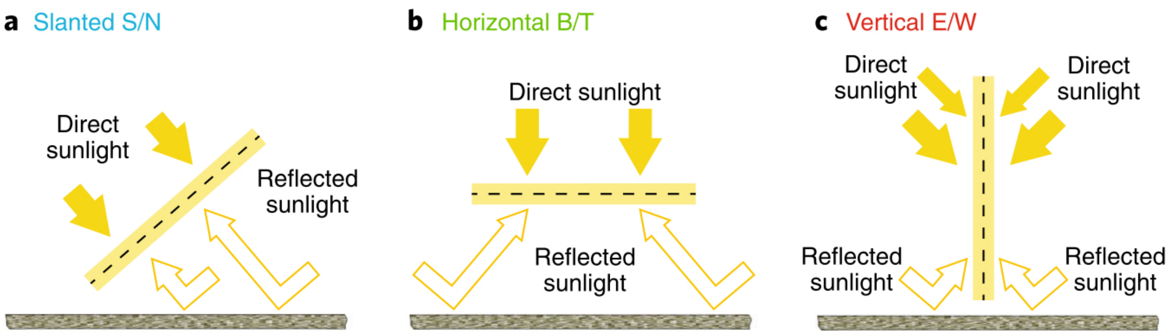



Figure 1.7: Different configurations of bifacial PV systems. Adapted from [6]

Regarding another focus on the validation of bifacial PV systems, it is necessary to understand the economics governing the deployment of this technology and how it is compared to the most broadly used monofacial one. In most electricity markets, renewable energy sources are usually sold at base load price levels and via bilateral purchase agreements. In this type of transactions, a previously established cost per unit of energy [$/kWh] is calculated to define the selling price. Given that operation costs of solar PV generation are very low and there is no fuel cost, a marginal cost is therefore negligible. Because of this, the most suitable mechanism to value the energy produced by the PV system is the levelized cost of energy (LCOE) which considers the capital cost of the infrastructure and the cost of financing the project, divided by the and an total energy output expected during the lifetime of the system which

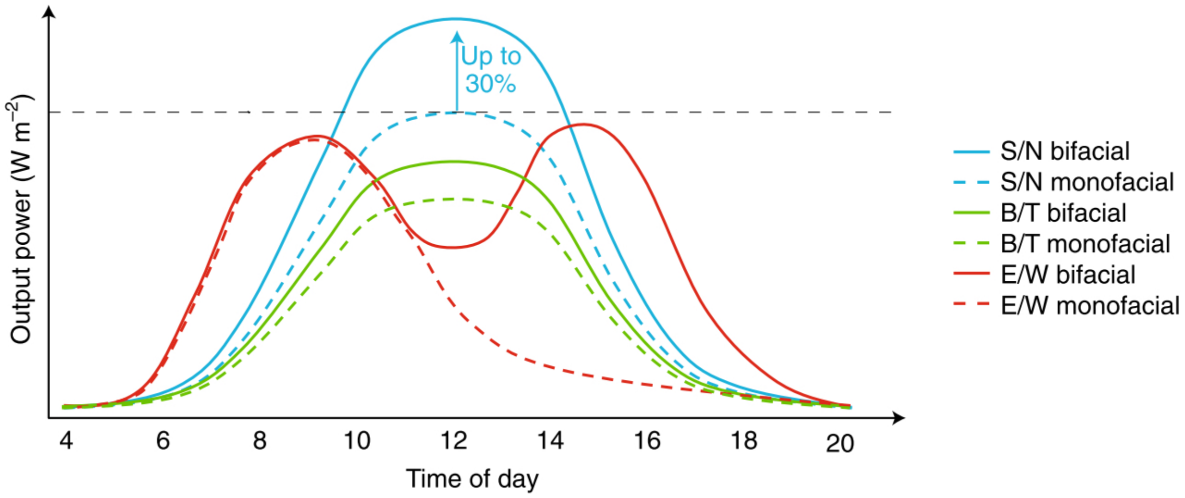



Figure 1.8: Energy output comparison for bifacial vs. monofacial systems at different configurations. Adapted from [6]

is commonly considered to range between 20 to 25 years. Low-cost financing reduces the cost of the energy [3] but accessing this resource requires low risk in the investment and high certainty in the forecast of the energy output [6]. Financial institutions are currently interested in models that simulate the behaviour of bifacial PV systems and which provide reliable data for the calculation of risk [6].

The Photovoltaic Materials and Devices (PVMD) research group at Delft University of Technology has worked in recent years in developing tools that allow the modelling of devices and systems. One of these tools, the PVMD Toolbox, aims to reproduce the behaviour of solar PV systems of different architectures. The case of bifacial systems is within the scope of this tool and the next phase in its development includes validation the results produced by its simulations with empirical data.

## 1.4. Research questions

In the previous sections the Innozowa project was introduced and the necessity of reliable modelling of bifacial systems was presented. Considering this problematic, the present work will focus in the following objectives:

**First:** A monitoring system must be developed in order to store historical data for later research purposes and validation of yield models.

**Secondly:** How accurately can the PVMD Toolbox predict energy yields of bifacial systems?

**Thirdly:** Knowing the degree of confidence provided by the PV Toolbox, what configuration from Innozowa's pilot case is expected to perform better?

The research questions in this thesis are developed in three main sections: development of a monitoring system, validation of toolbox for the simulations of PV systems and assessment of the energy production of the InnoZoWa project. Chapter 2 presents the mechanical and electrical definition of the InnoZoWa system on which the monitoring system is developed and presented in chapter 3. Then, chapter 4 introduces a toolbox developed by the PVMD group at TU Delft and elaborates on a validation to establish its accuracy in forecasting energy yield of bifacial systems. Following this validation, the toolbox is used for the simulation of the InnoZoWa project in order to establish the energy produced by the system in its different study cases. This is presented in chapter 5. Finally the general conclusions of this thesis are provided in chapter 6.

# 2

# InnoZoWa PV System

The InnoZoWa project is subsidised by the 'Stimulation of Sustainable Energy Production' (SDE+) grant from the Netherlands Enterprise Agency (RVO). SDE+ aims at making the production of renewable energy more affordable through innovative technologies [36]. This is one of the policy instruments put forward by the Dutch government in order to accelerate the deployment of renewable energy technologies and the transition of the energy sector into carbon neutrality. Following the innovative purpose of the SDE+ grant, InnoZoWa has the objective of developing a floating bifacial solar PV system that:

- Can be applied primarily to inland backwater areas such as water retention ponds
- Competes with and is an addition to conventional ground-mounted solar PV
- Has added value for the policy objectives of the water authority
- Can be retractable and movable for maintenance practices of the water bodies

The goal of the project's pilot phase is to identify the highest producing PV system configuration in terms of kWh per square meter. In order to find this, it is necessary to produce different study cases including monofacial and bifacial modules at horizontal and tilted configurations. It is also necessary to test the supporting structures for the floating system since they will be developed from scratch by Blue21 and Hakkers. An electrical design is produced to fit the different PV study cases on two floating structure designs and a land based system.

The development of InnoZoWa's pilot posses challenges that concern different engineering disciplines. The partners hold knowledge on design, mechanics, construction, electrical engineering and project management. This chapter will elaborate on those challenges and the solutions provided to solve them. Section 2.1 deals with the development of the floating structures supporting the PV modules. Later on, the electrical design is presented in section 2.2 and the collaborations from this thesis to this phase of the project will be explained. Finally, the technical considerations for the development of a monitoring system will be enlisted in section 2.3.

## 2.1. Mechanical specifications

The starting point for the development of the structures that will support the solar modules on water are the physical characteristics of the water basin and the conditions of operation of that water body. Subsection 2.1.1 will detail these parameters. Then, the solutions proposed by the partners in charge of mechanical design and construction, Blue21 and Hakkers, are presented in subsections 2.1.2 and 2.1.3. Finally, the purpose of an additional ground-based system is explained in subsection 2.1.4.

### 2.1.1. Water basin physical characteristics

The water authority Rivierenland built a water basin in its Weurt premises in 2016. For the interest of InnoZoWa's pilot we must focus on parameters such as water level, distance to land, distance to the grid and networks, surrounding skyline and any changing conditions in the operation of the basin. This water body is located next to a water treatment plant and the water is fed from the nearby river Waal. The area of the basin is approximately 15,200 square meters and water level depends strongly on the level of the Waal. If the level of the river is too low, the water basin will not be capable of maintaining its water and could drop to only 50 cm in that case. Although the changes in the water level can be significant, according to Bijorn Prudon, from the water authority Rivierenland, the level of the basin in the years 2019 and 2020 is expected to remain between 95 and 100% of its capacity, which for purposes of the pilot does not represent a risk. Water depth is relevant for the construction of the floating devices which should be able to lay on the ground in case of very low water levels but also for the cables which should not hang from any structure in order to avoid damage.

The structures will be located at the eastern corner of the basin, this location can be seen in figure 2.1. The shortest distance from the structures to land is 15 meters for option 1 and 33 meters for option 2. Distance to the land is important for the laying of cables from the PV modules to the inverters, and this value should be considered for the calculation of resistive loses. Also, the distance to a fixed internet connection is of particular interest in this thesis for purposes of connecting the monitoring system to a remote server. Given the location of the pilot in the water basin, using satellite images to measure the distance between the PV system and the closest building, it is estimated that the closest point of connection to a fixed line service is 400 meters.

The works of maintenance to be carried out at the water basin are basically mowing of algae and dredging. This maintenance is performed with boats. In order to avoid conflict with the maintenance works, the floating structures should be built in such a way that they can be retracted or totally removed to allow the boat to move around the area. The distance between the structures should be at least 4 meters for the boats to move between them and 6 by 6 meters for the boats to make turns. Such mobility should not diminish the stability of the structure in case of a wind burst or other disturbances on the lake.

### 2.1.2. Floating option 1

The partner Blue 21 developed the design of the floating structure 1 which can be seen in figure 2.2. The principle of operation is a system fixed to the bottom of the water basin by four pillars that will hold two suspension lines. From these lines, five floating devices are united. On top of the floaters, the reflective devices and the PV module rack are mounted. Each floater holds six PV modules in the pilot setup. In order to allow the mobility of boats performing maintenance on the water basin, the floating device can be retracted to either the front or the back. From figure 2.3 a side view of the structure is provided. The distance between the water level and the suspension lines allow the boats to move underneath them.

In this setup, three study cases will be built. In the front row a mono facial array will be

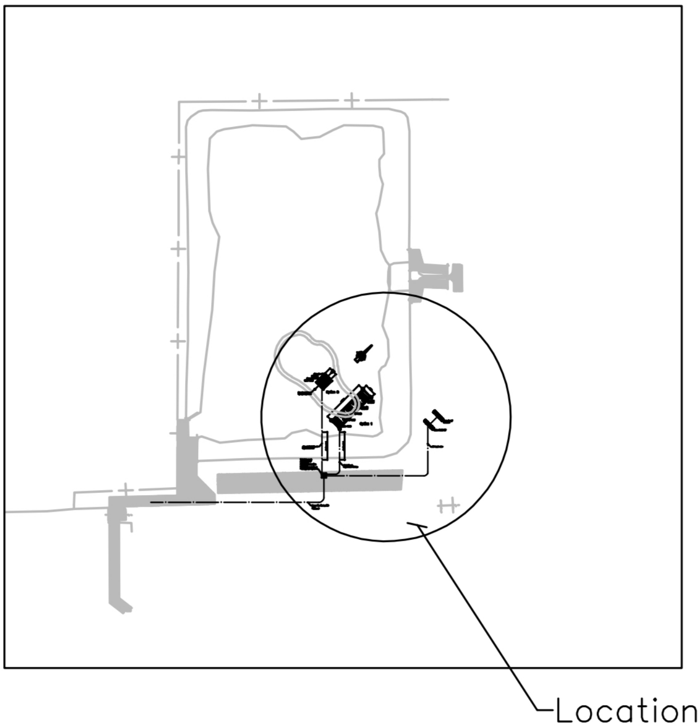



Figure 2.1: Location of the pilot in reference to the water basin

mounted. In the second and third rows, bifacial arrays will be located. Finally, in the fourth and fifth rows, bifacial arrays with reflectors will be mounted. Each row will hold six PV modules. In total, the system will support thirty modules.

### 2.1.3. Floating option 2

The second proposal for a floating structure comes from the partner Hakkers. They have built a monolithic structure that will float on water. There is no fixed structure to the bottom of the basin. This structure will support up to sixteen PV modules as can be seen in figure 2.4. The issue of mobility is solved by completely moving the structure to the edge of the basin in order to allow the movement of maintenance boats. An interesting feature of this structure is its ability to tilt on its sides by filling water into either side of it. This tilt will work as a single axis sun tracking capability and allows to include one additional factor to study in this pilot setup that could increase the yield of the system. In figure 2.5 a) the tracking capability is shown. Figure 2.5 c) shows that the front two rows are located at the base of the structure while the last two rows are located one meter above with a reflector underneath. Also, the second and fourth rows are tilted at 15 degrees. This setup will provide with four study cases of four PV modules each.

### 2.1.4. Land system

In addition to the floating study cases, a land based system will be installed at the location right next to the water basin. This setup will consist of one row of four monofacial PV modules and a second row of four bifacial PV modules with reflector, both rows tilted at 15 degrees. It

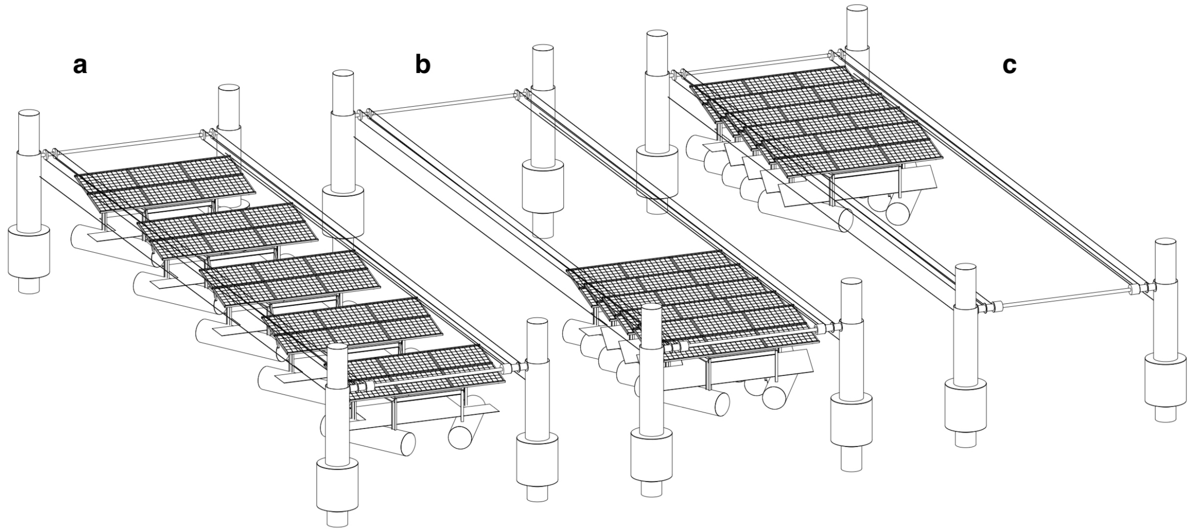



Figure 2.2: Axonometry of the floating structure 1. a) Operating position, b) and c) Retracted positions for mowing works

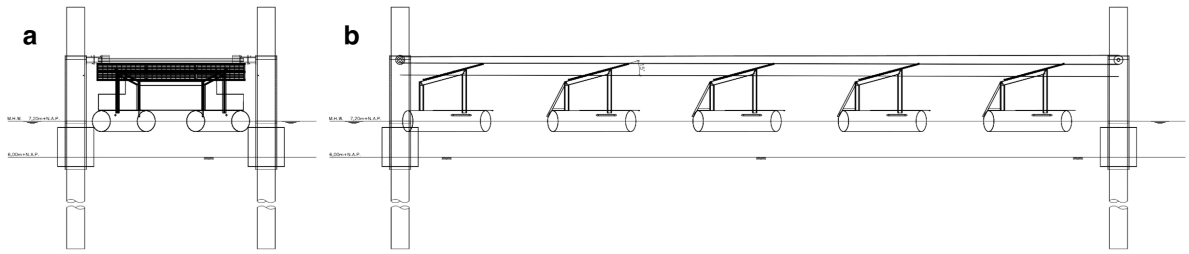



Figure 2.3: Detailed view of structure 1. a) Front section, b) Side view in operating position

will server as a reference case in order to compare the output of a traditional land based system, both with monofacial and bifacial panels, in the same weather conditions. This validation will provide with solid data to measure the effective gain from water based systems.

The nine study cases for water and land systems are summarized in table 2.1.

## 2.2. Electrical specifications

The design of the PV system and the components up to the conversion to AC are within the scope of tasks assigned to TU Delft. In phases previous to the definition of the mechanical and electrical design some estimations were made in order to evaluate the feasibility of different orientations and configurations of monofacial and bifacial PV modules in floating systems. In the current phase of this project it has been decided to use a North-South orientation and to combine flat with tilted configurations. In previous phases of the project an optimal angle of 27º facing the south was calculated [cite previous progress report] . For the purposes of the pilot this angles was not used but instead an angle of 15º for convenience in the installation of the modules on the floating structures and to reduce the shading effect between rows.

In order to obtain data that can be compared properly between monofacial and bifacial

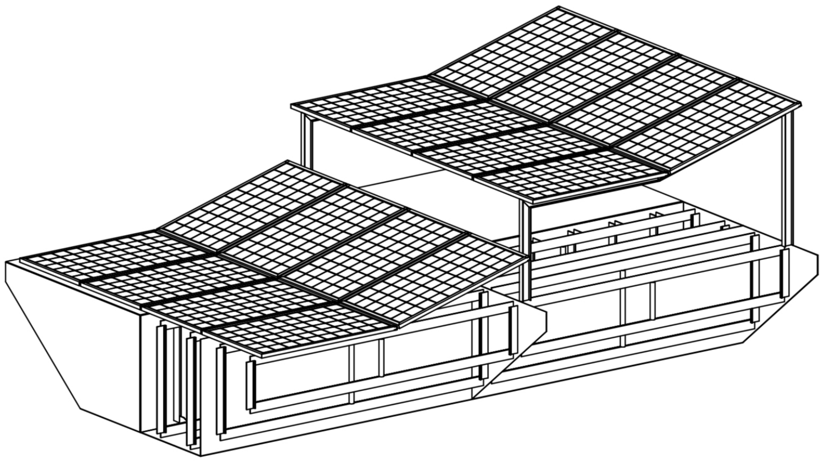


Figure 2.4: Axonometry of the floating structure 2

Table 2.1: Summary of study cases

| Case No. | Type | Details |
|---|---|---|
| *Land* | | |
| 1 | Monofacial | Tilted 15º |
| 2 | Bifacial | Tilted 15º, with reflectors |
| *Water Option 1* | | |
| 3 | Monofacial | Tilted 15º |
| 4 | Bifacial | Tilted 15º, no reflector |
| 5 | Bifacial | Tilted 15º, with reflector |
| *Water Option 2* | | |
| 6 | Monofacial | Horizontal |
| 7 | Monofacial | Tilted 15º |
| 8 | Bifacial | Horizontal, with reflector |
| 9 | Bifacial | Tilted 15º, with reflector |

technologies, it is necessary to select PV modules of similar cell characteristics. Therefore, LG modules were chosen given that this manufacturer produces monofacial and bifacial modules with the same cell technology. Both types of modules are based on monocrystalline N-type silicon. The monofacial module considered is LG Neon 2 LG300N1C-G4 with a rated power of 300 W and dimensions of 1,000 x 1,640 mm [37]. The bifacial module selected is the LG Neon 2 LG375N2T-A5, with rated power of 375 W and dimensions of 1,024 x 2,064 mm [38].

After some iterations in the definition of the electrical design it has been proposed to use single phase Fronius Primo inverters because of the following reasons:

- It complies with the latest Dutch norms and is available in the market [1].
- Empirical data is available for the evaluation of the inverter's performance following the Sandia National Laboratory inverter performance model [39].
- It is possible to connect two PV strings in the same inverter where each of them has a designated maximum power point tracker (MPPT) [40].

[1]For instance, from April 2019, Fronius Galvo inverters are not compatible with Dutch norms anymore.

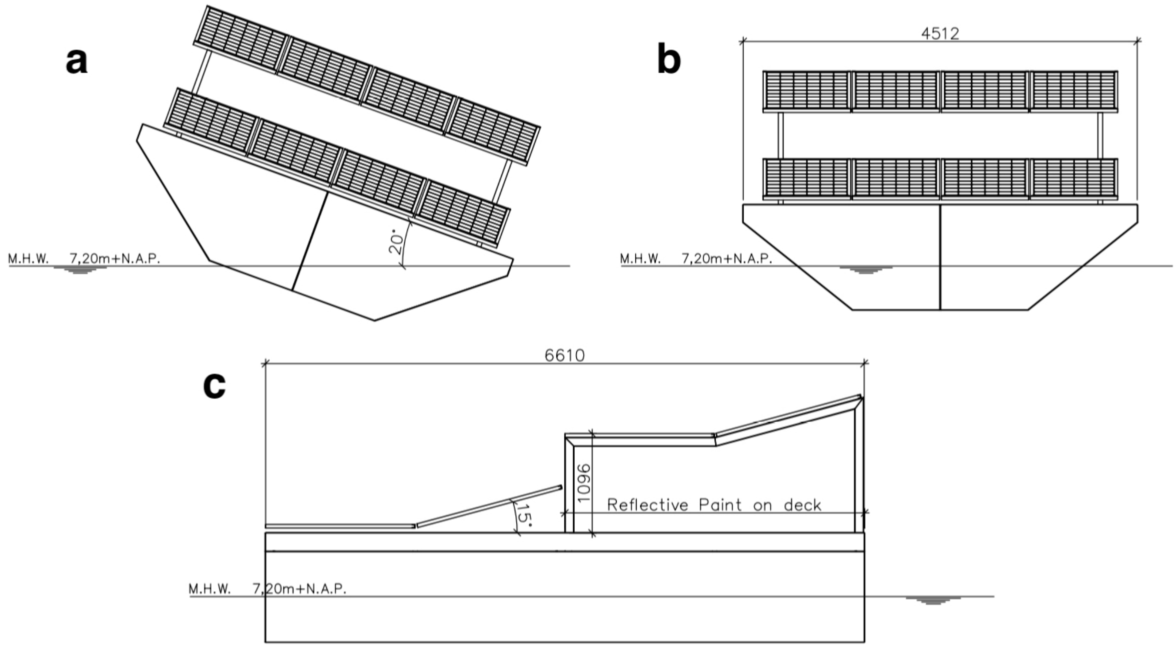



Figure 2.5: Detail of structure 2 a) View of tracking capability b) Front view c) Side view

- Voltage compatibility of PV array as for floating structure number 2, only four PV modules are connected in series, resulting in relatively low voltage.
- It is possible to obtain the production for each MPPT separately in order to analyse each study case individually [40].
- The number of commands run to obtain the data from all study cases is reduced since the same equipment returns the information of two study cases [7].

Additionally, the use of less inverters reduces the initial cost of the system. Although this analysis is outside of the scope of the pilot it is a positive feature to consider in following phases of the project when the system is up-scaled.

The distribution of the PV modules in the different arrays, their total rated power and the corresponding inverter are summarized in table 2.2. In appendix A the electrical diagram for the system is included.

## 2.3. Implications for the monitoring system

From the physical and electric characteristics of the system some considerations must be taken for the development of the monitoring system. The first of which is the connection to an stable internet service. It was mentioned previously that the distance between the room where the inverters will be located and the closest connection to fixed internet is around 400 meters. In this regard, it will be necessary to evaluate if a fixed or mobile connection is more appropriate.

In total, six inverters will obtain the information from nine PV strings. This means that the information gathers by some of them must be divided into different tables in the data base

Table 2.2: Distribution of PV string among inverters

| Case No. | Type | No. of modules | Total rated power | Inverter |
|---|---|---|---|---|
| *Land* | | | | |
| 1 | Monofacial | 4 | 1,200 W | Primo 3.0-1 |
| 2 | Bifacial | 4 | 1,500 W | |
| *Water Option 1* | | | | |
| 3 | Monofacial | 6 | 1,800 W | Primo 3.0-1 |
| 4 | Bifacial | 12 | 4,500 W | Primo 5.0-1 |
| 5 | Bifacial | 12 | 4,500 W | Primo 5.0-1 |
| *Water Option 2* | | | | |
| 6 | Monofacial | 4 | 1,200 W | Primo 3.0-1 |
| 7 | Monofacial | 4 | 1,200 W | |
| 8 | Bifacial | 4 | 1,500 W | Primo 3.0-1 |
| 9 | Bifacial | 4 | 1,500 W | |

and the calculation of the inverter performance must account for the share of the DC power provided by each string.The inverters selected for the system are Fonius Primo. The manufacturer of these equipment provides a framework of development for monitoring solutions [41]. In chapter 3 the different possibilities to acquire data from the system are explored and compared in order to choose the most suitable one.

Finally, the different study cases established in the pilot will be part of the analysis run by the PVMD Toolbox developed by TU Delft. Chapter 4 will elaborate on this analysis of the nine cases and will present the results regarding the configuration expected to perform better among all study cases. After simulating the energy forecast a further step provided in chapter 4 will consist on deploying the highest yield configuration to the rest of the water basin considering the available area and the restrictions on the space for maintenance work vehicles.

# 3
# Monitoring system

Building up on the mechanical and electrical specifications of the study cases in the InnoZoWa pilot, the current chapter will elaborate on the monitoring system specifications. This system answers to two purposes. First, it will enable the acquisition of production data for the analysis of the performance of the different study cases of the InnoZoWa pilot. Secondly, it will enable the validation of an energy yield forecasting model developed by the Photovoltaic Materials & Devices group at TU Delft. This tool, called "PVMD Toolbox", is able to characterize bifacial cell structures and it is also able to simulate PV systems based on such devices [42].

In section 3.1 the general functionality specifications of the system is provided. Later on, the alternatives to build this functionality in terms of hardware and software options are provided in sections 3.2 and 3.3, respectively. As we will see, different options of hardware and software, both from the inverter's manufacturer and third parties are available. The most suitable solution will be the one that provides a reliable connection to the system and storage of information, while allowing the practical operation from the staff and students involved in the project. Based on advantages and disadvantages of the explored solutions a website and database architecture are developed and presented in sections 3.4 and 3.5, respectively. The configuration of scheduled tasks on the server is explained in section 3.6. Finally, a discussion on the recommended future work on this system is provided in 3.7.

## 3.1. Functionality

The monitoring system for the InnoZoWa project is intended to work as a data storage system. It should provide its users with simple access to real time information of the PV system via a website. It should also provide means to retrieve historical data in a graphical display or as a downloadable file. There are two types of users expected to have access: general public and authorized users. The general public will access the website portal and will be able to observe a general state of the system's current production as well as some general information about the project. Authorized users will be able to log-in to the portal in order to access more detailed data and the historical information of the system.

In order to define the limitations to the functionality of the monitoring system, it is necessary to refer to the specifications of the inverters. These equipment will work as a the source of the information given that they receive the power in direct current (DC) and convert it to alternating current (AC). Therefore, at this point in the system it is desirable to measure all values related to the production of energy before it is supplied to the grid. This will allow the accounting of all efficiencies and losses inside the system. In section 2.2 of chapter 2 the selection of the inverters was explained based on the characteristics of the study cases. The Fronius Primo inverters' specification are detailed in [40].

Subsection 3.1.1 describes the data values to be retrieved from the system. Subsection 3.1.2 describes the mechanisms to access that data. Subsection 3.1.3 describes additional features of the system.

### 3.1.1. Measured values

There are two types of variables to be recorded from the systems: weather data and production data. The following variables of the first type are obtained from multiple sensors located in the proximity of the PV system:

- Wind speed [m/s], 1 measurement
- Air temperature [℃], 1 measurement
- Module temperature [℃], 5 measurements
- Irradiance [W/m$^2$], 2 measurements

The values of the second type are obtained from the inverters and provide information on the electricity generated by the system. Such measurements may be obtained both in DC and AC:

- Power [W]
- Voltage [V]
- Current [A]
- Frequency [Hz], only AC

The reading of the values should be performed every 5 minutes in order to obtain a near real-time view of the system. This small time step will provide with a high resolution of the data for any eventual analysis.

### 3.1.2. Storage and retrieval of data

The data obtained from the PV system must be stored in a remote database with the capability of recording several years of information. A calculation of the total amount of information to store per year is provided in chapter 3.5. This data repository must be accessible via a website in order to make the information available among the different partners from anywhere. Some manufacturers, including Fronius, provide its customers with proprietary remote monitoring solutions. In the case of Fronius, this tool is called "Solar.Web". This solution includes data storage and retrieval via graphs and downloadable reports [41]. However, for the purposes of the pilot and analysis of data it is preferable to develop a tool for which TU Delft has complete autonomy. "Solar.Web", therefore, can operate only as back-up tool.

The information on energy production and weather values will be displayed in the website in the form of graphs. To download the data for external use of the information, a commonly used format is a "comma separated values" (CSV) file which allows feeding data into other tools for analysis such as Matlab. The information will be downloadable for each study case or for the total values of the system for a desired time frame. This functionality will only be available for authorized users.

### 3.1.3. Supporting features

In addition to the acquisition and display of information, three supporting functionalities are necessary to implement in the monitoring system:

- Status of the system: In case of error, a flag must be displayed in the general view of the system.
- User management: A mechanism must be included for the creation and administration of authorized users who will have access to all recorded data.
- Back-up logging of the data: Additionally to the storage in the database, a logging device must be installed in order to ensure the recording of the information in case of lost communication between the PV system and the remote database.

## 3.2. Hardware

The hardware equipment required for the monitoring system is summarized in three parts: Data gathering, internet connection and server. The following subsections will elaborate on the details of these elements.

### 3.2.1. Data gathering

The equipment manufacturer, Fronius, has implemented in its equipment a network functionality called Solar Net [43]. The principle of operation is a bus network topology in which all inverters of a PV system are connected in series along a single string of cable for data transmission. Figure 3.1 provides an example of a typical Solar Net string including three inverters and a sensor box. In this network, one of the inverters behaves as a master, which collects data via a "Datamanager" from the rest of the inverters working as slaves. Also, the execution of commands is initiated by the master and delivered to the slaves for them to fulfill instructions such as reporting tasks or equipment reconfiguration. The relevant equipment involved in the collection of data are the following:

- Datamanager: This is a device inserted in all Fronius inverters and provides the network related functionalities to the equipment. In the same network, or Solar Net, one of the Datamanagers must be configured as master while the rest must be set to slave mode [7].
- Sensor box: This equipment gathers the readings from the sensors which can be either in analogue or digital form and translates it into a digital signal manageable by the Solar Net. The sensor box is considered to be a slave in the Solar Net configuration [44].
- Third party devices: An additional possibility for the collection of data from the inverters is the use of third party hardware using standard protocols such as Modbus TCP which is a communication mechanism developed for communication and control purposes in industrial networks. This solution is not implemented in the development of this project

as it is considered to increase the complexity of the monitoring system's architecture and does not provide additional advantages to the use of the Datamanager.

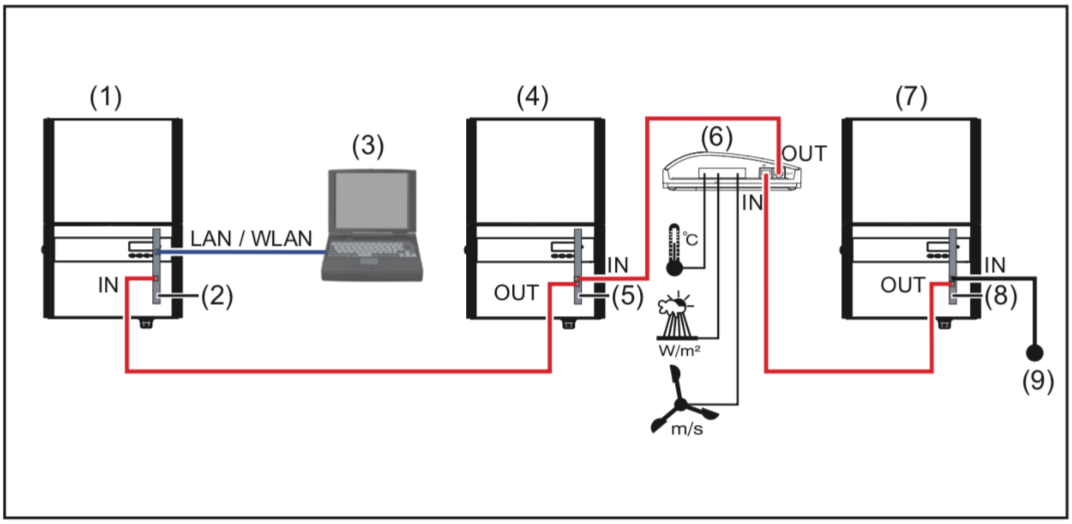



Figure 3.1: Topology example of a Solar Net ring of Fronius inverters and sensor box. 1) Fronius inverter, 2) Datamanager, 3) Local PC, 4) Fronius inverter, 5) Fronius Com Card, 6) Fronius sensor box, 7) Fronius inverter, 8) Fronius Com Card, 9) Fronius Solar Net termination plug. Adapted from [7].

### 3.2.2. Internet connection

After the information is collected in the master Datamanager it must be sent to an external repository via internet. The common physical connections consists of a cable based on optic fiber, coaxial or telephone line. In section 2.1.1 the distance to a suitable cable connection was presented as a potential issue for the deployment of a connection of this type. Therefore, it is necessary to analyse alternatives that provide the flexibility required for a system of this nature, specially considering that future developments of this kind will experience the same limitations and could even be completely detached from fixed communication lines. The alternative to this constraint is a mobile internet 4G LTE connection. The parameters to evaluate the feasibility of this connection are:

- Data transmission speed: The speed of data transmission in a 4G LTE connection is comparable to that of a fixed line connection. With up to 150 Mbit per second for download and 50 Mbit per second for upload speeds it is expected to perform similarly a standard optic fiber connection [45].
- Network coverage: The project is located in an urban area. Therefore, there is no complication regarding the provision of service in the zone. In [46], a map of the service area covered by the network operator used in this project, KPN, is provided and confirms the availability of service in the point of interest.
- Connectivity to the monitoring system: Mobile internet networks operate with different mechanisms as opposed to those of fixed line networks. In a typical network users are identified via an IP address. Given that most users in a mobile network are constantly moving and switching between different antennas, the identification of those users inside the network is dynamic. The most practical solution is a fixed Internet Protocol (IP) address. An internet service provider (ISP), Eilie B.V., is selected to provide the service

in the pilot. This company functions as a mobile virtual network operator (MVNO) and uses the network of KPN to provide internet with fixed IP addresses to its clients.

The internet settings are divided into external and internal. The external parameters are provided by the ISP and the internal once are configured in the router and the Datamanager. An important setting to configure is the local IP address of the equipment. Figure 3.2 provides an overview of the public and local areas in an internet connection. In the external interface or wide area network (WAN), a fixed public IP must be implemented in the 4G connection as previously mentioned. This is the address to which all external communication will be directed from the ISP. On the internal interface or local area network (LAN), a local IP must be assigned to the inverter so that the router (RUT) is able to locate the equipment and to direct requests and commands directed to it. The mechanism used by the router to receive commands from the internet and to direct them to a specific equipment in the LAN is called port forwarding and most routers in the market include this capability.

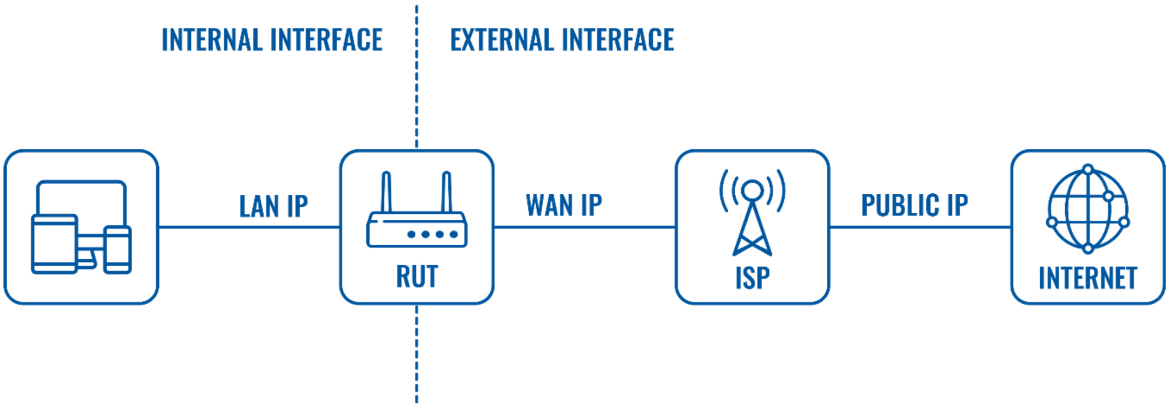



Figure 3.2: Division between local (LAN) and public (WAN) networks. Adapted from [8]

The address assigned by Eilie B.V. to the connection is 77.62.145.114 and it will be configured in the scheduled scripts on the LAMP server as section 3.6 will elaborate on. Also, the router, tp-link TL-MR6400, was selected to test the connectivity of the system. On this equipment, the master Datamanager is assigned the IP address 192.168.1.100. According to the specifications of the router, the range of local IP addresses is between 192.168.1.100 to 192.168.1.199 [47].

### 3.2.3. LAMP Server

For the hosting of the website and the database a reliable solution available at TU Delft is a server based on Linux operating system, Apache web server, MySQL database and PHP scripting language, commonly called LAMP. This server is used in other projects from the PVMD group where web and database services are required. An additional advantage of this platform is the potential integration with the other projects developed by the research group. The advantages of using this resource are:

- Large storage capacity
- Expandable storage capacity if required
- Infrastructure owned by the institution with support from the local IT team

- Consolidation of the PVMD group's projects on a single platform

Figure 3.3 provides a simple schematic representation of how the LAMP server connects the data gathering and website display.

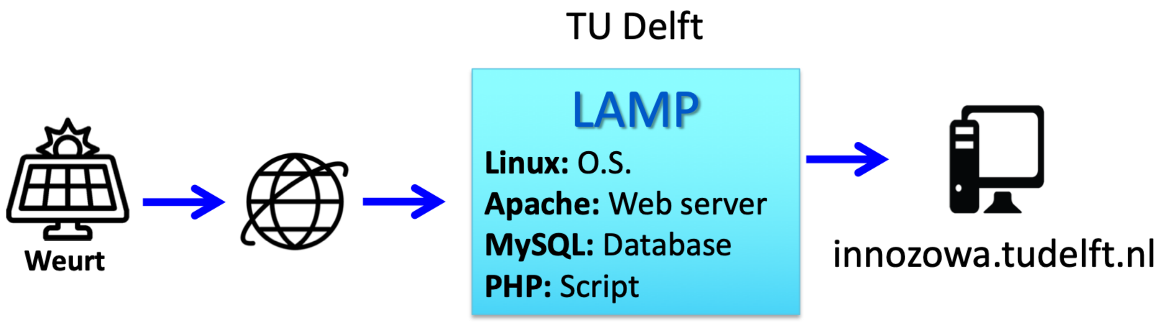



Figure 3.3: Flow of production data from the PV system to display on website

## 3.3. Coding languages

The scripting languages involved in the monitoring system are given by the environment of the LAMP server. A clarification on the specific purposes of each of language is provided:

- PHP: This programming language is used for the definition of commands to control the connection to the remote location, as well as to execute the commands on the MySQL databasee and the calculations performed on the data acquired from the system. This language is easily integrated with HTML code and is able to interpret data transmision structures such as CSV and JavaScript Object Notation (JSON) files. The latter kind is the format in which information is provided by the Fronius Datamanager.

- HTML: This is the common language for website development. In the same script file, PHP and HTML codes are integrated and usually share information with each other depending on the functions required from each of them in the display or manipulation of information on a webpage.

- JavaScript: Some sections of the website are based on JavaScript given that this language is suitable for applications that require interaction from the user and display of dynamic content such as graphs and data forms.

- MySQL: The database is based on MySQL. This type of database is managed by its own commands which must be integrated within the PHP scripts.

## 3.4. Website

The details of the website are treated in this section:

- URL: InnoZoWa's monitoring system is reached via ***https://innozowa.tudelft.nl***

- Main page: On the main page the general public can observe the current status of the production from the total system. Also, some relevant measurements are included such as irradiance, energy yield on the current day and total energy yield. Figure 3.4 provides a view of the main page design showing a graph at the center, measurements on the right-hand side and the "Log-in" button at the right-hand side top corner of the screen.

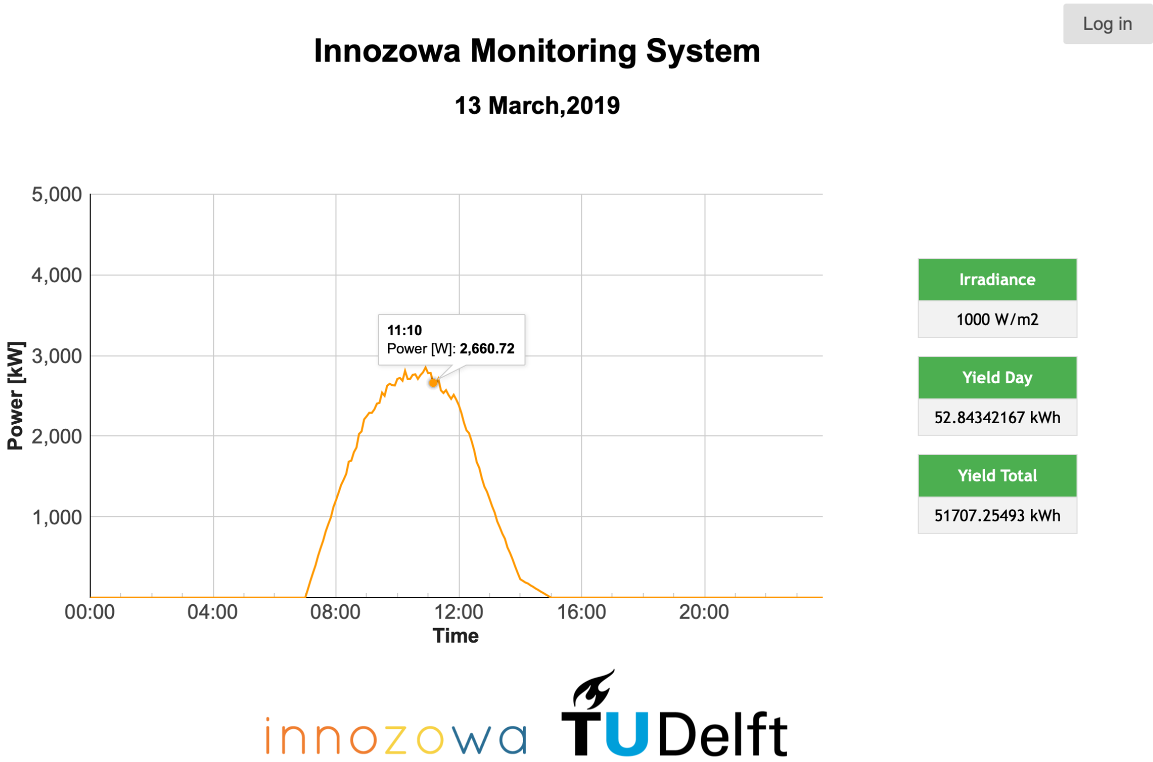
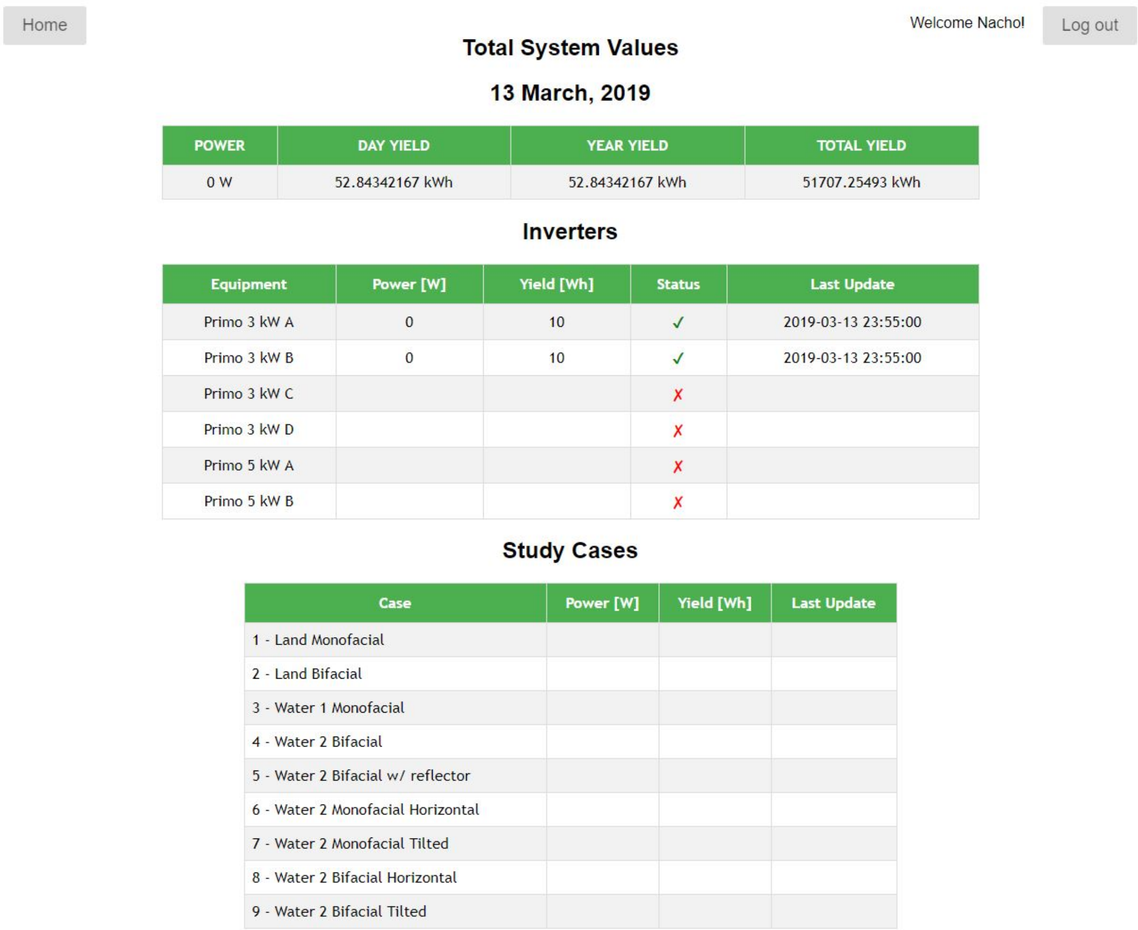



Figure 3.4: Screen view of the website's main page

- User authentication and user creation: The log-in system is enabled with a functionality to generate a new user. This is possible after providing an access code after which the user must fill-in a form with data such as name, organization, user name, password and password confirmation. This mechanism includes a verification of the data so that no duplicate user names exist and also to check if the password is provided correctly in the "password confirmation" section. This data is stored in the same database on the LAMP server.
- Portal: Authorized users are able to access the portal where the complete information on the system is available. Figure 3.5 provides a view of this page where a summary of the total system is displayed on the left-hand side, followed by a table with an entry for each inverter in the system. On the right-hand side a table with the readings from the weather measurements is included. Finally, after the sensors' table, the section to download historical data is located.
- Data download: In order to access historical data it is necessary to supply a date frame and the equipment of interest. This service will generate a CSV file including all readings available for the date frame selected starting with hour 00:00 and ending at 23:55.
- Specific data display: For each of the inverters displayed on the portal page a detailed view is provided by clicking on its corresponding row. This action opens a window as shown in figure 3.6 where the current production of the inverter is provided as well as daily, yearly and total energy yield values. At the bottom of the page, it is possible to select a different day to display its production curve.


Home

Welcome Nachol

Log out

**Total System Values**

**13 March, 2019**

| POWER | DAY YIELD | YEAR YIELD | TOTAL YIELD |
|---|---|---|---|
| 0 W | 52.84342167 kWh | 52.84342167 kWh | 51707.25493 kWh |

**Inverters**

| Equipment | Power [W] | Yield [Wh] | Status | Last Update |
|---|---|---|---|---|
| Primo 3 kW A | 0 | 10 | ✓ | 2019-03-13 23:55:00 |
| Primo 3 kW B | 0 | 10 | ✓ | 2019-03-13 23:55:00 |
| Primo 3 kW C | | | ✗ | |
| Primo 3 kW D | | | ✗ | |
| Primo 5 kW A | | | ✗ | |
| Primo 5 kW B | | | ✗ | |

**Study Cases**

| Case | Power [W] | Yield [Wh] | Last Update |
|---|---|---|---|
| 1 - Land Monofacial | | | |
| 2 - Land Bifacial | | | |
| 3 - Water 1 Monofacial | | | |
| 4 - Water 2 Bifacial | | | |
| 5 - Water 2 Bifacial w/ reflector | | | |
| 6 - Water 2 Monofacial Horizontal | | | |
| 7 - Water 2 Monofacial Tilted | | | |
| 8 - Water 2 Bifacial Horizontal | | | |
| 9 - Water 2 Bifacial Tilted | | | |

Figure 3.5: Screen view of the portal after login

## 3.5. Database

A database consists of tables were the information is stored in records. Data tables are configured to receive records. Records can be limited to specific characteristics such as types of data, length, nullity [1], value increment, uniqueness [2], among others [48]. The tables in InnoZoWa's database are classified in 5 types: users, total system, inverters, study case and sensors. The number of tables of each kind and their function are provided in table 3.1. In tables 3.2 to 3.5 the detail on variables stored and type of data is provided.

[1] If a record may be empty it is said that the value is null.

[2] In MySQL databases at least one record must be unique, this means that it may not be repeated in any other record.

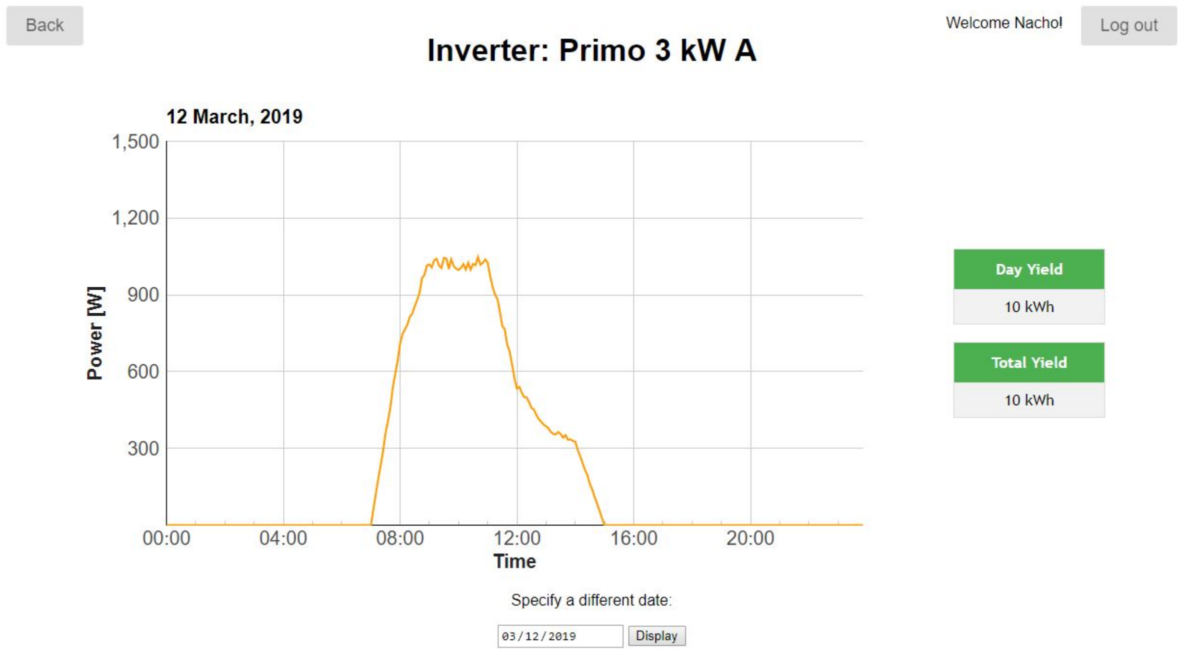



Figure 3.6: Screen view of the page for a specific inverter

Table 3.2: "Users" table, includes the authentication information of the portasl's users

| # | Name | Type and lenght | Other details |
|---|---|---|---|
| 1 | Name | Char, 20 | |
| 2 | Institution | Char, 20 | May be null |
| 3 | Username | Char, 8 | |
| 4 | Password | Char, 8 | |
| 5 | ID | Int, 11 | Primary key, Auto increment |

Table 3.3: "Total System" table. Stores historical data of the complete pilot PV system.

| # | Name | Variable | Type | Details |
|---|---|---|---|---|
| 1 | DateTime | Date and time of reading | datetime | Primary key |
| 2 | PAC | Power in AC | double | [W] |
| 3 | DAY_ENERGY | Energy produced on current day | double | [Wh] |
| 4 | YEAR_ENERGY | Energy produced on current year | double | [Wh] |
| 5 | TOTAL_ENERGY | Total energy production | double | [Wh] |

Table 3.1: Summary of tables in database

| Type | No. of tables | Table(s) name(s) | Details |
|---|---|---|---|
| Users | 1 | "users" | Stores the information of the authorized users of the portal |
| Total system | 1 | "TotalSystem" | Production of the entire system |
| Sensors | 1 | "sensors" | Data from all sensors in one table |
| Inverters | 6 | "PRIMO3A"<br>"PRIMO3B"<br>"PRIMO3C"<br>"PRIMO3D"<br>"PRIMO5A"<br>"PRIMO5B" | One table per inverter |
| Study case | 9 | "LandMono"<br>"LandBi"<br>"Water1Mono"<br>"Water1Bi"<br>"Water1BiRef"<br>"Water2MonoHor"<br>"Water2MonoTilt"<br>"Water2BiHor"<br>"Water2BiTilt" | One table per study case in the pilot. Tables' names refer to study case situation. |

Table 3.4: "Inverter" table. Stores data for each inverter

| # | Name | Variable | Type | Details |
|---|---|---|---|---|
| 1 | DateTime | Date and time of reading | datetime | Primary key |
| 2 | PAC | AC power | double | [W] |
| 3 | SAC | AC power | double | [W] |
| 4 | IAC | AC current | double | [A] |
| 5 | UAC | AC voltage | double | [V] |
| 6 | FAC | AC frequency | double | [Hz] |
| 7 | IDC | DC current | double | [A] |
| 8 | UDC | DC voltage | double | [V] |
| 9 | effi | Inverter efficiency | double | [%] |
| 10 | DAY_ENERGY | Energy produced on current day | double | [Wh] |
| 11 | YEAR_ENERGY | Energy produced on current year | double | [Wh] |
| 12 | TOTAL_ENERGY | Total energy production | double | [Wh] |
| 13 | Status | Power in AC | int, 11 | [W] |

Table 3.5: "Sensor" table. Stores data of the weather measurements and module temperature.

| # | Name | Variable | Type | Details |
|---|---|---|---|---|
| 1 | DateTime | Date and time of reading | datetime | Primary key |
| 2 | Irradiance 1 | irr1 | double | [W/m$^2$] |
| 3 | Irradiance 2 | irr2 | double | [W/m$^2$] |
| 4 | Irradiance 3 | irr3 | double | [W/m$^2$] |
| 5 | Air temperature | tempA | double | [ºC] |
| 6 | Module temperature 1 | tempM1 | double | [ºC] |
| 7 | Module temperature 2 | tempM2 | double | [ºC] |
| 8 | Module temperature 3 | tempM3 | double | [ºC] |
| 9 | Module temperature 4 | tempM4 | double | [ºC] |
| 10 | Module temperature 5 | tempM5 | double | [ºC] |
| 11 | Wind speed | wind | double | [m/s] |

Table 3.6: "Study case" table. Stores the historical information for each study case in the pilot.

| # | Name | Variable | Type | Details |
|---|---|---|---|---|
| 1 | DateTime | Date and time of reading | datetime | Primary key |
| 2 | IDC | DC current | double | [A] |
| 3 | UDC | DC voltage | double | [V] |
| 4 | PDC | DC power | double | [W], PHP script calculation |
| 5 | DAY_ENERGY | Current day energy yield | double | [Wh], PHP script calculation |
| 6 | YEAR_ENERGY | Current year energy yield | double | [Wh], PHP script calculation |
| 7 | TOTAL_ENERGY | Total energy yield | double | [Wh], PHP script calculation |

## 3.6. Scheduled PHP scripts

In the previous section the information stored in the database and its structure has been presented. The information stored there is retrieved from the PV system, however, it is received in the form of a JSON file and must be interpreted with PHP scripts into data values to store in the tables. This section elaborates on how the requests to the Datamanager are made and how the information is translated into data values compatible with the database. Subsection 3.6.1 provides the general structure of an HTTP request and the parameters require for their use in Fronius equipment. Then, subsection 3.6.2 explains how such requests are generated in the LAMP server and the logic in which they are running periodically.

### 3.6.1. HTTP request & Fronius API

The Hypertext Transfer Protocol (HTTP) is a communication protocol for the transfer of information between clients and servers. It works under the principle of request and response, where the former is initiated by the client [49]. There are different methods in which an HTTP request interacts with a server and they differ in terms of the allowed actions of the client on the information stored on the server. For the interest of this project and according to the specifications of the Fronius API, we will focus on GET requests which can only request data and are not intended for sensitive data such as passwords [50]. The basic structure of this request is a URL and paramaters, for example:

***URL.php?parameter1=value1&parameter2=value2***

In our case the URL consistst on two sections. First it starts with the public IP of the 4G router provided in subsection 3.2.2. The second part is defined in the Fronius Solar API [10]. For example, the URL for the HTTP requests of real time data is the following:

***/solar_api/v1/GetInverterRealtimeData.cgi***

A complete URL to reach the Datamanager is therefore the following:

***http://77.62.145.114/solar_api/v1/GetInverterRealtimeData.cgi***

Following the URL, some parameters must be set to distinguish between commands directed to retrieve information from the whole system or from specific equipment. Table 3.7 provides the parameters to set at the end of the command.

Table 3.7: Possible parameters to set in an HTTP request to Fronius Solar API [10].

| **Parameter** | **Type** | **Value** | **Description** |
|---|---|---|---|
| Scope | String | "Device"<br>"System" | Query specific device or whole system<br>(uses "CumulationInverterData") |
| DevideId | String | Solar Net:<br>0 to 99 | Only needed for Scope "Device"<br>Determines which inverter to query. |
| DataCollection | String | "CumulationInverterData"<br>"CommonInverterData"<br>"3PInverterData"<br>"MinMaxInverterData" | Only needed for Scope "Device"<br>Selects the collection of data that<br>should be required from the device. |

An example of a complete request to retrieve system data is the following:

***http://77.62.145.114/solar_api/v1/GetInverterRealtimeData.cgi?Scope=System***

Another example of a complete request to retrieve "common inverter data" from the equipment number 1 in the Solar Net:

***http://77.62.145.114/solar_api/v1/GetInverterRealtimeData.cgi?Scope=Device&DeviceId=1&DataCollection=CommonInverterData***

The aforementioned requests are of particular interest for the moniroting system since they will be implemented for the retrieval of data for the complete system and for specific inverters. Tables 3.8 and 3.9 provide a summary of the values delivered by the Datamanager when a request is executed to retrieve information on the total system and specific equipment respectiveley.

Table 3.8: Values provided for a total system overview [10].

| Value name | Data type | Description |
|---|---|---|
| PAC | integer | AC power |
| DAY_ENERGY | unsigned integer | Current day energy yield |
| YEAR_ENERGY | unsigned integer | Current year energy yield |
| TOTAL_ENERGY | unsigned integer | Total energy yield |
| DeviceStatus | object | Status information about inverter |

Table 3.9: Common values provided for a specific device [10].

| Value name | Data type | Description |
|---|---|---|
| PAC | integer | AC power |
| SAC | unsigned integer | AC power (not implemented in all inverter models) |
| IAC | number | AC current |
| UAC | number | AC voltage |
| FAC | number | AC frequency |
| IDC | number | DC current |
| UDC | number | DC voltage |
| DAY_ENERGY | unsigned integer | Current day energy yield |
| YEAR_ENERGY | unsigned integer | Current year energy yield |
| TOTAL_ENERGY | unsigned integer | Total energy yield |
| DeviceStatus | object | Status information about inverter |

The last type of request that is used in the monitoring system is related to the sensors. It is built as follows:

***http://77.62.145.114/solar_api/v1/GetSensorRealtimeData.cgi?Scope=System***

After an HTTP request is taken by the Datamanager a response is generated in JSON format. Although this format of data transmission is more lengthy than a typical CSV file, it provides some advantages such as:

- Content is organized in a "tree" structure rather than a table.
- Detail on the units of the variables measured.
- Easy to decode in PHP scripts on the server.
- Simplified transmission of data in either number or string type.

Appendix A provides an example of JSON content delivered in an HTTP response from the Fronius Datamanager.

### 3.6.2. PHP scheduling

The protocol of operation of an HTTP request has been previously presented: The request is initiated by the "client" and fulfilled by the "server". However, it is important to notice that for the effects of data retrieval from the PV system the entity triggering the communication is the LAMP server. This means that the LAMP server functions as the "client", generating the HTTP request, while the master Datamanager, receiving the request, is the "server". To trigger the client-server communication periodically and according to the time resolution of 5 minutes, it is necessary to configure the LAMP server to run specific PHP scripts contaning the commands to excecute the corresponding HTTP requests. Table 3.10 summarizes the scheduled scripts and their function in the monitoring system.

Table 3.10: "Study case" table. Stores the historical information for each study case in the pilot.

| **Request** | **No. of scripts** | **Purpose** |
|---|---|---|
| System | 1 | Gathers acumulated production of complete system |
| Device | 6 | Request current production of each inverter |
| Sensors | 1 | Request current weather measurements |

## 3.7. Discussion on the monitoring system

In this chapter a solution for the acquisition of floating PV systems for research purposes has been developed. During the development, some technical challenges such as limited connection to an internet connection have been foreseen. A solution for the connection of the system to internet via mobile networks is presented as a viable way to deploy in projects developed on inland water bodies with limited fixed line network access. Also, the monitoring system was integrated using different software components and IT resources from TU Delft that have been implemented in other projects from the PVMD group. Further integration and the creation of a knowledge repository is advised. This will enable future students and staff to promptly acquire the necessary skills to manage, develop and advance the infrastructure and projects of the research group.

# 4

# Validation of PVMD Toolbox

The second part of this thesis constitutes an analysis of the different study cases proposed in the InnoZoWa pilot. The goal of this analysis is to predict the output of each configuration in order to evaluate which one will perform better. This evaluation will enable a further prediction of how much energy can be harnessed should the system size be increased to cover the total available surface of the water basin in Weurt.

In order to carry out the analysis, it is necessary to use a PV system modelling tool. Within the PVMD group a toolbox has been developed, the PVMD Toolbox. This is an opportunity to bring together both the development of InnoZoWa and the PVMD Tollbox in order to advance the knowledge of the team on complex architecture forecasting models. As a first step, it must be established how accurately the PVMD Toolbox can predict a PV system's output. Given that the InnoZoWa project is still under construction, it is necessary to obtain real production data of bifacial systems from a different source. This data is provided by a partner of TU Delft, Tempress Systems, who is currently developing bifacial modules in the Netherlands.

This chapter will elaborate in section 4.1 on the validation process. Then, section 4.2 presents the results on the evaluation of the study cases. Finally, a discussion is carried out in section 4.3 regarding the validation process, findings and general feedback on the PVMD Toolbox.

## 4.1. Validation with empirical data

Two possibilities have been considered in order to establish the degree of accuracy of the PVMD Toolbox: validation against empirical data from a bifacial PV system and validation against simulation with similar software. The latter option, however, is not the optimum way to do it given that, as previously exposed, validated bifacial PV systems modelling is still a discipline in development. The first option is therefore chosen for this step. The acquisition of bifacial PV data is presented in subsection 4.1.1. In order to carry out a simulation of the production system, weather data must be fed into the PVMD Toolbox and it must be as close as possible to the actual contidions of operation of the system. This topic is treated in subsection 4.1.2. Later, all relevant inputs to feed into the PVMD Toolbox are presented in subsection 4.1.3 in order to prepare the simulation of the real system.

### 4.1.1. Tempress study

Tempress Systems is a manufacturer of furnaces for the production of solar photovoltaic devices. In the development of their products, they carry out benchmark validations versus products available on the market. This practice allows them to know the quality that can be achieved by producing PV modules with their furnaces. In a recent study, Tempress has compared several bifacial and monofacial technologies on a testing site in Vassen, the Netherlands [51]. Part of their market analysis involves scenarios where bifacial PV modules are tested. One of them uses a module of the same technology considered to be implemented in InnoZoWa. This is an N-type monocristaline silicone panel. The specifications of the module are found in [11]. Tempress has provided us with all relevant technical information of this testing setup and this has allowed us to have a data of high quality and reliability for us to perform a validation of the PVMD Toolbox with empirical data.

In order to perform an accurate validation, all parameters of the study setup must be known and fed into the PVMD Toolbox as inputs. These parameters are divided into geometrical and electrical specification. Subsection 4.1.3 will elaborate on how this parameters are fed into the toolbox while explaining its operation. The geometrical and electrical parameters are provided in tables 4.1 and 4.2, respectively.

Table 4.1: Geometrical parameters of Tempress study.

| Parameter | Value | Unit |
|---|---|---|
| Cell width | 16.17 | cm |
| Number of cell rows | 10 | |
| Number of cell columns | 6 | |
| Module thickness | 4 | cm |
| Cell spacing | 0.4 | cm |
| Edge spacing | 2 | cm |
| Module Tilt angle | 37.9° | |
| Module Azimuth (South is 0°) | 15° SE | |
| Height of lower module's edge from ground | 1.05 | m |
| Distance between rows, measured at the middle of the module | 4.9 | m |
| Side distance between centre of modules | 1.8 | m |

Table 4.2: Electrical parameters of Tempress study. Specs refer to front side rating [11]

| Parameter | Value | Unit |
|---|---|---|
| Open Circuit Voltage (Voc) | 40.8 | V |
| Short Circuit Current (Isc) | 10.12 | A |
| MPP Voltage (Vmpp) | 33.5 | V |
| MPP Current (Impp) | 9.41 | A |
| Temperature coefficient of Voc | -0.27 | %/°C |
| Temperature coefficient of Isc | 0.03 | %/°C |

Tempress has run this test since April 2018. For the purposes of the validation it has been established that the data of four months, between June and September 2018, will be used. The time resolution of the weather data used in the validation is 1 hour. As we will see later, some advantages and disvantages arise from this time step. The main advantage is a smaller calculation time while the main disadvantage is that fluctuations occurring within that hour are not accounted for.

### 4.1.2. Weather data

The PVMD Toolbox uses weather data for the calculation of the operation conditions that influence the performance of the PV module. One of the calculation modules implemented in the toolbox is the fluid dynamic model. This model calculates the temperature of operation of the module which will impact directly the operation values of Voc and Isc. To calculate this temperature of operation, the irradiance, ambient temperature, wind speed, thermal coefficients and heat transfer coefficients of the surroundings are required [31].The weather parameters used by the toolbox are listed in table 4.3.

Table 4.3: Weather data used by the PVMD Toolbox.

| Parameter | Unit |
|---:|---|
| Sun azimuth | degrees, South = 0° |
| Sun altitude | degrees |
| Direct Normal Irradiance (DNI) | $W/m^2$ |
| Diffuse Horizontal Irradiance (DHI) | $W/m^2$ |
| Global Horizontal Irradiance (GHI) | $W/m^2$ |
| Ambient temperature | ℃ |
| Wind speed (10 m above ground) | m/s |

A first validation approach consisted in using meteorological data acquired from Meteonorm. This method delivered results with a large deviation from the actual values. In some cases, the forecasted energy yield was 95% lower than the actual production. See figure 4.7 for reference. After reviewing the possible causes for such a large deviation, two reasons were identified: (1) the number of rays used for the calculation of the sensitivity map during the characterization of the module and (2) the difference between meteorological data and weather data from 2018, which was the year with a significantly higher irradiance than a typical year. More on the first reason is provided in subsection 4.1.3.

After realizing that meteorological data would not suffice to perform an accurate validation, real weather data was searched. Within the set of data that Tempress gave us access to, the irradiance profiles for each day since the beginning of the study were available. These values are given, however, in terms of GHI so it is necessary to perform a calculation of both DHI and DNI components in order to be compatible with the PVMD Toolbox. To perform this, a model implemented in another tool also developed in the PVMD group, the Dutch PVP Portal, was used. This model, called BRL after its developers, uses GHI values, geographical location, the sun's apparent position, the clear sky index derived from the eccentricity of the sun and the irradiance constant at the top of the atmosphere [52]. The BRL model was implemented in the Dutch PV Portal 2.0 by Veikko Schepel [53]. This implementation has been validated within the PVMD Group and provides a reliable tool for the separation of irradiance into its direct and diffuse components.

Figure 4.1 provides an example of the data provided by Tempress. From that graph, the irradiance and the power output of the system at the testing site are shown in the same graph. A disadvantage of this data source is the unavailability of data in an organizes text format. It was therefore necessary to digitize the information displayed on this graph before performing the direct and diffuse components calculation. Given the time consuming process that this represented it was decided to use a 1 hour step to extract the irradiance data. The problem foreseen in this matter is that for day with rapidly changing instantaneous irradiance, the variations within the hour step will not be reflected in the data. An example of this is provided in figure 4.2 where the irradiance profile for a day with a mix of sunny and cloudy conditions.

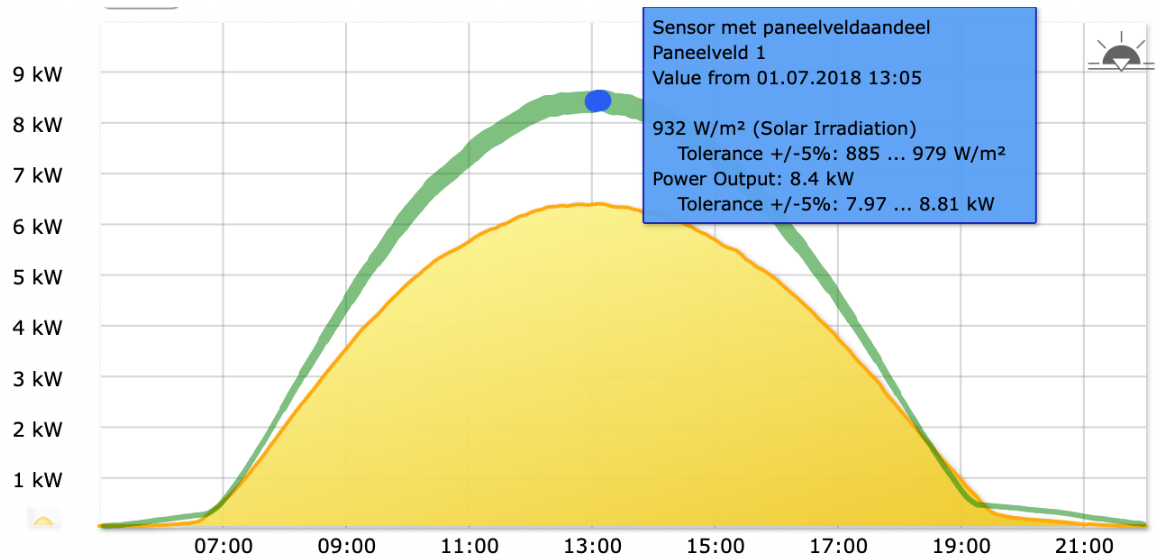



Figure 4.1: Tempress testing site on July 1st, 2018. Green: Irradiance [W/m$^2$]. Yellow: Output of the total test system [kW].

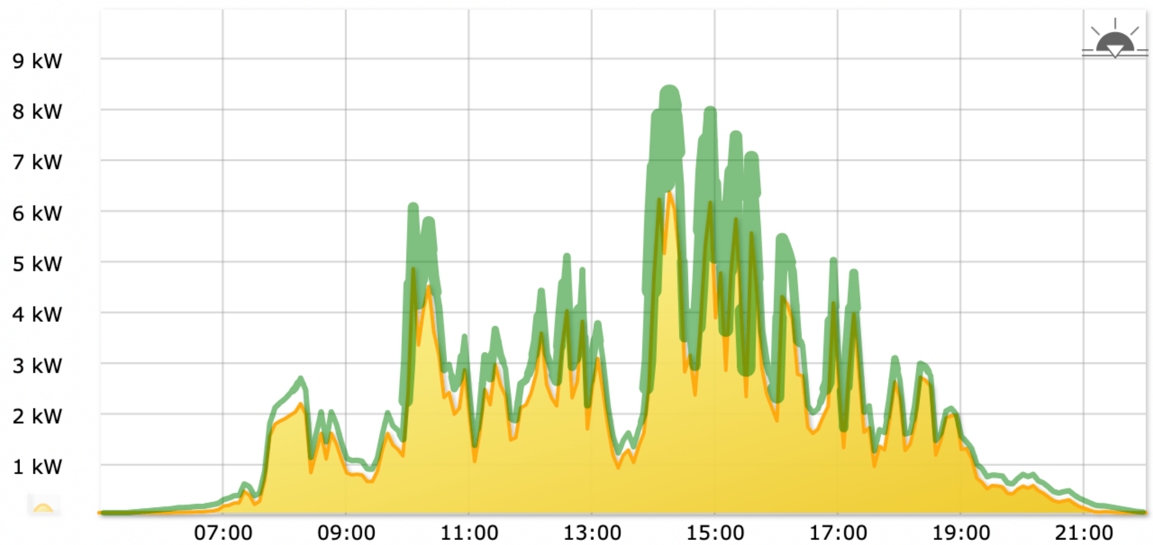



Figure 4.2: Tempress testing site on July 11th, 2018. Green: Irradiance [W/m$^2$]. Yellow: Output of the total test system [kW].

### 4.1.3. PVMD Toolbox operation

The PVMD Toolbox consists of four steps run in series:

1. Cell: Generates a characterization of the light absorption and transmission in the different layers of a PV cell in function of the angle of incidence of light. This characterization can be performed for monofacial, bifacial or tandem cell currently. In this project monofacial and bifacial cell characterizations have been used.

2. Module: After the cell light absoption characteristics have been generated it is necessary to describe the architecture of the module. The inputs in this section have been presented in table 4.1. In this step, a simulated module structure is generated, it can bee seen in figure 4.3. The sensitivity map for that bifacial module is also generated as shown in figure 4.4.

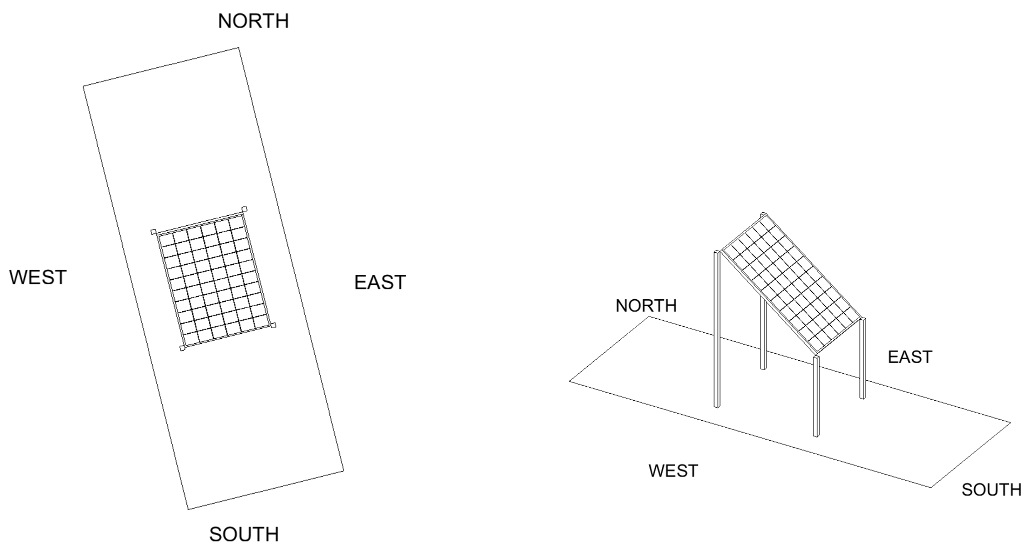
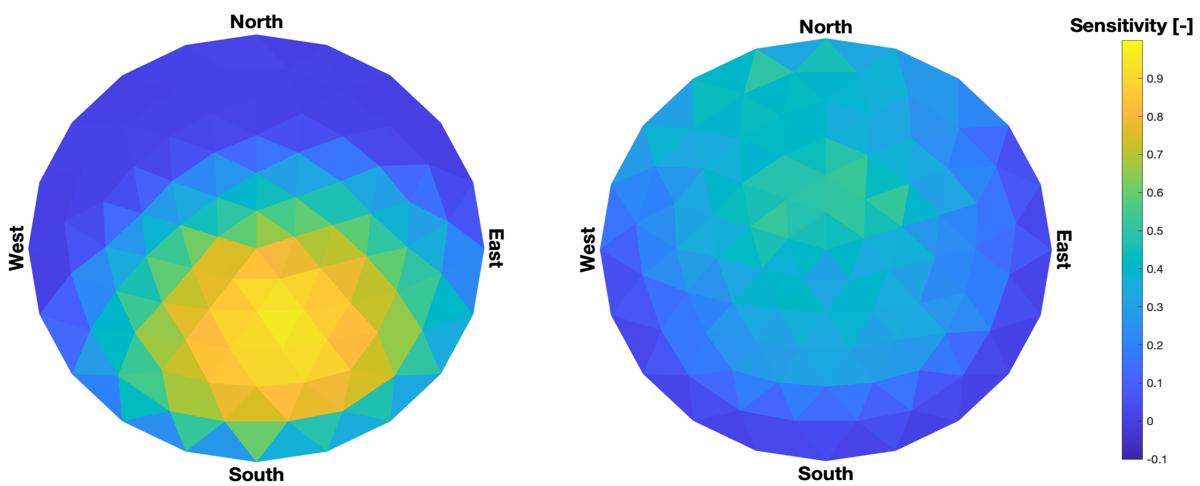



Figure 4.3: Schematic view of module's orientation, top view (left) and side view (right).




(a) Front (b) Back

Figure 4.4: Sensitivity map for the module tested by Tempress

3. Weather: Once the module has been characterized, the weather data is fed into the simulation. This data is taken by the toolbox from an Excel file with the following columns:

    - Year [YYY]
    - Month [MM]
    - Day [DD]
    - Hour [HH]
    - Sun Azimuth [South = 0°, West = 90°, North = -180°, East = -90°]
    - Sun Altitude [degrees]
    - DNI [W/m$^2$]
    - DHI [W/m$^2$]
    - Ambient Temperature [°C]
    - Wind Speed [m/s]
    - GHI [W/m$^2$]

    At the end of this step a Matlab object is generated with the module's temperature at each instant provided in the weather data file. These values will impact the energy generation calculated in the following step.

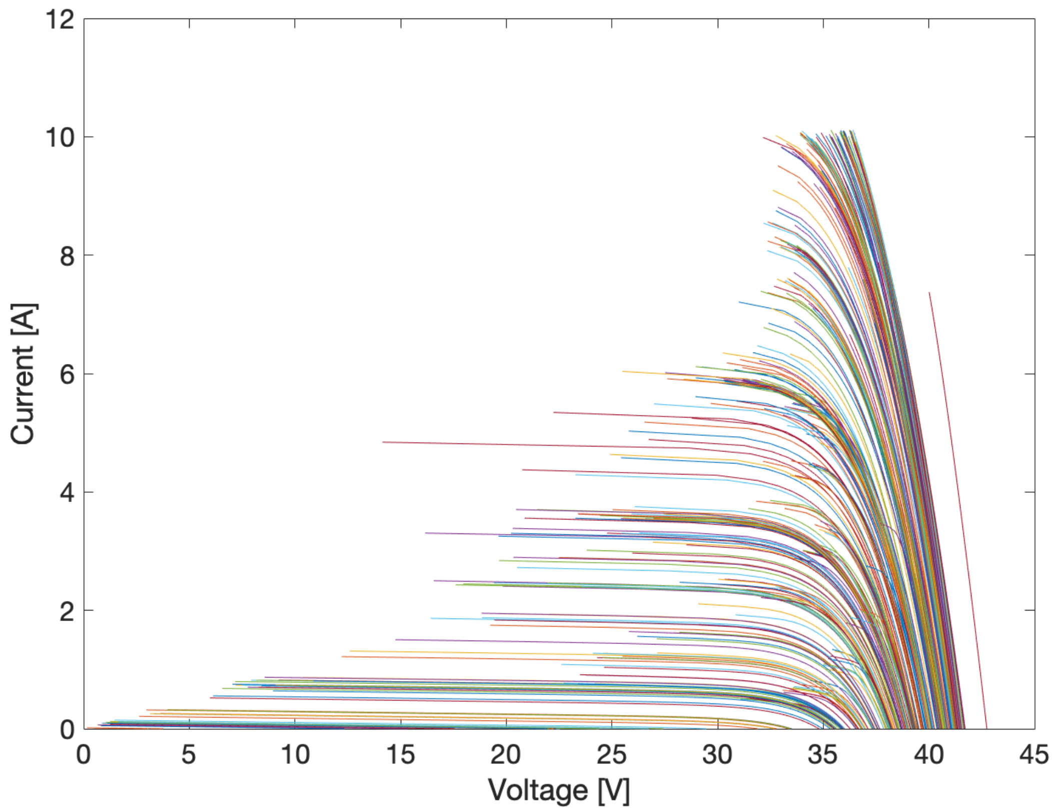



Figure 4.5: IV curves calculated for each hour with irradiance during July 2018.

4. Electric: Finally, the electrical simulation of the PV module requires the electrical characteristics of the equipment as provided in table 4.2. During this step, the electrical shunt and series resistance of the PV module are simulated and accounted for during

the calculation of the energy yield. For each point fed via the weather data file an IV curve is generated and this is used to estimate the power point at which the module would operate in that specific moment. The vertical axis of the IV curves represent the current, which is limited by the cell of lowest operating current and the IV curve is drawn up to that current value. According to Zidan Wang, current developer of the PVMD Toolbox, in a newer version of the toolbox the IV curves will be generated for the complete range of voltages between 0 and Voc. In figure 4.5 the IV curves for the month of July are shown as they are provided by the PVMD Toolbox. At the end of the electrical step, a profile of the production in Wh is provided in a graphical and numerical way. Figure 4.6 provides an example of the energy yield for the first seven days of July 2018.

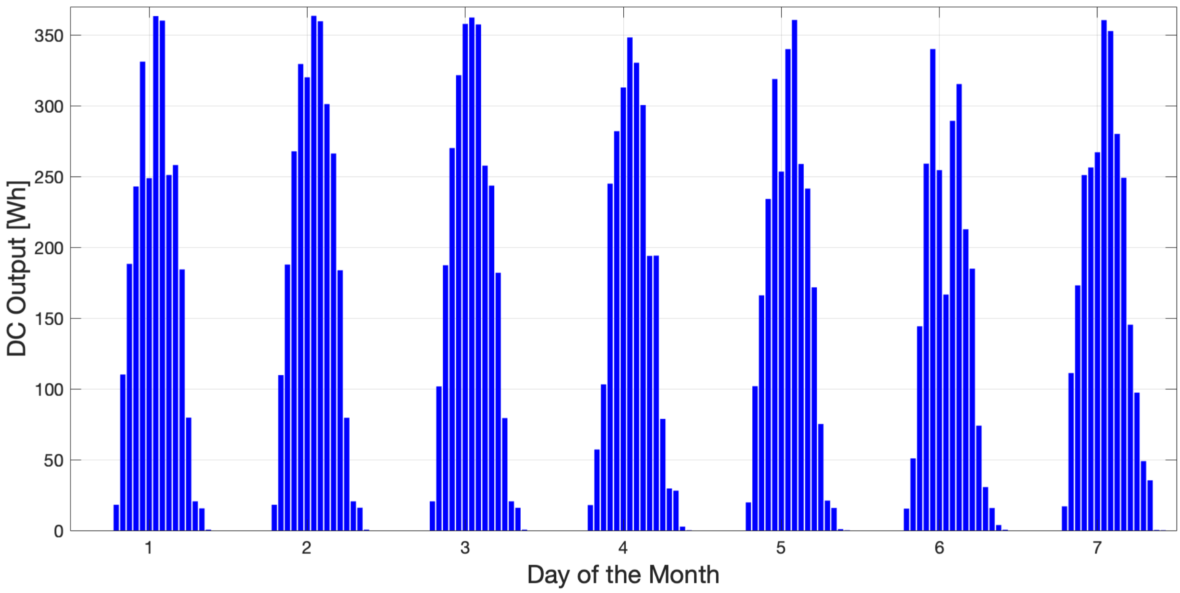



Figure 4.6: Tempress' panel production simulation during first 7 days of July 2018

## 4.2. Validation results

The validation was performed in different stages in order to observe the sensitivity of the toolbox to different settings in terms of: (1) number of rays for the characterization of the sensitivity map of the module and (2) the type of meteorological data, climate or weather. First, a simulation of the Tempress system was carried out assuming an albedo value of 0.8 and using 1,000 rays to reproduce the sensitivity map in the second step, "module". Also, climate data was used in this validation. The results from this first validation did not approximate the real system's output. It was in some cases close to 48% lower than the actual production measured from the panel at the testing site. Figure provides a summary of the results for each month tested comparing the production from the Tempress system in blue and the values delivered by the PVMD Toolbox in red.

Given that the results from the first simulation did not describe the actual behaviour of the real system a review of the parameters was perform with the team involved in the development of the toolbox. Two modifications for the validation process were proposed: (1) to modify the number of rays used for the characterization of the sensitivity map from 1,000 to 50,000 and 100,000 (2) to utilize measured weather data from the testing site instead of climate data in order to reproduce the exact same operating conditions. The first modification was set in the code of the toolbox which is developed in Matlab. The second one required extraction of weather data and its conditioning as previously described in subsection 4.1.2 for it to be compatible with the PVMD Toolbox. In figures 4.7 through 4.11 the results for the different validation scenarios are presented.

The results delivered from the simulation with 50,000 rays and weather data showed a significant improvement in terms of their description of the actual values measured at the testing site. The largest deviation in this case was 14%. Figure 4.8 provides the summary of results from the reviewed validation. From these validation a degree of precision close to ±15% can be established in the results from the PVMD Toolbox considering the number of rays used in the second step of the simulation and the resolution of the weather data provided to the tool in the third step.

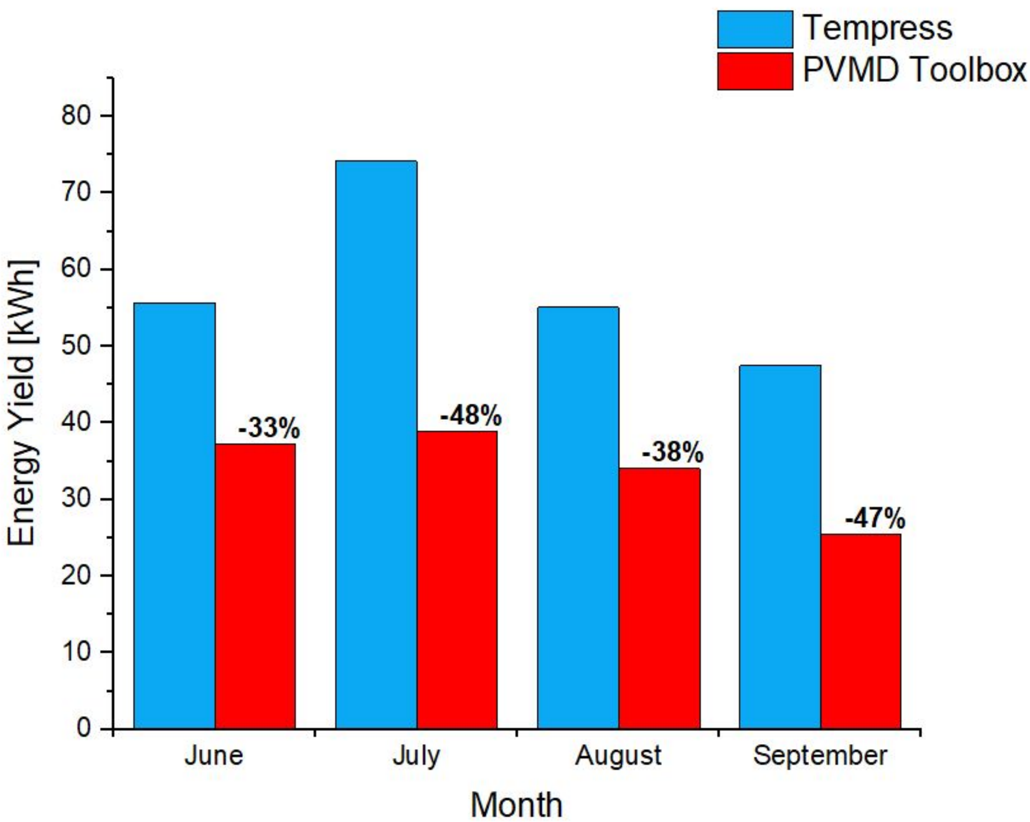



Figure 4.7: PVMD Toolbox validation using 1,000 rays and climate data

It is necessary to point out that as the number of rays is increased for the characterization of the sensitivity map, the computation time is increased linearly. The same PC was used to run all simulation scenarios and computation times for this step increased from 9 minutes for 1,000 rays to 4 hours for 100,000 rays.

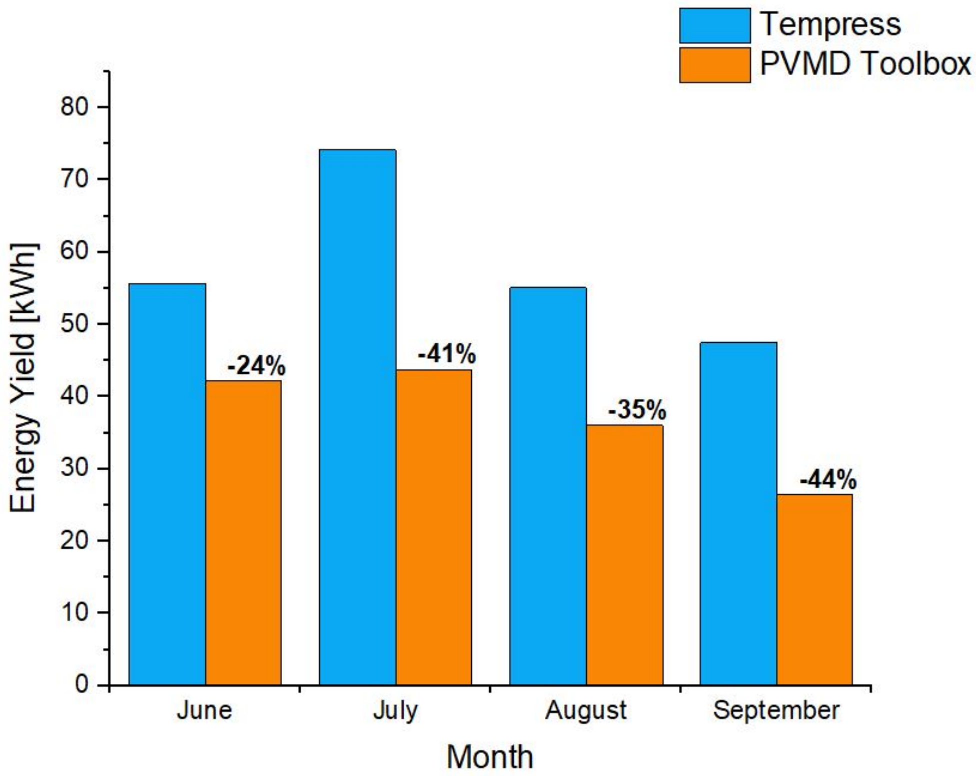



Figure 4.8: PVMD Toolbox validation using 50,000 rays of rays and climate data

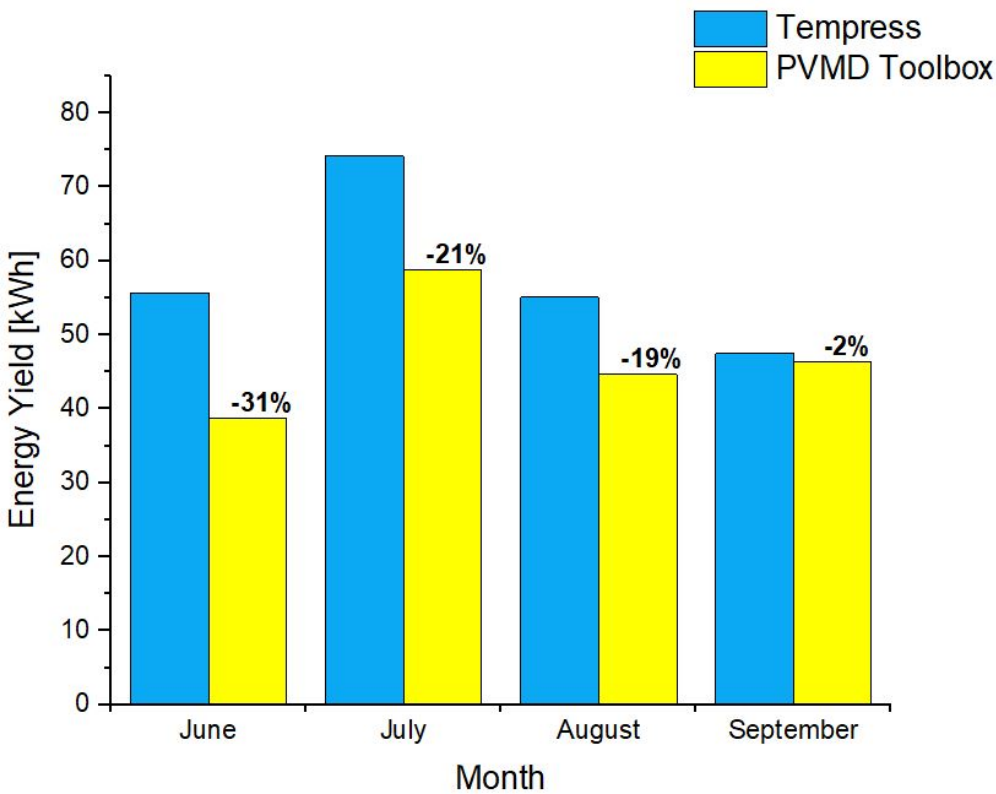



Figure 4.9: PVMD Toolbox validation using 1,000 rays and weather data

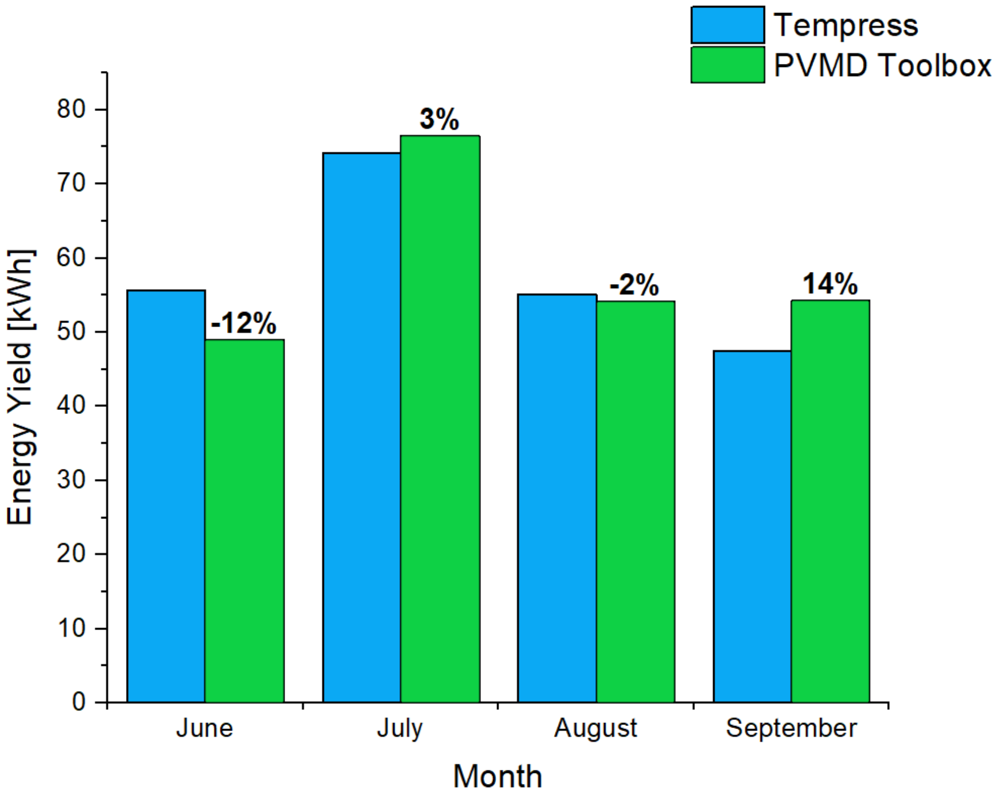



Figure 4.10: PVMD Toolbox validation using 50,000 rays and weather data

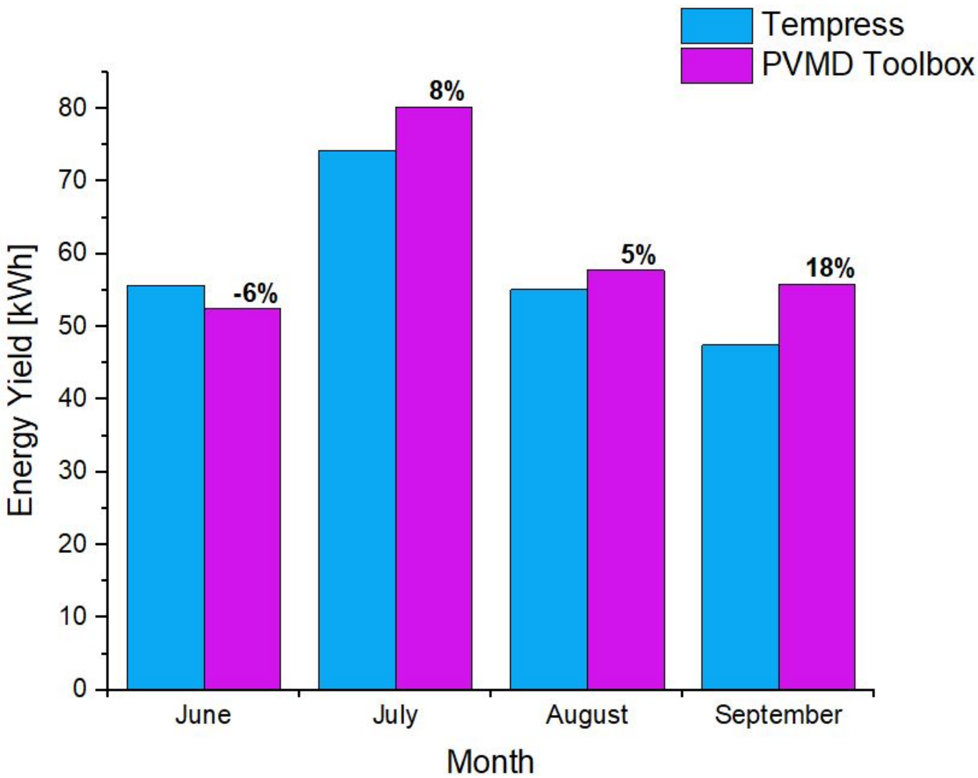



Figure 4.11: PVMD Toolbox validation using 100,000 rays and weather data

## 4.3. Discussion on validation process and results

The exercise of validation of the PVMD Toolbox with empirical data is one of the first steps to measure the accuracy of the tool. From this experience it is possible to provide some recommendations and insight views that can server as considerations for future developers of the tool. The following list provides the main findings:

- During the validation process it was necessary to learn how to use the PVMD Toolbox without guidance or documented instructions. The creation of a user manual would allow new users to have a faster understanding of the inputs, processes and outputs of the tool.
- Some of the parameters involved in the simulations such as albedo, number of rays are inserted in the code of the tool and not shown in any of the dialogue boxes that shown to the users. In some simulation cases it is necessary to modify those values and the optimum way to do it is one where it is not necessary to explore through the code to modify them. A dialog box is also a more secure way to avoid modifying other sections of the code.
- When the number of rays was increased to 50,000 rays in the second iteration for the simulation the time to run the module characterization increased significantly from 3 minutes to above 2 hours. Also, because of this modification, the electric step became more time consuming increasing from a couple of minutes to around 20 minutes.
- In some stages, such as the electrical one, it is not possible to visualize the progress of the simulation. It would be useful for the users to know the state of the calculation process. A dialogue box with a percentage of the progress would be an practical way to display it.
- The complete process of simulation requires the interaction of the user with the tool in different stages. For each step there is a different input required. It would be also practical to provide the tool with all inputs from the beginning and let the complete process run all at once.
- The validation run with 50,000 rays and measured weather data, seen in figure 4.10, was the closest approximation to the actual system's energy output. However, the months of June and September show a large deviation compared to the months of July and August. The main reason for this is the weather variations occurring during June and September. Figure 4.2 provides an example of a typical day during those months. In contrast, figure 4.1 represents the irradiance profile for a typical day during July and August. The variations in irradiance are not captured in the resolution of the weather data which is 1 hour. It is therefore necessary to use a smaller time step in the weather data provided to the toolbox in order to obtain more accurate results from the simulation.
- The computational time increases significantly as the number of rays used for the simulation is increased above 50,000. Comparing figures 4.9, 4.10 and 4.11 can be observed that a higher number of rays produces a higher energy production, this is related to the randomly generated rays reaching each cell. However, the accuracy in the replication of the behaviour of the real system does not improve significantly. It is advisable to use 50,000 rays and use a higher data resolution.

The most important concern about the performance of the PVMD Toolbox is the time taken for the calculations. This will be discussed more on chapter 5 as a simulation is run for the production of an entire year. Similarly, a validation for longer period instead of only four months is recommended. Also, it is advisable to run a validation using weather data with a higher resolution.

# 5

# InnoZoWa pilot simulation and up-scaling

Following the validation of the PVMD Toolbox with empirical data and the degree of accuracy has been established, it is possible to evaluate the performance of nine study cases proposed in the InnoZoWa project. This analysis requires establishing the geometric and electric differences between the scenarios in order to effectively predict the output differences between them. The results of this simulation will server as a forecast of the energy production to be expected from the study cases in order to determine which one is the best performing configuration. With this information, a system up-scaling will be carried out assuming the deployment of the highest yielding configuration in the total usable area of the water basin.

Section 5.1 provides the simulation process of the study cases. Then, in section 5.2 the upscaling is described. Finally in section 5.3 a discussion of the results is provided.

## 5.1. Simulation of study cases

Subsection 5.1.1 starts by providing the general specifications of the different study cases in order to identify the main differences in terms of geometrical and electrical variables. Then, subsection 5.1.2 provides the findings from the results of the simulation.

### 5.1.1. Study case criteria for the use of the PV toolbox

In chapter 2 the mechanical and electrical specifications of the InnoZoWa pilot were introduced. In this part of the project those characteristics will be translated into inputs for the simulations to be performed with the PVMD Toolbox. These cases can be divided in monofacial and bifacial. Given that the project is in development phase during this thesis and the final specifications may change, it is necessary to choose a module of reference to perform the study case simulation. The module of reference is a bifacial LG LG375N2T-A5 module with frontal rated power of 375 W [13]. In order to perform an evaluation of comparable monofacial and bifacial PV systems, the frontal power rating of the bifacial module will define the characteristics of the monofacial module in this simulation. The geometric and electrical characteristics of the module are provided in table 5.1. Regarding the geometrical characteristics of the PV system in each study case, table 5.2 provides these differences. The albedo values for the ground surrounding the water basin and the water itself were measured by TU Delft students and researchers during the initial stage of the project [42]. The albedo for the cases with reflectors under the PV modules is set to a relatively high value of 0.8 as in similar projects making use reflective membranes [54]. This will provide results for bifacial study cases in terms of their potential energy yield.

Table 5.1: Characteristics for panel characterization. Extracted from [12] and [13]

| | |
|---|---|
| **Manufacturer** | LG Electronics |
| **Model** | LG375N2T-A5 |
| **Cell width [cm]** | 16.17 |
| **Number of cell rows** | 12 |
| **Number of cell columns** | 6 |
| **Module thickness [cm]** | 4 |
| **Cell spacing [cm]** | 0.4 |
| **Edge spacing [cm]** | 2 |
| **Voc [V]** | 48.9 |
| **Isc [A]** | 10.03 |
| **Vmpp [V]** | 40.2 |
| **Impp [A]** | 9.34 |
| **Voc temp. coefficient [%/℃]** | -0.27 |
| **Isc temp. coefficient [%/℃]** | 0.03 |

Table 5.2: Geometrical characteristics for study case simulation

| **Parameter** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|
| **Tilt Angle** | 15 | 15 | 15 | 15 | 15 | 0 | 15 | 0 | 15 |
| **Ground clearance [m]** | 0.6 | 0.6 | 1.1 | 1.1 | 1.1 | 0.1 | 0.1 | 1.1 | 1.1 |
| **Row distance [m]** | 4 | 4 | 4 | 4 | 4 | 1 | 1 | 1 | 1 |
| **Albedo** | 0.1084 | 0.8 | 0.056 | 0.056 | 0.8 | 0.056 | 0.056 | 0.8 | 0.8 |

### 5.1.2. Results of the simulation

The simulation process was the same as described in 4.1.3. It was run for each of the case studies and required a total of aproximately 30 hours of calculation time. Some recomendations regarding this large time constraint will be provided at the end of this chapter. After obtaining the energy yield from each study case a comparison was done as show in figure 5.2. One important aspect to consider is the similarity in the yield obtained in horizontal and tilted configuration in the water based Option 2. The difference between horizontal and tilted configurations was 6.75% in the monofacial case and 4.17% in the bifacial case with reflectors. This small difference can be understood by looking at the sensitivity maps provided in figure 5.1. In that picture it is possible to visualize that both panel configurations are sensitive to high solar altitudes which only occur during the summer months. The tilt angle selected for the pilot, 15°, is actually low for the Netherlands were the optimum angle is aproximately 34° [55]. This angle, however, may be appropriate for InnoZoWa given the space constraints of the floating structures were the spacing between panel rows is restricted. This configuration would hold feasible only with the incorporation of reflectors underneath the panels. Without reflecting devices the yield can decrease by 39.4% as can be seen comparing study cases 5 and 4. Also, it is important to point out the small difference between study cases 3 and 4 which shows that the albedo of water is so low that there is basically no difference between the output of a monofacial and bifacial PV module installed on water without reflectors. This can be seen It can be concluded that the tilted bifacial configuration with reflectors are expected to be the best performing in the pilot system. Considering the accuracy level previously obtained for the PVMD Toolbox of ±15%, the annual yield can range between 394 and 533 kWh per panel.

In a study performed by the PVMD group for the InnoZoWa project, the gain for PV system with dual axis was simulated. The tracking angles of this simulation were limited to 3°<tilt<15°, where the zenith is 90°, and 9°< azimuth<267°, where North is 0° and West is 270°. The estimated gain for the module's frontal side production is 6.92%. Applying this gain to the frontal share of study case 9, its estimated energy yield increases to 486.23 kWh per module. Accounting for the margin of precision of the toolbox this yield forecast ranges between 421.8 and 570 kWh. However, the gain benefits of the tracking functionality can be hindered by its own energy consumption. At this stage of the project it is not clear how this will be implemented by Hackers in the PV system.

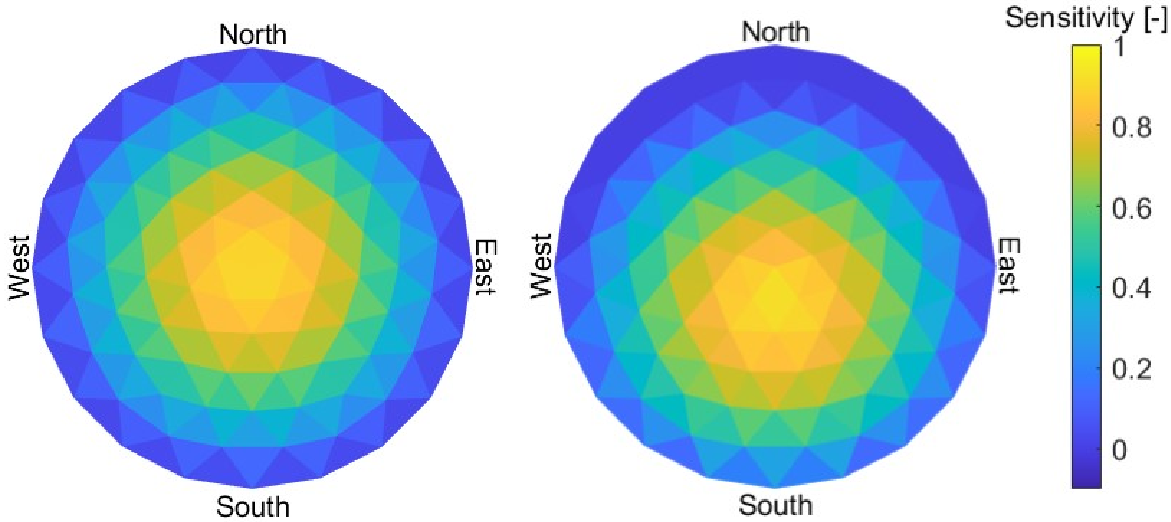



Figure 5.1: Sensitivity maps for a horizontal panel (left) and tilted at 15° (right)

## 5.2. Up-scaling of the system

It has been found that study cases 5 and 9 are expected to deliver the most energy among all cases in the pilot. In this section an analysis is performed to forecast the energy production in the eventual expansion of the best performing configuration on the total area of the water basin at the water authority in Weurt. Before continuing, it is necessary to establish an important difference between study case 5 and 9. Study case 9 is expected to replicate a two axis tracking system by pumping water in different internal sections of the floating structure. The benefits of this mechanism have been presented in the previous section but also the uncertainty about its actual performance. Another aspect to consider regarding study case 9 is the space available in the structure. It would allow the installation of only two rows of panels considering the space of 4 meters between each row. All things considered, it is not possible to determine the actual yield of study case 9 with the implementation of the tracking system

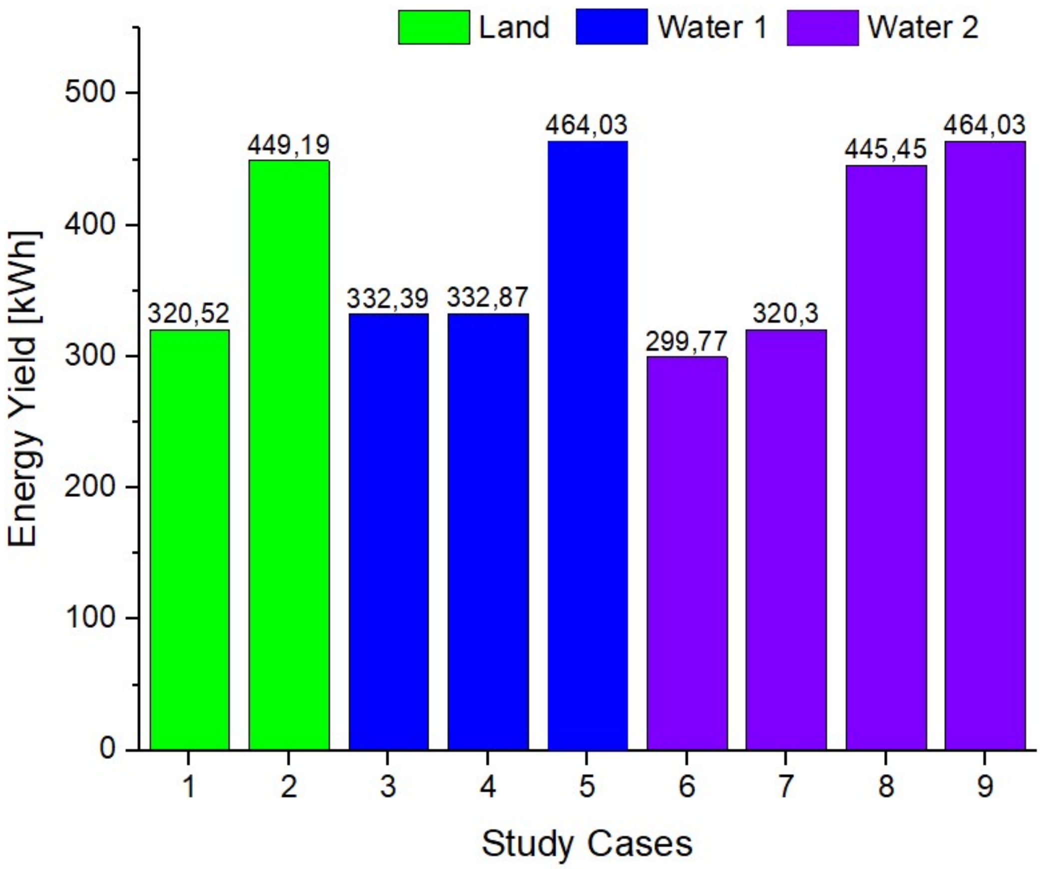



Figure 5.2: Energy yield per module for each study case

and the space required by such structure in a fixed tilted angle would not be able to accommodate the largest amount of panels in the up-scaling of the system. Study case 9, however, is interesting to study as a tracking system with a horizontal configuration with reflectors.

Given the uncertainty regarding study case 9, and for the purposes of the up-scaling analysis, study case 5 will be used. In a recent update of the project development it has been established that the solar panel to be used in the pilot is a LG 395 W model. This panel will therefore be used in the up-scaling analysis.

Subsection 5.2.1 presents the procedure to determine the final size of the up-scaled system. Then, subsection 5.2.2 provides a calculated value for the total energy production of the system and the maximum expected power.

### 5.2.1. System sizing

The dimensions of the structure of study case 5 in length by width are 24 x 6.4 $m^2$. The dimensions of the water basin are approximately 140 x 75 $m^2$. Considering the orientation of the basin towards the south-east, the required orientation of the panels towards the south and the space margins required for the movement of working boats on the basin, a disposition showed in figure 5.4 is proposed. In this configuration 510 panels can be installed. With a


Figure 5.3: Water basin site satellite view. [9]

rated power per module of 395 W, the system rated power rises to 201 kW.

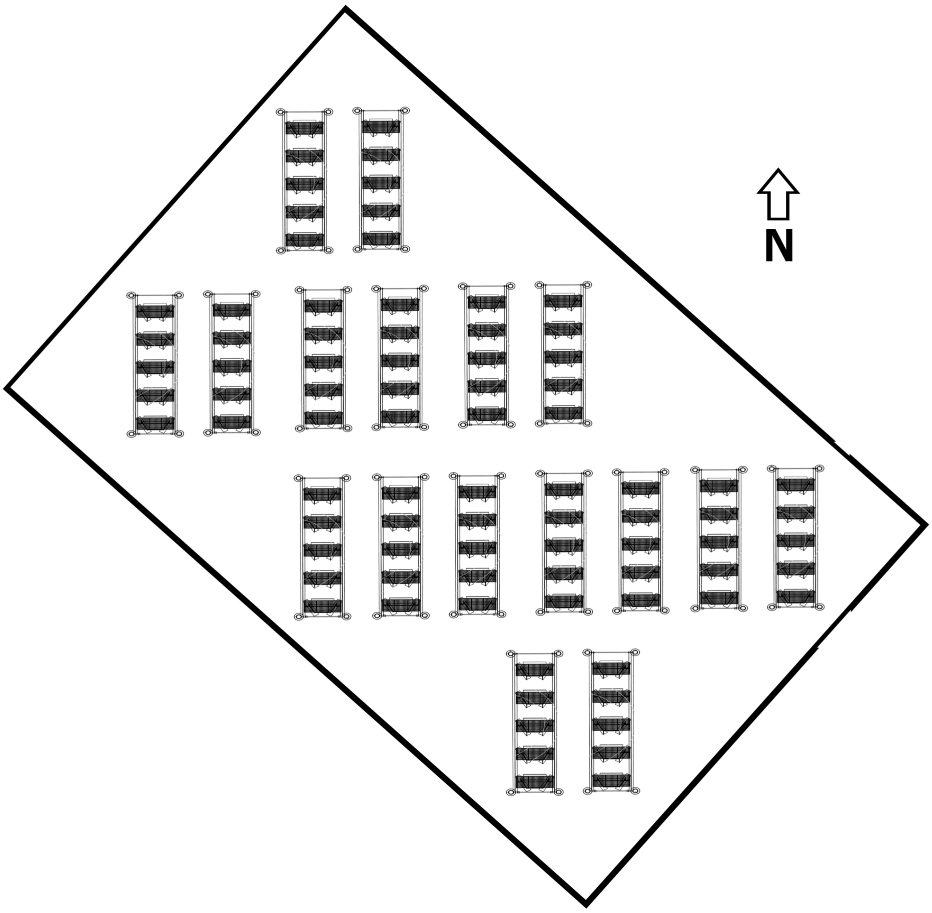



Figure 5.4: Disposition of panels in the up-scaled version of InnoZoWa's PV system.

### 5.2.2. Highest power peak

An additional simulation is run for the case of the up-scaled system and meteorological data is used. The result from the simulation delivers an annual energy yield per panel of 471 kWh. For the total system this yield increases to 240 MWh. An important value to estimate in this scenario is the peak power that the system may deliver at a moment of time with high irradiance. Looking at the plot for the energy yield production in figure 5.5, such a peak is located during the summer season. Observing June 6, the maximum power per panel can reach up to 456 W and 232.5 kW for the total system.

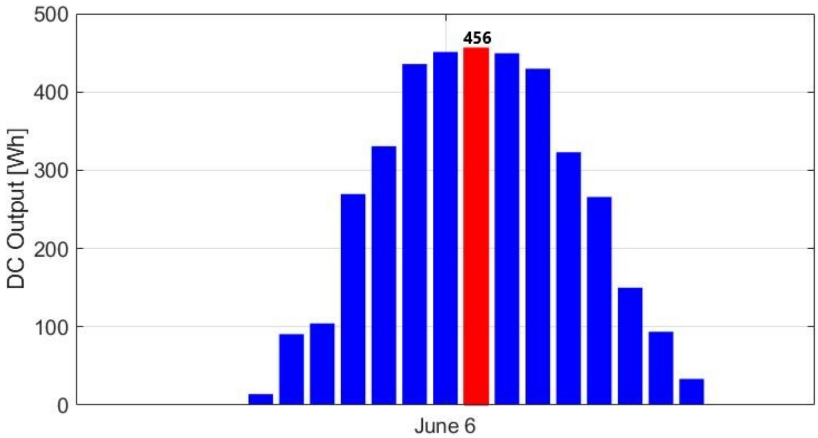



Figure 5.5: Maximum power output for a meteorological year, per panel, in the up-scaled version.

## 5.3. Discussion on this chapter

In this chapter the PVMD Toolbox was used to simulate the annual energy production of a system currently in development phase. Similar to the experience with the toolbox during the validation phase in chapter 4, one observation must be done: the time required to run the simulation can pose a disadvantage of the toolbox in relation with other software in the market. Specialized products such as PVSyst and System Advisor Model (SAM) are able to run simulations in matter of minutes or even seconds. From the perspective of the user this is a very important factor, specially when a large number of scenarios must be run.

In terms of the results from the simulations, two main findings can be mentioned: First, it was found that the highest energy generation will be provided by the configuration with tilted bifacial panels with reflectors. Secondly, the difference between the horizontal and tilted configurations in water option 2 is relatively small. This small difference calls for attention towards the possibility of optimizing the energy production of the horizontal panel with the use of a tracking functionality. In order to establish the feasibility of this case a detailed analysis must be performed on the energy consumption of the tracking function. Study case 8 is a promising solution if that energy consumption does not hinder significantly the yield of the system.

# 6 Conclusion

This chapter englobes the general conclusions of this thesis and provides recomendations for future work. These final remarks are related to the three research questions presented in the first chapter of this report. They focus on the following topics: InnoZoWa's monitoring system, in section 6.1, the validation of the PVMD Toolbox, in section 6.2 and the simulation of the InnoZoWa pilot, in section 6.3.

## 6.1. Conclusions on the monitoring system

The monitoring system for the InnoZoWa pilot has been developed in the first section of this thesis. The final solution involves infrastructure previously used by the PVMD group such as the LAMP server. However, in order to grasp a good understanding of how this infrastructure works at least three weeks were spent in the gathering of information and reaching out to the appropriate staff inside TU Delft. Given that more and more thesis projects are involving web and database applications it is advisable to develop a knowledge repository dedicated to all projects of this nature in the PVMD group. For the specific case of InnoZoWa's monitoring system an user manual has been produced in order to allow future master students to continue working on the system.

One of the recommendations for future work for this project is to improve the user interface. One possibility is to include more graphical content in order to allow users to visualize diagrams of the PV system so that those not familiar with the electrical design of the system can understand the flow of energy and information throughout the Fronius Solar Net.

Another recommendation is to merge this project's website with other web-based projects of the PVMD group such as the Dutch PV Portal. This should not only include the interconnection via the website itself but also in terms of organization and design so that the PVMD group develops a graphical identity in its web based content.

## 6.2. Conclusions on the PVMD Toolbox

The PVMD Toolbox is a software currently under development and is intended to serve as support for the PVMD group in the development of PV systems. Ideally this tool should serve as a reference in the field of PV systems and be equally reliable as the tools developed by other institutions working in the same field. Having said this, the toolbox must be subject to evaluation in terms of its accuracy, computation speed and convenience.

Regarding accuracy, it was found that the number of rays used during the characterisation of the PV module has a significant impact on the accuracy of the results produced by the toolbox. It is therefore necessary to establish a minimum optimum number of rays which in this validation was found to be 50,000. The modifications and improvements of the tool should be performed considering this configuration. Further improvements should focus on reducing the computation time which increases linearly in relation to the number of rays.

Computation time for PV system design software in the market range in the order of minutes for the forecast of a whole year's production. The PVMD Toolbox requires up to 4 hours for a simulation with 50,000 rays for a whole year with data resolution of 1 hour. For simulation purposes, meteorological data at this resolution may be feasible and accurate enough. Should a smaller resolution be used, the computation time would increase linearly at the same rate of the resolution increases.

A final observation for the toolbox is regarding its convenience for users. It is advised to enable users to make a complete system configuration in a single step instead of several iterations. Also, some parameters set directly in the code of the toolbox should be available for the user to modify such as the albedo of the surrounding and the structure of the cell itself. Additionally, an user manual with a clear overview of all the functionalities and settings of the tool would enable new users to profit from it more efficiently.

## 6.3. Conclusions on the expected outcome from Innozowa

Following the validation of the PVMD Toolbox for bifacial PV systems it was possible to perform a simulation of the nine study cases of the InnoZoWa pilot project. Two conclusions can be drawn from the results of the simulations: (1) bifacial systems with reflectors outperform other configurations and (2) tracking systems pose a promising solution but the actual performance in terms of self consumption of energy must be evaluated.

The recommended future work in the following stages of the project, once the inverters begin producing data, is to focus on the differences between study case 5 and 9. An assessment on the real gain from the tracking system can be effectively carried out with empirical data. However, it is necessary to consider that a power meter must be installed in the system pumping the water into and out of the floating structure. This way an effective evaluation of study case 9 can be done. Even better, including the data produced by such a power meter into the monitoring system would put together all variables involved in the system's performance.

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# Appendices

# Appendix A: JSON reply example for "Device"

**URL Request:**

GetInverterRealtimeData.cgi?Scope=Device&DeviceId=0 &DataCollection=CommonInverterData

**Reply from inverter:**

{
"Data" : {
"DAY_ENERGY" : {
"Value" : 8000,
"Unit" : "Wh"
},
"FAC" : {
"Value" : 50,
"Unit" : "Hz"
},
"IAC" : {
"Value" : 14.54 ,
"Unit" : "A"
},
"IDC" : {
"Value" : 8.2,
"Unit" : "A"
},
"PAC" : {
"Value" : 3373,
"Unit" : "W"
},
"SAC" : {
"Value" : 3413,
"Unit" : "VA"
},
"TOTAL_ENERGY" : {
"Value" : 45000 ,
"Unit" : "Wh"
},
"UAC" : {
"Value" : 232,
"Unit" : "V"
},
"UDC" : {

"Value" : 426,
"Unit" : "V"
},
"YEAR_ENERGY" : {
"Value" : 44000 ,
"Unit" : "Wh"
},
"DeviceStatus" : {
"StatusCode" : 7,
"MgmtTimerRemainingTime" : -1,
"ErrorCode" : 0,
"LEDColor" : 2,
"LEDState" : 0,
"StateToReset" : false
}
}
}