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Technical and Economic Assessment of a 1 MWp Floating Photovoltaic System

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

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Andrzej Boduch

Abstract

This thesis aimed to assess the application of a 1 MWp floating photovoltaic system on the upper reservoir of the pumped-storage hydropower plant in Poland.

The work considered a specific system location, the technical and economic selection processes of main components (modules, inverters, floating mounting system, transformer station, etc.), assemble recommendations, and interconnection with the medium-voltage power grid. To forecast the energy yield of the system, simulations of performance in PVsyst with extensive descriptions of methodology were conducted. The outcomes of the simulations were further used in the economic analysis for the scenario of the auction system. The price range for MWh was derived from the 2020 auction for solar and wind systems with the capacity installed under 1 MW. To validate the floating PV system, an equivalent ground-mounted PV system was designed, simulated, and treated as a reference point for the analysis.

The results were not satisfactory from the investor's point of view. According to the analysis, the assurances of a large increase in the energy yield caused by intensified heat transfer of FPV proved to be exaggerated in the Polish latitude. Significantly higher CAPEX makes it difficult to maintain the liquidity of the project and extends the return on investment by several years comparing to the equivalent ground-mounted system. It is predicted that this technology needs to enter the next phase of maturity to become more competitive in Poland.

Keywords

Floating Photovoltaics, Auction System, PVsyst, Technical and Economic Assessment, Sensitivity Analysis

Resumo

Esta tese tem como objetivo avaliar a aplicação de um sistema fotovoltaico flutuante de 1 MWp no reservatório superior de uma central hidroelétrica de armazenamento reversível na Polónia.

O trabalho considera a localização de um sistema específico, os processos de seleção técnica e económica dos componentes principais (módulos, inversores, sistema de montagem flutuante, transformador, etc.), e recomendações de montagem e interligação com a rede elétrica de média tensão. Para prever o rendimento energético do sistema, são realizadas simulações de desempenho em PVsyst. Os resultados das simulações são posteriormente utilizados na análise económica aplicada a um sistema de leilões. A faixa de preço do MWh é obtida a partir do leilão de 2020 para sistemas solares e eólicos com capacidade instalada inferior a 1 MW. Para validar o sistema fotovoltaico flutuante proposto, projetou-se um sistema fotovoltaico equivalente montado no solo, de modo a comparar desempenhos.

Os resultados económicos obtidos não são satisfatórios do ponto de vista do investidor. De acordo com a análise efetuada, não se provou um grande aumento no rendimento energético causado pela intensificação da transferência de calor na latitude da Polónia. O CAPEX significativamente mais alto torna difícil manter a liquidez do projeto e estende o retorno sobre o investimento por vários anos em comparação com o sistema equivalente montado no solo. Enquanto a tecnologia não for mais madura, a sua competitividade económica na Polónia não está assegurada.

Palavras-chave

Sistema Fotovoltaico Flutuante; Sistema de leilões; PVsyst; Avaliação técnico-económica; Análise de sensibildade

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Nomenclature

AC	alternating current
CAPEX	Capital expenditures
DC	direct current
E_g	material's energy bandgap, eV
FIT	Feed-In-Tariff
FPV	Floating photovoltaic
G	global irradiance on a horizontal plane, W/m^2
G_b	bream component of irradiance on a horizontal plane, W/m^2
G_d	diffuse component of irradiance on a horizontal plane, W/m^2
G_{eff}	effective irradiance on a tilted plane, W/m^2
G_r	reflection component of irradiance on a horizontal plane, W/m^2
G_{ref}	reference incidence irradiance, 1000 W/m^2
G_T	global irradiance on a tilted plane, W/m^2
HDPE	high density polyethylene
IT	Isolated - Earth
kWh	kilowatt-hour
kW_p	kilowatt-peak
LPS	lightning protection system
MPPT	maximum power point tracking
NOCT	Nominal Operating Cell Temperature
NPV	net present value
OPEX	operating expenditures
P	generated power, W
PID	potential induced degradation
PPA	power purchase agreement
PV	photovoltaics
PR	performance ratio
r	discount rate, %
Rb	geometric factor
Rs	series resistance, Ω
R_{sh}	shunt resistance, Ω
SPD	surge protection device
STC	Standard Test Conditions
T	ambient temperature
T_{cell}	cell temperature, K
V	voltage at the terminals of a PV module, V
V_{mp}	voltage at maximum power point, V
V_{oc}	open-cicruit voltage, V

List of Software

Autodesk AutoCAD 2019	for creating of a layout of modules
MeteoNorm 7.1	for acquiring weather data
PVsyst 6.8.8	for simulating PV performance and detailed sizing
Microsoft Excel 2016	for building the economic model

1. Introduction

1.1. OUTLINE OF THE PROBLEM

In August 2015, the persistently high air temperatures contributed to the high demand for power in the Polish power system, reaching the level of approx. 22 GW. The summer power demand has increased lately due to the increased use of air-conditioning devices, which, according to the national Central Statistical Office, has doubled its number in the last five years.

Moreover, high temperatures led to the deterioration of hydrological conditions. The cooling of conventional thermal blocks, which inject over 75% of electricity into the Polish grid, has become problematic since the low water level in rivers and reservoirs appeared. Some generating units worked with reduced power or were completely switched off. To cover the demand of the national power system, the transmission system operator has undertaken actions involving cooperation with operators from the Czech Republic and Slovakia. At the critical moment, the generating unit in Bełchatów also failed.

The result of a series of these events was a power deficit in the national power system. Therefore, administrative restrictions on electricity consumption were introduced, which mainly covered large consumers consuming more than 300 kW. The blackout has been avoided.

1.2. MOTIVATION

The situation described above exposes two critical problems of the Polish power system.

Firstly, Poland faces problems related to poor hydrological conditions. The energy sector is dependent on water, as it is a major colling agent for thermal units in Poland. Lack of water equals overheating of units, which poses a risk of a unit failure.

Secondly, the installed capacity in Poland is not high enough to cover the peak power demand. The amount of power provided by neighboring countries is increasing [1]. The risk of the whole system blackout is stated as high [2].

Both problems may be addressed by the developing technology of the floating photovoltaics. Peak power of electricity generation of floating photovoltaic systems covers a first peak power in a power grid and improves poor hydrological state in Poland. Floating systems reduce water evaporation in reservoirs.

This is why it was decided to devote the following thesis to the topic of floating photovoltaic systems and its implication in Poland.

1.3. THESIS STRUCTURE

The master's thesis has been divided into seven sections.

The first element is an in-depth analysis of the literature. In this section, the focus is on the technology of floating photovoltaic systems, their types, components, advantages, and disadvantages.

The next section covers the theoretical background. At a later stage of the thesis, the yields of photovoltaic systems were simulated. To understand the computation methodology of the software, basic concepts and computational models were introduced.

Then, all assumptions related to the construction of the designed floating photovoltaic system, its power, and location are described in detail.

The choice of the main components of the system has a direct impact on energy yields and economic results. The "Main components selection" describes the process of selecting the main components of a floating PV system: modules, inverters, and floating structure.

The “Project design” section is an integral part of this type of investment. Each element of the system was described step by step along with the theoretical explanations and justification for the selection of specific solutions. It also includes installation recommendations.

The next section contains the result of the simulation for the designed system. It was also decided to simulate the operation of a comparable photovoltaic system - conventionally mounted on the ground. The simulations were performed in the PVsyst software.

The last part of the work is devoted to the economic analysis carried out for both floating and ground-mounted systems.

2. Literature overview

2.1. INTRODUCTION

Photovoltaic farms usually cover large areas, on average 1.5-3.5 ha / MWp depending on the climate. They are best suited for construction in flat, unforested areas with low dustiness and no shading objects around. Moreover, in Polish conditions, an appropriate provision in the spatial development plan or a decision on land development is needed. As a result, selecting an appropriate area becomes problematic, especially since sometimes, the shape of a plot itself limits the use of its area. Therefore, floating photovoltaic (FPV) systems are gaining more and more interest. Currently, the capacity of the solar PV installations in water exceeds 1 GWp, and estimates show that the potential may be 400 GWp (considering only artificial water reservoirs) [3]. The fastest growth in this sector took place in 2015-2018, with particularly large progress in 2018 (Fig. 1.). In Poland, there is currently only one floating test installation located on the water reservoir in Łapina, which shows how broad are the prospects for the development of this sector [4].

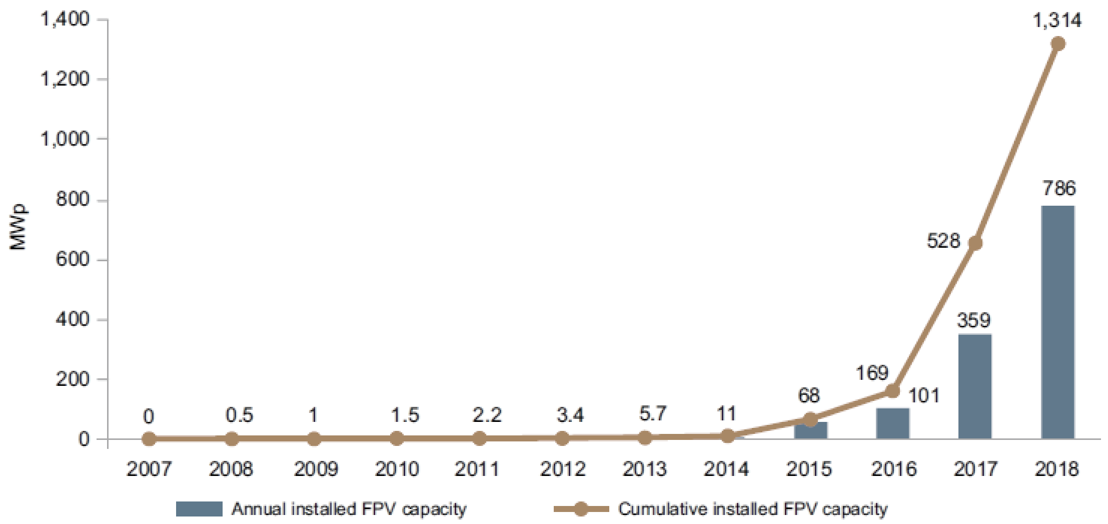

Fig. 1. Global installed FPV capacity and annual additions [3]

2.2. FLOATING TECHNOLOGIES

The main difference between floating and conventional photovoltaic farms is the supporting structure used. Some changes also take place at the stage of selecting and designing other components, but the construction should be given the greatest attention.

Floating PV farms are most often implemented using pontoon structures [3]. There are mainly two types of solutions commercially available. The first relies on suitably angled floats that immediately ensure the inclination of the modules (Fig. 2.). Then, individual floats with mounted modules are connected with quick couplers (also floating) into one platform. This type of product is offered by Ciel&Terre [5]. Alternatively, flat floats are used with mounting profiles between them similar to those used in conventional PV installations (Fig. 3.). Various variants of the arrangement of the floats are possible in both technologies. Most often, the floats are made of high-density polyethylene (HDPE).

Fig. 2. Pontoon Hydrelio® system by Ciel&Terre [29]

Fig. 3. Pontoon system by Ministry of Solar [3]

The entire system is then anchored to the shore or the bottom of the reservoir. The first solution is cheaper but is usually not suitable for large systems and deep reservoirs, so it is common for FPV farms to anchor them to the bottom, e.g. with nylon ropes [5].

The rest of the floating PV system consists of the same components as a conventional installation, except that they require additional protection against water. Similarly, both central and string inverters are used, which are mounted on floating platforms or the shore. In turn, AC and DC cables are run on or under the water surface in special sheaths. The diagram of an exemplary FPV system is shown In Fig. 4.

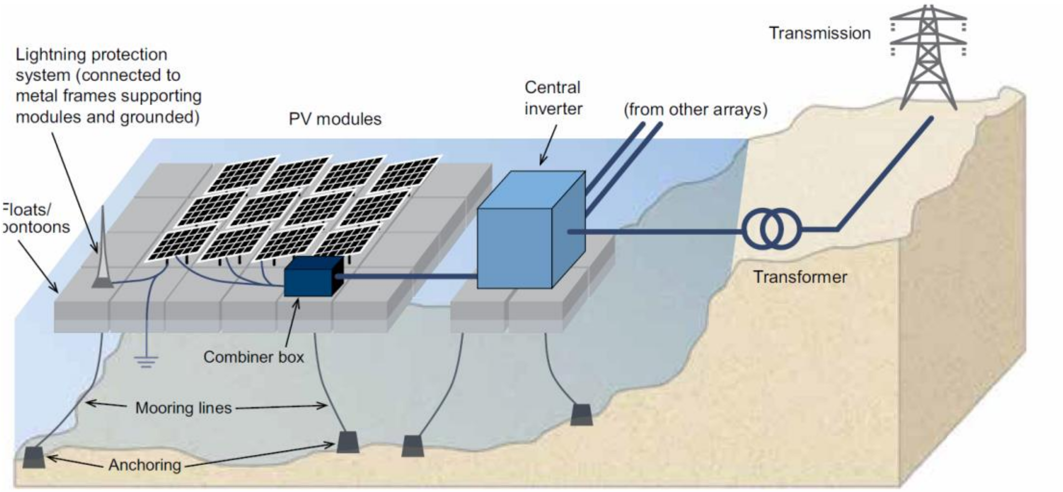

Fig. 4. Schematic representation of a large-scale FPV system [3]

There are also semi-submerged systems dedicated to single modules or small installations. Usually, floats are attached to the lightweight structure. As a result, the movement of the water causes the module to be submerged periodically. This reduces light reflections and avoids temperature drift, but at the same time water absorbs some solar radiation, negatively affecting the spectral range important from the photovoltaic point of view. Research has shown that in the case of a PV module immersed at a depth of 4 cm, the resultant effect of the above-mentioned effects increases its efficiency by 11% compared to the reference device. However, when the module was at a depth of 40 cm, its efficiency decreased by 23% [8]. In the event of strong winds or large waves, it is possible to submerge the module thanks to water filling the ballast tanks. An alternative idea to take advantage of the beneficial effects of water cooling is to mount the modules on the bottoms or edges of swimming pools. It has been suggested that amorphous rather than crystalline modules are better suited for this purpose [9].

In general, flexible modules are used for semi-submerged systems due to the stresses that can lead to microcracking. The use of pontoon structures reduces this type of risk. Besides, considering the much greater exposure of modules in water to degradation factors, they must be certified for compliance with the PN-EN 61701 standard (resistance to salt mist). Nevertheless, the negative impact of external factors on the corrosion of the frame (traditionally made of aluminum) may be so large that it will significantly shorten the lifetime of the entire module (ultimately 25-30 years), so the suggested solution would be to use frameless modules, e.g. glass-glass.

Semi-submersible modules are cooled passively by the washing water, while pontoon systems require active cooling systems. The proposed solutions include, among other nozzles or a water curtain. The profitability of this type of investment in the case of FPV is higher than for other systems due to the high availability of water. Taking into account the energy expenditure on powering the cooling system, the yields from such an installation increase by about 10% per year in relation to the installation on the ground [10]. Research with the use of a water curtain showed that the generation of electricity increased by 10-15% while powering the pump for the considered installation consumed 0.25% of the energy produced. Additional benefits of cooling were the absence of contamination and the reduction of aging of modules [11].

Regardless of the advantages of the FPV solutions, this technology faces numerous challenges and problems that need to be resolved before it can be widely disseminated. Currently, its rapid development is certainly blocked by higher initial costs, which are not necessarily compensated by higher yields. A structure itself may amount to about 25% of the total project CAPEX.

However, it should be expected that along with the improvement of the technology and the growing number of producers on the market, the price will decrease. Moreover, at the moment, long-term research on the real impact of floating photovoltaic installations on the flora and fauna were not noticed. On the other hand, no studies are describing the long-term influence of environmental factors on the degradation of modules. Another issue is the protection of FPV against freezing of water reservoirs and the possible adaptation of the structure to work at sea. Besides, many of the currently developed solutions in the field of design, tracking, focusing, and cooling systems require refinement before they can be introduced to the market.

2.3. ADVANTAGES AND DISADVANTAGES

The subject of FPV is relatively new, and therefore not all aspects of the considered technology have been fully verified so far. Moreover, the multitude of emerging concepts additionally broadens the research area. Nevertheless, all solutions have similar advantages and disadvantages, albeit to a different extent. They are presented below.

Advantages:

- increased generation of electricity compared to conventional PV installations by about 8-15% (with cooling) due to the high reflectivity of water and its cooling effect, as well as usually less dust; [10] [11] simulation carried out showed that the amount of electricity generated by FPV is 2% greater than by a solar farm on land even without cooling [12];
- saving of land that can be developed in other ways;
- improving water quality by limiting the growth of algae as a result of reducing the amount of solar radiation reaching the surface of the water reservoir;
- reduction of water evaporation thanks to partial shading of the water reservoir surface by the PV installation (depending on the reservoir by about 33-50%) [5];
- possibility of cooperation with a hydroelectric power plant, increasing the flexibility of electricity generation (in case of low water level or cloud cover); besides, the hydropower plant enables the "smoothing" of the production profile of the PV system through and also reduces the investment costs in FPV due to the lack of the need to build the power evacuation system from scratch;
- potentially quick installation (modular construction, no need for site preparation, ie alignment, foundation, etc.).

Disadvantages:

- potentially shorter lifetime due to the increased number of factors contributing to the degradation of photovoltaic modules (high humidity, water ripples, high winds, local sea fog, etc.);
- limiting the amount of solar radiation reaching deep into the water may harm flora and fauna (according to the authors' knowledge, there is no comprehensive research on this subject at the moment);
- difficult access to the reservoir for floating means (both for recreational and commercial purposes, e.g. fishing);
- larger initial financial outlay than for a conventional PV system by approximately 18-30% depending on the location, installed capacity, and type of construction [3] [13];

3. Theoretical Background

The analysis of the performance of a PV system imposes a set of time-consuming calculations to be used. To derive results more efficiently, a professional photovoltaic software, PVsyst, will be used in this master thesis. This chapter will summarise the main physical models that operate in the background of the PVsyst software.

Moreover, supplementary theoretical information related to PV systems designing, simulation performing, or economic analysis conducting can be found in each, devoted to the topic, section.

3.1. SOLAR GEOMETRY

Sun, from the Earth observer perspective, changes its position constantly. To understand the principles of the movement and to be able to precisely predict the position of the Sun, solar angles have been introduced. Sun position has a crucial impact on the energy yield of a PV system, thus its understanding is essential. Main angles of solar geometry [14]:

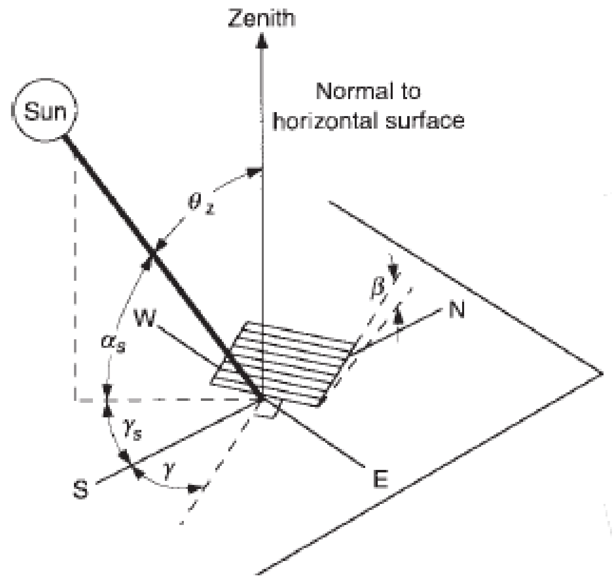

Fig. 5. Angles of solar geometry [14]

δ – Declination, which is the angle between the sun's position at solar noon and the equatorial plane. The angle varies between −23.45◦ ≤ δ ≤ 23.45◦ and takes positive values towards the north.

θ – Angle of incidence is the angle among the beam radiation on the surface and the normal to that surface.

θ_Z – Zenith angle, is the angle measured between the incidence of beam radiation on a horizontal surface and the vertical.

α_S – Solar altitude angle, is the angle measured between the incidence of beam radiation on a horizontal surface and the vertical. It is a complement of the zenith angle.

γ_S – Solar azimuth angle, the angular shift from the south of the projection of the beam radiation on the horizontal plane. Displacements west of the south are positive and east of the south are negative.

γ – Surface azimuth angle, is the angular displacement of the projection of the normal to the surface on a horizontal plane from the local meridian. The surface facing south is regarded as 0°, east takes negative, and west positive values; $-180^\circ \leq \gamma \leq 180^\circ$.

β – Tilt, describes the angular relationship between the plane of the surface under study and the horizontal. $0^\circ \leq \beta \leq 180^\circ$. Values of $\beta > 90^\circ$ indicate that the surface faces downward.

ω – Hour angle, is the angular shift of the sun east or west from the local meridian because of the Earth's rotation around its axis. Each hour counts for 15°, and solar noon is respected as 0°. Morning hours take negative and afternoon hours positive values.

3.2. EFFECTIVE IRRADIATION COMPUTATION

The amount of energy reaching a PV module depend on its tilt. To estimate it, the effective incident irradiance G_{eff} needs to be obtained in the following order [15].

Firstly, the horizontal global irradiance G data, which covers both beam G_b and diffuse G_d irradiances, is obtained for a specific location from the available meteorological sources. Then, the transformation of these values is performed by one of the transposition models. Eventually, from the horizontal irradiance, incident irradiance (on a tilted surface) is obtained. Here, the incident irradiance consists of three components: beam incident irradiance G_{Tb}, diffuse incident irradiance G_{Td} and ground reflected irradiance G_{Tr}.

This step is followed by the calculations of the effect of shading, which is generated by the near objects drawing visible shades on a PV module. Before photons reach a silicon wafer, which usually is a core of a PV module, they need to get through a glass cover of a PV module and an EVA plastic film (typically) that protect vulnerable cells from the external environment. This step leads to a certain amount of losses, due to some photons to be reflected by module layers. The indicator of this loss is called the Incidence Angle Modifier (IAM) and depends on the angle of sunlight. It is typical to include soiling loss, which corresponds to the amount and frequency of pollutants (soil, bird dropping, sand, snow) covering a PV module, thereby decreasing the amount of electric energy generated.

Following the steps, an effective irradiance G_{eff} on a PV module surface is obtained (W/m^2). Finally, effective irradiation may be computed, which is an effective irradiance over a specific period (kWh/m^2).

3.3. TRANSPOSITION MODEL

One of the physical models utilized to compute the incidence irradiance is the Perez transposition model. It relies on three separate calculations for each of the irradiance components: beam, diffuse and ground reflected [16]. The first one, beam irradiance, is a geometrical transformation. The geometric factor is derived from the following:

$$R_b = \frac{G_{Tb}}{G_b} = \frac{\cos\theta}{\cos\theta_z} \tag{1}$$

R_b – geometric factor

G_{Tb} – beam incidence component (tilted plane), W/m^2

G_b – beam component (horizontal plane), W/m^2

θ – incidence angle, °

θ_z – zenith angle, °

The diffuse component is composed of three elements. First of them is the isotropic diffuse, followed by the circumsolar, which is in a form of scattering of solar radiation. The third element is the diffuse received from around the horizon:

$$R_{Td} = G_d\left[(1-F_1)\left(\frac{1+\cos\beta}{2}\right) + F_1R_b + F_2\sin\beta\right] \tag{2}$$

G_{Td} –diffuse incidence component (tilted plane), W/m^2

G_d – diffuse component (horizontal plane), W/m^2

F_1, F_2 – brightness coefficients (empirically obtained)

β – a tilt of a PV module, °

The last component is the ground reflectance component. The irradiance reflected from the surrounding is computed by the view factor to the ground multiplied by the ground reflection factor and the horizontal global irradiance:

$$G_{Tr} = G\delta_z\left(\frac{1-\cos\beta}{2}\right) \tag{3}$$

G_{Tr}- reflection incidence component (tilted plane), W/m^2

G – Global irradiance (horizontal plane), W/m^2

δ_z – reflection factor of a ground

All three components - beam, diffuse, and reflection irradiance of a tilted plane, form together with the Perez model with global irradiance on a tilted plane G_T as the desired value. This equation enables to predict how much energy of the sun will reach a surface tilted at any angle.

$$G_T = G_b R_b + G_d \left[(1 - F_1)\left(\frac{1 + \cos\beta}{2}\right) + F_1 \frac{a}{b} + F_2 \sin\beta\right] + G\delta_z \left(\frac{1 - \cos\beta}{2}\right) \quad (4)$$

3.4. PV CELL ONE - DIODE AND FIVE PARAMETERS MODEL

The electrical performance of a PV cell in PVsyst software is computed with the one-diode model based on five parameters (Fig. 6). With the assumption that all cells are identical, the model is applicable for modules or an array of modules [17].

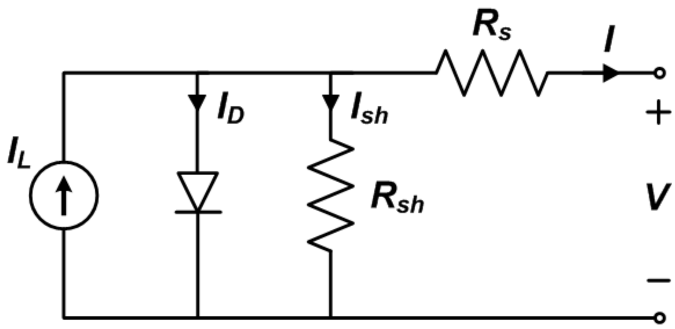

Fig. 6. One-diode (five parameters) model circuit [17]

At a fixed solar irradiance and temperature behavior of a PV module can be described as follows [17]:

$$I = I_L - I_D - I_{sh} = I_L - I_0 \left[\exp\left(\frac{q(V + R_s I)}{\alpha k T}\right) - 1\right] - \frac{V + R_s I}{R_{sh}} \quad (5)$$

I – current generated by a PV cell, A

I_L – photocurrent, A

I_D – diode current, A

I_0 – reverse saturation current, A

V – voltage at PV cell terminals, V

R_s – series resistance, Ω

R_{sh} – shunt resistance, Ω

k – Boltzmann's constant, J/K

q – charge of the electron, C

T – cell temperature, K

α – ideality factor

Reference conditions and data provided by a manufacturer cover information to compute all five parameters: photocurrent, diode current, series resistance, shunt resistance, and ideality factor. Therefore, for any given conditions, parameters are determined concerning the reference values, which are measured in Standard Test Conditions (STC). These conditions are characterized by the following [18]:

- Incidence irradiance G_{ref} = 1000 W/m^2,
- Cell temperature $T_{cell,ref}$ = 25°,
- Air mass AM = 1.5

3.5. TYPES OF MODULE DAMAGES

There are many types of damage to photovoltaic modules. Some of them, such as delamination or junction box defects, apply to all common types of modules, and others are characteristic of silicon modules. Among them, the most common are [15]:

EVA foil discoloration - usually caused by the low quality of the component, which under the influence of external conditions undergoes chemical reactions leading to local discoloration. These types of defects are mainly considered to be aesthetic defects that do not significantly affect the operation of the module

PV cell microcracks - due to the fragility of silicon wafers, excessive pressure is often applied to their surface during production, transport, or assembly, and consequently, cracks usually invisible to the naked eye appear. Over time, their propagation may occur, leading to the isolation of some of the cells and, as a result, a significant decrease in power and efficiency

Hot-spot - local overheating of a module, usually caused by reverse current flow caused by other damage, can lead to burning marks on the surface of a module. The phenomenon itself usually does not significantly deteriorate the parameters of the module.

PID effect - this phenomenon occurs due to the potential difference between semiconductors and, for example, an aluminum frame or solar glass, and leads to electrochemical corrosion of the p-n junction, which reduces the energy yield

LID effect - that is, the boron-oxygen defect. During the first exposure to solar radiation, positively charged oxygen molecules (pollution during production) diffuse through the crystal lattice of silicon, and then their chemical reaction with the acceptor - boron. The resulting molecules create their energy levels and trap electrons and holes, reducing the power of the module. The power loss is assumed to be around 2%. Of course, the phenomenon only applies to boron-doped silicon wafers.

Unconnected cells - it happens that due to the low quality of soldering, one of the cells in a module may not be connected to the others, which, taking into account the series connection of cells, significantly reduces the power of a module.

4. Assumptions

It is assumed that the floating photovoltaic system, which is a subject to this master thesis, would be treated as a pilot installation. If only the investment pays off as expected, the potential of the reservoir can be exploited to a greater extent by increasing installed capacity, and in consequence, generate more energy. The potential of the reservoir and area needed for a 1MWp system is calculated and described in detail in the next sections.

The investment idea below depends on many factors that have to be assumed at this stage of the project. Nevertheless, each of the assumptions in the following section has been described and supported based on a literature review or business practices.

4.1. CAPACITY INSTALLED

Currently, 1MWp of power installed is a trend in Poland regarding newly constructed PV power plants.

To fulfill EU energy mix requirements, several national support mechanisms for producers of renewable energy have been introduced. PV systems exceeding 500 kWp of installed capacity can be assigned to the auction mechanisms resembling contracts for differences (CfD). Producers sell energy generated on the Polish Power Exchange for a price regulated by the market relations: mainly supply and demand. The auction support mechanism provides producers with a constant price per unit of energy sold, which mitigates the risk of the investment at the same time. However, price is not constant for each producer, as it occurs in the feed-in-tariff mechanism. Government issues a call for tenders (auctions) to increase renewable energy capacity to a certain degree. Investment developers participating in the auction submit a bid with a price they treat as high enough to make their projects feasible. Bidders who fulfill specific criteria and offer the lowest prices sign a contract.

Two separate auctions are being conducted for RES projects - below and above 1 MW of installed capacity. Since wind and solar projects are in the same auction "baskets", electricity prices for projects over 1MW are regulated mainly by the windmills investors – prices are too low for PV projects to meet a break-even point in a reasonable time, thus a minority of solar projects win an auction. Therefore, there are significantly higher prices per unit of energy yield to be obtained in the projects below 1 MW.

Taking into consideration the discussion above, it is assumed that the 1MWp floating PV (the subject of this master thesis) will take part in the auction mechanism and the project will have slightly less capacity installed to meet the requirement of the projects below 1MW. The detailed value of installed capacity is given in the "Design" section, as it strongly depends on the components' selection and inverters' limitations.

4.2. MARKET ANALYSIS (POLAND)

The selection of the potential location of the floating PV system was limited by the author to Poland. The rapid and promising boom in the solar energy market creates opportunities for investment success. Only in 2019, 900 MWp of photovoltaic power was connected to the distribution network, while according to the Institute for the Renewable Energy, the total value of installed power exceeded 1,950 MWp in May 2020 [19].

The data provided above includes low- and high-voltage installations, however, the largest increases are achieved by micro-installations (installations up to 50 MWp) aimed at reducing electricity consumption from the network, not at direct sales of energy. This trend is dictated by the recently changed legal regulations and introduced support programs, as well as the extension of the definition of a prosumer (producer-consumer). Currently, most of the enterprises can benefit from the prosumer energy accounting system, which was available before for natural persons only. Moreover, the VAT rate for purchase and assembly of PV systems has been reduced from 23% to 8%. Thanks to the "thermo-modernization" tax exemption program, natural persons may qualify their investments related to the ecological modernization of buildings (inter alia PV, solar collectors, or heat pumps) as eligible costs. Such a procedure allows an individual to generate additional savings due to reduced income tax.

In the case of projects that are not classified as prosumer-type, dynamic growth was also recorded lately. Although 2019 was not the best in terms of installed capacity from renewable energy sources in Poland (wind energy investments legislatively frozen), the share of commercial photovoltaic systems in the energy mix increased significantly likewise [20]. At the end of 2019, the installed capacity of PV systems increased by 331 MWp - to the level of 478 MWp [21]. This is a direct effect of the capacity market introduced in Poland in 2017. Interestingly, the data shown above reflect built and fully operational systems, and thus still large amount of MWp is waiting for its construction.

The above brief analysis of the current state of photovoltaics in Poland shows how absorptive this market is. Forecasts appearing in the reports seem to be very optimistic. For example, the IEO Institute for Renewable Energy report includes two national energy development strategies in Poland [22]. PEP 2040, the country's energy policy strategy envisages an increase in the share of photovoltaics in 2040 up to 20.2 GW, while the forecast of KPEiK 2030, the National Energy and Climate Plan, reaches 15.7 GW in the same year. The exact numbers are not reliable indicators in the author's opinion, however, there is a high probability that the upward trend will be maintained.

4.3. LOCATION

The subject of this work is a 1 MWp floating photovoltaic system. Therefore, the choice of installation location is limited to inland water reservoirs.

Poland is a country with strong hydrogeological sensitivity. Any action to limit water evaporation is advisable and to some extent has a positive effect on the state of water management. The photovoltaic modules covering a water reservoir receive some of the solar radiation. As a result, the temperature of the surface water layer (epilimnion) is lower compared to a reservoir not equipped with a PV system, which in turn directly affects the reduced water loss in the form of water vapor.

Epilimnion is warmer and has typically a higher concentration of dissolved oxygen and carbon dioxide. Combined with sunlight, phytoplankton is being created. A natural water reservoir covered with modules could reduce this phenomenon, thus interference with the water ecosystem would appear. Due to social and ecological aspects, it was decided to limit the choice to those created artificially – mitigation of environmental impact.

One should not forget that energy generated in the PV system probably would not be consumed locally. Power transmission requires power lines, and so does a PV system. Another requirement is access to the power grid.

Two facilities meeting all requirements were selected in this way of elimination - upper reservoirs of two Polish pumped-storage hydropower plant: the ESP Żarnowiec and the ESP Porąbka-Żar. Both facilities are owned by the partially state-owned largest Polish power company PGE Polska Grupa Energetyczna S.A., and more specifically its subsidiary PGE Energia Odnawialna S.A. By design, both power plants buy excess (cheaper) electric energy from the grid to pump water to fill in an upper water reservoir. If necessary, water is being drained while driving water turbines. The system is able to supplement power shortages in the national system.

According to the transmission system operator (PSE S.A.) data, two peaks in the daily instantaneous power demand in the national power system can be distinguished. The first between 8 a.m. and 2 p.m., and the second between 4 p.m. and 9 p.m. [23] The exact time of peaks depends on many factors, but the key is a day of the week and temperature.

Solar radiation reaches the highest values around noon, which directly translates into the efficiency of the solar system. Hence, the system's power generation is the largest at the time of the first of the two peaks. This convergence makes the hybrid system of the pumped-storage power plant with a photovoltaic system suitable.

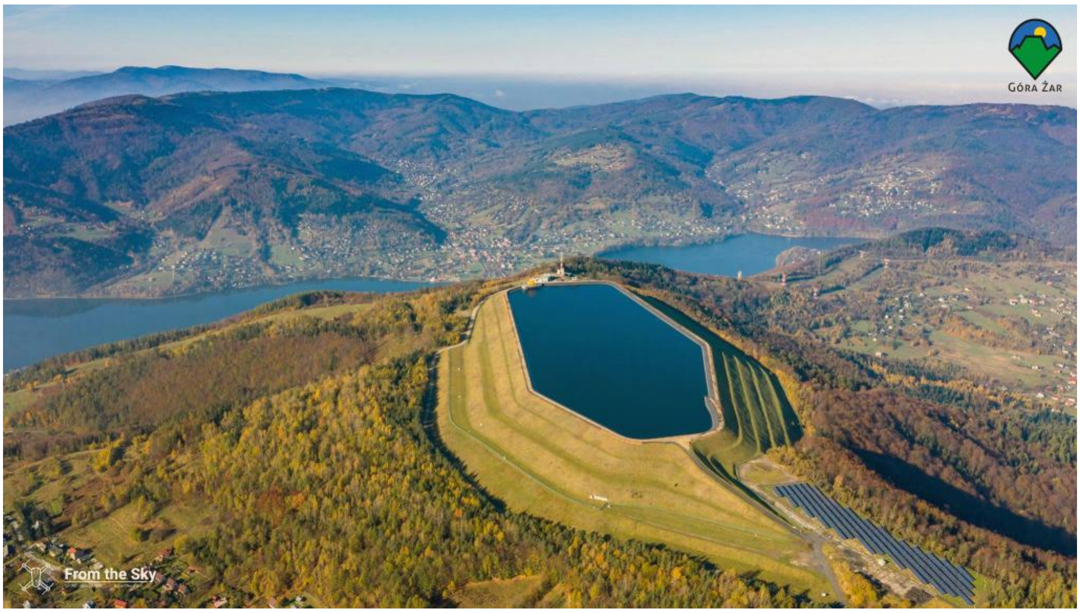

Fig. 7. Aerial view of the upper water reservoir of the Porąbka Żar pumped - storage hydropower plant [25]

Finally, the pumped-storage hydropower plant Porąbka-Żar is chosen as a designated place for the 1 MWp floating photovoltaic system. The choice has been made due to the unit's experience in the photovoltaic sector. There is a ground-mounted system installed with a capacity of 0.6 MWp [24]. This shows that managers of the unit are aware of the economic and ecological benefits associated with photovoltaics.

4.4. LOCATION CONDITIONS

The design process of the floating photovoltaic system requires detailed knowledge of the potential location.

Sub-zero temperatures occur in Poland regularly during the winter season. The water in the upper reservoir of the Porąbka-Żar pumped storage hydropower plant is not in constant motion, and experience shows that the freezing of the surface layer can occur. This is crucial information, especially for the mounting system selection process. Its durability should be tested in this respect, and a manufacturer should take responsibility in the event of a failure in the form of a warranty contract.

Once a year, water in the reservoir is completely drained for maintenance purposes. During this period, which usually lasts a week or two, the reservoir concrete surface is cleaned and repaired if any cracks occur. However, this does not equal the disqualification of the floating system. There are mounting systems on the market that allow a photovoltaic system to settle on the ground in such cases. Only manufacturers that can provide it will be considered during the selection process. The question is if the operator of the power plant finds the maintenance process doable with the system placed on the ground. This issue will be possibly answered in the next phase of the project.

Moreover, the bottom of the reservoir is not perfectly flat. Settlement of the FPV system on uneven ground could lead to inefficient operation, and eventually its damage. The connection of the bottom of the reservoir with its walls is rounded, therefore the usable area for the floating system is limited. Adequate distance from the edge of the reservoir is required.

The last element characterizing the selected location is the risk associated with shading. There are no buildings, tall trees, or other objects posing such a risk in the vicinity. However, when the water level in the tank decreases, its walls in the case of low sun position could negatively affect the performance of the system. Therefore, it is necessary to move the system away from the edge (especially the southern) and provide a safe distance, which has been included in the design.

5. Main Components Selection

5.1. SELECTION OF MODULES

Large-scale PV systems consist of several components, however, the vast majority of the initial investment cost is dedicated to modules. Thus, cautious selection of modules is crucial during the design process, especially if the system operates in unfavorable conditions. A floating PV system is exposed to a high humidity level, which leads to higher corrosion risk as water (electrolyte in the electrochemical metal corrosion) accelerates the process. Such conditions make modules extremely vulnerable to defects.

Thus, humidity resistance is the first factor considered while selecting modules for this specific project. The Ingress Protection (IP) code classifies the degree of protection of a device by casing against water, dust, intrusion, and accidental contact. IP67 is the second-highest available rank provided by modules manufacturers and such modules can withstand harsh conditions.

Another limitation is a manufacturer as itself. It is recommended that large-scale PV projects should rely on verified PV module manufacturers with a solid financial condition. Not only the performance of a device matters but also assurance, that a company will still exist if warranty claims are issued in the future. Modules are protected by a manufacturer usually for 25 years or more. To be sure that the module selection process is properly performed, Bloomberg L.P. quarterly shares a list (TIER 1) of solar modules manufacturers with the highest-ranked bankability [26]. The manufacturer of modules selected for the project is required to be listed there.

Two main technologies cover the market: polycrystalline and monocrystalline. The monocrystalline technology, the more efficient one, has always been considered significantly more expensive, thus large-scale projects were usually not exploiting this technology. It has changed and a rapid drop in prices of this technology has been witnessed. Moreover, a floating structure is constantly subjected to different force combinations. Monocrystalline modules are less prone to microcracks resulting from thermomechanical stresses due to the homogeneous structure of the silicon grains. Thus, the module selection is further reduced to monocrystalline technology only.

Many other factors should be taken into consideration while selecting modules for an investment. Performance indicators, such as STC peak power, efficiency, fill factor, certification (especially IEC 61701 - “Salt Mist Corrosion Testing of Photovoltaic (PV) Modules”) or guarantee terms – all are crucial. Electrical parameters and their dependence on the temperature of modules are important either. Combined with price and accessibility on the market makes it finally feasible to compare modules.

The abovementioned aspects have been verified with modules that are produced by TIER 1 manufacturers accessible on the Polish market. The module that fulfilled all of the crucial requirements (IP67 water resistance, 1500 V maximum system voltage, salt mist corrosion certification, MC4 connectors) and showed both good performances with competitive price is **JinkoSolar JKM320M-60-V** (Tbl. 1, full datasheet in the appendix)**.** The auction mechanism, described in the previous section, imposes the total DC power to be close to 1 MWp but not above.

Tbl. 1. JinkoSolar JKM320M-60-V module data sheet (own elaboration based on Fig. 44.)

Module Type	**Jinko JKM320M-60-V**			
Specifications			**Mechanical characteristics**	
max. power, P_max	320	Wp	*no of cells*	60
max. power voltage, V_mpp	33.4	V	*dimensions*	1665x1002x235mm
max. power current, I_mpp	9.59	A	*weight*	19 kg
open-circuit voltage, V_oc	40.9	V	*junction box*	IP67
short-curcuit current, I_sc	10.31	A	*connector*	JKO3M
module efficiency	19.18	%		
max. system voltage	1500	Vdc		
max. system fuse rating	20	A		
power tolerance	0~+3	%		
temperature coefficients of P_max	-0.37	%/°C		
temperature coefficients of V_oc	-0.28	%/°C		
temperature coefficients of I_sc	0.048	%/°C		
NOCT	45	*C		

5.2. SELECTION OF INVERTERS

After completion of the module selection process, the second most important elements of the system are left for the selection - inverters. Due to the first assumptions established, the choice was limited to transformerless inverters. Other solutions are not that popular on the market, hence their accessibility is limited. Moreover, parameters such as weight, efficiency at different loads, and a wide range of voltage compatibility indicate that no discussion is needed in this case.

Questions arise now: string inverters or central inverter? The answer is – it depends. Each PV project designer takes different aspects into account as a priority, such as price, durability, maintenance ease, and cost or landform.

It is assumed, that panels of modules may slightly rotate and wave, which can contribute negatively to the energy yield with a central inverter solution. On the other hand, problems may occur while mounting string inverters due to the limited space. Nowadays, manufacturers release new string solutions with high DC power capacity. It vanishes a clear difference between string and central technologies and simultaneously combines all of the advantages of a string solution with a relatively low price per kW. Thus, the project which is the subject of this master thesis will take advantage of large string inverters.

Some already mounted installations include floating platforms for inverters and electrical equipment. However, usually, humidity resistance in floating photovoltaics is not that problematic, because DC cables are wired together and put out of the reservoir to the designated and insulated place. This is the scenario to be used in the master thesis project. It requires special attention, while such a solution poses a risk of voltage loss. The cross-sectional area of DC cables should be adjusted carefully then.

A thorough market research analysis combined with compliance to aspects mentioned above led to the selection of Huawei inverters, which are currently ranked 1st worldwide according to the number of inverters sold [27]. The one that fulfilled all of the requirements is **Huawei SUN2000-105KTL-H1** – a 105 kW string inverter with 12 DC inputs and 6 maximum power point trackers (MPPT) (Tbl. 2, full datasheet in the appendix). Moreover, this inverter can withstand harsh conditions with the IP65 rating and has a fuse-free design. Price and accessibility in Poland make it a perfect choice for the floating PV power plant.

Tbl. 2. Huawei SUN2000-105KTL-H1 inverter data sheet (own elaboration based on Fig. 45.)

Inverter Type	**Huawei SUN2000-105KTL-H1**		
Efficiency		**Output**	
max. efficiency	99.0 %	*rated AC active power*	105,000 W
European efficiency	98.8 %	*max. AC apparent power*	116,000 VA
		max. AC active power	116,000 W
Input		*rated output voltage*	800 V
		rated AC grid frequency	50/60 Hz
max. input voltage	1500 V	*rated output current*	75.8 A
max. current per MPPT	25 A	*max. output current*	84.6 A
max. s-c current per MPPT	33 A		
start voltage	650 V		
mppt operating voltage range	600 -1500 V		
rated input voltage	1080 V		
number of inputs	12		
number of MPP trackers	6		

5.3. FLOATING SYSTEM SELECTION

Floating PV technology strengthens its market position. There are many solutions for floating mounting systems based on various materials available, however, the most common design used in large PV systems are pontoon-type floats [3]. These self-buoyant floats are created in the blow molding technology process. The base raw material in the process is recyclable high-density polyethylene, due to which the production is relatively low-cost. On the other hand, very good mechanical strength parameters and chemical properties allow long operation in harsh conditions. The angle of a tilt of modules is fixed.

Among several pontoon-type floats manufacturers, one has been selected - French Ciel & Terre. The portfolio of completed systems exceeding in total 300 MWp and presence on the European market make Ciel&Terre the only candidate as a floaters supplier for the pumped-storage hydropower plant [28]. The selected reservoir is conditioned by certain features described in the “Location conditions” section. One of them is limited water movement and sub-zero temperatures occurring during the winter seasons. As a consequence, the top layer of water covers with ice easily, and therefore the thicker the ice cover, the greater the forces acting on the mounting system. Ciel&Terre’s projects, apart from the largest range in Asia and Western Europe, also exist in climatic conditions comparable to Poland. An example is the installation in Sweden, operating since 2015, regularly exposed to low temperatures and snowfalls.

One of the Ciel&Terre technologies, Hydrelio® Classic, is offered in three different variants of the module tilt angle: 12°, 15°, and 22° (*Fig. 8)* [29]. None of the available angle variants is optimal for Polish latitudes. There is also no way to conveniently adjust other dimensions, such as distances between rows. In the "Project design" section, an analysis was carried out on which of the available versions gives the best yields in relation to the price of the structure. The analysis of the selection of a specific model is conducted in the next section. It was mentioned that once a year the reservoir is drained and cleaned, therefore the structure must be adapted to work on the ground without any risk of damage. The manufacturer ensures that the Hydrelio® Classic technology fulfills this function.

Fig. 8. Ciel&Terre Hydrelio® Classic technology [30]

Apart from the supply of floating systems, Ciel&Terre conducts the implementation of the anchoring system. Designing such a system is not the subject of this thesis, thus it is assumed that Ciel&Terre, having experience in this topic, would design and supply it. In the case of the Porąbka-Żar power plant reservoir, this system is a major engineering challenge - a frequent change of water level with high amplitude occurs. It is possible to anchor the system to the banks of a reservoir, to its bottom, or to concrete piles embedded in the bottom. In some situations, the combination of all three options mentioned above is used. The choice is up to the designer and depends among others on the location, bottom shape (bathymetry), soil or bottom condition, or changes in water level [3]. A slight movement of the system is permitted, however, the southern direction (in the case of the northern hemisphere) must be kept. The efficiency of the entire system depends on it.

Lastly, Ciel & Terre offers a 10-year standard warranty on the reliability of its design. It is also possible to extend it for another 15 years.

6. Project Design

6.1. MODULES LAYOUT

6.1.1. NUMBER OF MODULES

As explained in the section *4.1 CAPACITY INSTALLED*, the cumulative installed power of modules cannot exceed 1 MWp, however, it is intended to be as close as possible to the following value. The number of modules will strictly depend on inverters' voltage limits and modules' temperature coefficient of V_{oc}.

Due to these assumptions, the modules distribution scheme has been proposed as follows:

- 8 independent arrays connected to separate string inverters,
- 12 strings on 6 MPPTs within each array,
- 32 modules in series forming one string.

According to the modules peak power, which is defined by the manufacturers as 320 Wp, the scheme presented above results in **983.04 kWp** in total. The corresponding calculations proving the temperature, voltage, and current match of this layout, are placed in the next section *6.2 Inverters*.

6.1.2. TILT ANGLE AND INTER-ROW DISTANCE

In floating photovoltaics, the tilt angle of modules depends highly on the technology used. Overall, ready-to-install mounting systems have already fixed angle that manufacturers find the most universal for the market needs. The supplier of mounting systems to be used in the following thesis, Ciel&Terre, and its Hydrelio® Classic technology is available in three different angle variants: 12°, 15°, and 22°.

The latitude of the designated area requires a significantly greater tilt angle to achieve the best possible performance by the PV system. According to the PVsyst software, the highest energy yield would be achieved with modules lifted between 37° to 41°, however, such systems generally do not exist in the commercial market (usually maximum tilt is 30°). It is clear, that the Hydrelio® Classic technology variants do not fit the angles considered as most suitable for the site.

Following the practice, the distance between rows of PV modules is calculated based on the highest position of the sun achieved on the shortest day of the year, which is December 21st/22nd [31]. The designated location for the floating PV system (latitude: 49.79°) is characterized by 16.78° [Fig. 9]. The angle of sunbeams, the distance between rows, and, as a consequence, shading generated on modules, are strictly related to the amount of energy produced by the system. Hence, it is important to take this guideline into account.

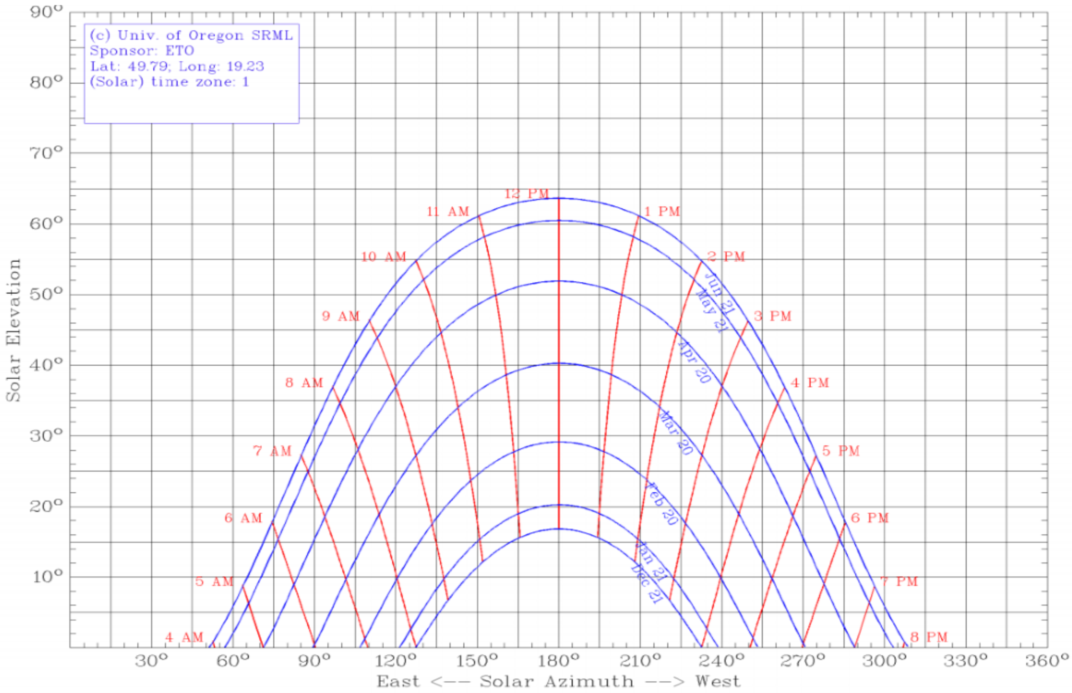

Fig. 9. Sun path chart for the designated location [32]

According to the equation (6), the distance is derived as follows:

$$distance\ between\ rows = \frac{width_{PV} * \sin(tilt_{PV})}{\tan\,(angle_{sun})} \tag{6}$$

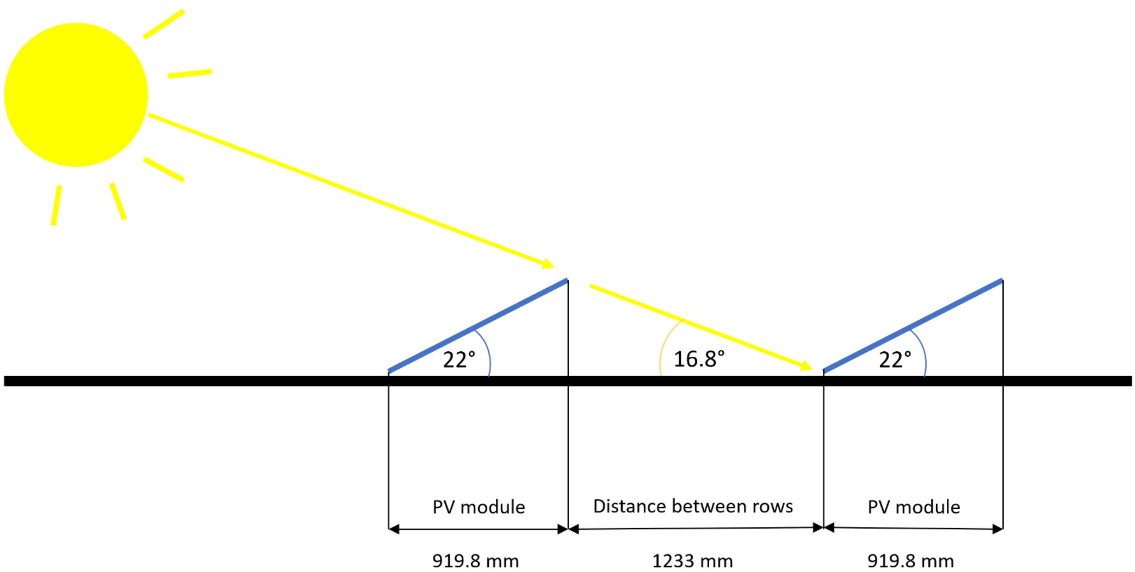

Fig. 10. Scheme of tilted modules (22°) on the shortest day of the year (own elaboration)

Unfortunately, the limitation not only exists in terms of the tilt angle of PV modules but also in the distance between rows. The manufacturer imposes this dimension by floaters that keep the whole structure together, which are called "bridge floaters". If one "bridge floater" does not provide enough distance between modules it is doable to connect two of them in parallel (Fig. 11).

Fig. 11. Hydrelio® Classic technology with two "bridge floaters" between "module floaters"

Eventually, none of the considered combinations of tilt angle with a number of "bridge floaters" does reach the distance obtained from the equation (6). Nevertheless, to find the best possible solution the optimization analysis has been conducted. One array of 12 strings containing 32 sample modules (384 modules in total) was subjected to the optimization evaluation (Tbl. 3). The optimization evaluation considered assumptions described in the "Simulation" section.

Tbl. 3. The optimization evaluation results based on PVsyst

	tilt	number of "bridge floaters"	annual energy yield, MWh	specific production, kWh/kWp	performance ratio PR	shortest day shading
variant 1	22°	2	117	969	0.855	12%
variant 2	22°	1	112	924	0.815	25%
variant 3	15°	1	114	940	0.849	15%
variant 4	12°	1	114	946	0.866	8%

The best performance is witnessed for the 22° tilt and two "bridge floaters" variant. The difference between yields of variant 1 compared to variant 3 and 4 is not significant. Combined with additional investment cost associated with an increased number of floaters does not make variant 1 the best possible option, thus it is not selected as a combination for further consideration. Among variants 3 and 4, slightly better performance is obtained by 12° tilt. Moreover, the variant 4 performs best in the performance ratio (PR) and is least influenced by the shading effect. The variant 2 diverges considerably among others and is not selected.

To conclude, for the further calculations, 12° Hydrelio® Classic technology with one "bridge floater" is selected. According to the PVsyst software, loss with respect to the optimum angle equals 8.1%.

6.1.3. MODULES LAYOUT

The bottom of the reservoir is not completely flat. The connection of the walls with the bottom is rounded, hence it is not possible to place the PV system at the very edge of the reservoir. Besides, if the turbine of the pumped-storage power plant is operating and water is being drained, or if the reservoir is empty, placing the system too close to the walls would cause beam losses. Therefore, it is necessary to move the system away from the edges of the reservoir, as is shown in the figure below (Fig. 12).

As described earlier, the system is based on 8 arrays of 384 modules facing south, which sum up to 3072 modules. Each array consists of 12 rows, which represent each string, and together are designed to be facilitated by one string inverter (Fig. 13). The whole system covers over 0,801 ha. As part of better system organization and easier fault detection in the event of a decrease in generated energy, the arrays are clearly separated from each other.

Fig. 12. FPV system layout

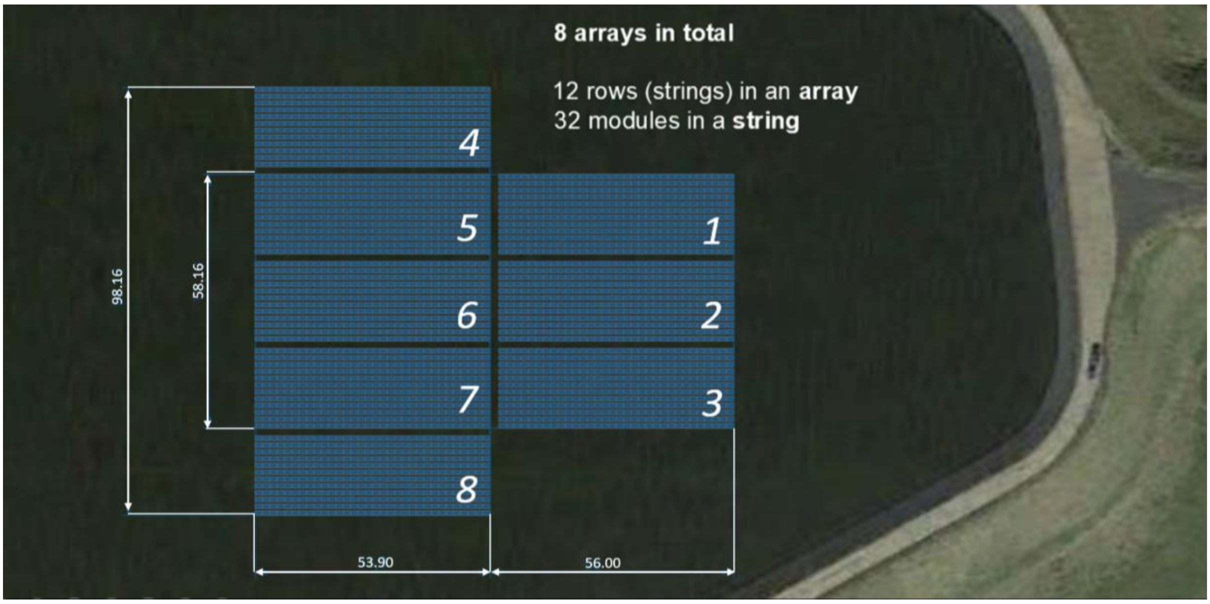

Fig. 13. FPV arrays layout

6.1.4. POTENTIAL OF THE RESERVOIR

The figure below represents the reservoir FPV potential (Fig. 14). Assuming the equal components selection and the equal arrays placement scheme, the under-study reservoir would fit 56 arrays. The total number of modules would reach 21,504, while the power in STC conditions would exceed 6.88 MWp. This means that the current, almost 1 MWp, system accounts for around 14.3% of the potential of the entire reservoir.

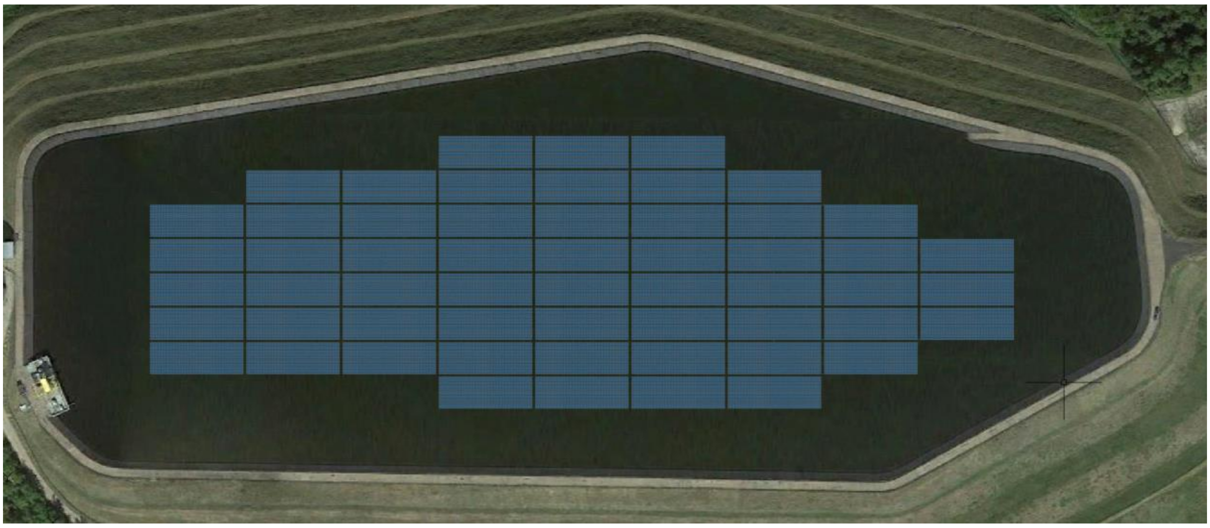

Fig. 14. FPV potential of the reservoir

6.2. INVERTERS

The solar cell performance worsens with increasing temperature, owing to increased internal carrier recombination rates, caused by increased carrier concentrations. The operating temperature plays a key role in the conversion process, as both the electrical efficiency and the power output of a PV module depend linearly on the operating temperature [15]. On the other hand, inverters should operate properly independently on temperature-driven modules' performance changes. Modules manufacturers incorporate the *temperature coefficient* on their products' datasheets to anticipate, how the operating temperature will affect voltage and current values. These calculations result combined with the inverter's DC input voltage ranges can give insights on how to wire modules in strings and parallel.

Firstly, operating temperatures of a selected PV module are calculated from the formula (7) below:

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20°}{0.8}\right) G \tag{7}$$

T_{cell} –operating temperature of a cell/module

T_{amb} - ambient temperature

NOCT – Nominal Operating Cell Temperature

G – solar irradiance, kW/m^2

The design conditions section in PVsyst requires adjusting reference temperatures for array design with respect to the inverter input voltages. The designated reservoir is located in the southern part of Poland, which is assigned to the Zone III according to PN-EN 12831 [33]. The design outdoor temperature required to be used for calculations is -20 °C. Thus, the minimum operating temperature of a module is 10°C. However, PVSyst makes use of the design outdoor temperature as a minimum operating temperature. This method is a common practice, as sunlight may suddenly appear on the array while its temperature is ambient. The maximum temperature is assigned directly to the PVSyst default value and equals 60°C.

6.2.1. MAXIMUM NUMBER OF MODULES IN SERIES

To perform calculations for a maximum number of modules in series, the input parameters are needed (Tbl. 4).

Tbl. 4. Input parameters – the maximum number of modules in series

Input parameters	
open-circuit voltage, V_oc	40.9 V
temperature coefficients of V_oc	-0.28 %/°C
temperature coefficients of V_oc	0.115 %/°C
min. temperature, T_min	-20.0 °C
temperature STC, T_ref,stc	25 °C
max. input voltage	1500 V
max. power voltage, V_mpp,stc	33.4 V
max mppt operating voltage	1500 V

- Maximum Open Circuit Voltage

$$V_{OC,max} = V_{OC,STC} - temperature\ coefficient\ * \left(T_{min} - T_{ref,STC}\right) = 46.09\ V \quad (8)$$

- Maximum number of modules in series (open circuit)

$$N_{max,series} = \frac{maximum\ input\ voltage}{V_{OC,max}} = \ 32.5 \rightarrow max\ 32\ \ modules\ in\ series \quad (9)$$

- Maximum Power Point – maximum voltage

$$V_{MPP,max} = V_{MPP,STC} - temperature\ coefficient\ * \left(T_{min} - T_{ref,STC}\right) = 38.55\ V \quad (10)$$

- Maximum number of modules in series (MPP)

$$N_{max,series} = \frac{max\ MPPT\ operating\ voltage}{V_{MPP,max}} = 38.9 \rightarrow max\ 38\ \ modules\ in\ series \qquad (11)$$

According to the calculations (8, 9, 10, 11), the maximum acceptable number of modules wired in series is 32.

6.2.2. MINIMUM NUMBER OF MODULES IN SERIES

To perform calculations for a minimum number of modules in series, the following input parameters are needed (Tbl. 5):

Tbl. 5. Input parameters – the minimum number of modules in series

Input parameters		
open-circuit voltage, V_oc	40.9	V
temperature coefficients of V_oc	-0.28	%/°C
temperature coefficients of V_oc	0.115	%/°C
max. temperature, T_max	60	°C
temperature STC, T_ref,stc	25	°C
start voltage	650	V
max. power voltage, V_mpp,stc	33.4	V
min mppt operating voltage	600	V

- Minimum Open Circuit Voltage

$$V_{OC,min} = V_{OC,STC} - temperature\ coefficient\ * \left(T_{max} - T_{ref,STC}\right) = 36.86\ V \qquad (12)$$

- Minimum number of modules in series (open circuit)

$$N_{min,series} = \frac{start\ voltage}{V_{OC,min}} = 17.6 \rightarrow min\ 18\ \ modules\ in\ series \qquad (13)$$

- Maximum Power Point – minimum voltage

$$V_{MPP,min} = V_{MPP,STC} - temperature\ coefficient\ * \left(T_{max} - T_{ref,STC}\right) = 29.36\ V \qquad (14)$$

- Minimum number of modules in series (MPP)

$$N_{min,series} = \frac{min\ MPPT\ operating\ voltage}{V_{MPP,min}} = 20.4 \rightarrow min\ 21\ modules\ in\ series \quad (15)$$

To satisfy both minimum start voltage and minimum MPP tracking voltage of selected inverters, a string of modules should consist of at least 21 elements.

6.2.3. DC INPUTS AND MPPTs

The selected string inverter, Huawei SUN2000-105KTL-H1, has 12 DC inputs with 6 independent maximum power point trackers (MPPTs). Each MPPT input has constraints regarding maximum DC current and maximum short circuit current, which is 25 A and 33 A, respectively. PV modules selected reach 9.68 A as a maximum power current, and 10.31 A as a short circuit current (Tbl. 1).

Current, in oppose to voltage, depends strongly on irradiance, instead of temperature. According to the PN-HD-60364-7-712:2016 standard, safety issues require to multiply short circuit current value provided by the manufacturer of modules by 1.25 [34]. The datasheet parameters have been measured in STC conditions. Strong reflection or concentration of sunbeams on the edge of clouds may lead to the increase of current generated in strings over the values stated in products' datasheets.

Thus, wiring string of modules in parallel would be impossible, since 2 inputs of 2 strings connected in parallel would exceed acceptable 33 A per MPPT input by 18 A. It was established that the maximum allowed number of modules wired in series and connected to each DC input will bring the best possible performance, and on the other hand, the whole system will not exceed 1 MWp of installed capacity.

Moreover, the SUN2000 provides 12 DC input terminals, which are controlled by its two DC switches. DC SWITCH 1 controls DC input terminals 1–6 (MPPT 1–3) and DC SWITCH 2 controls DC input terminals 7–12 (MPPT 4–6) (Fig. 46, appendix).

6.2.4. NOMINAL POWER RATIO

Each inverter can operate within a certain range of power, voltage, and current. When choosing components, special attention to the appropriate range of inverter input parameters should be paid, to ensure that power-changing PV modules operate optimally in a wide range. The universally accepted principle of choosing the ratio of peak power of PV generators to the power of the inverter is in the range of 0.8 to 1.25 for systems facing south in latitudes corresponding to Poland [35]. However, it is rare for PV modules in Poland to generate power according to data measured under STC conditions. Most often they reach only 80% / 90% of their peak power [31]. Also, at high values of solar irradiance, there is usually a high temperature, which leads to the voltage (and power) drop (as demonstrated in section *6.2.1. Maximum number of modules in series*). Therefore, the power of the inverters in this paper is slightly lower than the total peak power of the PV panels. The Nominal Power Ratio is equal to 1.17

Tbl. 6. The Nominal Power Ratio of the system

Component	Quantity	Power, W	Power in total, W	Nominal Power Ratio
PV modules	3072	320	967680	1.17
Inverters	8	105000	840000	

6.2.5. ARRANGEMENT OF INVERTERS

The inverters are designed to be placed on the walls of the transformer station (Fig. 15). According to the manufacturer, Huawei string inverters are certified with the degree of protection equal to IP65, thus they can be installed outdoors. Enough space around inverters should be reserved for installation ease and heat dissipation. Specific dimensions are provided by the manufacturer in the manual and they were followed in the arrangement process. Moreover, extra protection from rainwater is added by the hood above the inverters. Walls with inverters are facing south-east and south-west to prevent inverters from sunlight overheating.

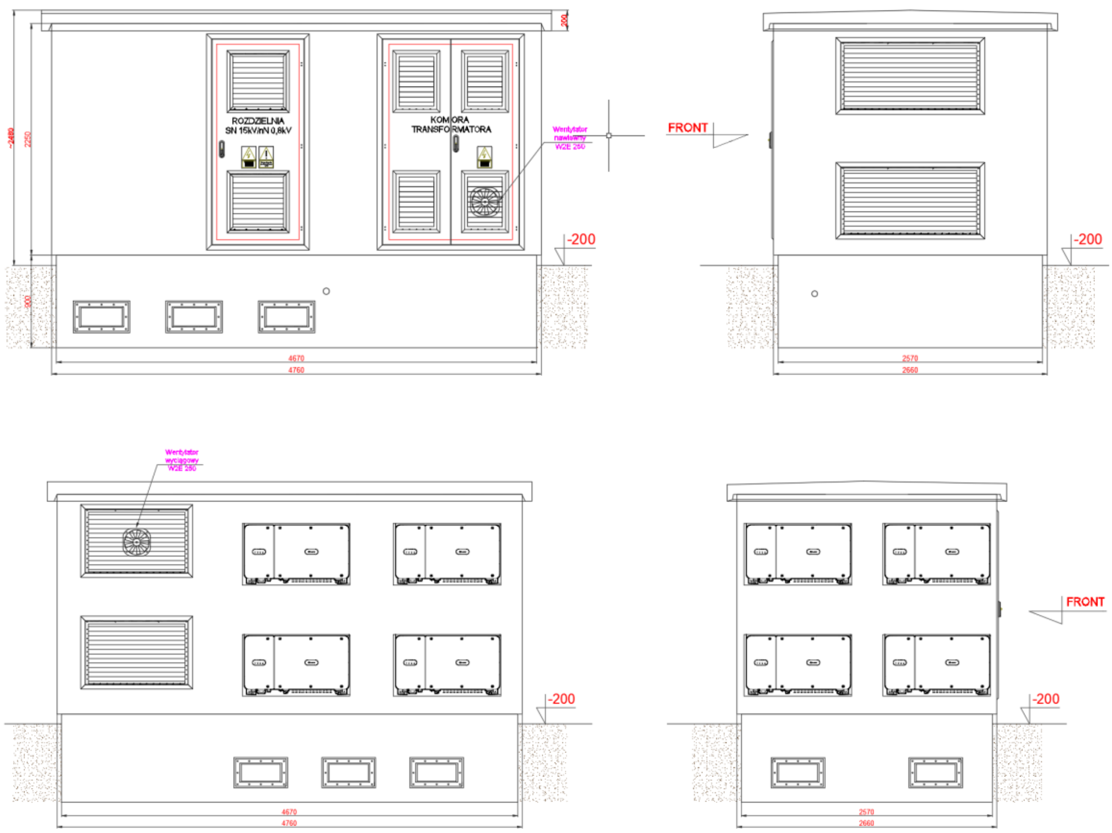

Fig. 15. The arrangement of inverters on the transformer station's walls [own elaboration based on ZPUE]

6.3. DC ELECTRIC EQUIPMENT

6.3.1. DC CABLES

Unlike ordinary electrical installations, photovoltaic systems require dedicated cables with appropriate insulation. It should be noticed that most of them are mounted outside the building and thus exposed to harsh conditions. Cables in photovoltaic systems differ from standard electric cables by thicker insulation and the color of the tinned copper wires. The cables have high resistance to UV radiation and ozone, but it is recommended to route them in a covered way, not exposed to direct radiation.

The minimum cross-sectional area of a DC cable is calculated based on the maximum linear voltage drop over the length of a cable. It is assumed that losses in PV systems should not exceed 1%. However, to decrease the cost of an investment, big-scale PV projects accept voltage drop not higher than 3% [36]. Thus, according to this practice cable sizes will be selected. It should also be remembered that the permissible current of the selected size of a cable should be greater than the current flowing in the circuit.

Arrays are at different distances away from the place intended for inverters. According to the formula (16) and average lengths of circuits, a cross-sectional area of cables needed for strings in each array has been calculated (Tbl. 7).

$$A = \frac{P * l}{U^2 * k * 0.03} \tag{16}$$

A – minimum cross-sectional area of cable needed, mm
k – power in the circuit, W
l – length of cables in the circuit, m
U – voltage in the circuit, V
k – specific conductivity of copper, m/Ohm*mm^2
0.03 – acceptable voltage drop in the circuit (3%)

Helukabel, with its Solarflex® DC cables, is a manufacturer with great experience in the PV industry. The product with appropriate cross-sectional dimensions and other requirements fulfilled is Helukabel Solarflex®-X H1Z2Z2-K1500. The maximum circuit voltage on the DC side is lower than the highest voltage the cable can withstand (1500 V DC). Table 7 presents the cross-sectional areas of cables selected for each array. All of the arrays may be routed with 4 mm^2 cross-sectional area cables.

Even though solar cables are double insulated, additional protection in the form of an electrical conduit is required by the manufacturer. Thus, it is assumed that DC cables are routed in the electrical conduit resistant to UV radiation. Moreover, cables should be secured with, also UV resistant, cable ties, and minimum bending radius should not be exceeded.

Tbl. 7. Cross-sectional area of cables needed for each array

array #	avg. length of a circuit	min. c-s area of cable, mm2	c-s area of cable selected, mm2	voltage drop, %	voltage drop, V
1	400	2.2	**4**	1.64%	17.52
2	440	2.4	**4**	1.81%	19.27
3	520	2.9	**4**	2.14%	22.77
4	550	3.0	**4**	2.26%	24.09
5	580	3.2	**4**	2.38%	25.40
6	640	3.5	**4**	2.63%	28.03
7	670	3.7	**4**	2.75%	29.34
8	700	3.9	**4**	2.88%	30.66

Fig. 16. DC solar cable - Helukabel Solarflex®-X H1Z2Z2-K1500 (Fig. 47)

List of components:

- Helukabel Solarflex®-X H1Z2Z2-K1500 4 mm^2: 44 000 m (88 of 500 m drums)

6.3.2. DC CONNECTORS

Solar modules are usually equipped with two cables with one male and one female MC4-type connector. The use of these cables allows easy connection of modules installed side by side, thus forming a series. Further modules are connected until the required DC voltage level is reached. These connectors are specially designed for photovoltaic systems. Whenever a solar module is exposed to radiation, it generates voltage, thus protection is necessary.

According to the Polish PV Solar Association (SBF), one of the main causes of fire hazards in PV systems is an incorrect connection on the DC side. Due to different tolerances used by manufacturers, not all MC4-type connectors are compatible with each other, which in some cases may lead to dangerous electric arc. One type of connection is recommended. Lack of compatibility usually occurs at the DC inputs to the inverter and the ends of the strings. It is important to use the connectors attached by the manufacturer of the inverters. Interestingly, in practice, some installers cut connectors from modules at the ends of strings to maintain compatibility, unless the warranty conditions of the modules allow it [37].

As proved in the section *6.3.1 DC cables*, the cross-sectional area of all DC cables is 4 mm^2. Unfortunately, the original Stäubli MC4 connectors are not providing the best possible protection for floating application, since connectors are rated IP65 and system rated voltage cannot exceed 1000V. In this case, it was decided to use a replacement that is available on the market and is produced by a reputable manufacturer of surge protectors - Phoenix Contact. The Sunclix series connectors provide protection rated at IP68, withstand system voltages of 1500V, and are compatible with 4 mm^2 solar cables.

Connectors should be separated from the sun and placed under modules. To do so, one can use the holes in the module frame and immobilize the connectors with cable ties or strap them to the supporting structure. Connectors laying on the ground create the risk of moisture getting inside and leakage currents causing the inverter to disconnect.

Fig. 17. example of a connector - Stäubli MC4 [38]

List of components:

- Phoenix Contact Sunclix 4 mm^2 connectors: 192

6.3.3. PROTECTION AGAINST ELECTRIC SHOCK AND FIRE

The two main features of conventional PV arrays are their high DC voltage levels and that they cannot be disconnected as long as PV modules are exposed to the sun. The short circuit current generated by the PV modules is too low to activate the automatic disconnection of the power source. Therefore, the most commonly used protective measures do not apply to PV systems.

IEC 60364-712 states that PV systems whose maximum U_{OC_MAX} is higher than 120V DC should use reinforced or double insulation as a protection against electric shock [34]. Protections, such as fuses or circuit breakers on the DC side, do not provide protection against electric shock because there is no automatic disconnection of the power source. Overcurrent protection, if used, protects PV cells against reverse current and cables against overload. Reinforced or double insulation is a protective measure against electric shock, but it does not entirely exclude the risk of insulation damage. The probability of insulation failure and touching of live parts of the installation at the same time is very low. However, insulation failures themselves are more common. A DC insulation fault may be even more dangerous because automatic extinguishing of the electric arc is less likely than with AC systems [39].

In the case of a system designed in this paper, it is assumed to use a cable dedicated to solar systems. The thickness of the cable was calculated in the section *6.3.1 DC cables* and ensures sufficiently low transmission losses for the rated operating parameters of the system. A suitable solar cable is an important element, because its failure, break of insulation, can lead to temperature rise and, as a consequence, constitutes a high risk of fire [39].In the assembly process, special attention should be paid to routing DC cables to reduce the possibility of damaging wire insulation. For this purpose, appropriate conduits that protect against mechanical defects and UV radiation should be used.

Moreover, the inverter selected is equipped with a DC insulation resistance detection unit. To ensure device safety, the inverter detects the insulation resistance of the input side with respect to the ground when it starts a self-check. If the detected value is less than the nominal value, the inverter does not connect to the grid [40].

6.3.4. REVERSE CURRENT PROTECTION

Another situation that may potentially lead to an increase in the temperature of modules and wires, and as a result of a fire, is reverse current in PV strings. A short circuit in a PV module or faulty wiring can cause a reverse current. This happens if the voltage in an open circuit of one string is significantly different from the open voltage of parallel strings connected to the same inverter. Current flows from undamaged strings to the faulty ones instead of flowing to the inverter and supplying power to the AC grid [34].

If there is only one string, there is no risk of reverse current. If there are two chains with the same number of PV modules connected in parallel, the reverse current will always be lower than the maximum reverse current. Therefore, when the photovoltaic system is formed by only one or two chains, there is no need to protect against the reverse current. Otherwise, it is required (according to the standard) that each of the chains should be protected by an overcurrent fuse [34].

In the designed system, the number of strings per maximum power point tracker is equal to 2, therefore there is no need to use overcurrent protection on the PV strings.

6.3.5. OVERCURRENT PROTECTION

Protection against thermal influence caused by short-circuit current flow should be provided in any electric system. As stated above, string overcurrent protection is not necessary. This is true if the following assumptions given by the IEC 60364-712 standard are considered [34]:

- 712.433.1 Overload protection may be omitted for PV chain and PV system cables when the continuous current load of the cable is equal to or greater than 1.25 times the I_{SC_STC} at any location.

The assumption is fulfilled, therefore the overcurrent protection is not required on the DC side.

6.4. DC SURGE PROTECTION

Surge can occur in electrical installations for various reasons [39]:

- in the distribution network as a result of lightning or maintenance work carried out,
- lightning (near PV building and system or in lightning rods),
- changes in the electrical field as a result of lightning.

Like all outdoor structures, photovoltaic systems are exposed to the risk of lightning, and therefore preventive and lightning protection systems should be provided. Although surge protection is a part of the DC electric equipment, its complexity and importance make the next subsection devoted to it.

6.4.1. EQUIPOTENTIAL BONDING

The first surge preventing element is protection with equipotential bonding. This protection consists of a wire connection between conductive components of a photovoltaic installation. This equalizes the potential at all points in the system.

The equipotential bonding (galvanic contact) is usually done by copper (Cu) cables with a cross-sectional area of at least 6 mm^2 to 16 mm^2 [3]. It should be noted that the floating system is exposed to a highly corrosive environment. The mounting system is made of high-density polyethylene, hence equipotential bonding is required directly to modules' frames. Different-metal connections need to be properly secured, thus it is assumed in the thesis that the single-string equipotential bonding is achieved by short lengths of spiral H07V-K 16 mm^2 (Cu) cables with zinc-coated copper cable lugs. Moreover, the abovementioned string equipotential cables are connected in stainless grounding bars (mounted on the floating platform) to array equipotential cables, which are H07V-K 16 mm^2 (Cu).

List of components:

- H07V-K 16 mm^2 (Cu): 6800 m
- Equipotential bars: 8 pcs.

6.4.2. SURGE PROTECTION DEVICES (SPD)

Another protection measure is to equip the installation with surge protection devices (SPD), which refers to internal lightning protection. SPDs are especially important while protecting sensitive electrical equipment such as inverters. To be sure whether SPD devices are required for this system, the PN-HD 60364-7-712 standard recommends a risk analysis.

On the DC side of a PV system, SPDs should be installed if the following condition is met:

$$L \geq L_{crit}$$

L – maximum cable route length (m) between an inverter and the connection points of PV modules of different strings

L_{crit} - depends on the type of PV installation and is determined in accordance with the Table 712.102 of the PN-HD 60364-7-712 standard [34]

The L_{crit} parameter is also dependent on the flash density (discharge / m^2 / year) corresponding to the system location. In the selected location, this value reaches 20 bolts of lightning per m^2 per year. According to Table 712.102 of the PN-HD 60364-7-712 standard, the L_{crit} value is 10 m. In this case, the $L \geq L_{crit}$ condition is fulfilled, and thus the protection devices limiting overvoltage on the DC side are necessary. SPDs are meant to be installed on each string as close as possible to inverters.

However, the specific number of SPDs on the DC side depends on the cable lengths between solar panels and inverters. According to the PN-HD 60364-7-712 standard, if this length exceeds 10 meters, a second SPD per string is required to be mounted close to a panel of PV modules [34].

The selection of the surge protection devices depends mainly on two factors: the presence of the Lightning Protection System (LPS) and the separation distance between LPS and modules. It is assumed that the floating system is equipped with an LPS system and the separation distance is respected. Thus, according to the recommendations of the IEC 61643-31 SPD standard, both inverters and modules side should be equipped with type 1 SPDs [41]. To improve the overvoltage safety of the system, it was decided to use combined protections type 1 + 2. Moreover, SPDs installed next to modules will be equipped with a signaling contact to enable remote security checks.

Under STC conditions, the open-circuit voltage for the entire 32-module string reaches 1300 V. Therefore, it is necessary to use SPDs with a maximum voltage level of 1500 V. A device that meets all the above requirements is the SPD Dehn DCB YPV 1500 and its equivalent with built-in signaling contact SPD Dehn DCB YPV 1500 FM. Thus, the surge protection on the DC side will consist of a total of 192 surge arresters. The connection between the SPD with built-in communication contact and the transformer station is based on the RS485 data transmission standard. RS485 buses should be made with a gelled UTP category 5e cable.

Interestingly, it is possible to reduce the number of SPD devices by two, hence lower the investment cost significantly. It may be achieved by connecting two strings in parallel through a parallel DC cables connector, thus only one main cable is subjected to the surge protection, instead of two separate cables. Half of the inverters' DC inputs would be left unused. However, such a solution has certain consequences. Parallel wiring increases current by two, which leads to higher losses while transmitting. Limit of acceptable 3% loss imposes the use of greater cables' diameter. The cost analysis has been performed, and its outcome is that it is not cost-effective to reduce the number of SPDs. The increased cost of cables' diameter change would exceed the cost of surge protection devices.

Each of the SPDs mounted on the floating structure will be separated from the external conditions by HPL AJB-0101 combiner boxes, characterized by IP67 protection and compliance with the IEC 61439 standard (the compliance of a combiner box with the IEC 61439 standard is imposed by the PN-HD 60364-7-712 standard) [34].

On the other hand, SPDs from the side of the inverters should be grouped by 12 pieces (corresponding to the number of strings of one inverter) and assembled in separate switchboards, e.g. ABB Mistral65.

From the point of view of fire safety, it should be remembered that the protection devices should be mounted with appropriate tools with the torques corresponding to the manufacturer's recommendations.

The PN-HD 60364-7-712 standard recommends connecting SPDs both the AC and DC sides with the main equipotential bar by a copper wire with a minimum cross-section of 6 mm^2 (2nd class SPD) or 16 mm^2 (1^{st} class SPD). Thus, the earthing connection from the SPDs to the equipotential bar of each PV array should be done with a yellow-green H07V-K copper wire covered with PVC with a cross-section of 16 mm^2. The connection of array earthing bars with the main earthing bar is made with an H07V-K 25 mm^2 cable. Earth cables of floating systems can be grounded to the reservoir bed or dived in the sufficient water depths, however, neither the first nor second option is suitable for this reservoir. SPD earth cables are assumed to be routed to the transformer station main equipotential bar [3].

List of components:

- SPD Dehn DCB YPV 1500: 96 pcs.
- SPD Dehn DCB YPV 1500 FM: 96 pcs.
- H07V-K 16 mm^2 (Cu): 1100 m
- H07V-K 25 mm^2 (Cu): 6400 m
- UTP kat.5e U/UTP 4x2x0,5: 20400 m
- Equipotential bars: 16 pcs.

6.4.3. LIGHTNING PROTECTION SYSTEM (LPS)

Due to the complexity of this thesis, it was decided not to carry out a risk assessment according to the PN-EN 62305-2 standard. However, following the recommendations of similar-sized photovoltaic farm designers, it was assumed that the floating farm will be equipped with an LPS system of the third protection class. LPS refers to external lightning protection.

The rolling sphere method was used to identify places for the installation of the air-terminal rods. There is no risk of lightning in those places on the surface of the protected object where there is no contact with the "rolling sphere". The third class of LPS corresponds to a sphere with a radius of 45 m, thus based on that the placement of air-terminal rods was adjusted (red dots in Fig.18) and its height selected. Particular attention was paid to minimizing the influence of the rods on the shade cast on PV modules. It is important to move rods as far as possible from the front sides of PV modules. When installing the LPS, one should remember not to cross wires and keep the appropriate distances between the lightning protection and the photovoltaic system.

The greatest possible distance between adjacent air-terminal rods is 31.5 m. Therefore, the minimum height of the rods, taking into account the height of the modules themselves, is 3.44 m (Fig. 19). The best fit among standard sizes available from distributors is a 3.5 m air-terminal rod.

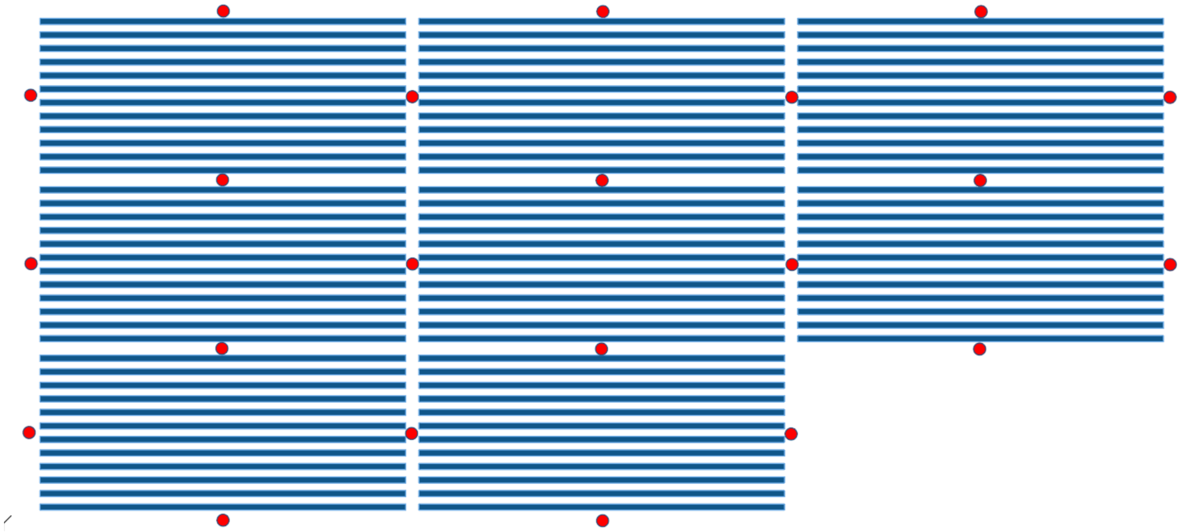

Fig. 18. Conceptual layout of air terminal rods (red dots) in the FPV system

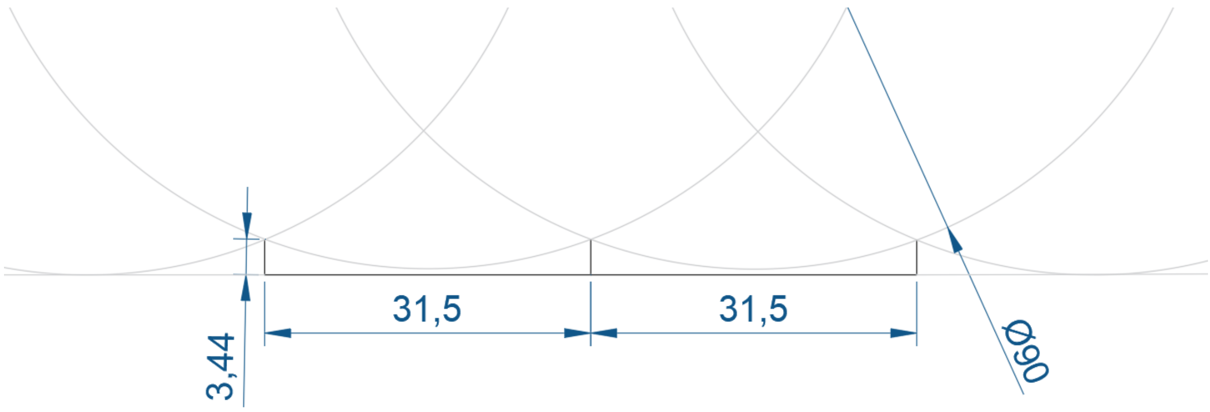

Fig. 19. Air terminal rods height (rolling sphere method for the 3rd class LPS)

Each air terminal rod should be mounted on a separate floater connected to the base part of the floating supporting structure. Due to the aggressive environment, and therefore the high risk of corrosion, it was decided to make the wiring between the air-terminal rods with a 50 mm^2 stainless steel wire (complying with the PN-EN 62561-2 standard) and stainless-steel T-type connectors. After routing the stainless wire to the shore, it should be connected to the main earthing bar of the transformer station. To ensure several parallel current paths, at least two individual connections should be made. Due to the characteristics of the floating system and the reservoir, it is not possible to ensure two connections, thus it is limited to one wire connecting LPS with the main grounding bar. It was decided to construct the LPS system based on Dehn components.

List of components:

- Air terminal rods Dehn 3.5 m: 23 pcs.
- T-connector Dehn ESTV RG: 25 pcs.
- Steel wire Dehn RD 8 STTZN R127M: 800 m

6.5. AC ELECTRIC EQUIPMENT

6.5.1. AC CABLES

The cable thickness on the AC side was selected similarly to the calculations performed in the 6*.3.1 DC Cables* section. Input parameters are the rated output current and rated output voltage of the Huawei inverter.

It was assumed that the inverters will be installed on the outer walls of the transformer station (details in the section *4.3 Inverters*), and therefore the necessity to run thick AC cables was avoided. Maximum acceptable loss stated as 1% results in a three-phase 16 mm^2 cable. The selected inverters operate in the IT earthing network (power grid supported), so a three-core cable N2XY 3x16 mm^2 consisting of three-phase conductors will be sufficient. The current capacity of the cable is 99A, thus more than the maximum current at the output of the inverter - the condition has been met.

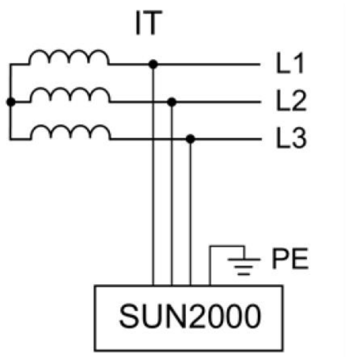

Fig. 20. Inverter connected to the grid (IT earthing network)

Eight sections of the N2XY 3x16 mm^2 cable with a length of 5 meters are required to connect the inverters to the main switchboard.

List of components:

- NKT N2XY 3x16 mm^2: 40 m

6.5.2. OVERCURRENT PROTECTION

Overcurrent protection is located on the main switchboard of the transformer station. Due to the proximity of the inverters to the transformer station, the protections on the AC side will not be duplicated at the inverters. The theoretical selection of overcurrent protection is as follows:

$$I_B \leq I_N \leq I_Z \quad (17)$$

$$I_2 \leq 1.45 * I_Z \quad (18)$$

where,

I_B - design long-term load current
I_N - rated current of the overcurrent protection device
I_Z - long-term current carrying capacity of the cable
I_2 - tripping current of the overcurrent protection device

Considering possible maximum and short-circuit currents, it is necessary to use a fuse with parameters up to 100A and voltage up to 1000V. An example of a protection device from a reputable manufacturer that meets the above parameters is the ETI WT-1 / gG 100A 1000V fuse. There are 9 AC outputs in the main switchboard (one for each inverter + one for SPD). Each of the outputs is secured separately. The AC overcurrent layout is shown in Fig. 23 in the subsection *6.7 Transformer station*

List of components:

- ETI WT-1/gG 100A 1000V: 9 pcs.

6.5.3. SURGE PROTECTION

The main switchboard of the transformer station is equipped with AC surge protection. As with overcurrent protection, the surge protection will not be duplicated in a separate AC box at the inverters due to the proximity of the main switchboard. Due to the characteristics of this protection and the economy, it was decided to place only one SPD in the switchboard on the main cable before splitting into 8 outputs. The selected overvoltage protection is the Citel DS253VG-1000 SPD, and its layout is shown in Fig. 23 in the subsection *6.7 Transformer station.*

List of components:

- Citel DS253VG-1000: 1 pcs.

6.6. WIRING DIAGRAM

Based on the photovoltaic components selected in the previous sections, and their protection devices, wiring diagrams have been drawn. The first diagram (Fig. 21) shows a simplified electrical layout of the entire system consisting of 8 string inverters. Each comes with 12 DC inputs working on 6 independent maximum power trackers - 96 strings in total. Each string is protected against overvoltage by two SPDs located next to the inverter and the modules themselves. AC protections, in turn, are located directly in the main switchboard of the transformer station.

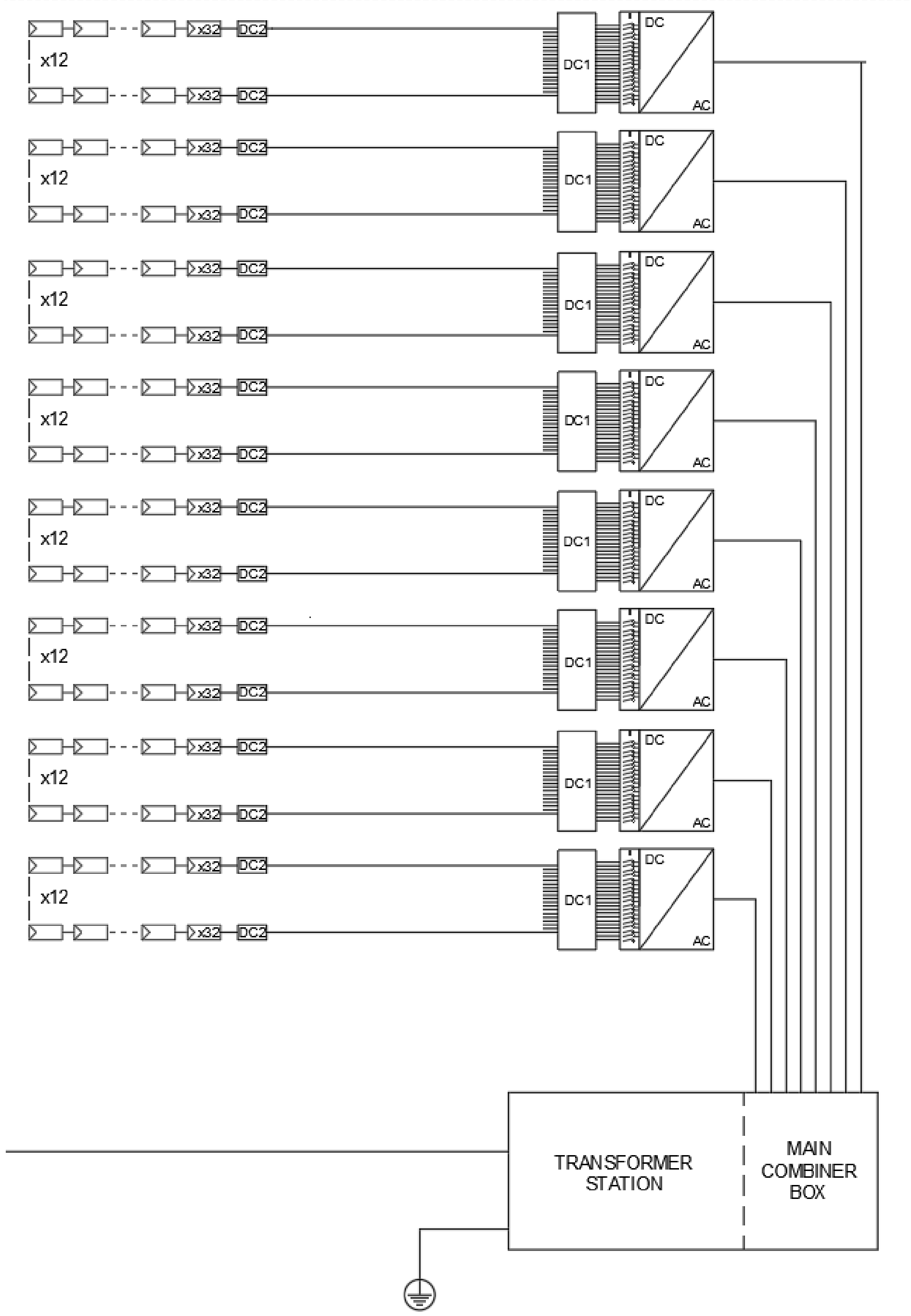

Fig. 21. Simplified wiring diagram of the FPV system (own elaboration)

The detailed electrical wiring is shown in Fig. 22, where one of the 96 strings consisting of 32 modules (3072 in total) was separated in the diagram. The orange box surrounding modules corresponds to the equipotential bonding. The *PV combiner box 2* is mounted on the floating platform and covers a surge protection device. There is a second SPD wired in the same DC string close to the inverter (*PV combiner box 1*). Both earth cables from surge protection devices and equipotential bonding converge in the main equipotential bar, which is directly connected to the transformer station ground.

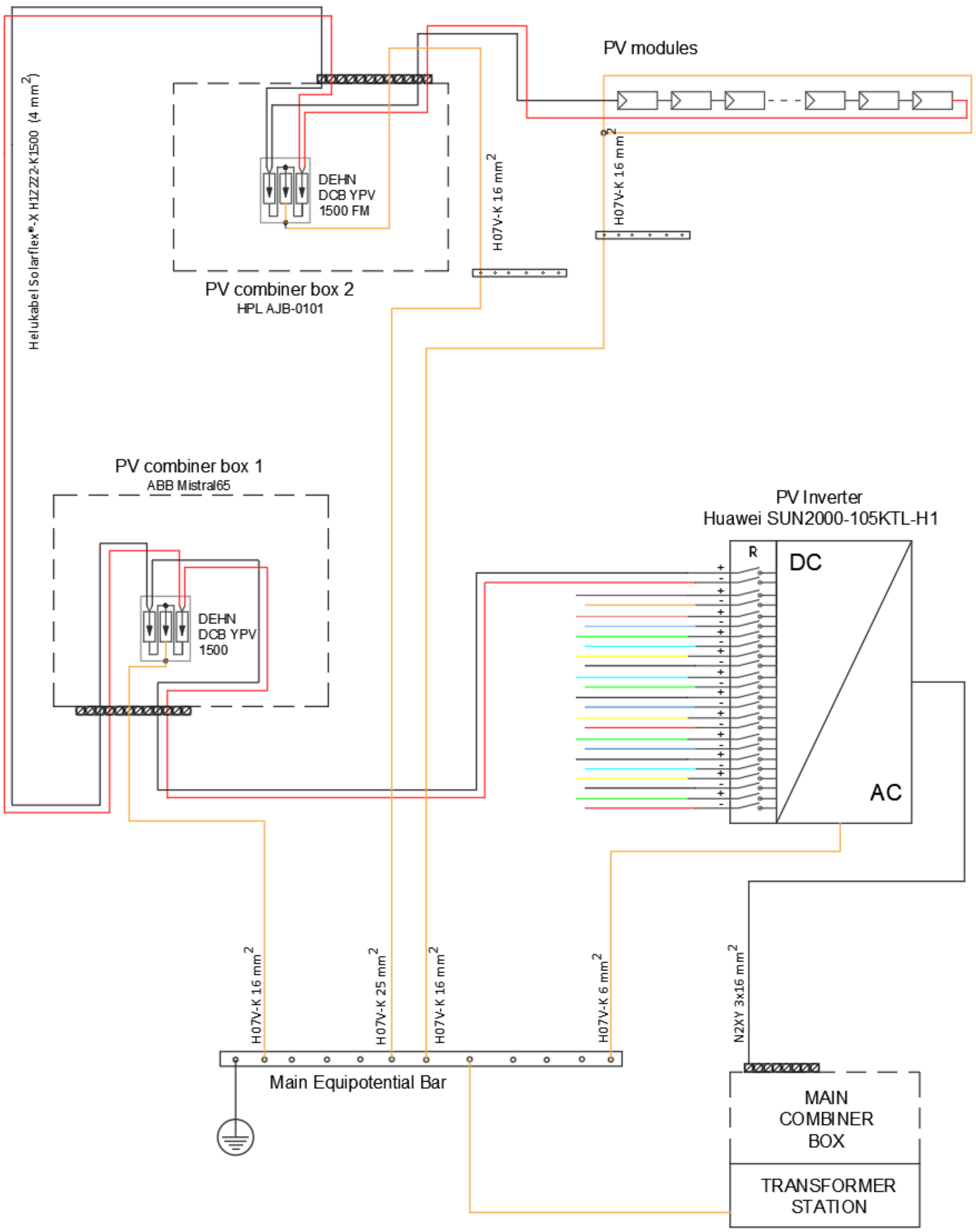

Fig. 22. Detailed wiring diagram of one PV string (own elaboration)

6.7. TRANSFORMER STATION

Electricity generated in photovoltaic modules of the designed floating system is not consumed, but it is assumed to be injected into the distribution network. For energy transport to be possible, it is necessary to change its voltage from low to medium in the transformer station. An integral element of solar farms is usually a container transformer station equipped with a transformer, low voltage switchgear, medium voltage switchgear, measuring apparatus, and power supply for internal installations. It is necessary to ensure an adequate grounding level for surge safety of the station itself as well as the photovoltaic system. For this purpose, one or two metal earth circuits are dug under the structure of the station. At their corners, vertical copper pylons with a depth of e.g. 3, 6, or 9 meters are driven into the ground. This is done until the appropriate value of grounding resistance is obtained, which depends mainly on the type of soil and its moisture level. Galvanized hoop iron connects earth circuits with the station switchboards. It is assumed that the resistance level obtained for a transformer station receiving energy from a floating solar farm is 5Ω.

Fig 47 (appendices) shows the wiring diagram of the transformer station model MRw-bpp 20 / 1000-3 PV 800V manufactured by ZPUE S.A., which is tailored to the needs of the farm. At the bottom of the diagram, there is a 9-pole low-voltage switchgear in the IT system equipped with AC protection devices described in the previous section. Following the main AC cable one can find the power quality analyzer and the main isolation switch of the solar farm. Behind the switch, there is a power supply for the auxiliary 230V switchgear powering, e.g. measuring board, station fans, lighting, or CCTV. An emergency UPS system is also connected to one of the poles. In the event of a power failure and its repair, the transformer station can be restored to work remotely through telemechanical systems.

The next element of the station, going further with the main AC cable, is its heart - a transformer changing the 800V voltage obtained from inverters to the medium voltage of 15.75 kV. On the medium voltage side, there are additional AC protections, telemechanical systems, a measuring board, and the main grid connection.

List of components:

- transformer station ZPUE MRw-bpp 20 / 1000-3 PV 800V

6.8. MONITORING AND SAFETY

The inverters are equipped with an RS-485 communication interface. The data logger should be connected to the bus. To monitor and gather basic parameters of the PV farm it was decided to use a solution from the same manufacturer as the inverters - Huawei SmartLogger3000. The device should be mounted inside the transformer station and power should be supplied from the closest possible point, using the N2XY 3x1.5 mm^2 cable. There is no need to connect the device to a wired internet network since the SmartLogger3000 is equipped with a SIM card slot allowing for a wireless internet connection. Then the data logger may remotely communicate with a computer terminal to store data. The place of installation of the computer terminal depends on the investor, and its power should be supplied from the transformer station 230V switchboard. The connection between the inverters and the data logger should be based on the RS485 data transmission standard. RS485 buses should be made with a gelled UTP category 5e cable.

To reduce the risk of vandalism, the area of a solar farm is usually surrounded by a fence. The reservoir of the Porąbka Żar pumped-storage power plant is already fenced, thus this cost can be avoided. Additionally, the area of the floating power plant should be equipped with at least four CCTV cameras, powered from a 230V switchboard.

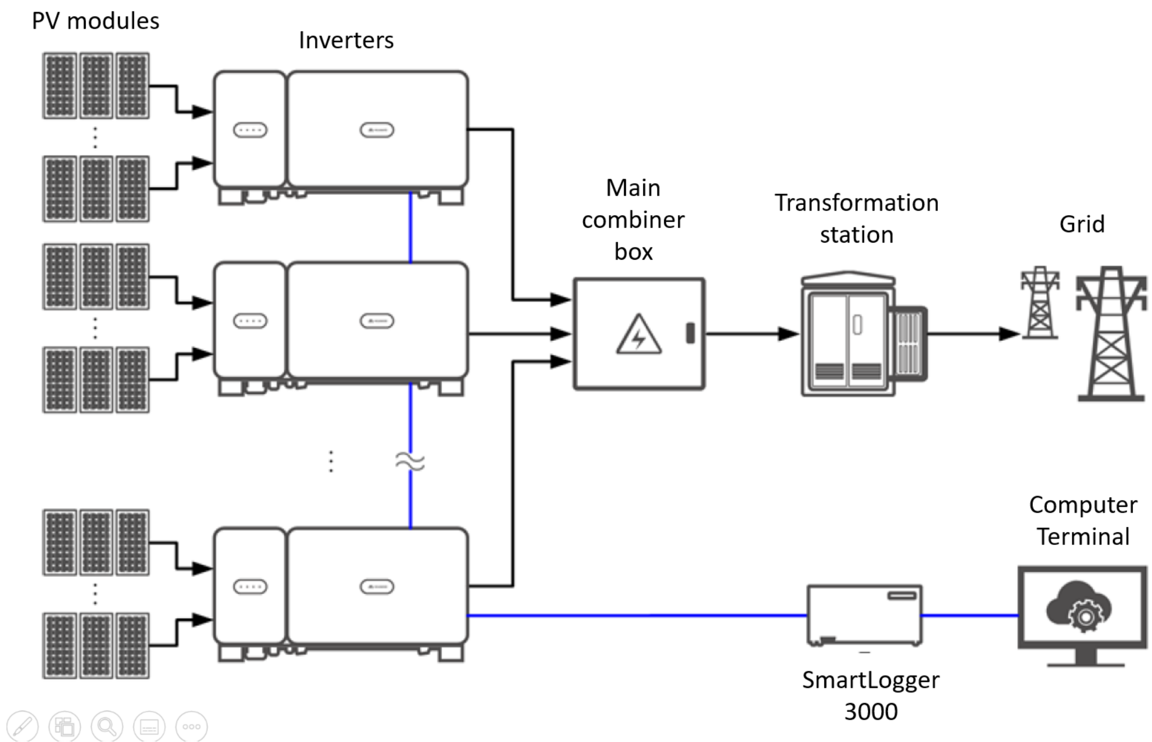

Fig. 23. SmartLogger3000 wiring diagram [40]

7. PVsyst Simulation

7.1. SIMULATION OF THE FLOATING PHOTOVOLTAIC SYSTEM (FPV)

7.1.1. ASSUMPTIONS AND PARAMETERS (FPV)

AZIMUTH AND TILT

The angle of tilt of the modules is forced by the floating Ciel & Terre system. The product variant used for this design gives a 12° tilt angle and is the best fit for this purpose (more in the section *6.1.2. Tilt angle and inter-row distance*). Therefore, losses resulting from angular mismatch account for 8.1%.

The system is assumed to be ideally oriented to the south. This assumption may differ from reality because the floating system may rotate slightly and change its shape due to forces of wind and waves. The anchoring system is not completely rigid and cannot be. This is prevented by the characteristics of the reservoir - frequent change of water level.

THERMAL PARAMETERS

The array electrical performance highly depends on the thermal parameters. The PVsyst software performs thermal balance computations at each step of the simulation. It provides modules, which are subjected to the simulation, with instantaneous operating temperature. The thermal behavior of the field is determined by the energy balance between ambient temperature ($T_{ambient}$) and cell's temperature (T_{cell}), which increases due to incidence irradiance (G_T) [42]:

$$U * (T_{cell} - T_{ambient}) = \alpha * G_T * (1 - \eta) \tag{19}$$

α – absorption coefficient of solar irradiation
U – thermal loss factor, W/(m^{2}K)
η – efficiency of a cell

The higher the thermal loss factor *U*, the lower the operating temperature of cells in a module. On the other hand, the lower the temperature of a module, the higher the voltage, and simultaneously greater the energy yield of a module.

$$U = U_C + U_V * wind\ velocity \tag{20}$$

The thermal parameters are described by the *field thermal loss factor U*, which consists of two elements [42]:

- *constant loss factor* U_C,
- *wind loss factor* U_V.

However, software creators advise not to use *wind loss factor* U_v, due to the common inaccuracy of this parameter in the meteorological data. PV systems are commonly mounted on a different height than wind velocity measurement instruments. Instead, it is recommended to include an anticipated wind impact on the performance of the array in the *thermal constant loss* factor [42].

Therefore, PVsyst, based on its experience, suggests values for different mounting systems [42]:

- U_C = 29 W/(m²K) - free air circulation around the modules,
- U_C = 20 W/(m²K) - semi-integrated modules with an air duct behind,
- U_C = 15 W/(m²K) - integrated (back insulated) modules (only one surface participates to the convection/ radiation cooling).

As seen above, there are no parameters established in PVsyst for floating systems in which a higher coefficient of thermal exchange gives an advantage over conventional systems. Thus, the thermal parameters needed to be derived from scientific papers.

Firstly, the research conducted by Haohui Liu et al [43] compares different types of floating systems and their effect on the energy performance of modules operating on the Singapore Tengeh Reservoir. One of the mounting systems tested was the aforementioned Ciel&Terre Hydrelio® Classic (12° angle version). Its performance was classified in U_C range between 26 W/m²K and 34 W/m²K [43].

It should be noted that the Ciel&Terre floating system in this paper was intended to be divided into 8 arrays with the separation distance between, hence airflow in the system is increased. Thus, it is assumed, for simulation purposes, that the U_C parameter equals 34 W/m²K.

Secondly, due to the water cooling effect, the average ambient temperature on the water is lower by 5°C according to Luyao Liu et al [12]. The meteorological site parameters of the designated location in the simulation have been adjusted.

ALBEDO

Albedo factor measures the rate of diffused reflection of solar radiation. The lowest point on the scale corresponds to the perfectly light-absorptive black body (0), while the highest stands for bodies that reflect entire incident radiation - white body (1). Based on the study conducted by Trapani et al [44] albedo coefficients of water have been examined. The albedo depends on sun height as shown in the Tbl. 8.

According to the following data and its interpretation [45], the average albedo coefficient that was used as an input value for the PVsyst simulation is ρ = 0.096. Compared to the default albedo stated by the software, it can be observed that the ground reflectivity (ρ = 0.2) is approximately 2 times higher than water.

Tbl. 8. Albedo of water as a function of solar height [44]

Sun height γ [°]	Albedo ρ
10	0.128
20	0.103
30	0.084
> 40	0.070

Poland is classified in a humid continental climate region (Köppen climate classification) with cold winters. Thus, it is assumed for the simulation that the top layer of water freezes and covers with snow in December and January. The albedo value suggested by the PVsyst for these two months equals ρ = 0.82 (fresh snow).

DESIGN CONDITIONS

The design conditions section in PVsyst requires adjusting reference temperatures for array design with respect to the inverter input voltages. The designated reservoir is located in the southern part of Poland, which is assigned to the Zone III according to PN-EN 12831. The design outdoor temperature required to be used for calculations is -20 °C.

OHMIC LOSSES

The DC side losses have been limited to less than 3%. Exact calculations were performed in the PVsyst software.

AC side losses in a floating PV system were not taken into account due to the proximity of inverters to the main switchboard. Losses arising in the process of low to medium voltage conversion in the transformer station are not considered. The scope of the simulation covers the system from modules to the main switchboard before the transformation.

MODULE QUALITY LOSS/GAIN

Manufacturers of solar modules assure their customers with the quality of a product by the power output tolerance parameter. JinkoSolar with its JKM320-60-V module states that the output power is not worse than the STC peak power stated in the datasheet (320 Wp), and can only be higher by 10 W. PVsyst default procedure is to find a quarter between the difference of minimum and maximum power tolerance. In the module selected in this thesis, the module quality gain is equal to 2.4 W (0.75 %).

LIGHT INDUCED DEGRADATION (LID)

Light Induced Degradation, also known as LID, is a parameter foreseeing loss of performance related to the first few hours of module exposition to the sun. In laboratory conditions, the loss is shown as a ratio of power generated in STC conditions after a 5 kWh exposure to the STC flash test performed after the production process. JinkoSolar, the manufacturer of modules harnessed in this thesis, certificates their products as LID effect free. Thus, LID loss is assumed to be 0%.

MISMATCH LOSS

Modules in an array do not have equal I/U characteristics and slight differences in performance may occur. The worst module with the lowest current shapes current of the whole string. With 32 modules wired in one string there is a high probability that one of them will show performance lower than others. The mismatch loss copes with that problem as a constant loss during the simulation. PVsyst default value (1% constant loss) has been used for each array [42].

SOILING LOSS

The performance of a system may be decreased by any pollution covering a PV module's surface. These vary according to the surrounding. The frequency of snow, sand, or dust presence changes locally and is difficult to quantify. It is assumed, in line with a PVsyst default value, that soiling loss in both cases equals 3%.

Increased risk of bird droppings in the water environment is not considered. Haohui Liu et al [43] recognized the problem and propose to investigate birds' behavior and schedule maintenance accordingly. In severe cases, it may even lead to hot spot creation and accelerate module degradation.

IAM LOSSES

The incidence loss refers to the differences in solar irradiance reaching silicon wafers comparing to the irradiance perpendicular to the module. Lowering the angle of the sun, reflection of glass outer layer and EVA layer increases causing a drop of irradiance reaching the core of a module, lowering the performance as a consequence. In the PVsyst practice, the ASHRAE parametrization is used as default.

AGEING

The comparison of the floating and ground-mounted systems performance is performed only according to the first year of operation. There is a risk that degradation of modules in the FPV system may occur faster due to high humidity, corrosive environment, potentially higher tension forces, and stronger winds. The insufficient number of scientific papers on this subject leaves the effects of the mentioned factors solely uncertain. The aging factor is used in the economic analysis and is derived from the PVsyst aging tool.

UNAVAILABILITY

PVsyst software lets a user foresee, in the number of days, any failures or periods with electricity shortage that may impact the PV system generation.

There is a time (mentioned in the section *4.4 LOCATION CONDITIONS*) during which annual maintenance and cleaning works of the reservoir occur. Water is drained at that time and the system would settle at the bottom of the reservoir. These works will affect the operation of the PV generators, as walls of the reservoir may create shades, however, will not interrupt it completely. The uncertainty associated with the duration of that work and occurring irradiation, force not to consider it in the simulation.

SPECTRAL CORRECTION

Irradiance exists in three forms: beam, sky diffuse, and ground diffuse. The ratio of these three highly depends on the scattering and absorption effect of light in the atmosphere, which in turn depend on humidity, aerosols in the atmosphere, and the traveling distance of light. It is expressed as Air Mass (AM) parameter. Several models are available in PVsyst to quantify the effect of these factors on the system performance, however, the default one is used in this simulation. Further study could be done here, as the water content in the atmosphere for FPV systems is significantly higher, which may lead to increased scattering of light and lower yield in contrast to corresponding systems mounted on the ground.

AUXILIARIES

Auxiliaries losses refer to additional devices that operate and use energy in the area of a PV system. It may be air conditioning systems, fans, lights, cameras, or any other energy-consuming device influencing the output energy yield. In the comparison conducted in this thesis, these losses are assumed to be negligible and will not be covered in the economic analysis.

7.1.2. SIMULATION RESULTS ANALYSIS (FPV)

The simulation was carried out in the PVsyst software, given all inputs mentioned in the *7.1.1 Assumptions and Parameters (FPV)* and the exact location of the system designed. Fig. 25 and Fig. 26 present an illustrative 3D model used to analyze the yields of the floating solar farm.

In the first year, a yield of **934.2 MWh** is forecasted. To illustrate the result more clearly, 1 kWp of installed capacity generates approx. 950 kWh of electricity.

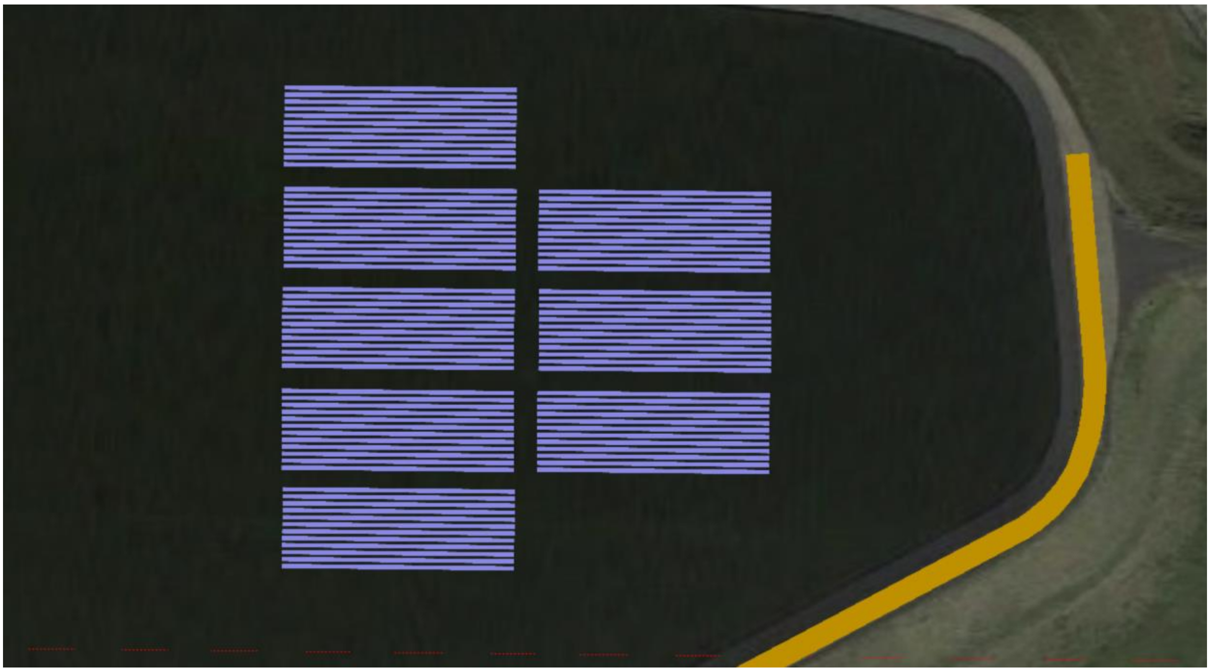

Fig. 24. 3D model of the FPV system designed in PVsyst v1

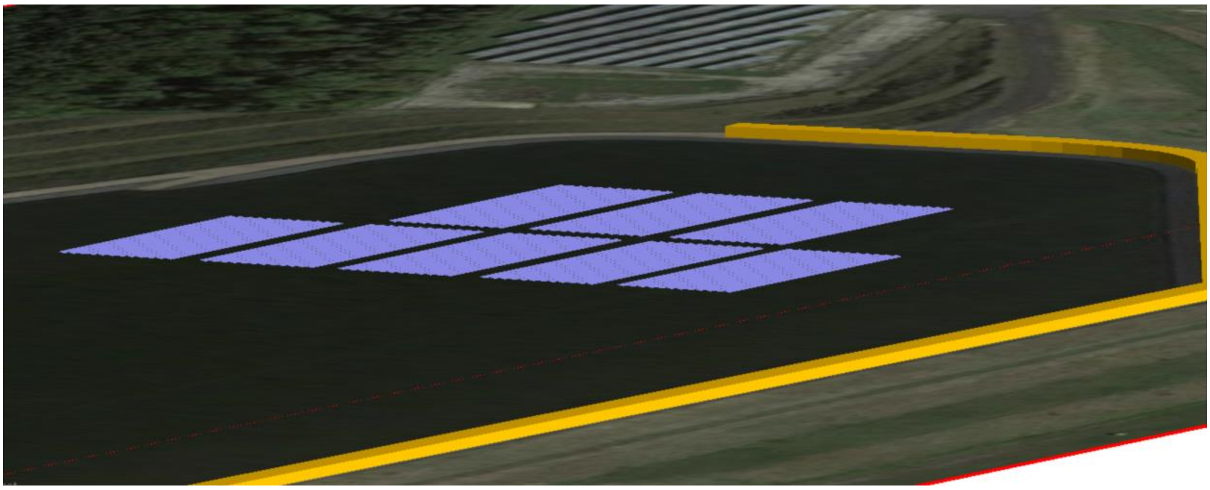

Fig. 25. 3D model of the FPV system designed in PVsyst v2

The performance ratio (PR) is the ratio of the energy effectively produced to the energy which would be generated if a system was continuously operating at its nominal STC efficiency. It means that the PR ratio covers optical losses, array losses, and system losses. Thus, it is an important metric in the PV industry to assess the performance of the designed system. The simulated floating system is evaluated at 87.07%.

Both energy production and performance ratio are broken down into months on the graphs (Fig. 28, Fig. 49, appendix). The highest yield is observed during the spring and summer months when the daytime is longer and the sky in Polish conditions is rather clear. It is also observed that the share of losses is significantly higher during this time. These are mostly collection losses, which result from increased temperature, thus lower performance of a PV module in the energy conversion process. Consequently, it reflects the PR ratio which is also lower from May to August.

On the other hand, there is a month, December, which significantly diverges from the pattern with its low-performance ratio. High losses are assumed to be followed by the increased shading during the wintertime – most of the time sun is low over the horizon. It is not cost-effective to eliminate this by extending inter-row distances, as energy yield during this time is modest compared to the annual production.

Main system parameters	System type	**Sheds on ground**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	12°	azimuth	0°
PV modules	Model	JKM 320M-60V	Pnom	320 Wp
PV Array	Nb. of modules	3072	Pnom total	**983 kWp**
Inverter	Model	SUN2000_105KTL	Pnom	105 kW ac
Inverter pack	Nb. of units	8.0	Pnom total	**840 kW ac**
User's needs	Unlimited load (grid)			
Main simulation results				
System Production	**Produced Energy**	**934.2 MWh/year**	Specific prod.	950 kWh/kWp/year
	Performance Ratio PR	87.07 %		

Fig. 26. General results of the FPV system simulation

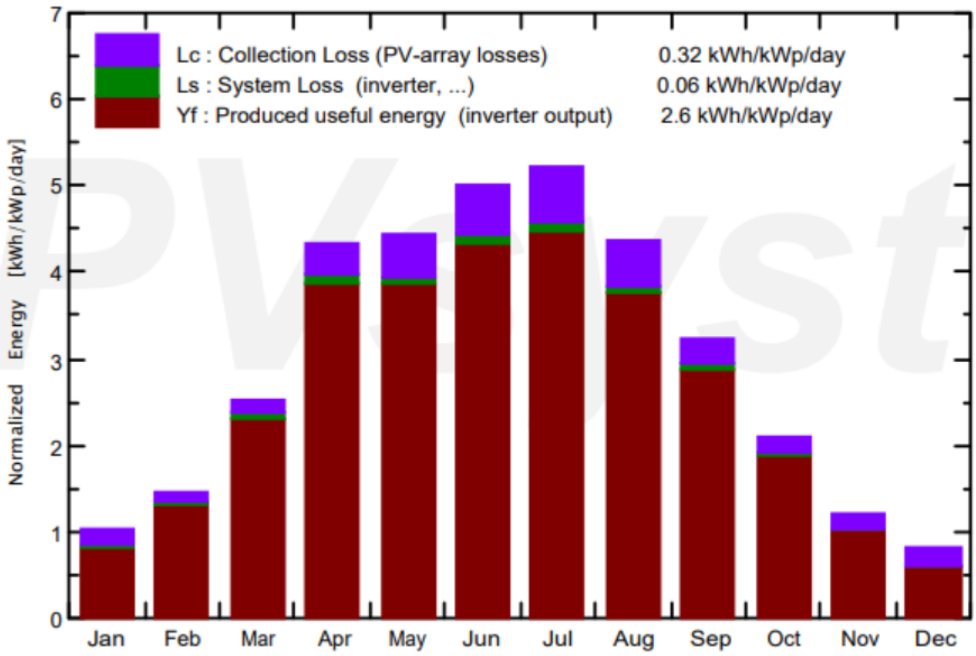

Fig. 27. Daily average normalized production per kWp of the FPV system

The PVsyst simulation report apart from the energy yield forecasted and general information shows losses of the system in detail. The Sankey diagram (Fig. 29) represents the "path" of energy conversion, transmission, and transformation processes and its consequences in the form of energy lost. The upper section of the diagram shows energy lost (photons) before it reaches a PV cell, due to near shading, soiling, and reflection of photons. On the other hand, there is a gain of over 8% witnessed here, as modules operate in a tilt in comparison to the reference plane, which is horizontal.

Conversion of photons that reached silicon wafers is calculated at the efficiency of modules in STC conditions. Further losses are related to a PV array, such as shadings, module quality, mismatch, or ohmic. Due to the increased heat exchange of the floating system, a gain of 0.73% occurred in the temperature loss.

Further losses are strictly correlated to the inverter performance and stand for around 2.5%. Finally, the energy injected into the grid is 934 MWh.

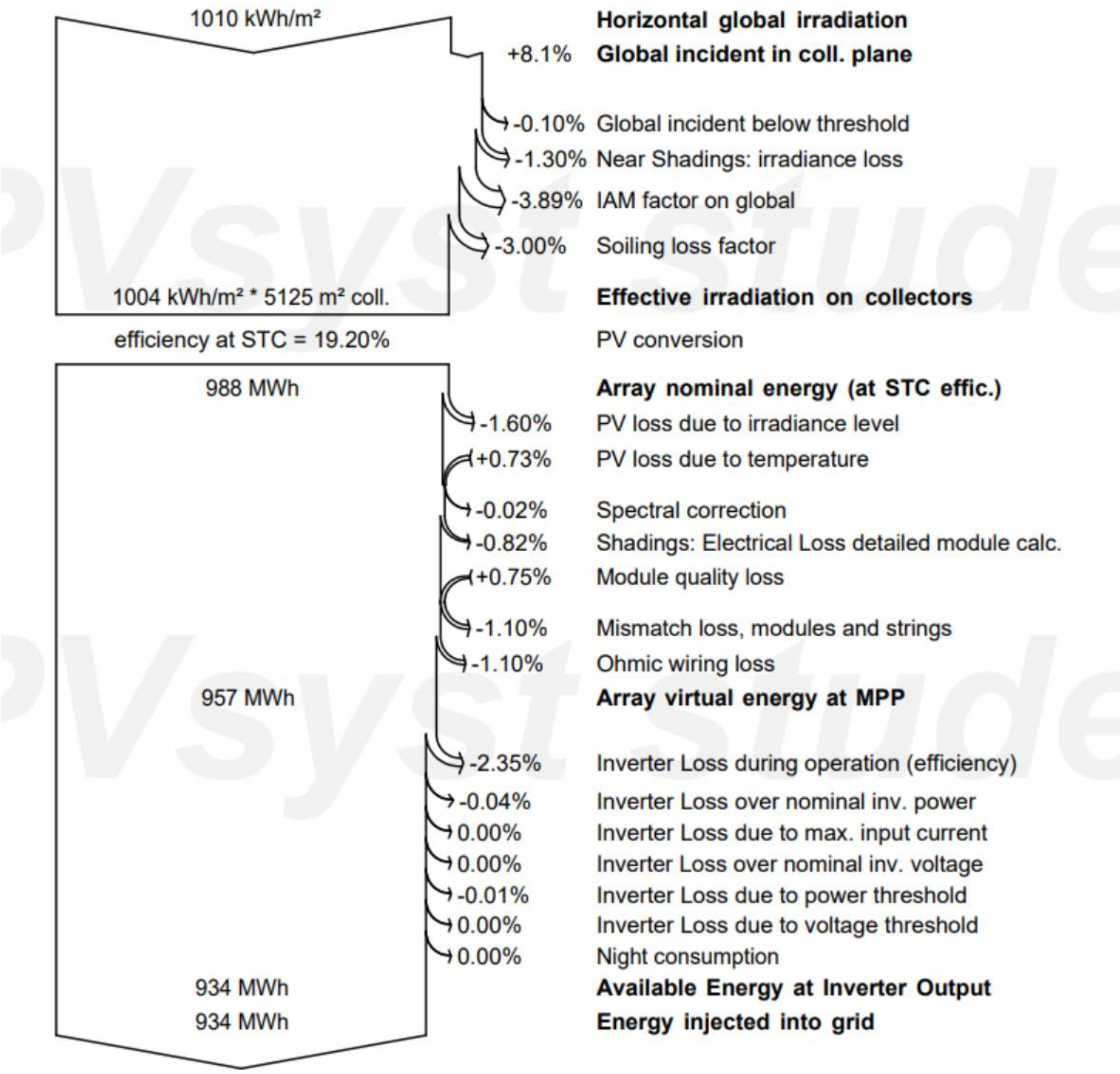

Fig. 28. Sankey diagram of losses/gains in the FPV system

While forecasting irradiation, hence the amount of energy reaching a 1m^2 horizontal surface on the ground, there is great uncertainty about its result. Therefore, PVsyst generates a Gaussian distribution graph of the amount of produced energy to its probability in the report.

With 95% certainty, it is possible to predict the annual generation of electricity at the level of 906 MWh, while with a probability of 50% annual generation is estimated at 934.2 MWh. The PVsyst report is attached in the appendix.

7.2. SIMULATION OF THE GROUND-MOUNTED PHOTOVOLTAIC SYSTEM (GMPV)

The configuration of the main components, i.e. modules and inverters, has not changed. Thanks to this, it is possible to compare the two systems quite accurately, both in technical and economic terms, which was established as the purpose of this work. However, the two systems differ in some respects. Efforts were made to keep both projects as close as possible to the realities of solar farms and correct design practices.

The next subsection describes the changes that occurred when performing simulations for a free-standing system. In order not to repeat information previously contained, detailed descriptions of individual losses and gains can be found in the subsection *7.1 SIMULATION OF THE FLOATING PHOTOVOLTAIC SYSTEM (FPV).*

7.2.1. ASSUMPTIONS AND PARAMETERS (GMPV)

GENERAL ASSUMPTIONS

A simulation for the farm on the ground with modules tilted at an angle of 12° was not performed, because in real conditions such systems are usually not built. At least not in the latitude range corresponding to Poland. Therefore, the simulation was made based on the Polish reputable mounting structure manufacturer - Corab. Its product, WS-004M structure with a 25° angle of tilt is used (Fig. 48, appendix). This specific tilt (25°) is usually harnessed in Poland and gives a good ratio of the tilt angle close to optimum for the short inter-row distance. According to PVsyst, such a tilt angle assuming selected latitude and south azimuth deviates only by 2.2% from the optimal angle. For comparison, the 12° angle used in the floating system is a loss of 8.1%.

The arrangement of the modules themselves relative to the structure differs from that seen in the FPV system. Configuration of modules in free-standing solar farms, due to the optimization of construction costs, consists of two or more rows of modules. In case of the structure selected for the simulation, Corab WS-004, modules are installed in the landscape orientation in four rows. It is assumed that the soil underneath is suitable for the construction empaled into the ground.

Besides, it is possible to mount inverters on the structure itself - thanks to this, the DC cables are maximally short, and therefore it is not required to route a significant number of DC cables.

The inter-row distance was calculated according to the method described in the *6.1.2 TILT ANGLE AND INTER-ROW DISTANCE* subsection. In this case, there are no limitations associated with this dimension. It can only be imposed by the plot size, but it has been assumed that there are no such restrictions.

THERMAL PARAMETERS

The thermal loss coefficient has been changed to that proposed by PVsyst for solar farms with construction characterized by full air circulation. Thus, the coefficient used in the simulation is 29 $W/(m^2K)$. The ambient temperature was not reduced, unlike the FPV system, which was the result of the presence of a water reservoir.

ALBEDO

Albedo factor has also changed. It is assumed that the system is laid on grass, and hence the coefficient is more favorable than for water. Its exact value for 10 months of the year is now 0.2 (value proposed by PVsyst for grass). The remaining two months were left with the Albedo coefficient corresponding to the reflectance of fresh snow (0.82).

DESIGN CONDITIONS

No changes compared to the FPV system. The design outdoor temperature required to be used for calculations is -20 °C.

OHMIC LOSSES

As mentioned above, inverters can be located on the mounting system of each array. Thanks to this, it is not necessary to route thick DC cables of individual strings to the transformer station, in oppose to the designed FPV system. Here, the connection inverter - transformer station was made in its main part with 8 three-core YKY 3x25mm^2 AC cables. Losses on the wires are still less than 1%, which was taken into account in the simulation. AC losses in the floating PV system are considered not significant, due to the proximity of the inverters to the main switchboard. Losses arising in the process of converting low to medium voltage in a transformer station are included.

OTHER PARAMETERS

No changes compared to the FPV system regarding module quality loss/gain, light induced degradation, mismatch loss, soiling loss, IAM losses, aging, unavailability, spectral corrections, auxiliaries.

7.2.2. SIMULATION RESULTS ANALYSIS (GMPV)

The second simulation was performed for a conventional system – mounted on the ground. Fig. 30 and Fig. 31 present the layout of the system and the transformer station.

Electricity production is estimated at 972.8 MWh in the first year. The utilization factor, which is the yield converted to 1 kWp of installed capacity, amounts to 990 kWh per year. PR indicator, the ratio of energy yield including losses to energy yield with modules continuously operating in STC conditions, is 86.27%.

Losses intensify in the spring and summer period, which translates into a lower PR level in the months from April to September. This is likely the effect of high temperatures, whereby the efficiency of photovoltaic modules drops below the efficiency obtained under STC conditions. Total losses are estimated at 0.5 kWh per day from 1 kWp of installed power (Fig. 50, appendix).

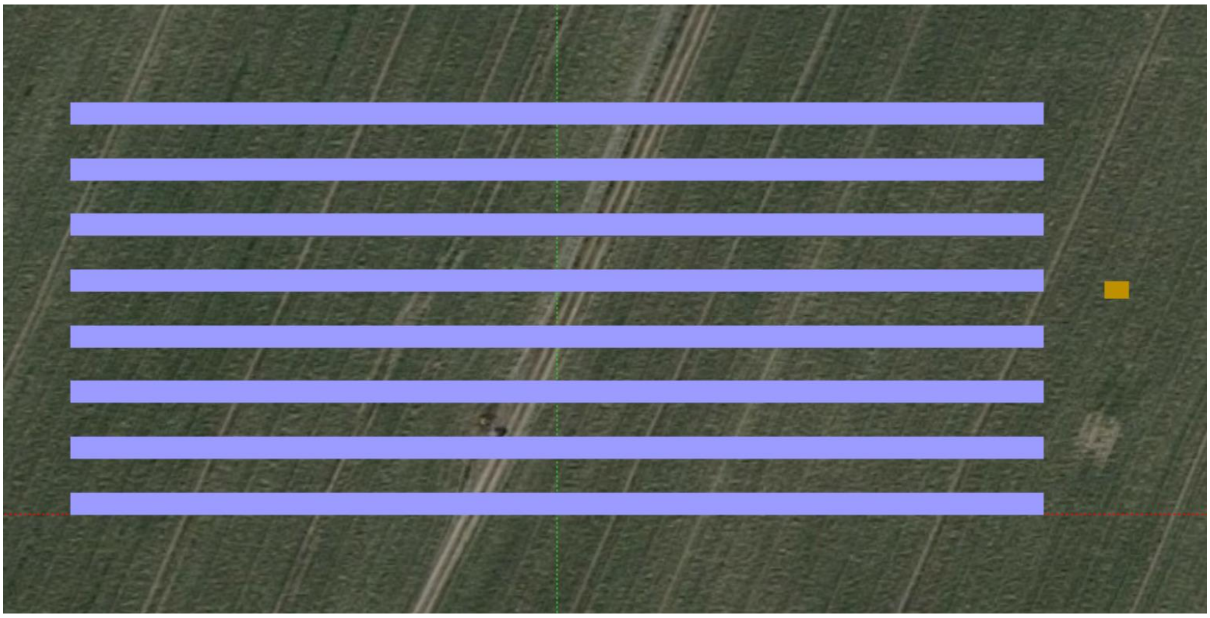

Fig. 29. 3D model of the GMPV system designed in PVsyst v1

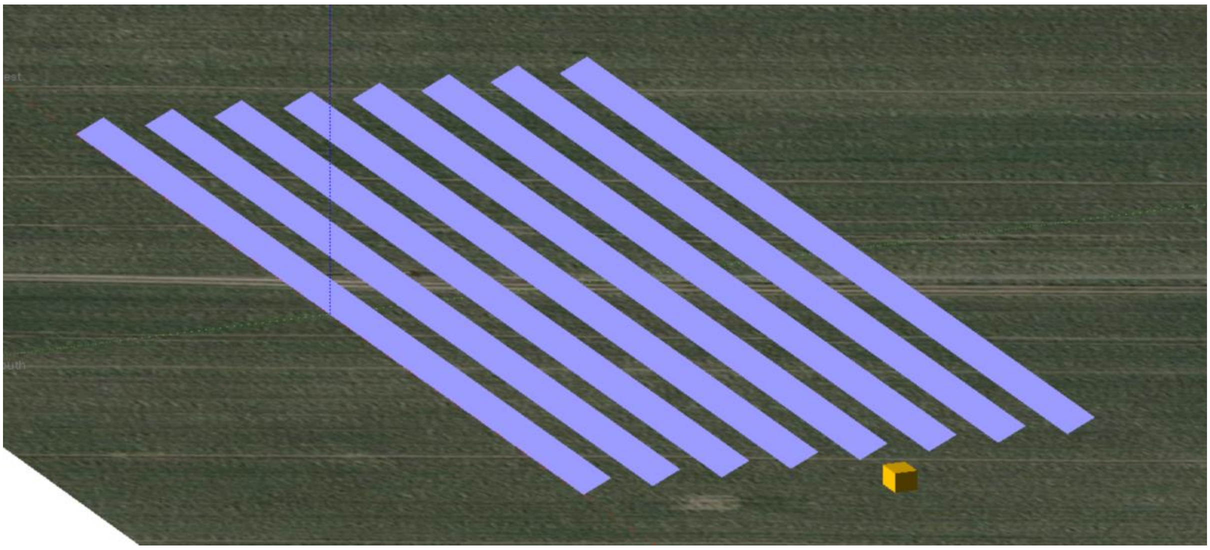

Fig. 30. 3D model of the GMPV system designed in PVsyst v2

Main system parameters	System type	**Sheds, single array**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	JKM 320M-60V	Pnom	320 Wp
PV Array	Nb. of modules	3072	Pnom total	**983 kWp**
Inverter	Model	SUN2000_105KTL	Pnom	105 kW ac
Inverter pack	Nb. of units	8.0	Pnom total	**840 kW ac**
User's needs	Unlimited load (grid)			
Main simulation results				
System Production	**Produced Energy**	**972.8 MWh/year**	Specific prod.	990 kWh/kWp/year
	Performance Ratio PR	86.27 %		

Fig. 31. General results of the GMPV system simulation

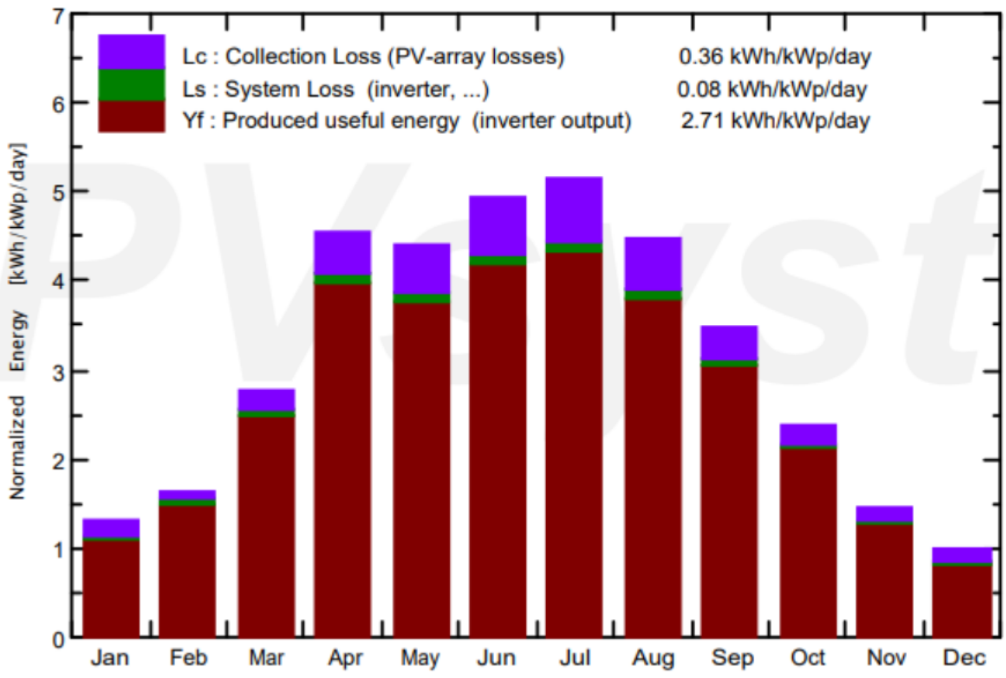

Fig. 32. Daily average normalized production per kWp of the GMPV system

The Sankey diagram (Fig. 34) shows the gain of 13.6% due to the increase of irradiation reaching the inclined (25° tilt) modules surface. Losses related to the IAM effect, near shading, and soiling add up to less than 9%.

Conversion of photons energy into electricity results in the highest loss described by the efficiency index from a module datasheet. Due to the irradiance level, high temperature, shadings, and mismatch of modules in series there is a drop of energy yield from 1033 MWh to 1002 MWh.

Finally, there is the efficiency of inverters and losses on AC cables. As a result, the useful energy injected into the grid is 973 MWh.

According to the Gaussian distribution graph, there is a 95% chance that at least 943 MWh will be injected into the grid, following the 973 MWh considered as 50% probable. The full PVsyst report is attached in the appendix.

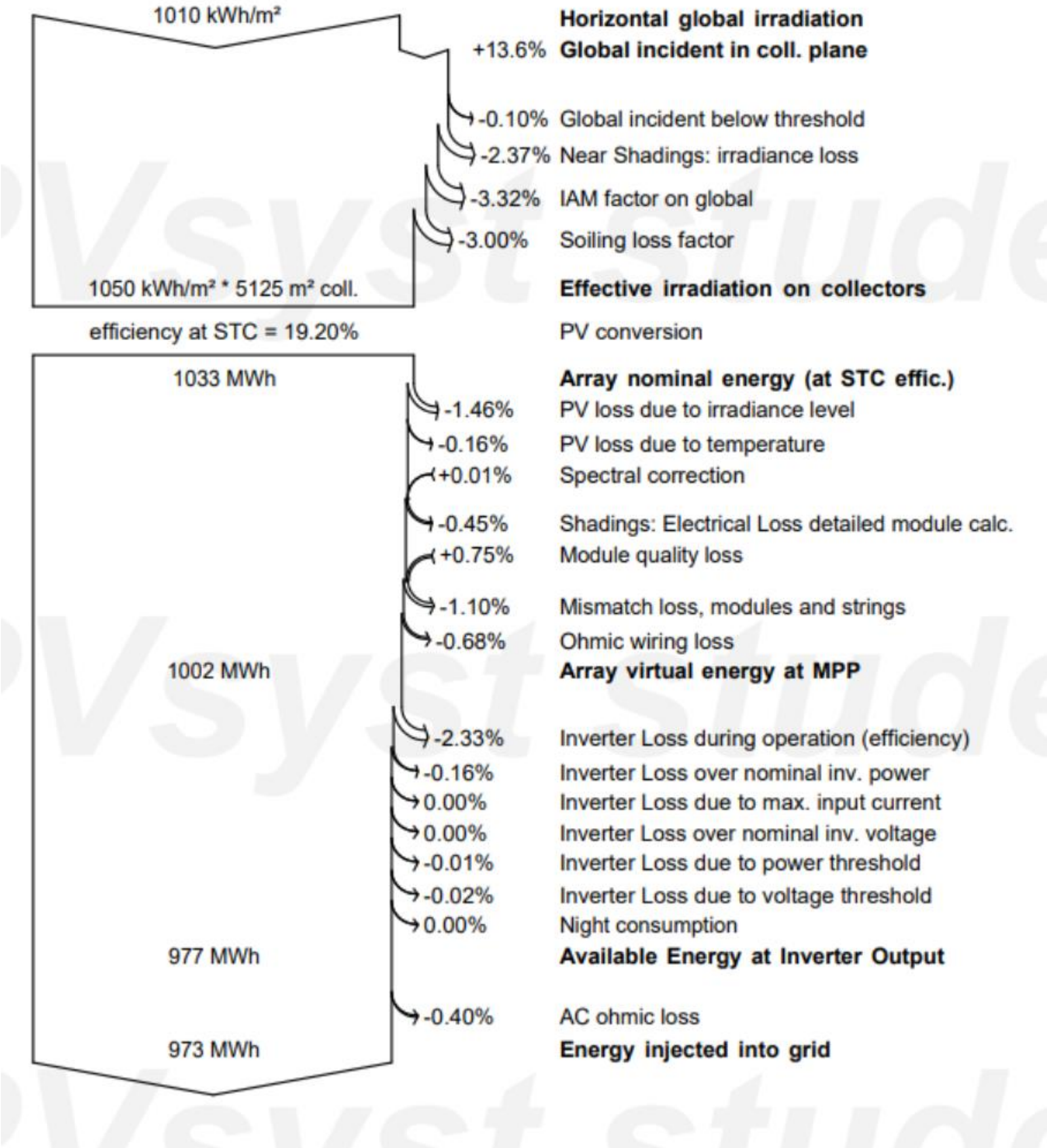

Fig. 33. Sankey diagram of losses/gains in the GMPV system

7.3. FPV AND GMPV PERFORMANCE COMPARISON

Having both systems simulated with all input parameters covered, first performance conclusions can be made.

By analyzing both Sankey diagrams (PFV – Fig. 29, GMPV – Fig. 34), it is easy to trace which factors have the greatest influence on the difference in the amount of energy obtained. The initial value for both systems is identical due to the same location and amounts to 1010 kWh/m^2. The value relates to the amount of energy reached per m^2 of a horizontal surface.

The difference begins in the further step - the amount of energy reaching the inclined surface according to the incidence angle of the supporting structures. GMPV exceeds FPV by as much as 5.5 pp in terms of *irradiation gain*. This means that the incidence angle (25°) of a ground-mounted structure is better suited to the latitude of this design than FPV 12°.

Near shading is unfavorable for both systems. The FPV structure with a horizontal module layout, despite not keeping the recommended distances between rows, generates lower near shading loss than GMPV by almost 1pp.

As a result of both abovementioned factors, the effective irradiation on collectors for the floating system is equal to 1004 kWh/m^2, while for the conventional system - 1050 kWh/m^2.

The conversion of solar energy reaching the module is calculated following the energy conversion efficiency declared by the manufacturer. This means that the annual energy generated by the PV modules of the system (before losses, after conversion) is 988 MWh for FPV and 1033 MWh for GMPV.

Subsequent losses, such as the efficiency inverter, are identical to each other, except for two. The influence of the module temperature on their generation brings a profit of 0.73% in favor of the floating system. This is the effect of the increased efficiency of heat collection from the modules by the water reservoir. For a free-standing structure, there is a loss of 0.16% here.

Another difference occurs in the *DC Ohmic wiring*. Due to the long route of solar cables stretched between the modules and the reservoir bank where the inverters are installed, the Ohmic loss is 1.1%. In turn, for the system on land, this loss is only 0.68%.

Finally, the amount of generated electricity at the output of the inverter is as follows: FPV system - 934 MWh and GMPV system - 973 MWh.

8. Economic Analysis

8.1. INTRODUCTION

The economic analysis will be carried out for two types of installation: the floating PV system designed in the previous sections of the thesis, and a ground-mounted PV system corresponding with parameters and main components to the floating system. Both projects were established in Polish realities. The ground-mounted system is assumed to be placed on a 4th or lower-class land that does not meet the appropriate conditions for cultivation. The system of guarantees of origin (green certificates) has been replaced by the auction mechanism resembling a contract for difference. Like most solar farms of this type in Poland, it was assumed that the mechanism in which both farms will operate is the auction mechanism preceded by an auction conducted by the Energy Regulatory Office.

8.2. ASSUMPTIONS

According to the Polish Renewable Energy Sources Act (RES Act), the period of support for producers participating in the auction system is 15 years, but no longer than until December 31, 2039 (the date was extended from 2035 to 2039 with the entry of the amendment to the RES Act and a positive decision issued by the European Commission) [46]. After this period, energy will be sold on market terms. This analysis will cover a financially secure period from the investor's perspective - 15 years. After this period, the capitalization of the company will be calculated in the form of the residual value of fixed assets. All values given in the analysis are net prices (excluding VAT). The limited liability company (LLC) established to sell energy from a solar farm is assumed to be an active VAT payer and can count on its full return.

The discount rate is used to express an investor's expected gain, which depends on the risk associated with the investment decision. General risk can be broken down into business, industry, and market risks (political and financial aspects). In the base model, the discount rate was adopted at the level of 8%.

The auction mechanism forces RES systems to generate and sell at least 85 percent of the electricity declared during the auction. The amount of generated and sold electricity is verified every three years. A fine is imposed on the owner of the RES system who fails to reach this threshold. It is assumed that no fines have been imposed on the investor and both systems generate electricity as simulated. Moreover, the amendment to the RES Act introduced a requirement that the amount of electricity covered by bids accepted in each auction may not exceed 80 percent of the total amount of electricity offered in this auction. This mechanism is expected to increase competition between bidders, as at least 20 percent of the bids (the most expensive) will not be selected.

Under the updated RES Act, a producer that wins the auction may benefit from support through the auction system if a RES installation is built and starts selling electricity within a specified period after the auction, i.e. 24 months in the case of solar farms.

To participate in a RES auction, bidders are obliged to collect the following documents:

- valid building permit,
- grid connection conditions or a grid connection agreement,
- material and financial schedule for the project implementation,
- a diagram of a RES system with the indication of the installation location, grid connection points, and measurement devices.

It was assumed that the floating solar farm is qualified as a photovoltaic installation that can participate in RES auctions. As this technology is entering Europe, there are no mentions in the RES Act about how this type of renewable energy system should be treated.

Until 2015, it was necessary to present to the President of the Energy Regulatory Office a legally valid decision on environmental conditions before participating in an auction. However, this has been changed since the Construction Law requires such a decision before issuing a building permit. This provision was abolished in order not to duplicate documents submitted.

It is when investors of floating photovoltaic systems may encounter problems. The impact of the photovoltaic system on the environment and the ecosystem may disqualify such a project from issuing a positive environmental decision. To minimize this risk, only artificial reservoirs used for energy purposes were taken into account when selecting the location. It is therefore assumed that such a positive decision was granted.

It is also unclear whether a floating photovoltaic structure is subject to the building permit, which in turn is required by the President of the Energy Regulatory Office. It is assumed here that the investor was granted the building permit and the project may compete in the auction.

The remaining items, i.e. connection conditions, construction schedule, and detailed system diagram, are not a major challenge and are considered successfully collected.

Besides, the results from the last RES auction in Poland (as of 2/07/2020) was used for the analysis. The last basket (auction AZ/9/2019) was intended for new small wind and solar systems. According to the results published by the president of the Energy Regulatory Office, the lowest price at which energy was contracted was PLN 269/MWh, and the maximum price was PLN 327/MWh. The sensitivity analysis will therefore be based on auction prices in the range between PLN 269/MWh (approx. EUR 60/MWh) and PLN 327/MWh (approx. EUR 73/MWh).

The deadline for the settlement of receivables by Zarządca Rozliczeń S.A. (Energy Regulatory Office company responsible for billing receivables) is one month after submitting the results of energy injected into the grid within a month. This means that receivables, e.g. from December, are settled in February, creating complications in cash flows. To simplify the analysis, it is assumed that the receivables are settled at the end of a billing month.

This has little impact on the overall results presented, as it concerns only the 11th and 12th months of the year, which have a marginal share in the annual energy sales.

To define energy yield for each year in the 15-years-long analysis PVsyst aging tool has been used. It uses a Monte Carlo method to find the rate of degradation of modules.

8.3. AUCTION SYSTEM

Two steps of energy sale in the auction system:

- First sale channel - sale of energy at the exchange price (Polish Power Exchange). Brokers offer energy purchases at prices adjusted to the daily TGeBASE index, which is the arithmetic mean of the weighted average hourly prices of a given delivery day, calculated based on hourly, block, and weekend contracts. Additionally, the investor can count on a bonus of about PLN 26 (app. EUR 6) for producing 1 MWh of energy (PV market profile). This premium is related to the convergence of the generation profile of PV systems and the first daily peak.

- Second sale channel - Zarządca Rozliczeń S.A. once a month compensates the renewable energy producer's account balance with the difference between the daily average TGeBASE price and the corrected (due to valorization) contracted price - settlement of the negative balance. The adjusted price is the auction price reduced by the received investment aid in the form of, for example, subsidies. Such a procedure is aimed at maintaining competitiveness during the auction process. In the case of this analysis, it is assumed that no public aid is granted.

It should be remembered that the auction price is indexed by the average annual consumer price index from the previous year (information provided by the Central Statistical Office) [46]. The National Bank of Poland forecasts a large increase in CPI in 2020 at the level of approx. 3.7%, along with a slower increase in 2021 at the level of 2.7%. The year 2022, the last year in the forecast, hovers around 2.4%. The indexation of the subsequent analyzed years was adopted at the level of the inflation target - 2.5% [47].

Thanks to the auction system, it is not important for the investor what form the TGeBASE price will take in the coming years and there is no need to forecast it. This is a difficult task because Poland's long-term energy strategy is still not adopted (as of 07/07/2020) and the inevitable energy transformation of the country will be very costly. Wholesale electricity prices will certainly increase, but it is not known yet at what pace this trend will continue.

8.4. CAPEX

Capital expenditures (CAPEX) are investment expenditures incurred for the development of a product - in this case, a photovoltaic farm.

CAPEX includes:

- photovoltaic components, electrical equipment, and other farm elements,
- projects and permits,
- interest on loan and commission before the first sale.

The CAPEX statement (appendix A.3) is one of the elements of economic analysis. All items have been divided into main subgroups: initial expenditures, transformer station, mounting system, inverters, PV modules, cables, electrical equipment, LPS, monitoring and safety, and installation work. To make the statement clear and easy to compare, interest on loan and commission are not listed here.

The share of subgroups of capital expenditures (apart from interest on loan and commission) for both systems is visible in the following pie charts (Fig. 35):

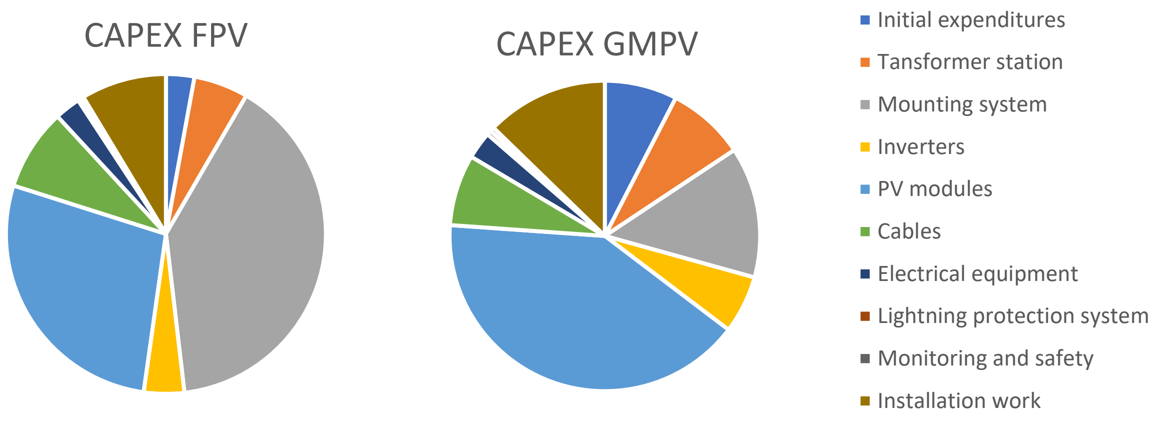

Fig. 34. Share of expenditures in the CAPEX statement of FPV and GMPV systems

All the values used for the analysis have been thoroughly verified. The prices given are the prices that the investor can expect when making an investment decision. To make them realistic, therefore conduct more accurate analysis, inquiries to distribution companies (mainly photovoltaic and electric) were sent on behalf of a local electric company.

Contrary to the conventional photovoltaic farm, PV modules do not constitute the major expenditure in the floating photovoltaic system. The key element determining its price is the floating structure. The expenditures incurred in the first year of constructing a floating farm are almost 50% higher than the expenditures incurred for the construction of the corresponding farm on land. The CAPEX of the designed ground-mounted system is approx. EUR 590,000 (approx. EUR 600/MWp), while the floating system is EUR 760,000 (approx. EUR 773,000/MWp).

It turned out to be a big obstacle to list the price of the floating structure itself. According to one of Ciel & Terre's representatives, the company offers end-to-end customer service for the construction of a floating solar farm and does not sell floating structures alone. The difficulty was also encountered in the valuation of the anchoring system, as its design was not in the scope of this study, and the method of its implementation depends mainly on the conditions of the reservoir on which the floating structure is to be located. The Colombian company Ingeneria Flotante dealing with floating solutions were extremely helpful. Thanks to their commitment and experience, it was possible to evaluate both missing values.

Moreover, the CAPEX statement (appendix A.3) includes the proposed residual values of each asset and depreciation costs following the depreciation rates of fixed assets included in the Classification of Fixed Assets issued by the Polish Central Statistical Office.

8.5. OPERATIONAL COSTS

In addition to the capital expenditures incurred at the beginning of the project, operating costs are an integral part of the operation of solar farms.

8.5.1. DEPRECIATION OF ASSETS

The key cost that qualifies as the operational cost is the depreciation of assets. According to the depreciation rates for fixed assets included in the Classification of Fixed Assets issued by the Polish Central Statistical Office, a list of depreciation charges of fixed costs of both solar farms (appendix A.3) has been created. It should be noted that in year 12 all inverters are assumed to be replaced. When evaluating inverters, the decreasing value of money and constantly falling prices of photovoltaic components in Poland were considered. For most of the 15-years project duration, the annual depreciation charges for the floating and ground-mounted systems are EUR 64,629 and EUR 43,034 respectively.

8.5.2. TAXES

The uncertainty over floating solar farms also applies to property taxes - a tax on land and a tax on buildings. Due to the lack of legal regulations, the fact that the floating structure is located on a private reservoir and is not permanently attached to the land, it was assumed that both property taxes are not imposed on the investor in this case.

A different situation affects solar farms permanently attached to the land. Therefore, the tax on land related to running a business, regardless of its classification in the Land and Property Register, amounts to PLN 0.89 (approx. EUR 0.2) per 1 m^2 of area per year. It is likely that the municipality cuts the tax locally or eliminates it when, for example, the land is used to generate emission-free energy. Interestingly, there are cases of investors organizing sheep grazing on solar farms, thanks to which a municipality office may then qualify the land as agricultural. As a result, an investor is exempt from land tax entirely.

Another element of uncertainty is the area of the total leased land qualified for land tax. It may be only a part of the land occupied by metal stands for supporting structures, it may be a part of the land directly covered with PV modules, or it may be the entire leased land. Land tax is a major source of income to local municipal budgets, and individual municipal authorities are responsible for its collection. Thus, tax land regarding PV farms often raises many doubts in Poland. This is why investors often apply for individual tax rulings to protect their interests.

It is assumed that the area declared for tax on land in this paper is 100% of its area in the maximum amount - PLN 0.89 / m^2 (approx. EUR 0.2/m^2).

As for the tax on buildings, not everything is legally regulated either. According to the decision of the Supreme Administrative Court in 2018, in a dispute with an investor, photovoltaic arrays do not constitute a structure by law. Therefore, it was assumed that, for the economic analysis, only the structural elements of ground-mounted farms and the costs of their assembly work in the amount of 2% of their net value would be subject to the tax on buildings.

8.5.3. LAND TENANCY

The floating photovoltaic farm was designed for a specific water reservoir - the upper reservoir of the pumped-storage power plant in Porąbka-Żar. The site of the power plant is a private property belonging to the power company PGE Energia Odnawialna S.A., which is the investor in this study, therefore no fees are provided for the lease of the land.

On the other hand, the operating costs of the ground-mounted solar farm include the land lease. This is the most common situation in photovoltaic business models in Poland. The leased land is land with low or very low soil quality, hence the rental price of the plot was estimated at PLN 15,000 (approx. EUR 3,350) per year.

8.5.4. INSURANCE

Insurance is important not only from the point of view of security of assets but also may prove necessary when applying for financing from any financial institution. Its cost was estimated at PLN 9,000 (approx. EUR 2,000) per year, considering the annual 5% decrease in the insurance policy price related to the declining value of assets.

The policy should include such items as protection against fire, vandalism, theft, loss of profit caused by random events, or civil liability during the implementation and operation of the investment. The units providing insurance for photovoltaic projects in Poland are, for example, Vienna Insurance Group AG, Warta S.A., or PZU S.A.

8.5.5. COMPANY MAINTENANCE / BOOKKEEPING

A company must be established for the purpose of billing. In this thesis, it will be a limited liability company whose sales revenues will not exceed EUR 2 million. Then it qualifies for the status of a "small taxpayer" and the effective income tax falls from the standard 19% to 9%.

There are certain costs associated with the activity of a company. It is required when running a limited liability company to submit financial statements annually. Along with the submission of the financial statements, the cost of full accounting is directly related, which entails another operational cost.

8.5.6. OTHER

Other operational costs included in the analysis are costs related to:

- control of the performance of a system,
- electric maintenance,
- security,
- equipment repair,
- land maintenance/cleaning

However, it is not known how quickly the floating structure will overgrow with algae, and how a significant obstacle bird dropping will be in keeping the photovoltaic modules clean. However, there is no problem with grass growing around the modules, so it is assumed that both values for a floating and ground-mounted system are identical.

It is also worth noting that the above-mentioned costs were indexed with the forecasted annual average consumer price index CPI (analogous to the increase in contracted auction prices).

Besides, operating costs also include elements depending on the amount of MWh generated - the cost being the broker's commission, and the cost of commercial balancing, i.e. reporting on the performance of the electricity sale agreement.

8.6. INVESTMENT FINANCING

The scale of investments in a photovoltaic farm with a capacity of up to 1 MWp is a large project. Investors usually use external sources of financing. Several banks are financing such projects in Poland, incl. Bank Gospodarstwa Krajowego S.A., Bank Ochrony Środowiska S.A., Pekao S.A., Millennium S.A., ING Bank Śląski S.A., EBOR S.A.

The set of documents necessary for a bank to finance investments in renewable energy sources includes the following items (among others):

- business investment plan,
- document confirming winning the auction (issued by the Energy Regulatory Office),
- farm productivity simulation,
- land lease agreement,
- documents enabling the assessment of the borrower's economic and financial standing,
- insurance policy for the project being implemented.

The common condition for receiving a loan is having an insurance policy that protects investments against several unforeseen events, such as fire or vandalism, as well as a civil liability during the implementation and operation of the investment.

Moreover, Bank Gospodarstwa Krajowego SA (BGK) offers from May 2019 a guarantee of repayment of the loan granted for an investment project of pro-ecological innovation, including a photovoltaic farm. The guarantee covers 80% of the loan value and the maximum guarantee amount is EUR 2.5 million. BGK helps investors to improve their credit history and obtain lower interests for a longer time.

Therefore, in the base model, it is assumed that a commercial loan will be drawn in the amount of 80% of the net investment costs, assuming that all the bank's requirements are met. The loan has an interest rate of 4.5% and a commission of 1%. Its repayment period is 15 years and is secured with a BGK guarantee. The remainder (20% of net CAPEX), VAT, credit commission (1%), and operating expenses are financed with equity or cash from inflows.

8.7. BASE MODEL INPUT PARAMETERS

Based on the key assumptions and cost statements the main input parameters of the base model are as follows:

Tbl. 9. Main input parameters of the base economic model

input parameter	unit	FPV	GMPV
capacity installed:	kWp	983.04	983.04
annual energy yield (1st year):	MWh	932.80	971.40
CAPEX:	EUR	759,631	589,761
operational costs:	EUR	64,915	59,086
residual:	%	13.38%	15.42%
residual value:	EUR	101,614	90,919
long-term loan:	EUR	607,704	471,809

The table (Tbl.9) contains the main economic data of both systems and the results of simulations carried out in PVsyst, determining the forecasted amount of energy sold, and thus the number of revenues. Only the installed capacity remains identical for both projects.

The difference in capital expenditure between the floating system and the ground-mounted system is mainly dictated by different support systems for photovoltaic modules. The expenditures incurred in the first year are higher by almost 50% than the expenditures incurred for the construction of the corresponding farm on land.

Then, a universal for both systems input data table was prepared (Tbl. 10) and broken down into its main categories, i.e. contracted auction prices, discount rate, loan conditions, the degree of declining module efficiency, or costs incurred when selling electric energy.

Tbl. 10. Input parameters of the base economic model

AUCTION		
auction price (variable):	327	PLN
	73.0	EUR
Market profile (TGEBASE bonus):	15	years
TGeBASE bonus price:	26	PLN
	5.8	EUR
DISCOUNT		
discount rate:	8.0%	
FINANCING		
investment loan:	15	years
investor's equity:	20%	of CAPEX net
working capital (financial reserve):	10,000	EUR
interest rate (annually):	4.5%	
commision (total)	1%	
income tax:	9%	
PLN-EUR exchange	4.48	
YIELD		
1st modules efficiency drop	0.87%	
2nd modules efficiency drop	0.77%	
self-consumption	0.50%	
OPERATIONAL COSTS		
trade balancing:	3.5	PLN/MWh
	0.78	EUR/MWh
broker commision:	1.5	PLN/MWh
	0.33	EUR/MWh
inverters exchange after:	12	years

8.8. RESULTS

8.8.1. FINANCIAL STATEMENT AND INDICATORS

The following economic model consists of three integral elements of a financial statement:

- profit and loss account,
- balance of assets and liabilities,
- cash flow statement.

On the other hand, the profitability of the project is measured by 2 indicators used in this type of investment: NPV and IRR. NPV (Net Present Value) applies to a series of cash flows throughout the investment project. There is a difference between a value of the same amount of money at the point of the investment decision and later [48]. Thus, NPV is the sum of the discounted net cash flow over the entire life cycle of the investment (investment, operational, and decommissioning process). If the net present value is positive, the project is considered viable. Otherwise, it is considered financially unfeasible.

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t} \tag{17}$$

where,

NPV – net present value

NCF – net cash flows in a single period t

r – discount rate

t – number of periods

Net cash flows (NCF) of each year were calculated as follows. In year zero, cash reflects the investor's contribution only. In years 1 to 15, net cash flows consist of three elements: cash flows from operating activities, net cash flow from operating activities, and net cash in financing activities (appendix A.3)

Cash flows from operating activities consist of *net profit/loss* derived from the model's Profit & Loss Account. However, it does not represent the physical amount of cash in an investor's hand. The Profit & Loss Account considers depreciation and is used to calculate income after paying income tax. In the first years of investment, it is equal zero - operating costs and depreciation incurred exceed revenues in both cases. To obtain cash flows from operating activities, depreciation of assets should be excluded from the *net profit/loss*. Receivables, stock, and liabilities should also be included here (in case of the project – they are all zero).

Net cash from operating activities, in turn, are investment expenses incurred at the beginning of the project and during its duration (e.g. replacement of inverters), as well as VAT refund, which is not applicable here. It is assumed that VAT is fully refunded, thus the analysis is based on net values only.

The last element of the cash flow statement is net cash in financing activities. It is simply revenue from a long-term loan and payment of its installments in the following years.

Net cash flow for the year 15 is additionally enlarged by the residual value of the investment.

The internal rate of return (IRR) is a discount rate that makes the net present value (NPV) of total cash flows equal to zero in a discounted cash flow analysis. IRR calculations rely on the same formula as NPV.

8.8.2. MODEL OUTCOMES – AVERAGE AUCTION PRICE

Based on the above indicators and the data contained in the base input parameters, the first conclusions can be drawn. Assuming an auction price to be 67 EUR/MWh, which is a mid-point price of the last auction held in Poland (as of 07/07/2020), the floating PV project is able to exceed the investor's equity with cumulative cash flows within 15 years of the analysis (Fig. 36). However, in the first years of the system operation, the installments of the 15-year long loan alone exceed the revenues from the sale of energy and the bonus of the market profile. Consequently, the cumulative cash flow is negative, and therefore it is not possible for the investor to cover the annual operating expenses.

General information

Auction price:	67 EUR/MWh
Capacity installed:	983.04 kWp
Annual energy yield:	932.8 MWh
CAPEX:	759,631 EUR
Operational costs:	64,915 EUR
Residual value:	101,614 EUR
Long term loan:	607,704 EUR

Financial indicators

Project NPV:	- 45,888
NPVR:	-0.28
IRR:	4.81%

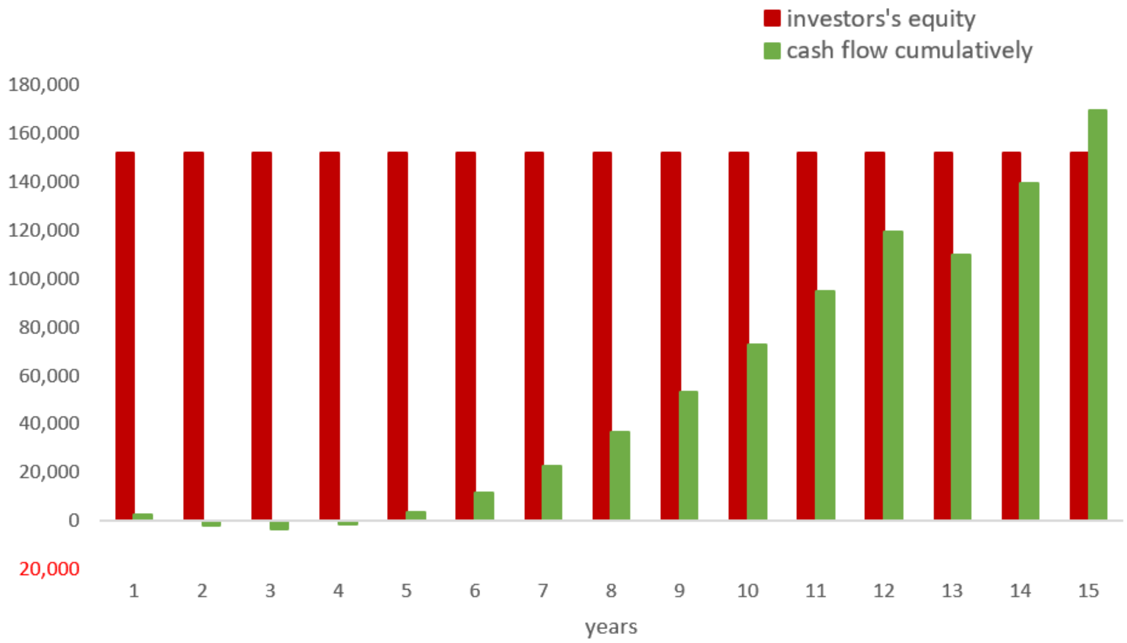

Fig. 35. Analysis outcomes (67 EUR/MWh) combined with cash flow/investor's equity graph (FPV)

The poor economic performance of the project is reflected in the indicators. The NPV indicator is negative at the level of approx. 46,000 reflecting the project as not feasible. The IRR indicator showed a low value, which can be defined in this way: the project could be profitable if an investor would expect the discount rate to be 4.81% or less, which is not happening in reality.

The situation is different for a ground-mounted farm (Fig. 37). The values of the indicators can be considered satisfactory. At an 8% discount rate, the NPV is over 50,000, while the IRR is close to 12.5%. Year-on-year cash flows are positive. Cumulative cash inflow exceeds investor's equity in year 9th.

General information		
Auction price:	67	EUR/MWh
Capacity installed:	983.04	kWp
Annual energy yield:	971.4	MWh
CAPEX:	589,761	EUR
Operational costs:	59,086	EUR
Residual value:	90,919	EUR
Long term loan:	471,809	EUR

Financial indicators	
Project NPV:	50,012
NPVR:	0.41
IRR:	12.39%

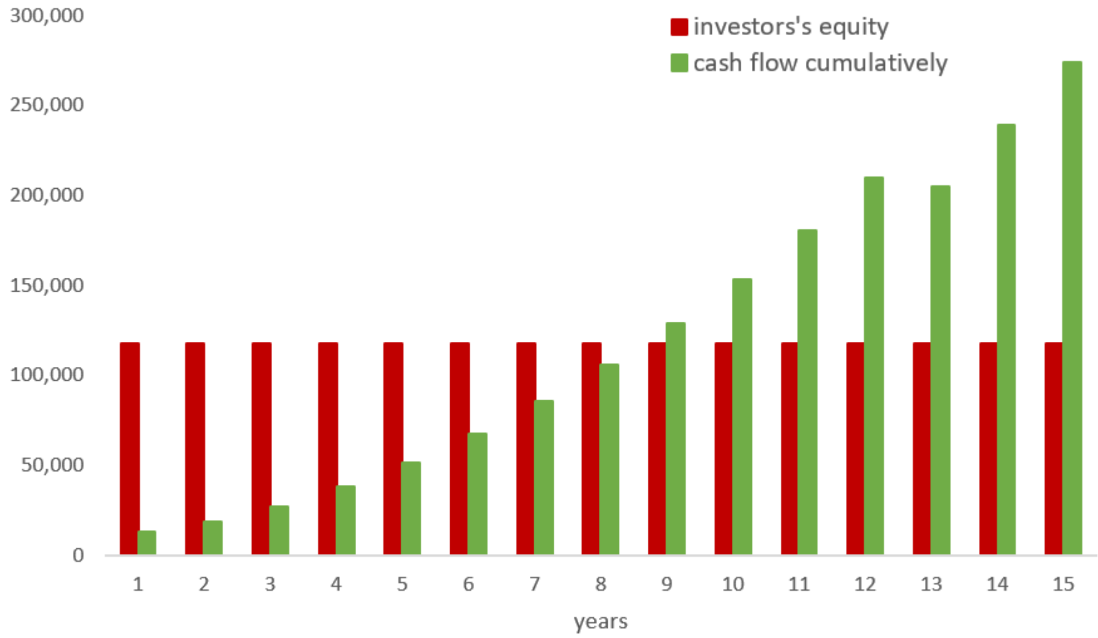

Fig. 36. Analysis outcomes (67 EUR/MWh) combined with cash flow/investor's equity graph (GMPV)

8.8.3. MODEL OUTCOMES – MAXIMUM AND MINIMUM AUCTION PRICE

As stated in the assumptions of the economic analysis, the financial performance of the systems designed is verified by auction prices of the last held auction in Poland. The minimum obtained value is 269 PLN/MWh (60 EUR/MWh), while the maximum is 327 EUR/MWh (73 EUR/MWh).

The minimum price does not bring satisfactory results for both projects. The NPV indicator is highly negative for a floating system, reaching over 104,000 (Fig. 38). Cash flow throughout 10 first years of the operation would not make It possible for an investor to cover expenditures. There is no such point during the lifetime of the analysis, that the investor's equity is paid back.

The ground-mounted project is reaching a break-even point, however, it is achieved at the end of the 15-year-long analysis, which may be perceived as not economically viable (Fig. 39).

Auction price:	60 EUR/MWh	*Project NPV:*	- 104,228
Annual energy yield:	932.8 MWh	*NPVR:*	-0.53
CAPEX:	759,631 EUR	*IRR:*	0.65%
Operational costs:	64,915 EUR		

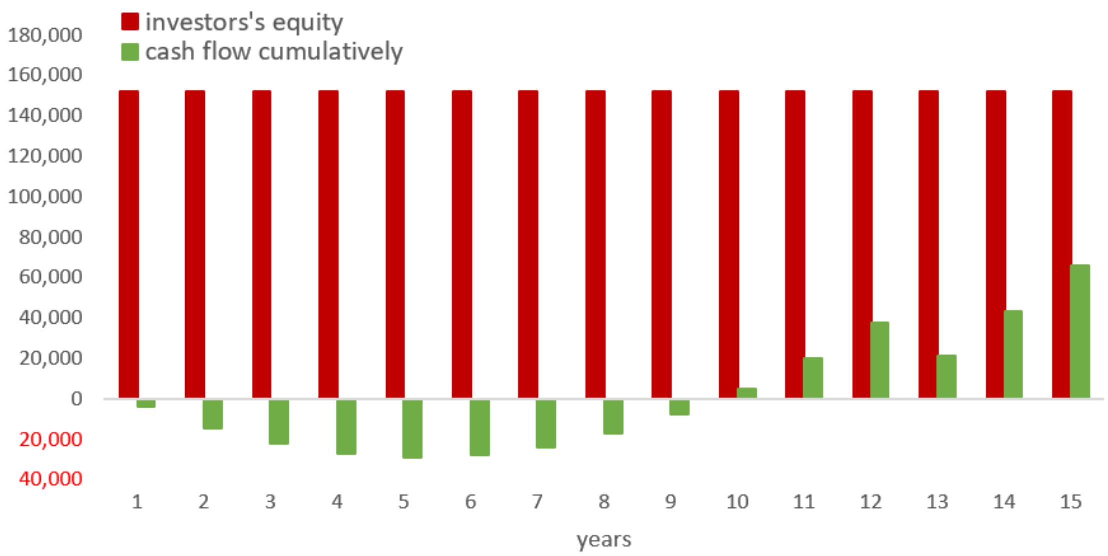

Fig. 37. Analysis outcomes (60 EUR/MWh) combined with cash flow/investor's equity graph (FPV)

Auction price:	60 EUR/MWh	*Project NPV:*	- 9,090
Annual energy yield:	971.4 MWh	*NPVR:*	-0.07
CAPEX:	589,761 EUR	*IRR:*	7.20%
Operational costs:	59,086 EUR		

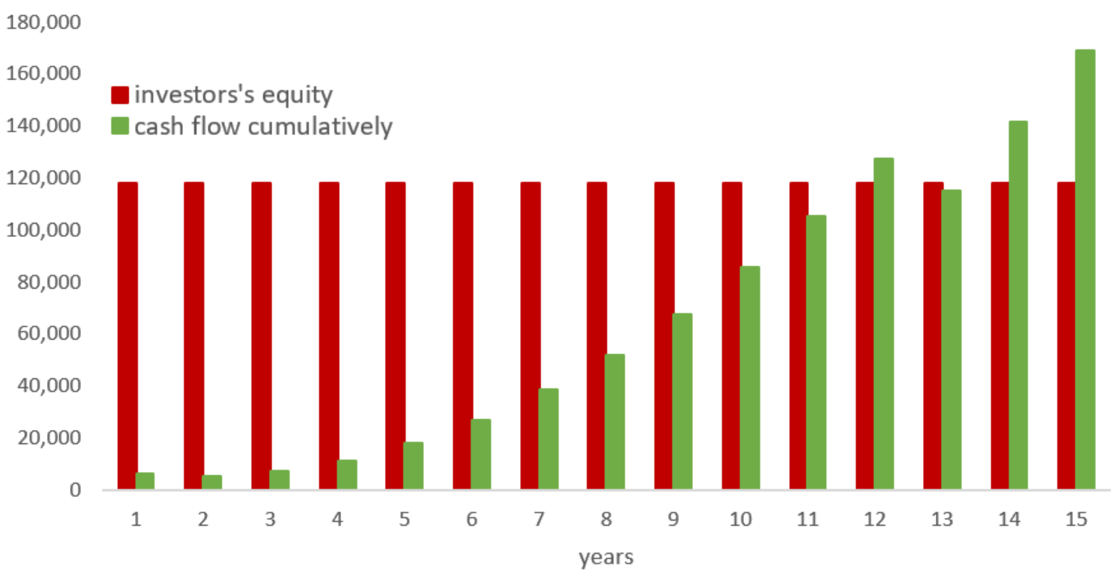

Fig. 38. Analysis outcomes (60 EUR/MWh) combined with cash flow/investor's equity graph (GMPV)

Better results may be seen for the highest obtained auction price (as of 07/07/2020) – 327 PLN/MWh (73 EUR/MWh).

Auction price:	73 EUR/MWh		*Project NPV:*	11,641
Annual energy yield:	932.8 MWh		*NPVR:*	0.08
CAPEX:	759,631 EUR		*IRR:*	8.80%
Operational costs:	64,915 EUR			

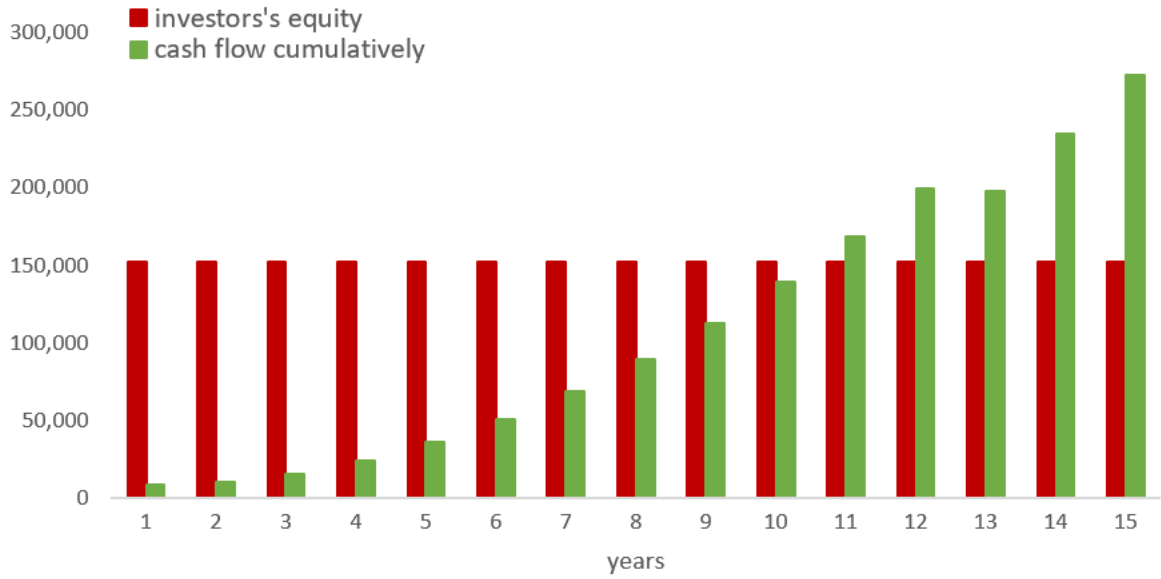

Fig. 39. Analysis outcomes (73 EUR/MWh) combined with cash flow/investor's equity graph (FPV)

Finally, positive NPV indicator values may be witnessed. The break-even point is achieved in the 11th year of operation for the FPV project (Fig .40). According to the analysis, it was not feasible before for an investor to cover operational expenditures during the first years. Installments were too high compared to the incomes.

On the other hand, a ground-mounted system performs even better reaching the NPV indicator equals 108,000 (Fig. 41).

Auction price:	73 EUR/MWh	*Project NPV:*	107,892
Annual energy yield:	971.4 MWh	*NPVR:*	0.91
CAPEX:	589,761 EUR	*IRR:*	17.43%
Operational costs:	59,086 EUR		

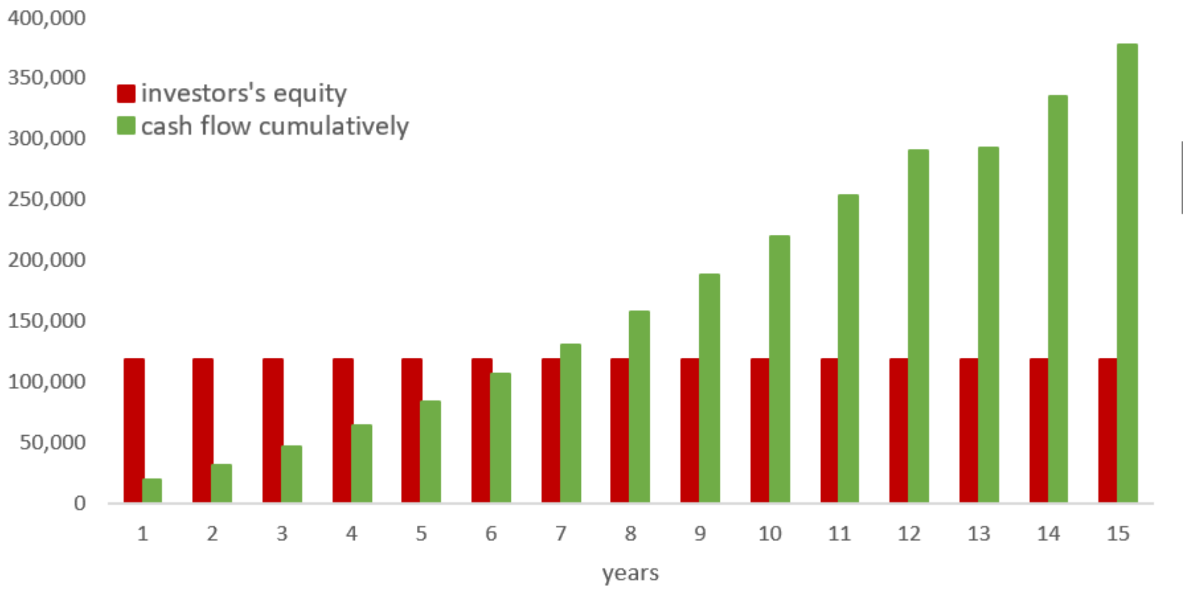

Fig. 40. Analysis outcomes (73 EUR/MWh) combined with cash flow/investor's equity graph (GMPV)

8.9. SENSITIVITY ANALYSIS

Due to the unsatisfactory outcomes of the economic analysis for the floating system, it was decided to conduct a sensitivity analysis for two variables: the auction price and the share of the investor's equity in CAPEX. Following the initial assumptions, the range of auction prices is limited to the prices obtained in the last auction held in Poland (as of 07/07/2020). It was decided to keep the discount rate at the same level - 8%. The indicator representing a given version of the project in the sensitivity analysis is the NPV indicator, thus making it possible to compare.Fig. 42 and Fig. 43 show the results of the sensitivity analysis for FPV and GMPV. The colors green and red, as well as their increasing intensity, indicate the direction in which the NPV becomes more favorable and less favorable, respectively (from the investor's point of view). Red numbers represent NPV values less than zero and therefore unprofitable.

According to the forecast and economic analysis, not every possible scenario of the auction price and the share of equity in the floating project would result in a financial loss. The NPV ratio is most favorable for the investor's equity equals 0%, 10%, or 20%, and obviously, for the highest auction prices - above 310 PLN/MWh (69 EUR/MWh). The best possible scenario, which is rather not feasible, due to the zero equity share, is described by the NPV indicator 41,029. The lowest auction price combined with no loan granted brings a worse result – NPV equals 221,345 negative.

A different set of NPV indicators comes from the ground-mounted farm sensitive analysis. It is possible to draw a straight line between the point characterized by the auction price 269 PLN/MWh (EUR 60 EUR/MWh) and the investor's 0% share of equity, and the point with the second-highest possible auction price combined with 100% equity. Therefore, almost all values on the left are positive, and thus considering the project as profitable. All values to the right – the project is considered unattractive. As in FPV, the highest NPV was achieved with zero equity and the highest auction price - over 131,000. The lowest, but still positive, NPV value was obtained for the 40% investor contribution and the auction price at the level of 285 PLN /MWh (64 EUR/MWh).

FPV	investor's equity, %										
auction price, PLN	0	10	20	30	40	50	60	70	80	90	100
269	75,449	89,839	104,228	118,617	133,025	147,471	161,972	176,544	191,225	206,118	221,345
270	73,427	87,816	102,205	116,594	131,013	145,459	159,972	174,555	189,258	204,170	219,443
275	63,315	77,704	92,093	106,508	120,954	135,452	150,007	164,657	179,448	194,492	209,946
280	53,202	67,592	82,003	96,449	110,932	125,458	140,065	154,794	169,696	184,875	200,533
285	43,090	57,498	71,944	86,412	100,930	115,516	130,186	144,984	159,989	175,317	191,127
290	32,993	47,439	61,891	76,409	90,968	105,594	120,330	135,222	150,326	165,820	181,720
295	22,934	37,380	51,889	66,419	81,026	95,716	110,520	125,486	140,739	156,392	172,313
300	12,875	27,369	41,887	56,477	71,124	85,866	100,748	115,823	131,191	146,986	162,906
305	2,849	17,367	31,928	46,535	61,245	76,055	91,009	106,185	121,694	137,579	153,500
310	7,153	7,380	21,987	36,653	51,401	66,274	81,320	96,603	112,251	128,172	144,093
315	17,155	2,562	12,061	26,775	41,591	56,535	71,658	87,065	102,845	118,765	134,686
320	27,111	12,504	2,183	16,937	31,799	46,817	62,050	77,568	93,438	109,359	125,279
325	37,052	22,410	7,695	7,127	22,061	37,155	52,468	68,110	84,031	99,952	115,873
327	41,029	26,361	11,641	3,203	18,166	33,290	48,637	64,348	80,268	96,189	112,110

Fig. 41. Sensitive analysis for FPV (variables: auction price, investor's equity share)

GMPV	investor's equity, %										
auction price, PLN	0	10	20	30	40	50	60	70	80	90	100
269	13,645	2,305	9,090	20,535	32,063	43,708	55,516	67,539	79,827	92,187	104,548
270	15,716	4,376	7,032	18,492	30,035	41,696	53,520	65,560	77,867	90,228	102,588
275	26,070	14,680	3,250	8,274	19,892	31,632	43,540	55,710	68,070	80,431	92,791
280	36,392	24,968	13,467	1,894	9,785	21,612	33,639	45,912	58,273	70,633	82,994
285	46,680	35,209	23,680	12,037	279	11,633	23,755	36,115	48,476	60,836	73,197
290	56,951	45,427	33,823	22,126	10,295	1,718	13,958	26,318	38,679	51,039	63,400
295	67,169	55,609	43,966	32,190	20,275	8,173	4,160	16,521	28,881	41,242	53,602
300	77,386	65,752	54,037	42,203	30,203	17,997	5,637	6,724	19,084	31,445	43,805
305	87,538	75,884	64,101	52,182	40,094	27,794	15,434	3,073	9,287	21,648	34,008
310	97,681	85,948	74,110	62,124	49,952	37,592	25,231	12,871	510	11,850	24,211
315	107,795	96,011	84,090	72,015	59,749	47,389	35,028	22,668	10,307	2,053	14,414
320	117,859	106,018	94,045	81,906	69,547	57,186	44,825	32,465	20,104	7,744	4,617
325	127,922	115,998	103,936	91,704	79,344	66,983	54,623	42,262	29,902	17,541	5,181
327	131,938	119,989	107,892	95,623	83,263	70,902	58,542	46,181	33,820	21,460	9,099

Fig. 42. Sensitive analysis for GMPV (variables: auction price, investor's equity share)

9. Comparison

The advantage of this master's thesis is its comprehensiveness. The comparison of floating and ground-mounted photovoltaic technologies concern design, performance, execution, and economic aspects. Thanks to this, it can be quite accurately assessed whether the floating technology entering the European market has a chance for rapid development.

DESIGN AND PERFORMANCE ASPECTS

The first conclusion concerns the intensified heat transfer between modules and water. The performance analysis shows that in Polish climatic conditions, the use of a floating structure brings only a 0.9% gain in energy yield comparing to a ground-mounted structure temperature gain. This is little compared to the results of scientific studies, where the increase in yield can even reach 20%. Floating systems are likely to perform better at latitudes closer to the equator, where high temperature degrades the module efficiency more.

It was also noticed that the tilt of modules and the distance between rows are much more important for both designed systems. Floating structures available on the market and their fixed-tilt are more adapted to the lower latitudes. In the equatorial regions, the inclination angles of modules of photovoltaic farms are comparable to the floating systems. Therefore, both systems can be assessed in almost identical configurations. In the case of this study, the module tilt angle in the floating system was significantly different from the optimal one. Potentially increased energy yields (increased heat transfer) are leveled by a non-optimally selected tilt. Maybe soon floating systems will be better adjusted to the latitudes of countries like Poland.

Unless it is about something completely different than maximizing energy yields or a shortening period of return on investment, e.g. improve water retention by limiting the evaporation of reservoirs. However, this requires careful research and confirmation in scientific publications. Thus, the financial aspects may not always be a major concern.

The study did not consider the higher risk associated with faster degradation of components, although the careful selection process with the appropriate certificates verification certainly minimized it. There is insufficient scientific evidence on how high humidity and a corrosive environment affect the long-term operation of a PV system.

On the other hand, inverters (or one central inverter) located next to modules on a floating platform could bring more profit. Such practices are used, however, protecting sensitive devices such as inverters from excessive moisture or even complete flooding would be another engineering challenge, and thus an additional risk of failure. In the case of the designed project, DC cables are routed from modules to the shore.

The result of the performance analysis is 932.8 MWh for the FPV system and 971.4 MWh for the GMPV system (first year).

EXECUTIVE ASPECTS

The challenge for the project implementation on the selected reservoir is also that the water is drained once a year. The structure lying at the bottom of the tank may make maintenance (cleaning and repair) impossible.

Another problem is the lack of legal mechanisms in Poland for this type of floating systems. The decisions of the authorities regarding the issuing of decisions on environmental conditions and building permits are unknown.

Banks require several documents, including system simulation results, hence several difficulties at the stage of obtaining external financing may occur. The connection conditions, in turn, should not pose a challenge.

ECONOMIC ASPECTS

Under market conditions, the FPV system has little chance of winning an auction with the GMPV system due to significantly higher CAPEX. Even if it happens, positive financial results may be obtained only with high auction prices over 300 PLN/MWh. However, the trend of auction prices continues to decline, so it will be more and more difficult to obtain the price that will allow satisfactory results.

There is a great chance for the development of FPV with PPA (Power Purchase Agreement) projects in places where it is not possible to install a ground system.

According to the economic analysis, the estimated CAPEX is approximately EUR 760,000 for the floating project and EUR 590,000 for the conventional system.

10. Conclusions

The master's thesis was divided into three main stages. The first and most extensive stage is the technical design of a floating solar farm. In the second and third stages, the system was analyzed, successively in terms of performance and then the economy. To better understand solar floating technology, it was decided to conduct a performance and economic analysis also for a comparable system installed on the ground. Such a procedure allowed to create a reference point for a comparative analysis of both technologies.

The results of the analysis of the floating system were not satisfactory from the investor's point of view. According to the analysis, the assurances of a large increase in energy yields caused by intensified heat transfer proved to be exaggerated. Floating systems were noticed to be of greater benefit in zones closer to the equator.

It is predicted that this technology needs to enter the next phase of maturity to find application in higher latitudes (e.g. Poland). Perhaps the stimulus for the development of floating technologies will simply be the lack of available space for conventional PV systems. For now, however, high CAPEX makes it difficult to maintain the liquidity of the project and extends the return on investment by several years. Many unknowns also appeared at the stage of formalities related to the administrative procedure for submitting such projects. The study analyzed the roadmap for reporting large photovoltaic projects to the local authorities.

Nevertheless, the photovoltaic market in Europe is relatively young and is undergoing very dynamic changes. New European regulations or local financial incentives (e.g. fixed prices for floating PV) may arise. The energy policy of the European Union shows that it is only a matter of time.

In the process of creating this master's thesis, several ideas for further research also appeared. The water-cooling systems in floating PV require a deeper study. There is also potential in the uniaxial tracking systems for floating PV.

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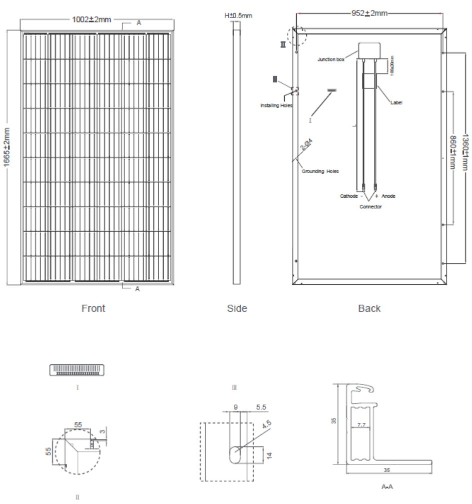
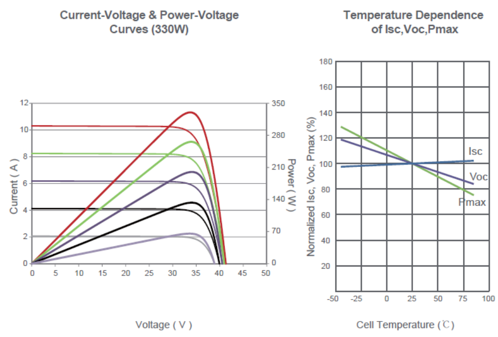
Appendices

A.1 FULL CHARACTERISTICS OF THE SELECTED COMPONENTS

Engineering Drawings



Electrical Performance & Temperature Dependence



Packaging Configuration

(Two pallets = One stack)

30pcs/pallet , 60pcs/stack, 840pcs/40'HQ Container

Mechanical Characteristics

Cell Type	Mono PERC 158.75×158.75mm
No.of cells	60 (6×10)
Dimensions	1665×1002×35mm (65.55×39.45×1.38 inch)
Weight	19.0 kg (41.9 lbs)
Front Glass	3.2mm, Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length 900mm or Customized Length
Connector	JK03M; Jinko PV Material

SPECIFICATIONS

Module Type	JKM310M-60-V		JKM315M-60-V		JKM320M-60-V		JKM325M-60-V		JKM330M-60-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	310Wp	231Wp	315Wp	235Wp	320Wp	239Wp	325Wp	242Wp	330Wp	246Wp
Maximum Power Voltage (Vmp)	33.0V	31.0V	33.2V	31.2V	33.4V	31.4V	33.6V	31.6V	33.8V	31.8V
Maximum Power Current (Imp)	9.40A	7.49A	9.49A	7.56A	9.59A	7.62A	9.68A	7.66A	9.77A	7.74A
Open-circuit Voltage (Voc)	40.5V	37.4V	40.7V	37.6V	40.9V	37.8V	41.1V	38.0V	41.3V	38.2V
Short-circuit Current (Isc)	10.15A	8.20A	10.23A	8.33A	10.31A	8.44A	10.50A	8.54A	10.61A	8.65A
Module Efficiency STC (%)	18.58%		18.88%		19.18%		19.48%		19.78%	
Operating Temperature (℃)	-40℃~+85℃									
Maximum System Voltage	1500VDC (IEC)									
Maximum Series Fuse Rating	20A									
Power Tolerance	0~+3%									
Temperature Coefficients of Pmax	-0.37%/℃									
Temperature Coefficients of Voc	-0.28%/℃									
Temperature Coefficients of Isc	0.048%/℃									
Nominal Operating Cell Temperature (NOCT)	45±2℃									

STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

Fig. 43. JinkoSolar JKM320M-60-V datasheet

SUN2000-105KTL-H1

Technical Specifications

Efficiency	
Max. Efficiency	99.0%
European Efficiency	98.8%
Input	
Max. Input Voltage	1,500 V
Max. Current per MPPT	25 A
Max. Short Circuit Current per MPPT	33 A
Start Voltage	650 V
MPPT Operating Voltage Range	600 V ~ 1,500 V
Rated Input Voltage	1,080 V
Number of Inputs	12
Number of MPP Trackers	6
Output	
Rated AC Active Power	105,000 W @40°C
Max. AC Apparent Power	116,000 VA @25°C
Max. AC Active Power (cosϕ=1)	116,000 W @25°C
Rated Output Voltage	800 V, 3W + PE
Rated AC Grid Frequency	50 Hz / 60 Hz
Rated Output Current	75.8 A
Max. Output Current	84.6 A
Adjustable Power Factor Range	0.8 LG ... 0.8 LD
Max. Total Harmonic Distortion	< 3%
Protection	
Input-side Disconnection Device	Yes
Anti-islanding Protection	Yes
AC Overcurrent Protection	Yes
DC Reverse-polarity Protection	Yes
PV-array String Fault Monitoring	Yes
DC Surge Arrester	Type II
AC Surge Arrester	Type II
DC Insulation Resistance Detection	Yes
Residual Current Monitoring Unit	Yes
Communication	
Display	LED Indicators, Bluetooth/WLAN + APP
USB	Yes
RS485	Yes
MBUS	Yes
General	
Dimensions (W x H x D)	1,075 x 605 x 310 mm (42.3 x 23.8 x 12.2 inch)
Weight (with mounting plate)	79 kg (174.2 lb.)
Operating Temperature Range	-25°C ~ 60°C (-13°F ~ 140°F)
Cooling Method	Natural Convection
Max. Operating Altitude	4,000 m (13,123 ft.)
Relative Humidity	0 ~ 100%
DC Connector	Amphenol UTX
AC Connector	Waterproof PG Connector + OT/DT Terminal
Protection Degree	IP65
Topology	Transformerless
Standard Compliance (more available upon request)	
Certificate	EN 62109-1/-2, IEC 62109-1/-2, IEC 62116, EN 50530, IEC 60068, IEC 61683, IEC 61727, UTE C15-712-1, RD 413, RD 1699, RD 661, RD 1565, P.O. 12.3, UNE 206007-1 IN, UNE 206006 IN, G59/3, CEI 0-16,VDE4120

Fig. 44. Huawei SUN2000-105KTL-H1 datasheet

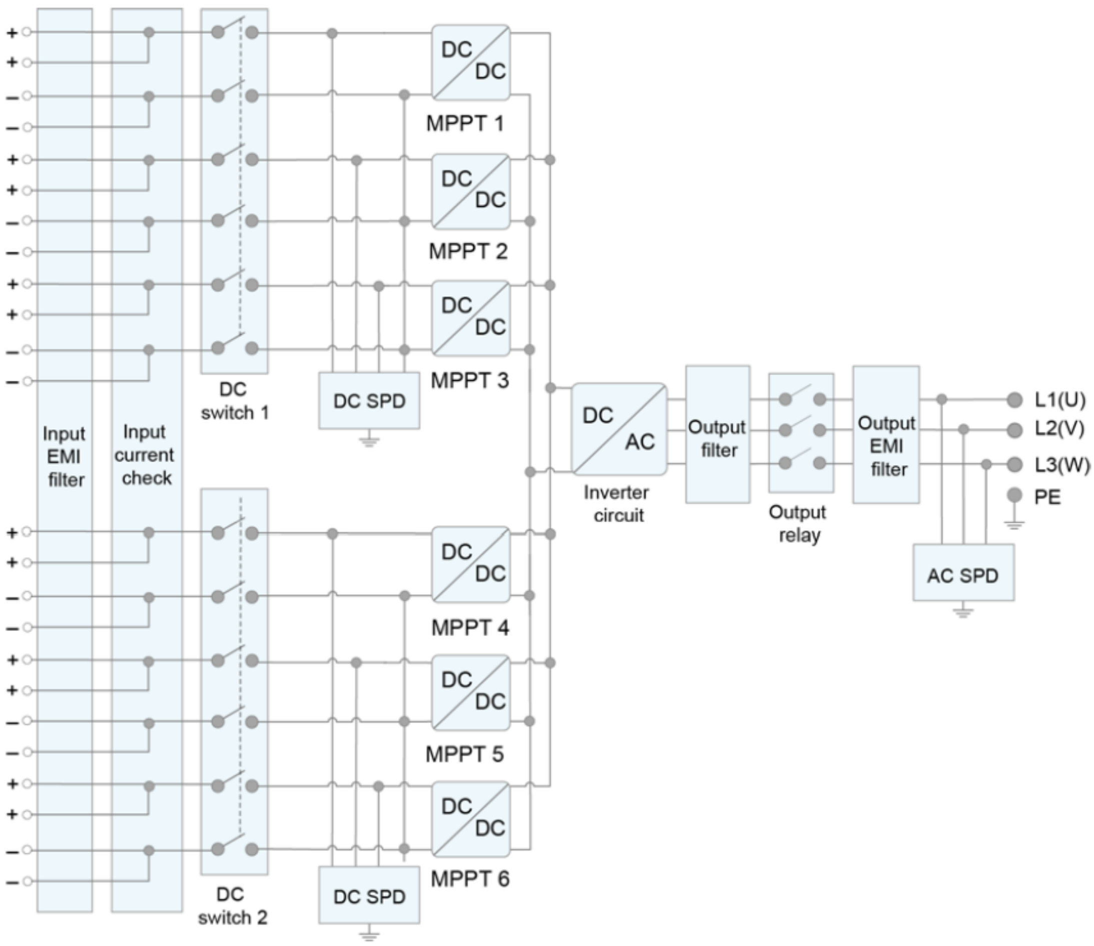
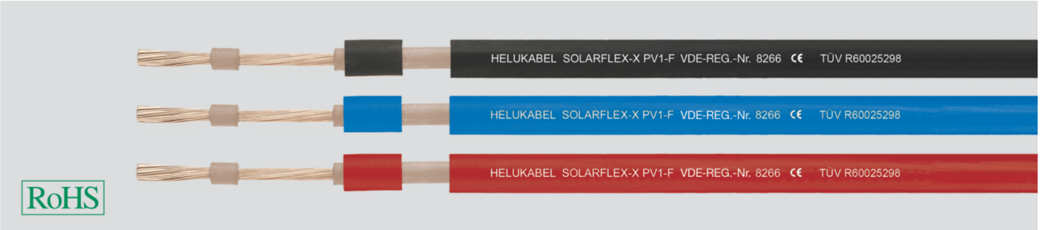


Fig. 45. Conceptual Huawei SUN2000-105KTL-H1 diagram

SOLARFLEX®-X PV1-F



Technical data

- **Temperature range**
  -40°C to +90°C
  max. temperature at conductor +120°C
- **Short circuit temperature**
  200°C (short circuit duration up to 5 s)
- **Nominal voltage**
  VDE 600/1000 V AC
  1800 V DC conductor/conductor
- **AC test voltage**
  10000 V
- **Minimum bending radius**
  flexing 10x cable Ø
  fixed installation 4x cable Ø
- **Highest permissible Voltage**
  - DC:
    Conductor/Conductor 1,8 kV
    Conductor/Earth 0,9 kV
  - AC: Conductor/Earth 0,7 kV
  - Three phase: Conductor/Conductor 1,2 kV

Cable structure

- Tinned copper-conductor, to DIN VDE 0295 cl.5, fine-wire, IEC 60228 cl.5
- Core insulation of cross-linked Polyolefin
- Core identification white
- Outer sheath of cross-linked Polyolefin
- Sheath colour see table below
- with meter marking

Properties

- Double-insulated
- Ozone resistant acc. to EN 50396
- Weather und UV resistant acc. to HD 605/A1
- Halogen-free acc. to DIN EN 50267-2-1, EN 60684-2
- Resistant to acid and bases acc. to EN 60811-2-1
- Flame retardant to DIN VDE 0482-332-1-2, DIN EN 60332-1-2/ IEC 60332-1 (equivalent DIN VDE 0472 part 804 test method B)
- Very robust and abraison-resistant sheath acc. to DIN EN 53516
- Anticipated service life: 25 year
- Hydrolysis and ammoniac resistant

Approvals

- According to PV1-F requirement profile for PV cable DKE / VDE AK 411.2.3
- VDE (Reg. 8266)
- TÜV (2 PfG 1169 / 08.2007, R60025298)
- UL certification in progress (UL Subject 4703)

Note

- Not for direct installation in ground
- Version with rodent protection available: SOLARFLEX®-X PV1-F NTS

Application

The SOLARFLEX®-X PV1-F is used for cabling solar modules.
CE= The product is conformed with the EC Low-Voltage Directive 2006/95/EC.

Part no.	No.cores x cross-sec. mm²	Sheath colour	Outer Ø app. mm	Cop. weight kg / km	Weight app. kg / km	AWG-No.
704225	1 x 2,5	black	4,5	24,0	42,0	14
705892	1 x 2,5	blue	4,5	24,0	42,0	14
705891	1 x 2,5	red	4,5	24,0	42,0	14
704226	1 x 4	black	5,2	38,4	60,0	12
705776	1 x 4	blue	5,2	38,4	60,0	12
705775	1 x 4	red	5,2	38,4	60,0	12
704227	1 x 6	black	5,9	57,6	82,0	10
705778	1 x 6	blue	5,9	57,6	82,0	10
705777	1 x 6	red	5,9	57,6	82,0	10
704228	1 x 10	black	6,9	96,0	123,0	8
705894	1 x 10	blue	6,9	96,0	123,0	8
705893	1 x 10	red	6,9	96,0	123,0	8
704229	1 x 16	black	8,3	153,6	190,0	6
706840	1 x 16	blue	8,3	153,6	190,0	6
706839	1 x 16	red	8,3	153,6	190,0	6
704230	1 x 25	black	10,0	240,0	285,0	4
704231	1 x 35	black	11,0	336,0	376,0	2
704232	1 x 50	black	13,0	480,0	530,0	1
704233	1 x 70	black	15,3	672,0	745,0	2/0
704234	1 x 95	black	17,0	912,0	960,0	3/0
705738	1 x 120	black	19,1	1152,0	1220,0	4/0
705739	1 x 150	black	22,7	1440,0	1550,0	300 kcmil
706288	1 x 185	black	25,5	1776,0	1930,0	350 kcmil
706289	1 x 240	black	28,3	2304,0	2550,0	500 kcmil

Dimensions and specifications may be changed without prior notice.

HELUKABEL®

Fig. 46. Helukabel Solarflex-X PV1-F datasheet

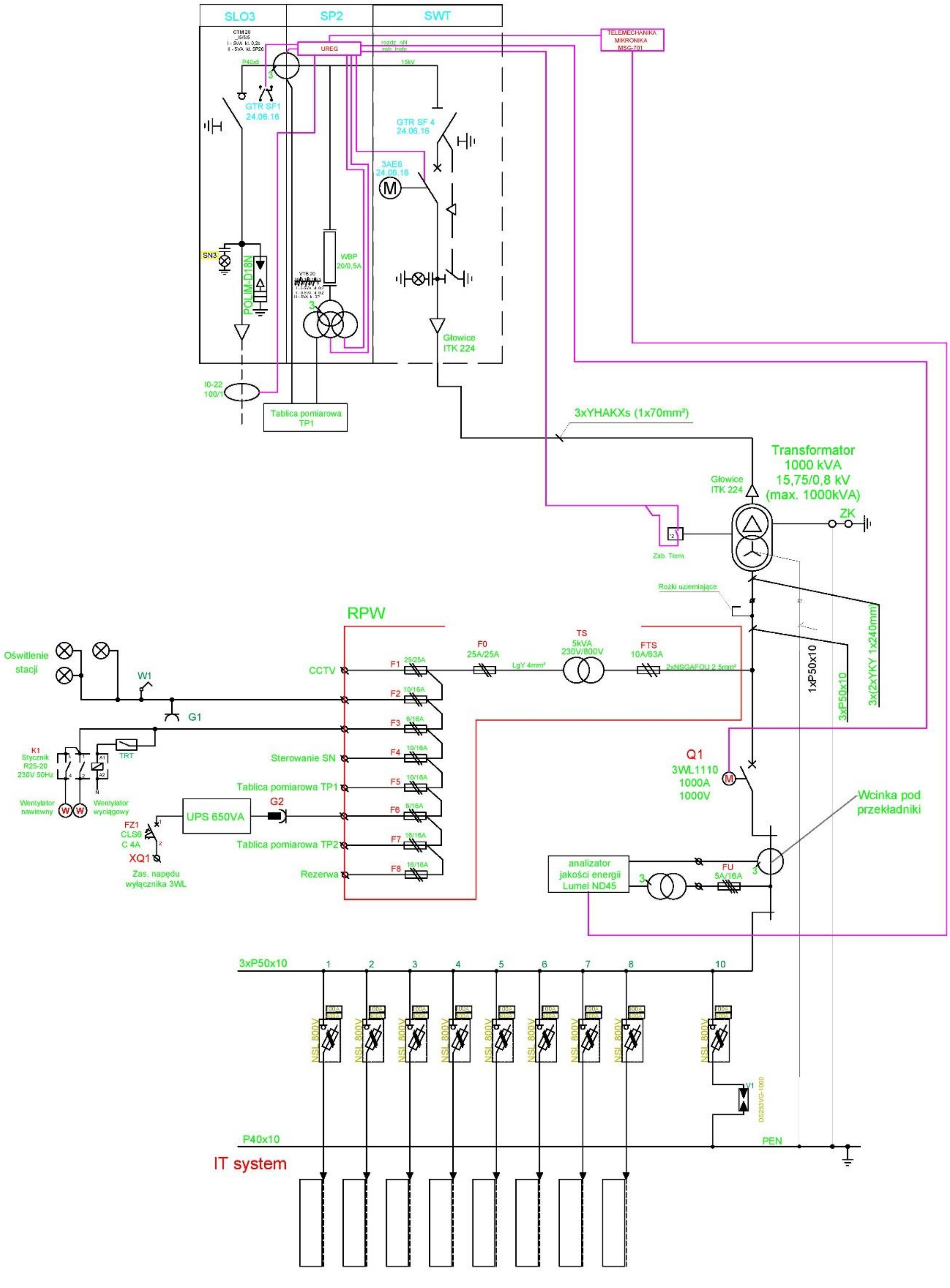
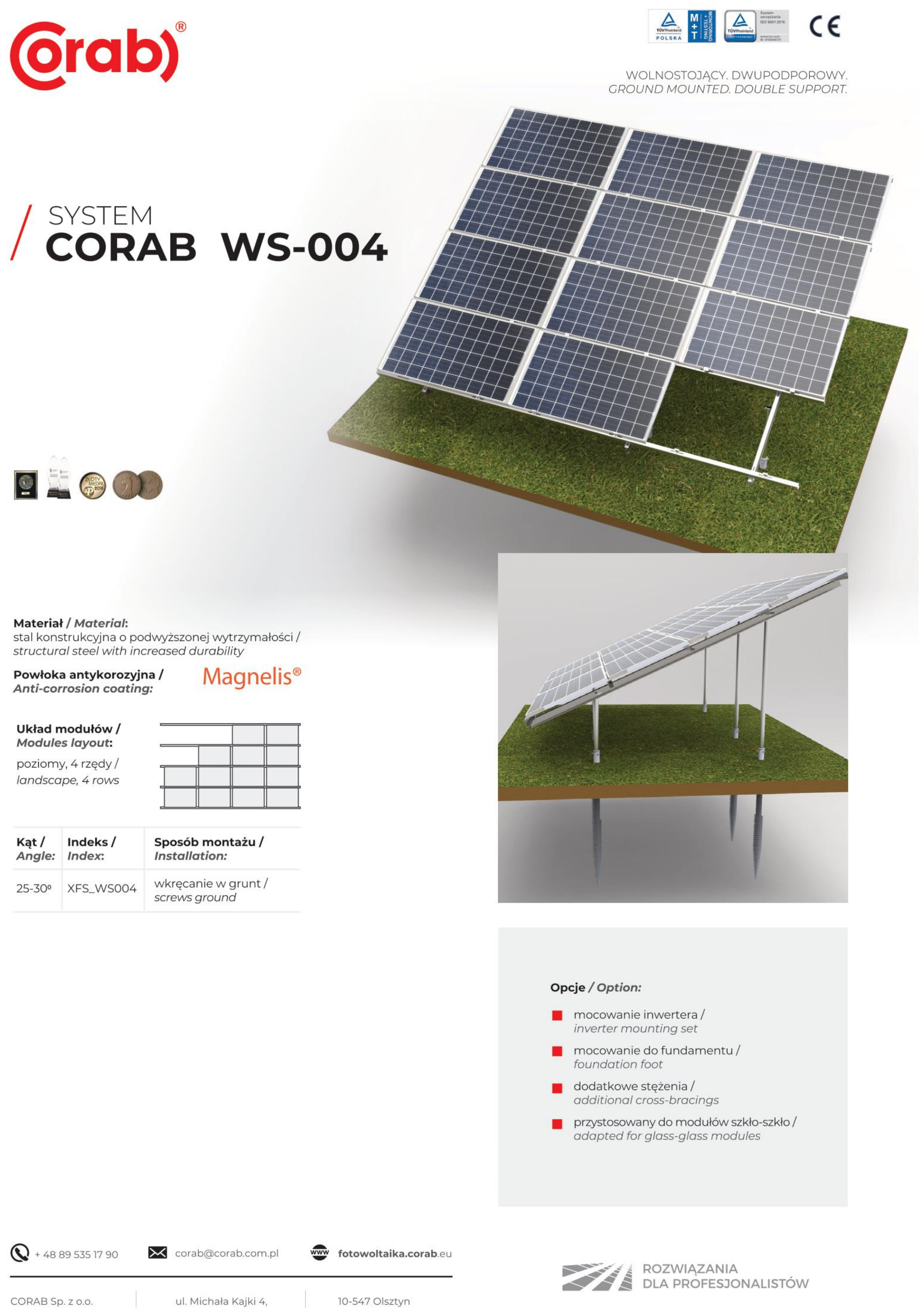


Fig. 47. Detailed wiring diagram of the transformer station (own elaboration based on ZPUE MRw-bpp)



WOLNOSTOJĄCY. DWUPODPOROWY.
GROUND MOUNTED. DOUBLE SUPPORT.

SYSTEM
CORAB WS-004

Materiał / ***Material*:**
stal konstrukcyjna o podwyższonej wytrzymałości /
structural steel with increased durability

Powłoka antykorozyjna / ***Anti-corrosion coating:*** Magnelis®

Układ modułów / ***Modules layout*:**
poziomy, 4 rzędy /
landscape, 4 rows

Kąt / ***Angle:***	**Indeks /** ***Index:***	**Sposób montażu /** ***Installation:***
25-30º	XFS_WS004	wkręcanie w grunt / *screws ground*

Opcje / ***Option:***

- mocowanie inwertera / *inverter mounting set*
- mocowanie do fundamentu / *foundation foot*
- dodatkowe stężenia / *additional cross-bracings*
- przystosowany do modułów szkło-szkło / *adapted for glass-glass modules*

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ROZWIĄZANIA DLA PROFESJONALISTÓW

Fig. 48. GMPV Corab WS-004 system datasheet

A.2 PVSYST REPORTS

PVSYST V6.83	Andrzej Boduch (Poland)	01/09/20	Page 4/8

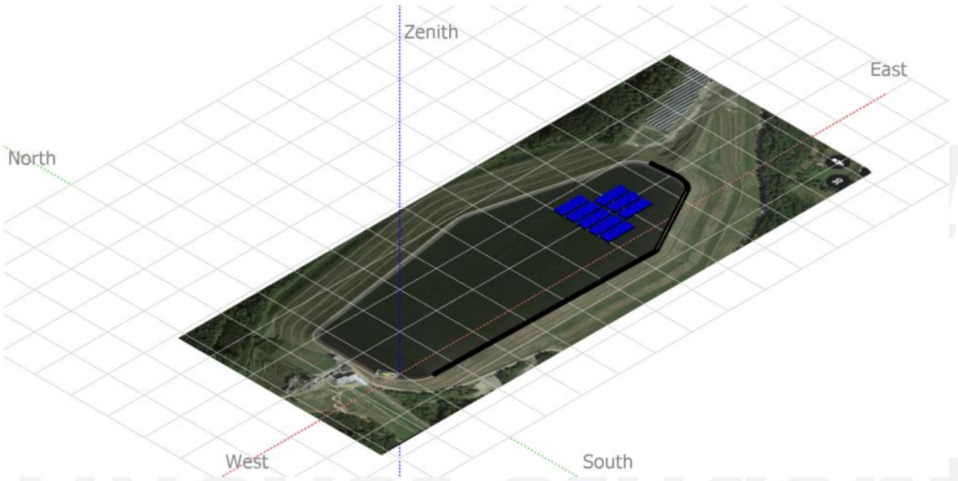
Grid-Connected System: Near shading definition

Project : **FPV**

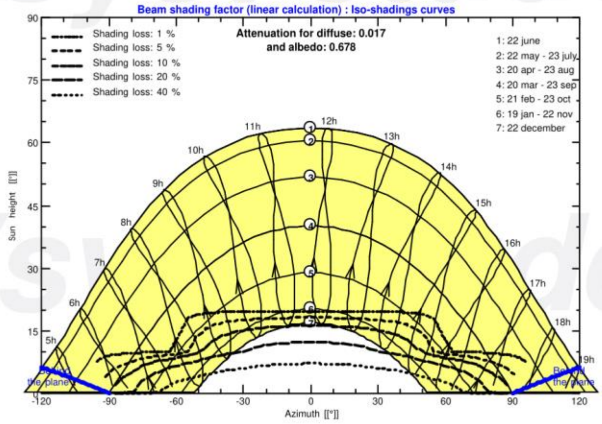
Simulation variant : **Wariant x (8x12x32JinkoSolar320, 8xHuawei105) + AGEING**
Simulation for the 1st year of operation

Main system parameters	System type	**Sheds on ground**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	12°	azimuth	0°
PV modules	Model	JKM 320M-60V	Pnom	320 Wp
PV Array	Nb. of modules	3072	Pnom total	**983 kWp**
Inverter	Model	SUN2000_105KTL	Pnom	105 kW ac
Inverter pack	Nb. of units	8.0	Pnom total	**840 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram



PVSYST V6.83	Andrzej Boduch (Poland)	01/09/20	Page 5/8

Grid-Connected System: Main results

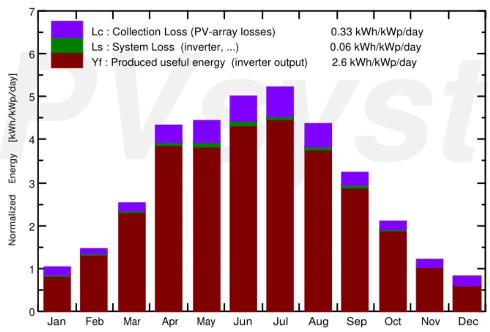
Project : **FPV**

Simulation variant : **Wariant x (8x12x32JinkoSolar320, 8xHuawei105) + AGEING**
Simulation for the 1st year of operation

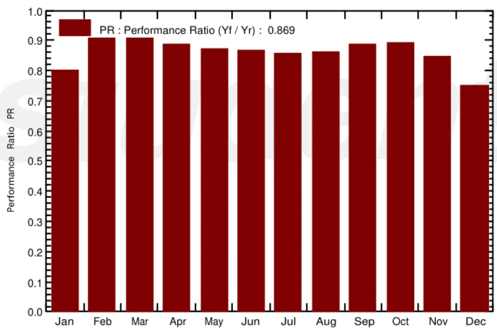
Main system parameters	System type	**Sheds on ground**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	12°	azimuth	0°
PV modules	Model	JKM 320M-60V	Pnom	320 Wp
PV Array	Nb. of modules	3072	Pnom total	**983 kWp**
Inverter	Model	SUN2000_105KTL	Pnom	105 kW ac
Inverter pack	Nb. of units	8.0	Pnom total	**840 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**932.8 MWh/year**	Specific prod.	949 kWh/kWp/year
	Performance Ratio PR	86.93 %		

Normalized productions (per installed kWp): Nominal power 983 kWp



Performance Ratio PR



Wariant x (8x12x32JinkoSolar320, 8xHuawei105) + AGEING

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	24.6	15.14	-3.91	32.6	28.4	26.4	25.7	0.800
February	34.3	20.91	-2.59	40.7	37.2	37.3	36.3	0.908
March	69.4	33.93	0.59	78.7	72.7	72.2	70.3	0.909
April	120.9	59.58	6.65	130.4	120.9	116.6	113.9	0.889
May	134.5	83.35	11.91	137.3	126.8	120.2	117.4	0.870
June	148.4	79.39	14.15	150.2	139.2	130.5	127.6	0.864
July	158.3	74.36	16.31	161.4	149.7	138.8	135.8	0.855
August	127.6	63.64	16.04	135.2	125.2	117.2	114.6	0.862
September	88.2	50.26	10.74	97.6	89.9	86.8	84.8	0.884
October	55.8	31.27	7.17	65.6	60.2	58.9	57.4	0.890
November	28.4	17.43	2.42	36.5	32.5	31.2	30.3	0.845
December	19.5	13.36	-2.39	25.3	21.7	19.3	18.7	0.752
Year	1009.8	542.63	6.48	1091.5	1004.4	955.4	932.8	0.869

Legends:
- GlobHor: Horizontal global irradiation
- DiffHor: Horizontal diffuse irradiation
- T_Amb: Ambient Temperature
- GlobInc: Global incident in coll. plane
- GlobEff: Effective Global, corr. for IAM and shadings
- EArray: Effective energy at the output of the array
- E_Grid: Energy injected into grid
- PR: Performance Ratio

Fig. 49. PVsyst simulation report (FPV)

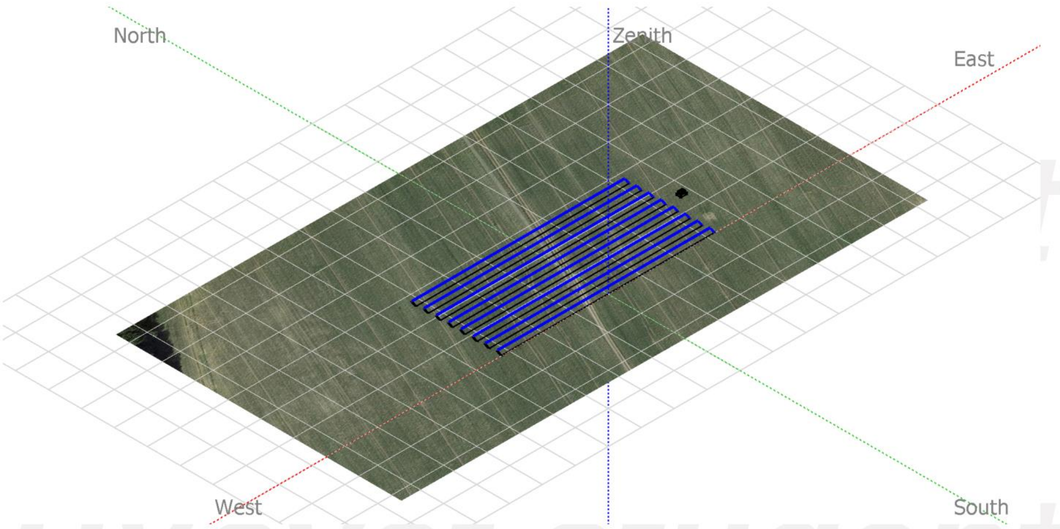
Grid-Connected System: Near shading definition

Project : **GMPV**

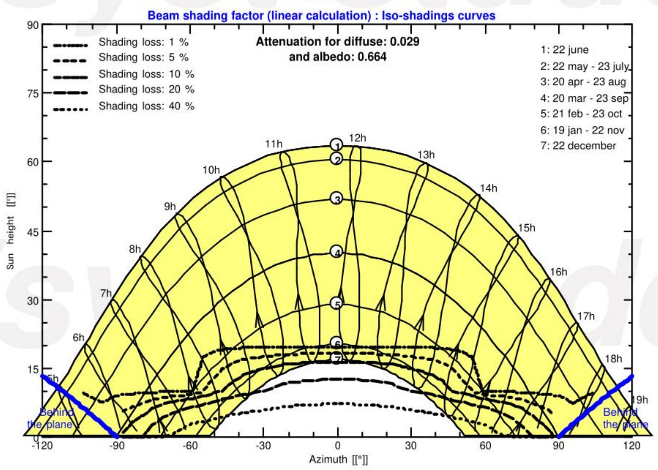
Simulation variant : **Wariant x (8x12x32JinkoSolar320, 8xHuawei105) + AGEING**
Simulation for the 1st year of operation

Main system parameters	System type	**Sheds, single array**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	JKM 320M-60V	Pnom	320 Wp
PV Array	Nb. of modules	3072	Pnom total	**983 kWp**
Inverter	Model	SUN2000_105KTL	Pnom	105 kW ac
Inverter pack	Nb. of units	8.0	Pnom total	**840 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram



Grid-Connected System: Main results

Project : **GMPV**

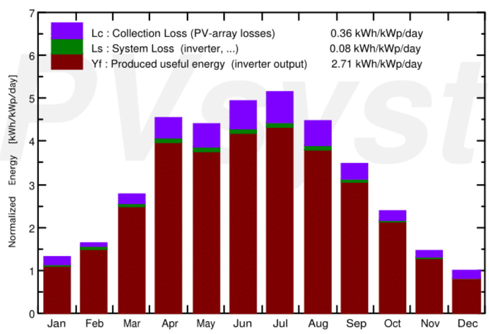
Simulation variant : **Wariant x (8x12x32JinkoSolar320, 8xHuawei105) + AGEING**

Simulation for the 1st year of operation

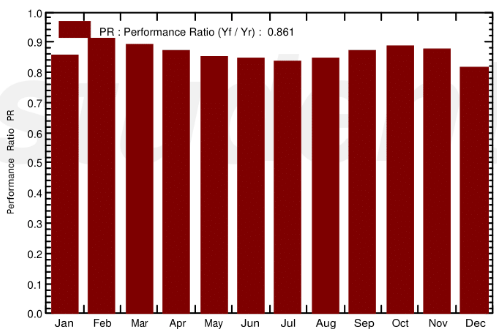
Main system parameters	System type	**Sheds, single array**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	JKM 320M-60V	Pnom	320 Wp
PV Array	Nb. of modules	3072	Pnom total	**983 kWp**
Inverter	Model	SUN2000_105KTL	Pnom	105 kW ac
Inverter pack	Nb. of units	8.0	Pnom total	**840 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**971.4 MWh/year**	Specific prod.	988 kWh/kWp/year
	Performance Ratio PR	86.14 %		

Normalized productions (per installed kWp): Nominal power 983 kWp



Performance Ratio PR



Wariant x (8x12x32JinkoSolar320, 8xHuawei105) + AGEING

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	24.6	15.14	-3.91	40.6	35.5	35.2	34.2	0.856
February	34.3	20.91	-2.59	46.4	42.6	42.9	41.6	0.912
March	69.4	33.93	0.59	86.2	79.6	78.0	75.7	0.894
April	120.9	59.58	6.65	136.1	125.5	120.2	116.9	0.873
May	134.5	83.35	11.91	136.6	125.0	117.7	114.6	0.853
June	148.4	79.39	14.15	148.0	135.9	126.7	123.3	0.847
July	158.3	74.36	16.31	159.9	147.0	135.3	131.7	0.838
August	127.6	63.64	16.04	139.1	128.1	119.1	116.0	0.848
September	88.2	50.26	10.74	104.6	96.1	92.2	89.8	0.873
October	55.8	31.27	7.17	74.1	68.1	66.5	64.6	0.887
November	28.4	17.43	2.42	44.2	39.8	39.2	38.0	0.875
December	19.5	13.36	-2.39	31.2	26.9	25.8	25.0	0.816
Year	1009.8	542.63	6.48	1147.1	1050.2	998.7	971.4	0.861

Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T_Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

Fig. 50. PVsyst simulation report (GMPV)

A.3 ECONOMIC ANALYSIS MODEL

input parameters	unit	**FPV**	**GMPV**
capacity installed	kWp	967.68	967.68
annual energy yield	MWh	937.1	950.3
CAPEX	EUR	892244.55	605261.61
Operational costs	EUR	74203.32	60147.03
residual	%	13.3%	15.3%
residual value	EUR	118342.37	92673.60
long-term loan	EUR	713795.64	484209.29

other parameters		
auction price	302	PLN/MWh
TGeBASE bonus price	26	PLN
discount rate	8.0%	
investment loan	15	years
investor's equity	20%	of CAPEX net
working capital (financial reserve)	10000	EUR
interest rate (annually)	4.5%	
commision (total)	1%	
trade balancing	3.5	PLN/MWh
broker commision	1.5	PLN/MWh
market profile (TGEBASE bonus)	15	years
auction price	variable	EUR/MWh
1st modules efficiency drop	0.87%	
2nd modules efficiency drop	0.77%	
self-consumption	0.50%	
VAT	-	
PLN-EUR exchange	4.48	
income tax	9%	

Fig. 51. Model input parameters

FPV long term loan	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
capital installment		47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €	47,586 €
left to be paid		666,209 €	618,623 €	571,037 €	523,450 €	475,864 €	428,277 €	380,691 €	333,105 €	285,518 €	237,932 €	190,346 €	142,759 €	95,173 €	47,586 €	- €
interest		32,121 €	29,979 €	27,838 €	25,697 €	23,555 €	21,414 €	19,272 €	17,131 €	14,990 €	12,848 €	10,707 €	8,566 €	6,424 €	4,283 €	2,141 €
commision	7,138 €															

GMPV long term loan	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
capital installment		32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €	32,281 €
left to be paid		451,929 €	419,648 €	387,367 €	355,087 €	322,806 €	290,526 €	258,245 €	225,964 €	193,684 €	161,403 €	129,122 €	96,842 €	64,561 €	32,281 €	- €
interest		21,789 €	20,337 €	18,884 €	17,432 €	15,979 €	14,526 €	13,074 €	11,621 €	10,168 €	8,716 €	7,263 €	5,811 €	4,358 €	2,905 €	1,453 €
commision	4,842 €															

Fig. 52. Projects financing

expenditures	item	unit price, PLN	unit price, EUR	residual value	depraciation rate	Classification of Fixed Assets	FPV			GMPV		
							quntity	wholesale cost, EUR	residual value, EUR	quantity	wholesale cost, EUR	residual value, EUR
Initial expenditures								**€ 25,625.00**	**€ 15,625.00**		**€ 45,714.29**	**€ 22,321.43**
	Conceptual design, building permit	PLN 30,000.00	€ 6,696.43	100%	7%	348	0.5	€ 3,348.21	€ 3,348.21	1	€ 6,696.43	€ 6,696.43
	Establishment of special purpose venture	PLN 15,000.00	€ 3,348.21	100%	7%	348	1	€ 3,348.21	€ 3,348.21	1	€ 3,348.21	€ 3,348.21
	Environmental permit	PLN 10,000.00	€ 2,232.14	100%	7%	348	1	€ 2,232.14	€ 2,232.14	1	€ 2,232.14	€ 2,232.14
	Purchase of land	PLN 0.00	€ 0.00	100%	-	031	0	€ 0.00	€ 0.00	0	€ 0.00	€ 0.00
	Connection conditions	PLN 30,000.00	€ 6,696.43	100%	10%	613	1	€ 6,696.43	€ 6,696.43	1	€ 6,696.43	€ 6,696.43
	Site preparation	PLN 25,000.00	€ 5,580.36	20%	4.5%	201	0	€ 0.00	€ 0.00	1	€ 5,580.36	€ 1,116.07
	Site fence	PLN 50,000.00	€ 11,160.71	20%	4.5%	201	0	€ 0.00	€ 0.00	1	€ 11,160.71	€ 2,232.14
	cash (financial reserve)	PLN 44,800.00	€ 10,000.00	0%	0%	-	1	€ 10,000.00	€ 0.00	1	€ 10,000.00	€ 0.00
Tansformer station								**€ 49,107.14**	**€ 7,366.07**		**€ 49,107.14**	**€ 7,366.07**
	Transformer ZPUE 0.8/15kV	PLN 202,000.00	€ 45,089.29	15%	10%	613	1	€ 45,089.29	€ 6,763.39	1	€ 45,089.29	€ 6,763.39
	Transformer station container	PLN 18,000.00	€ 4,017.86	15%	2.5%	101	1	€ 4,017.86	€ 602.68	1	€ 4,017.86	€ 602.68
Mounting system								**€ 354,866.07**	**€ 34,415.18**		**€ 82,595.54**	**€ 8,259.55**
	Floating system Ciel&Terre + anchoring	PLN 1,509,820.00	€ 337,013.39	10%	7%	778	1	€ 337,013.39	€ 33,701.34	0	€ 0.00	€ 0.00
	Floaters local transport	PLN 2,000.00	€ 446.43	0%	7%	778	24	€ 10,714.29	€ 0.00	0	€ 0.00	€ 0.00
	GM system Corab WS-004 (panels)	PLN 262,545.00	€ 58,603.79	10%	7%	348	0	€ 0.00	€ 0.00	1	€ 58,603.79	€ 5,860.38
	GM system Corab WS-004 (cantilever)	PLN 87,515.00	€ 19,534.60	10%	4.5%	201	0	€ 0.00	€ 0.00	1	€ 19,534.60	€ 1,953.46
	End clamp 35 mm	PLN 1.60	€ 0.36	10%	7%	348	12300	€ 4,392.86	€ 439.29	3072	€ 1,097.14	€ 109.71
	Mid clamp KS AL 50	PLN 1.60	€ 0.36	10%	7%	348	0	€ 0.00	€ 0.00	4608	€ 1,645.71	€ 164.57
	T-sliding nuts	PLN 0.60	€ 0.13	10%	7%	348	12300	€ 1,647.32	€ 164.73	7680	€ 1,028.57	€ 102.86
	Allen screws M8x35	PLN 0.40	€ 0.09	10%	7%	348	12300	€ 1,098.21	€ 109.82	7680	€ 685.71	€ 68.57
Inverters								**€ 36,433.93**	**€ 14,573.57**		**€ 36,433.93**	**€ 14,573.57**
	Huawei SUN2000 105KTL	PLN 20,403.00	€ 4,554.24	40%	7%	348	8	€ 36,433.93	€ 14,573.57	8	€ 36,433.93	€ 14,573.57
PV modules								**€ 246,857.14**	**€ 24,685.71**		**€ 246,857.14**	**€ 24,685.71**
	TrinaSolar TSM-DE05A (II)	PLN 360.00	€ 80.36	10%	7%	348	3072	€ 246,857.14	€ 24,685.71	3072	€ 246,857.14	€ 24,685.71
Cables								**€ 73,595.45**	**€ 12,426.57**		**€ 44,819.87**	**€ 6,518.30**
	Helukabel Solarflex® X H1Z2Z2-K1500 6 mm^2	PLN 2.34	€ 0.52	20%	7%	348	0	€ 0.00	€ 0.00	19500	€ 10,185.27	€ 2,037.05
	Helukabel Solarflex® X PV1 F 10 mm^2	PLN 4.05	€ 0.90	20%	7%	348	23500	€ 21,244.42	€ 4,248.88	0	€ 0.00	€ 0.00
	Helukabel Solarflex® X PV1 F 16 mm^2	PLN 7.01	€ 1.56	20%	7%	348	20500	€ 32,073.35	€ 6,414.67	0	€ 0.00	€ 0.00
	Phoenix Contact Sunclix 6 mm^2	PLN 9.00	€ 2.01	0%	7%	348	0	€ 0.00	€ 0.00	192	€ 385.71	€ 0.00
	Phoenix Contact Sunclix 10 mm^2	PLN 11.00	€ 2.46	0%	7%	348	120	€ 294.64	€ 0.00	0	€ 0.00	€ 0.00
	Phoenix Contact Sunclix 16 mm^2	PLN 13.00	€ 2.90	0%	7%	348	72	€ 208.93	€ 0.00	0	€ 0.00	€ 0.00
	H07V-K 25 mm^2	PLN 6.10	€ 1.36	10%	7%	348	6400	€ 8,714.29	€ 871.43	200	€ 272.32	€ 27.23
	H07V-K 16 mm^2	PLN 4.08	€ 0.91	10%	7%	348	7500	€ 6,830.36	€ 683.04	5500	€ 5,008.93	€ 500.89

expenditures	item	unit price, PLN	unit price, EUR	residual value	depraciation rate	Classification of Fixed Assets	FPV			GMPV		
							quntity	wholesale cost, EUR	residual value, EUR	quantity	wholesale cost, EUR	residual value, EUR
	H07V-K 6 mm^2	PLN 1.38	€ 0.31	10%	7%	348	2600	€ 800.89	€ 80.09	0	€ 0.00	€ 0.00
	N2XY 3x16 mm^2	PLN 11.60	€ 2.59	10%	7%	348	50	€ 129.46	€ 12.95	0	€ 0.00	€ 0.00
	N2XY 3x25 mm^2	PLN 18.40	€ 4.11	10%	7%	348	0	€ 0.00	€ 0.00	250	€ 1,026.79	€ 102.68
	UTP kat.5e U/UTP 4x2x0,5	PLN 0.55	€ 0.12	0%	7%	348	20600	€ 2,529.02	€ 0.00	18500	€ 2,271.21	€ 0.00
	Medium voltage cabel	PLN 115.00	€ 25.67	15%	7%	348	30	€ 770.09	€ 115.51	1000	€ 25,669.64	€ 3,850.45
Electrical equipment								**€ 23,251.79**	**€ 1,162.59**		**€ 17,225.67**	**€ 861.28**
	SPD Dehn DCB YPV 1500	PLN 451.00	€ 100.67	5%	10%	615	96	€ 9,664.29	€ 483.21	160	€ 16,107.14	€ 805.36
	SPD Dehn DCB YPV 1500 FM	PLN 530.00	€ 118.30	5%	10%	615	96	€ 11,357.14	€ 567.86	0	€ 0.00	€ 0.00
	WT-1/gG 100A 1000V	PLN 48.00	€ 10.71	5%	10%	612	8	€ 85.71	€ 4.29	8	€ 85.71	€ 4.29
	Equipotential bonding metal parts	PLN 1.00	€ 0.22	5%	10%	614	3520	€ 785.71	€ 39.29	100	€ 22.32	€ 1.12
	Equipotential bars	PLN 23.00	€ 5.13	5%	10%	614	40	€ 205.36	€ 10.27	25	€ 128.35	€ 6.42
	Combiner box HPL AJB-0101	PLN 38.00	€ 8.48	5%	10%	614	96	€ 814.29	€ 40.71	64	€ 542.86	€ 27.14
	Combiner box ABB Mistral65	PLN 190.00	€ 42.41	5%	10%	610	8	€ 339.29	€ 16.96	8	€ 339.29	€ 16.96
Lightning protection system								**€ 2,808.04**	**€ 252.23**		**€ 2,808.04**	**€ 252.23**
	Air terminal rods Dehn	PLN 420.00	€ 93.75	10%	10%	614	23	€ 2,156.25	€ 215.63	23	€ 2,156.25	€ 215.63
	T-connector Dehn ESTV RG	PLN 15.00	€ 3.35	10%	10%	614	24	€ 80.36	€ 8.04	24	€ 80.36	€ 8.04
	Steel wire Dehn RD 8 STTZN R127M	PLN 3.20	€ 0.71	5%	10%	614	800	€ 571.43	€ 28.57	800	€ 571.43	€ 28.57
Monitoring and safety								**€ 2,691.07**	**€ 134.55**		**€ 2,691.07**	**€ 134.55**
	Smart Logger 3000A	PLN 2,056.00	€ 458.93	5%	10%	624	1	€ 458.93	€ 22.95	1	€ 458.93	€ 22.95
	CCTV system	PLN 10,000.00	€ 2,232.14	5%	10%	624	1	€ 2,232.14	€ 111.61	1	€ 2,232.14	€ 111.61
Installation work								**€ 77,008.93**	**€ 7,700.89**		**€ 77,008.93**	**€ 7,700.89**
	transformation station	PLN 95,000.00	€ 21,205.36	10%	10%	613	1	€ 21,205.36	€ 2,120.54	1	€ 21,205.36	€ 2,120.54
	FPV system	PLN 250,000.00	€ 55,803.57	10%	7%	348	1	€ 55,803.57	€ 5,580.36	0	€ 0.00	€ 0.00
	GMPV system (panels)	PLN 175,000.00	€ 39,062.50	10%	7%	348	0	€ 0.00	€ 0.00	1	€ 39,062.50	€ 3,906.25
	GMPV system (cantilever)	PLN 75,000.00	€ 16,741.07	10%	4.5%	201	0	€ 0.00	€ 0.00	1	€ 16,741.07	€ 1,674.11
							SUM	**€ 892,244.55**	**€ 118,342.37**		**€ 605,261.61**	**€ 92,673.60**
								PLN 3,997,255.60	**PLN 530,173.82**		**PLN 2,711,572.00**	**PLN 415,177.75**
								residual	13.26%		*residual*	15.31%

Fig. 53. CAPEX

GMPV depreciation of assets	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
initial expenditures	€ 0	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282	€ 2,282
transformer station	€ 0	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 3,013	€ 0	€ 0	€ 0	€ 0
mounting system	€ 0	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293	€ 5,293
inverters	€ 0	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 729
inverters exchange (after 12y)	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 2,550	€ 2,550	€ 2,550
PV modules	€ 0	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 4,937
cables	€ 0	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 3,137	€ 896
electrical equipment	€ 0	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 1,723	€ 0	€ 0	€ 0	€ 0	€ 0
LPS	€ 0	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 0	€ 0	€ 0	€ 0	€ 0
monitoring and safety	€ 0	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 0	€ 0	€ 0	€ 0	€ 0
installation work	€ 0	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 5,608	€ 4,102	€ 0
Depraciation	**€ 0**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 39,165**	**€ 36,152**	**€ 38,702**	**€ 37,195**	**€ 16,688**

GMPV depreciation of assets	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
initial expenditures	€ 35,714	€ 33,432	€ 31,150	€ 28,867	€ 26,585	€ 24,302	€ 22,020	€ 19,738	€ 17,455	€ 15,173	€ 12,891	€ 10,608	€ 8,326	€ 6,044	€ 3,761	€ 1,479
transformer station	€ 49,107	€ 44,498	€ 39,888	€ 35,279	€ 30,670	€ 26,060	€ 21,451	€ 16,842	€ 12,232	€ 7,623	€ 3,013	€ 0	€ 0	€ 0	€ 0	€ 0
mounting system	€ 82,596	€ 77,302	€ 72,009	€ 66,716	€ 61,422	€ 56,129	€ 50,836	€ 45,542	€ 40,249	€ 34,956	€ 29,662	€ 24,369	€ 19,076	€ 13,782	€ 8,489	€ 3,196
inverters	€ 36,434	€ 33,884	€ 31,333	€ 28,783	€ 26,232	€ 23,682	€ 21,132	€ 18,581	€ 16,031	€ 13,481	€ 10,930	€ 8,380	€ 5,829	€ 3,279	€ 729	€ 0
inverters exchange (after 12y)	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 33,884	€ 31,333	€ 28,783
PV modules	€ 246,857	€ 229,577	€ 212,297	€ 195,017	€ 177,737	€ 160,457	€ 143,177	€ 125,897	€ 108,617	€ 91,337	€ 74,057	€ 56,777	€ 39,497	€ 22,217	€ 4,937	€ 0
cables	€ 44,820	€ 41,682	€ 38,545	€ 35,408	€ 32,270	€ 29,133	€ 25,996	€ 22,858	€ 19,721	€ 16,583	€ 13,446	€ 10,309	€ 7,171	€ 4,034	€ 896	€ 0
electrical equipment	€ 17,226	€ 15,503	€ 13,781	€ 12,058	€ 10,335	€ 8,613	€ 6,890	€ 5,168	€ 3,445	€ 1,723	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
LPS	€ 2,808	€ 2,527	€ 2,246	€ 1,966	€ 1,685	€ 1,404	€ 1,123	€ 842	€ 562	€ 281	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
monitoring and safety	€ 2,691	€ 2,422	€ 2,153	€ 1,884	€ 1,615	€ 1,346	€ 1,076	€ 807	€ 538	€ 269	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
installation work	€ 77,009	€ 71,401	€ 65,792	€ 60,184	€ 54,576	€ 48,968	€ 43,359	€ 37,751	€ 32,143	€ 26,535	€ 20,926	€ 15,318	€ 9,710	€ 4,102	€ 0	€ 0
Value of assets overall	**€ 595,262**	**€ 552,228**	**€ 509,194**	**€ 466,161**	**€ 423,127**	**€ 380,094**	**€ 337,060**	**€ 294,027**	**€ 250,993**	**€ 207,960**	**€ 164,926**	**€ 125,761**	**€ 89,609**	**€ 87,341**	**€ 50,146**	**€ 33,457**
Change of value of assets YoY	**€ 0**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 43,034**	**€ 39,165**	**€ 36,152**	**€ 2,268**	**€ 37,195**	**€ 16,688**

FPV depreciation of assets	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
initial expenditures	€ 0	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 1,295	€ 89	€ 0	€ 0
transformer station	€ 0	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 4,609	€ 3,013	€ 0	€ 0	€ 0	€ 0
mounting system	€ 0	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 24,841	€ 7,097
inverters	€ 0	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 2,550	€ 729
inverters exchange (after 12y)	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0		€ 2,550	€ 2,550
PV modules	€ 0	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 17,280	€ 4,937
cables	€ 0	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 5,152	€ 1,472
electrical equipment	€ 0	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 2,325	€ 0	€ 0	€ 0	€ 0	€ 0
LPS	€ 0	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 281	€ 0	€ 0	€ 0	€ 0	€ 0
monitoring and safety	€ 0	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 269	€ 0	€ 0	€ 0	€ 0	€ 0
installation work	€ 0	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 6,027	€ 4,688	€ 0	€ 0
Depraciation	**€ 0**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 64,629**	**€ 60,158**	**€ 57,144**	**€ 54,599**	**€ 52,373**	**€ 16,785**

FPV depreciation of assets	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
initial expenditures	€ 15,625	€ 14,330	€ 13,036	€ 11,741	€ 10,446	€ 9,152	€ 7,857	€ 6,563	€ 5,268	€ 3,973	€ 2,679	€ 1,384	€ 89	€ 0	€ 0	€ 0
transformer station	€ 49,107	€ 44,498	€ 39,888	€ 35,279	€ 30,670	€ 26,060	€ 21,451	€ 16,842	€ 12,232	€ 7,623	€ 3,013	€ 0	€ 0	€ 0	€ 0	€ 0
mounting system	€ 354,866	€ 330,025	€ 305,185	€ 280,344	€ 255,504	€ 230,663	€ 205,822	€ 180,982	€ 156,141	€ 131,300	€ 106,460	€ 81,619	€ 56,779	€ 31,938	€ 7,097	€ 0
inverters	€ 36,434	€ 33,884	€ 31,333	€ 28,783	€ 26,232	€ 23,682	€ 21,132	€ 18,581	€ 16,031	€ 13,481	€ 10,930	€ 8,380	€ 5,829	€ 3,279	€ 729	€ 0
inverters exchange (after 12y)	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 36,434	€ 33,884	€ 31,333
PV modules	€ 246,857	€ 229,577	€ 212,297	€ 195,017	€ 177,737	€ 160,457	€ 143,177	€ 125,897	€ 108,617	€ 91,337	€ 74,057	€ 56,777	€ 39,497	€ 22,217	€ 4,937	€ 0
cables	€ 73,595	€ 68,444	€ 63,292	€ 58,140	€ 52,989	€ 47,837	€ 42,685	€ 37,534	€ 32,382	€ 27,230	€ 22,079	€ 16,927	€ 11,775	€ 6,624	€ 1,472	€ 0
electrical equipment	€ 23,252	€ 20,927	€ 18,601	€ 16,276	€ 13,951	€ 11,626	€ 9,301	€ 6,976	€ 4,650	€ 2,325	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
LPS	€ 2,808	€ 2,527	€ 2,246	€ 1,966	€ 1,685	€ 1,404	€ 1,123	€ 842	€ 562	€ 281	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
monitoring and safety	€ 2,691	€ 2,422	€ 2,153	€ 1,884	€ 1,615	€ 1,346	€ 1,076	€ 807	€ 538	€ 269	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
installation work	€ 77,009	€ 70,982	€ 64,955	€ 58,929	€ 52,902	€ 46,875	€ 40,848	€ 34,821	€ 28,795	€ 22,768	€ 16,741	€ 10,714	€ 4,688	€ 0	€ 0	€ 0
Value of assets overall	**€ 882,245**	**€ 817,616**	**€ 752,987**	**€ 688,359**	**€ 623,730**	**€ 559,102**	**€ 494,473**	**€ 429,845**	**€ 365,216**	**€ 300,587**	**€ 235,959**	**€ 175,801**	**€ 118,657**	**€ 100,492**	**€ 48,119**	**€ 31,333**
Change of value of assets YoY	**€ 0**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 64,629**	**-€ 60,158**	**-€ 57,144**	**-€ 18,166**	**-€ 52,373**	**-€ 16,785**

Fig. 54. Deprecation of assets (FPV and GMPV)

Increase/decrease of expenses over time	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
index CPI	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
land tenancy	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
insurance	-	0%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
tax on land	-	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
tax on building	-	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
company maintenance, bookkeeping	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
control of performance	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
electric maintenance	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
security	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
land maintenance / cleaning	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
equipment repair	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
additional expenses	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
trade balancing	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
broker commision	-	3.7%	2.7%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%

FPV costs	total	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
depraciation of assets	-	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 64,629	€ 60,158	€ 57,144	€ 54,599	€ 52,373	€ 16,785
land tenancy	PLN 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
insurance	PLN 9,000	€ 2,009	€ 1,908	€ 1,813	€ 1,722	€ 1,636	€ 1,554	€ 1,477	€ 1,403	€ 1,333	€ 1,266	€ 1,203	€ 1,143	€ 1,086	€ 1,031	€ 980
tax on land	PLN 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
tax on building	PLN 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
company maintenance, bookkeeping	PLN 6,000	€ 1,389	€ 1,426	€ 1,461	€ 1,497	€ 1,535	€ 1,573	€ 1,612	€ 1,653	€ 1,694	€ 1,736	€ 1,780	€ 1,824	€ 1,870	€ 1,916	€ 1,964
control of performance	PLN 3,500	€ 810	€ 832	€ 852	€ 873	€ 895	€ 918	€ 940	€ 964	€ 988	€ 1,013	€ 1,038	€ 1,064	€ 1,091	€ 1,118	€ 1,146
electric maintenance	PLN 3,000	€ 694	€ 713	€ 730	€ 749	€ 767	€ 786	€ 806	€ 826	€ 847	€ 868	€ 890	€ 912	€ 935	€ 958	€ 982
security	PLN 2,500	€ 579	€ 594	€ 609	€ 624	€ 639	€ 655	€ 672	€ 689	€ 706	€ 723	€ 741	€ 760	€ 779	€ 798	€ 818
land maintenance / cleaning	PLN 3,000	€ 694	€ 713	€ 730	€ 749	€ 767	€ 786	€ 806	€ 826	€ 847	€ 868	€ 890	€ 912	€ 935	€ 958	€ 982
equipment repair	PLN 5,000	€ 1,157	€ 1,189	€ 1,217	€ 1,248	€ 1,279	€ 1,311	€ 1,343	€ 1,377	€ 1,412	€ 1,447	€ 1,483	€ 1,520	€ 1,558	€ 1,597	€ 1,637
additional	PLN 5,000	€ 1,157	€ 1,189	€ 1,217	€ 1,248	€ 1,279	€ 1,311	€ 1,343	€ 1,377	€ 1,412	€ 1,447	€ 1,483	€ 1,520	€ 1,558	€ 1,597	€ 1,637
trade balancing	-	€ 759	€ 729	€ 721	€ 715	€ 708	€ 702	€ 695	€ 689	€ 682	€ 675	€ 670	€ 664	€ 658	€ 652	€ 647
broker commision	-	€ 325	€ 313	€ 309	€ 306	€ 304	€ 301	€ 298	€ 295	€ 292	€ 289	€ 287	€ 284	€ 282	€ 280	€ 277
Total costs		**€ 74,203**	**€ 74,235**	**€ 74,287**	**€ 74,358**	**€ 74,438**	**€ 74,525**	**€ 74,622**	**€ 74,727**	**€ 74,840**	**€ 74,962**	**€ 70,622**	**€ 67,747**	**€ 65,350**	**€ 63,279**	**€ 27,855**

GMPV costs	overall	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
depreciation of assets	-	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 43,034	€ 39,165	€ 36,152	€ 38,702	€ 37,195	€ 16,688
land tenancy	PLN 15,000	€ 3,472	€ 3,566	€ 3,651	€ 3,743	€ 3,836	€ 3,932	€ 4,030	€ 4,131	€ 4,235	€ 4,340	€ 4,449	€ 4,560	€ 4,674	€ 4,791	€ 4,911
insurance	PLN 9,000	€ 2,009	€ 1,908	€ 1,813	€ 1,722	€ 1,636	€ 1,554	€ 1,477	€ 1,403	€ 1,333	€ 1,266	€ 1,203	€ 1,143	€ 1,086	€ 1,031	€ 980
tax on land	PLN 13,350	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980	€ 2,980
tax on building	PLN 4,800	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071	€ 1,071
company maintenance, bookkeeping	PLN 6,000	€ 1,389	€ 1,426	€ 1,461	€ 1,497	€ 1,535	€ 1,573	€ 1,612	€ 1,653	€ 1,694	€ 1,736	€ 1,780	€ 1,824	€ 1,870	€ 1,916	€ 1,964
control of performance	PLN 3,500	€ 810	€ 832	€ 852	€ 873	€ 895	€ 918	€ 940	€ 964	€ 988	€ 1,013	€ 1,038	€ 1,064	€ 1,091	€ 1,118	€ 1,146
electric maintenance	PLN 3,000	€ 694	€ 713	€ 730	€ 749	€ 767	€ 786	€ 806	€ 826	€ 847	€ 868	€ 890	€ 912	€ 935	€ 958	€ 982
security	PLN 2,500	€ 579	€ 594	€ 609	€ 624	€ 639	€ 655	€ 672	€ 689	€ 706	€ 723	€ 741	€ 760	€ 779	€ 798	€ 818
land maintenance / cleaning	PLN 3,000	€ 694	€ 713	€ 730	€ 749	€ 767	€ 786	€ 806	€ 826	€ 847	€ 868	€ 890	€ 912	€ 935	€ 958	€ 982
equipment repair	PLN 5,000	€ 1,157	€ 1,189	€ 1,217	€ 1,248	€ 1,279	€ 1,311	€ 1,343	€ 1,377	€ 1,412	€ 1,447	€ 1,483	€ 1,520	€ 1,558	€ 1,597	€ 1,637
additional	PLN 5,000	€ 1,157	€ 1,189	€ 1,217	€ 1,248	€ 1,279	€ 1,311	€ 1,343	€ 1,377	€ 1,412	€ 1,447	€ 1,483	€ 1,520	€ 1,558	€ 1,597	€ 1,637
trade balancing	-	€ 770	€ 740	€ 731	€ 725	€ 718	€ 712	€ 705	€ 698	€ 692	€ 685	€ 679	€ 673	€ 667	€ 661	€ 656
broker commision	-	€ 330	€ 317	€ 313	€ 311	€ 308	€ 305	€ 302	€ 299	€ 296	€ 294	€ 291	€ 289	€ 286	€ 283	€ 281
Total costs		**€ 60,147**	**€ 60,272**	**€ 60,409**	**€ 60,572**	**€ 60,744**	**€ 60,928**	**€ 61,123**	**€ 61,328**	**€ 61,545**	**€ 61,772**	**€ 58,143**	**€ 55,380**	**€ 58,191**	**€ 56,957**	**€ 36,733**

Fig. 55. Operational costs

		unit	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	auction price	PLN/MWh	302	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	index CPI	%	3.70%	2.70%	2.40%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%
	indexed auction price	PLN/MWh	-	313.17	321.63	329.35	337.58	346.02	354.67	363.54	372.63	381.94	391.49	401.28	411.31	421.59	432.13	442.94
	indexed auction price % growth	%	-	3.7%	6.5%	9.1%	11.8%	14.6%	17.4%	20.4%	23.4%	26.5%	29.6%	32.9%	36.2%	39.6%	43.1%	46.7%
	indexed TGeBASE bonus price	PLN/MWh	26.0	26.3	26.5	26.8	26.9	26.9	27.0	27.1	27.2	27.3	27.4	27.4	27.5	27.6	27.7	27.8
	auction price	EUR/MWh	67.41	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	index CPI	%	3.70%	2.70%	2.40%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%
	indexed auction price	EUR/MWh	-	69.90	71.79	73.52	75.35	77.24	79.17	81.15	83.18	85.26	87.39	89.57	91.81	94.11	96.46	98.87
	indexed auction price % growth	%	-	3.7%	6.5%	9.1%	11.8%	14.6%	17.4%	20.4%	23.4%	26.5%	29.6%	32.9%	36.2%	39.6%	43.1%	46.7%
	indexed TGeBASE bonus price	EUR/MWh	5.8	5.9	5.9	6.0	6.0	6.0	6.0	6.1	6.1	6.1	6.1	6.1	6.1	6.2	6.2	6.2
	Capacity installed	MWp	-	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968
	PV modules efficiency	%	-	100.0%	97.0%	96.1%	95.3%	94.4%	93.5%	92.6%	91.8%	90.9%	90.0%	89.2%	88.5%	87.7%	86.9%	86.2%
	efficiency system drop YoY	%	-	0.0%	3.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.8%	0.8%
	Annual yield	MWh	-	937.1	909.0	900.8	892.6	884.4	876.2	868.0	859.8	851.6	843.4	836.2	829.0	821.8	814.6	807.3
	Annual yield	MWh/MWp	-	968.4	939.3	930.9	922.4	913.9	905.5	897.0	888.5	880.0	871.6	864.1	856.7	849.2	841.8	834.3
FPV	Sale of energy by auction price	PLN	-	293,475	292,357	296,673	301,322	306,018	310,760	315,548	320,382	325,259	330,181	335,543	340,966	346,451	351,998	357,605
	Sale of energy by TGeBASE bonus	PLN	-	24,608	24,109	24,130	23,982	23,833	23,683	23,532	23,379	23,226	23,071	22,943	22,813	22,683	22,551	22,419
	Sale of energy overall	PLN	-	318,084	316,466	320,803	325,304	329,851	334,443	339,080	343,761	348,485	353,252	358,485	363,779	369,134	374,549	380,023
	Sale of energy by auction price	EUR	-	65,508	65,258	66,222	67,259	68,308	69,366	70,435	71,514	72,603	73,701	74,898	76,109	77,333	78,571	79,822
	Sale of energy by TGeBASE bonus	EUR	-	5,493	5,381	5,386	5,353	5,320	5,286	5,253	5,219	5,184	5,150	5,121	5,092	5,063	5,034	5,004
	Sale of energy overall	EUR	-	71,001	70,640	71,608	72,613	73,627	74,652	75,688	76,732	77,787	78,851	80,019	81,201	82,396	83,605	84,827
	Capacity installed	MWp	-	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.968
	PV modules efficiency	%	-	100.0%	97.0%	96.1%	95.3%	94.4%	93.5%	92.6%	91.8%	90.9%	90.0%	89.2%	88.5%	87.7%	86.9%	86.2%
	efficiency system drop YoY	%	-	0.0%	3.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.8%	0.8%
	Annual yield	MWh	-	950.3	921.8	913.5	905.2	896.8	888.5	880.2	871.9	863.6	855.3	848.0	840.7	833.3	826.0	818.7
	Annual yield	MWh/MWp	-	982.0	952.6	944.0	935.4	926.8	918.2	909.6	901.0	892.4	883.8	876.3	868.7	861.2	853.6	846.1
GMPV	Sale of energy by auction price	PLN	-	297,609	296,475	300,852	305,566	310,328	315,137	319,993	324,894	329,841	334,832	340,269	345,769	351,331	356,956	362,642
	Sale of energy by TGeBASE bonus	PLN	-	24,955	24,448	24,470	24,320	24,169	24,017	23,863	23,709	23,553	23,396	23,266	23,135	23,002	22,869	22,734
	Sale of energy overall	PLN	-	322,564	320,924	325,322	329,886	334,497	339,154	343,856	348,603	353,394	358,228	363,535	368,904	374,334	379,825	385,376
	Sale of energy by auction price	EUR	-	66,431	66,178	67,155	68,207	69,270	70,343	71,427	72,521	73,625	74,739	75,953	77,181	78,422	79,678	80,947
	Sale of energy by TGeBASE bonus	EUR	-	5,570	5,457	5,462	5,429	5,395	5,361	5,327	5,292	5,257	5,222	5,193	5,164	5,134	5,105	5,075
	Sale of energy overall	EUR	-	72,001	71,635	72,617	73,635	74,665	75,704	76,754	77,813	78,883	79,962	81,146	82,345	83,557	84,782	86,021

Fig. 56. Yield & Sales

FPV Profit and Loss Account	unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
sales revenue	EUR	71,001	70,640	71,608	72,613	73,627	74,652	75,688	76,732	77,787	78,851	80,019	81,201	82,396	83,605	84,827
energy sale	EUR	71,001	70,640	71,608	72,613	73,627	74,652	75,688	76,732	77,787	78,851	80,019	81,201	82,396	83,605	84,827
cost of goods sold	EUR	74,203	74,235	74,287	74,358	74,438	74,525	74,622	74,727	74,840	74,962	70,622	67,747	65,350	63,279	27,855
depreciation	EUR	64,629	64,629	64,629	64,629	64,629	64,629	64,629	64,629	64,629	64,629	60,158	57,144	54,599	52,373	16,785
other	EUR	9,575	9,607	9,659	9,730	9,809	9,897	9,993	10,098	10,211	10,333	10,464	10,603	10,751	10,906	11,070
gross profit / loss on sales	**EUR**	**3,203**	**3,595**	**2,679**	**1,746**	**810**	**127**	**1,066**	**2,006**	**2,947**	**3,889**	**9,398**	**13,453**	**17,046**	**20,325**	**56,971**
remaining operational revenues and costs	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
profit / loss from operations	**EUR**	**3,203**	**3,595**	**2,679**	**1,746**	**810**	**127**	**1,066**	**2,006**	**2,947**	**3,889**	**9,398**	**13,453**	**17,046**	**20,325**	**56,971**
finance income	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
finance costs	EUR	32,121	29,979	27,838	25,697	23,555	21,414	19,272	17,131	14,990	12,848	10,707	8,566	6,424	4,283	2,141
profit / loss before tax	**EUR**	**35,323**	**33,575**	**30,517**	**27,443**	**24,365**	**21,287**	**18,207**	**15,125**	**12,043**	**8,959**	**1,309**	**4,888**	**10,622**	**16,043**	**54,830**
tax expense	EUR	0	0	0	0	0	0	0	0	0	0	0	440	956	1,444	4,935
net profit / loss	**EUR**	**35,323**	**33,575**	**30,517**	**27,443**	**24,365**	**21,287**	**18,207**	**15,125**	**12,043**	**8,959**	**1,309**	**4,448**	**9,666**	**14,599**	**49,895**

GMPV Profit and Loss Account	unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
sales revenue	EUR	72,001	71,635	72,617	73,635	74,665	75,704	76,754	77,813	78,883	79,962	81,146	82,345	83,557	84,782	86,021
energy sale	EUR	72,001	71,635	72,617	73,635	74,665	75,704	76,754	77,813	78,883	79,962	81,146	82,345	83,557	84,782	86,021
cost of goods sold	EUR	60,147	60,272	60,409	60,572	60,744	60,928	61,123	61,328	61,545	61,772	58,143	55,380	58,191	56,957	36,733
depreciation	EUR	43,034	43,034	43,034	43,034	43,034	43,034	43,034	43,034	43,034	43,034	39,165	36,152	38,702	37,195	16,688
other	EUR	17,113	17,238	17,376	17,538	17,711	17,895	18,089	18,295	18,511	18,738	18,978	19,228	19,489	19,762	20,045
gross profit / loss on sales	**EUR**	**11,854**	**11,363**	**12,207**	**13,063**	**13,920**	**14,776**	**15,631**	**16,485**	**17,338**	**18,190**	**23,003**	**26,965**	**25,365**	**27,825**	**49,288**
remaining operational revenues and costs	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
profit / loss from operations	**EUR**	**11,854**	**11,363**	**12,207**	**13,063**	**13,920**	**14,776**	**15,631**	**16,485**	**17,338**	**18,190**	**23,003**	**26,965**	**25,365**	**27,825**	**49,288**
finance income	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
finance costs	EUR	21,789	20,337	18,884	17,432	15,979	14,526	13,074	11,621	10,168	8,716	7,263	5,811	4,358	2,905	1,453
profit / loss before tax	**EUR**	**9,936**	**8,974**	**6,677**	**4,368**	**2,059**	**250**	**2,557**	**4,864**	**7,170**	**9,474**	**15,740**	**21,154**	**21,007**	**24,920**	**47,835**
tax expense	EUR	0	0	0	0	0	22.4703892	230.158989	437.76137	645.264117	852.651219	1416.61871	1903.88309	1890.65254	2242.79165	4305.18798
net profit / loss	**EUR**	**9,936**	**8,974**	**6,677**	**4,368**	**2,059**	**227**	**2,327**	**4,426**	**6,524**	**8,621**	**14,324**	**19,250**	**19,117**	**22,677**	**43,530**

Fig. 57. Profit & Loss Account

FPV Cash Flows	unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
cash flows from operating activities	**EUR**	**29,305**	**31,054**	**34,111**	**37,186**	**40,263**	**43,342**	**46,422**	**49,503**	**52,586**	**55,670**	**58,848**	**61,592**	**64,265**	**66,972**	**66,681**
net profit / loss	EUR	35,323	33,575	30,517	27,443	24,365	21,287	18,207	15,125	12,043	8,959	1,309	4,448	9,666	14,599	49,895
depreciaion of assets	EUR	64,629	64,629	64,629	64,629	64,629	64,629	64,629	64,629	64,629	64,629	60,158	57,144	54,599	52,373	16,785
receivables	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stock	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
liabilities	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
net cash from operating activities	**EUR**	**882,245**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**36,434**	**0**	**0**
VAT refund (not taken into account)	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
investment expenditures	EUR	882,245	0	0	0	0	0	0	0	0	0	0	0	36,434	0	0
net cash in financing activities	**EUR**	**666,209**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**	**47,586**
revenue from a long-term loan	EUR	713,796	0	0	0	0	0	0	0	0	0	0	0	0	0	0
payment of a long-term loan	EUR	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586	47,586
Cash surplus / shortage	**EUR**	**186,730**	**16,533**	**13,475**	**10,400**	**7,323**	**4,245**	**1,165**	**1,917**	**4,999**	**8,083**	**11,262**	**14,006**	**19,755**	**19,385**	**19,094**
Cash (beginning of the period)	**EUR**	**178,449**	**8,281**	**24,814**	**38,289**	**48,689**	**56,012**	**60,257**	**61,422**	**59,505**	**54,506**	**46,422**	**35,161**	**21,155**	**40,910**	**21,525**
Cash (end of the period)	**EUR**	**8,281**	**24,814**	**38,289**	**48,689**	**56,012**	**60,257**	**61,422**	**59,505**	**54,506**	**46,422**	**35,161**	**21,155**	**40,910**	**21,525**	**2,431**

GMPV Cash Flows	unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
cash flows from operating activities	**EUR**	**33,098**	**34,059**	**36,357**	**38,666**	**40,975**	**43,261**	**45,361**	**47,460**	**49,558**	**51,655**	**53,489**	**55,402**	**57,819**	**59,873**	**60,219**
net profit / loss	EUR	9,936	8,974	6,677	4,368	2,059	227	2,327	4,426	6,524	8,621	14,324	19,250	19,117	22,677	43,530
depreciaion of assets	EUR	43,034	43,034	43,034	43,034	43,034	43,034	43,034	43,034	43,034	43,034	39,165	36,152	38,702	37,195	16,688
receivables	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stock	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
liabilities	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
net cash from operating activities	**EUR**	**595,262**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**36,434**	**0**	**0**
VAT refund (not taken into account)	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
investment expenditures	EUR	**595,262**	0	0	0	0	0	0	0	0	0	0	0	36,434	0	0
net cash in financing activities	**EUR**	**451,929**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**	**32,281**
revenue from a long-term loan	EUR	484,209	0	0	0	0	0	0	0	0	0	0	0	0	0	0
payment of a long-term loan	EUR	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281	32,281
Cash surplus / shortage	**EUR**	**110,235**	**1,779**	**4,076**	**6,385**	**8,694**	**10,980**	**13,080**	**15,179**	**17,277**	**19,374**	**21,208**	**23,121**	**10,896**	**27,592**	**27,938**
Cash (beginning of the period)	**EUR**	**121,052**	**10,817**	**12,596**	**16,672**	**23,057**	**31,751**	**42,731**	**55,812**	**70,991**	**88,268**	**107,642**	**128,850**	**151,972**	**141,076**	**168,668**
Cash (end of the period)	**EUR**	**10,817**	**12,596**	**16,672**	**23,057**	**31,751**	**42,731**	**55,812**	**70,991**	**88,268**	**107,642**	**128,850**	**151,972**	**141,076**	**168,668**	**196,606**

Fig. 58. Cash Flow

FPV assets	unit	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
non-current assets	**EUR**	**0**	**817,616**	**752,987**	**688,359**	**623,730**	**559,102**	**494,473**	**429,845**	**365,216**	**300,587**	**235,959**	**175,801**	**118,657**	**100,492**	**48,119**	**31,333**
intangible assets	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
tangible fixed assets	EUR	0	817,616	752,987	688,359	623,730	559,102	494,473	429,845	365,216	300,587	235,959	175,801	118,657	100,492	48,119	31,333
receivables	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
current assets	**EUR**	**178,449**	**8,281**	**24,814**	**38,289**	**48,689**	**56,012**	**60,257**	**61,422**	**59,505**	**54,506**	**46,422**	**35,161**	**21,155**	**40,910**	**21,525**	**2,431**
receivables	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
short-term investment, cash	EUR	178,449	8,281	24,814	38,289	48,689	56,012	60,257	61,422	59,505	54,506	46,422	35,161	21,155	40,910	21,525	2,431
total assets	**EUR**	**178,449**	**809,335**	**728,174**	**650,070**	**575,041**	**503,089**	**434,216**	**368,423**	**305,711**	**246,082**	**189,536**	**140,641**	**97,502**	**59,581**	**26,594**	**28,903**

FPV liabilities	unit	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
investor's equity	**EUR**	**178,449**	**143,126**	**109,551**	**79,033**	**51,591**	**27,225**	**5,939**	**12,268**	**27,394**	**39,436**	**48,396**	**49,705**	**45,257**	**35,591**	**20,993**	**28,903**
share capital	EUR	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449	178,449
net profit / loss	EUR	0	35,323	33,575	30,517	27,443	24,365	21,287	18,207	15,125	12,043	8,959	1,309	4,448	9,666	14,599	49,895
cumulative profit / loss	EUR	0	0	35,323	68,898	99,415	126,858	151,223	172,510	190,717	205,843	217,885	226,844	228,154	223,706	214,040	199,441
long-term liabilities	**EUR**	**0**	**666,209**	**618,623**	**571,037**	**523,450**	**475,864**	**428,277**	**380,691**	**333,105**	**285,518**	**237,932**	**190,346**	**142,759**	**95,173**	**47,586**	**0**
long-term loan	EUR	0	666,209	618,623	571,037	523,450	475,864	428,277	380,691	333,105	285,518	237,932	190,346	142,759	95,173	47,586	0
short-terms liabilities	**EUR**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
short-term loan	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
current liabilities	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total liabilities	**EUR**	**178,449**	**809,335**	**728,174**	**650,070**	**575,041**	**503,089**	**434,216**	**368,423**	**305,711**	**246,082**	**189,536**	**140,641**	**97,502**	**59,581**	**26,594**	**28,903**

GMPV assets	unit	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
non-current assets	**EUR**	**0**	**552,228**	**509,194**	**466,161**	**423,127**	**380,094**	**337,060**	**294,027**	**250,993**	**207,960**	**164,926**	**125,761**	**89,609**	**87,341**	**50,146**	**33,457**
intangible assets	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
tangible fixed assets	EUR	0	552,228	509,194	466,161	423,127	380,094	337,060	294,027	250,993	207,960	164,926	125,761	89,609	87,341	50,146	33,457
receivables	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
current assets	**EUR**	**121,052**	**10,817**	**12,596**	**16,672**	**23,057**	**31,751**	**42,731**	**55,812**	**70,991**	**88,268**	**107,642**	**128,850**	**151,972**	**141,076**	**168,668**	**196,606**
receivables	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
short-term investment, cash	EUR	121,052	10,817	12,596	16,672	23,057	31,751	42,731	55,812	70,991	88,268	107,642	128,850	151,972	141,076	168,668	196,606
total assets	**EUR**	**121,052**	**563,045**	**521,791**	**482,833**	**446,185**	**411,845**	**379,792**	**349,838**	**321,984**	**296,228**	**272,568**	**254,611**	**241,581**	**228,417**	**218,813**	**230,063**

GMPV liabilities	unit	opening balance	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
investor's equity	**EUR**	**121,052**	**111,117**	**102,143**	**95,466**	**91,098**	**89,039**	**89,266**	**91,593**	**96,020**	**102,544**	**111,165**	**125,489**	**144,739**	**163,856**	**186,533**	**230,063**
share capital	EUR	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052	121,052
net profit / loss	EUR		9,936	8,974	6,677	4,368	2,059	227	2,327	4,426	6,524	8,621	14,324	19,250	19,117	22,677	43,530
cumulative profit / loss	EUR	0	0	9,936	18,910	25,587	29,955	32,013	31,786	29,459	25,033	18,508	9,887	4,436	23,687	42,803	65,480
long-term liabilities	**EUR**	**0**	**451,929**	**419,648**	**387,367**	**355,087**	**322,806**	**290,526**	**258,245**	**225,964**	**193,684**	**161,403**	**129,122**	**96,842**	**64,561**	**32,281**	**0**
long-term loan	EUR	0	451,929	419,648	387,367	355,087	322,806	290,526	258,245	225,964	193,684	161,403	129,122	96,842	64,561	32,281	0
short-terms liabilities	**EUR**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
short-term loan	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
current liabilities	EUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total liabilities	**EUR**	**121,052**	**563,045**	**521,791**	**482,833**	**446,185**	**411,845**	**379,792**	**349,838**	**321,984**	**296,228**	**272,568**	**254,611**	**241,581**	**228,417**	**218,813**	**230,063**

Fig. 59. Assets & Liabilities (FPV)