Technical and Economic Assessment of a 1 MWp Floating Photovoltaic System

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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.

Keyword: Renewable Energy, Floating Photovoltaic, Design, PVsyst

INTRODUCTION

PROBLEM DEFINITION AND MOTIVATION

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.

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, therefore the risk of the whole system blackout is stated as high [1] [2].

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

Conventional photovoltaic farms usually cover large areas, on average 1.2-3.5 ha / MWp depending on the topography. They are best suited for construction in flat, unforested areas with low dustiness and no shading objects around. An appropriate provision in the spatial development plan or a decision on land development in certain countries is needed. As a result, selecting an appropriate area becomes problematic. 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 started in 2015, with particularly large progress in 2018. In Poland, there is currently only one 8-modules floating system (testbed) located on the water reservoir in Łapina, which shows how broad are the prospects for the development of this sector [4].

OBJECTIVES

The floating technologies are expected to develop rapidly in Europe, thus it was decided to focus on the use of it in Poland. The following paper covers the design process of a 1 MWp floating photovoltaic system and assesses its adoption in the realities of large photovoltaic projects in Poland. To be more specific, the designed FPV system is verified in the auction system among other projects with real-life auction prices scenarios. The investment profitability is calculated based on the expected costs incurred by the investor and the performance of the system, which is simulated in the PVsyst software. PVsyst is a professional powerful optimization tool for photovoltaic project developers. Both, the economic analysis and the PVsyst simulation were carried out for the corresponding ground-mounted PV system (GMPV) and treated as a reference point for the FPV project assessment.

The paper is divided into 4 main sections. The *Literature Review* section is an overview of the latest scientific articles and reports. It allows to understand the technologies of floating photovoltaic systems and the associated challenges. The *Methods* section is a description of the assumptions and activities carried out by the author in the design, simulation, and economic analysis processes. *Results and Discussion* section is devoted to the results of the undertaken analyses and their detailed interpretation. The *conclusion* section is a summary of the paper and its results, lessons learned, and the identification of challenges related to the project.

LITERATURE REVIEW

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. Then, individual floats with mounted modules are connected with quick couplers (also floating) into one platform. Alternatively, flat floats are used with mounting profiles between them similar to those used in conventional PV installations. Various variants of the arrangement of the floats are possible in both technologies. Most often, the floats are made of high-density polyethylene (HDPE).

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 [6]. 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 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; [9] [10] 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 [11];
- 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%) [6];
- 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, i.e 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);
- 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] [12];

METHODS

CAPACITY INSTALLED

In Poland, PV systems exceeding 500 kWp of installed capacity can be assigned to the auction mechanisms resembling contracts for differences. Regular producers sell generated energy 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 – offered prices for MWh 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 sold to be obtained in the projects below 1 MW.

it is assumed that the designed floating PV will take part in the auction mechanism and the project will have slightly less capacity installed to meet the requirement of projects below 1MW. If the value of 1 MWp is exceeded, the project enters the next basket, where it competes with large solar and wind projects.

LOCATION

The pumped-storage hydropower plant Porąbka-Żar owned by PGE Energia Odnawialna S.A. 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, the artificial nature of the water reservoir and the available medium-voltage grid. There is a ground-mounted system installed with a capacity of 0.6 MWp nearby [13].

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 floating 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 would be possibly answered in the next phase of the project.

MODULES

To select the main components for the project, a deep analysis for PV modules, inverters and a floating structure has been undertaken.

The checklist for PV modules to be applicable for the project covered humidity resistance, silicon technology used, performance indicators, financial condition of a manufacturer, warranty terms, 1500V system voltage, and finally price. All taken into account made it possible to select the JinkoSolar JKM320M-60-V module for further considerations.

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 open circuit voltage. 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 maximum power point trackers (MPPTs) within each array, 32 modules in series forming one string. Calculations proving the temperature, voltage, and current match of this layout have been performed.

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.

INVERTERS

The selection process of inverters was limited to transformerless inverters and large string inverters. 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. The inverter that fulfilled all the requirements (humidity resistance, performance indicators, price, accessibility, warranty terms) is Huawei SUN2000-105KTL-H1 – a 105 kW string inverter with 12 DC inputs and 6 maximum power point trackers (MPPT). The Nominal Power Ratio, which is a ratio of PV module capacity installed to the nominal power of inverters, is equal to 1.17 (Table.1). The inverters are designed to be placed on the walls of the transformer station.

Table. 1 The nominal power ratio of the system

Component	Quantity	Power, W	Power in total, W	Nominal Power Ratio
PV modules	3 072	320	967 680	**1.17**
Inverters	8	105 000	840 000	

FLOATING SYSTEM

The major condition for selecting a floating technology supplier was to meet all the requirements imposed by the location characteristics. As mentioned earlier, the system must be able to settle to the bottom of the tank once a year without any risk of damage. In the case of temperatures below zero and days when motion of water in the reservoir is reduced, high risk of ice in the top layer occurs. Moreover, extensive experience and presence in the European market were appreciated. All the above requirements have been met by the French manufacturer Ciel & Terre, which portfolio exceeds 300 MWp globally [14]. They provide customers with a 10-year standard warranty on the reliability of their design.

One of the Ciel&Terre technologies, Hydrelio® Classic, is offered in three different variants of the module tilt angle: 12°, 15°, and 22° [14]. None of the available angle variants is optimal for Polish latitudes. An optimization evaluation was carried out on which of the available versions gives the best yields in relation to the price of the structure. The outcome of the analysis was a selection of a 12° tilt version with one "bridge floater" between modules. The layout of 3072 PV modules grouped in 8 arrays is presented in Fig. 1.

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.

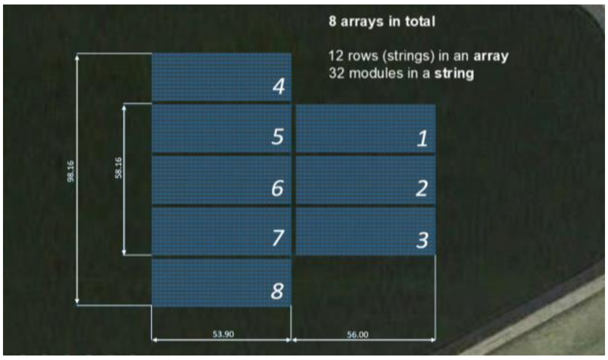

Fig. 1. FPV arrays layout

OTHER COMPONENTS

Apart from the main components selection process, additional equipment of the system was adjusted.

The DC side was equipped with 4 mm^2 H1Z2Z2 1500V solar cables and Phoenix Contact Sunclix connectors. 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 [15]. 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. IEC 60364-712 states that PV systems whose maximum open circuit voltage is higher than 120V DC should use reinforced or double insulation as a protection against electric shock, which is provided by certified solar cables [16]. 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. None of the additional fuses or breakers are applicable here either.

Surge protection is a major element of any photovoltaic protection system. Its application was carried out in three stages. The first step is the equipotential bonding of all conductive system components. Another element is the use of surge protection devices (SPDs). Their selection was carried out in accordance with the PN-HD 60364-7-712 standard following the distances between the system elements, the presence of a lightning protection system (LPS), as well as maintaining the separation distance. SPD devices mounted on a floating structure were equipped with signaling contacts to enable remote protection checks. The last step is to equip the system with an LPS of the third protection class. The rolling sphere method was used to identified places for the installation of air-terminal rods.

The AC side was designed with adjusted overcurrent protection and one surge protection device mounted in the main switchboard located in the transformer station.

Already transformed energy from DC to AC is entering a transformer station to be injected into the grid. 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. It is assumed that the resistance level obtained for a transformer station receiving energy from a floating solar farm is 5Ω. The transformer station MRw-bpp 20 / 1000-3 PV 800V manufactured by ZPUE S.A., which is tailored to the needs of PV farms, is used in the project.

SIMULATION CONDITIONS

The PVsyst simulation was performed based on the described components and module layout. The system is assumed to face perfectly south with the modules inclined by 12 degrees. The next assumptions to be used in the simulation concern parameters such as albedo values, Ohmic losses, module quality, Light Induced Degradation, mismatch or soiling.

However, the biggest change (compared to ground-mounted PV) concerns the thermal parameters, which highly influences the array electrical performance. 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 ($G_{incindence}$) [17]:

$$U * (T_{cell} - T_{ambient}) = \alpha * G_{incidence} * (1 - \eta)$$

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.

$$U = U_C + U_V * wind\ velocity$$

The thermal parameters are described by the *field thermal loss factor U*, which consists of two elements [17]:

- *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 [17].

Therefore, PVsyst, based on its experience, suggests values for different mounting systems [17]:

- 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 [18] 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 Ciel&Terre Hydrelio® Classic (12° angle version). Its performance was classified in U_C range between 26 W/m²K and 34 W/m²K [18].

It should be noted that the 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 [11]. The meteorological site parameters of the designated location in the simulation have been adjusted.

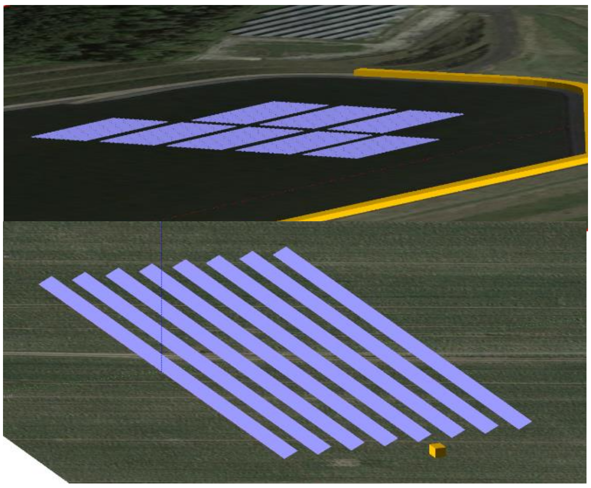

Fig. 2. 3D models of the FPV and GMPV system designed in PVsyst

To assess the FPV system accurately, a second PVsyst simulation was performed. The subject of this simulation was a ground-mounted photovoltaic system corresponding with its main components to the designed FPV system. The configuration of modules and inverters were not changed. Efforts were made to keep both projects as close as possible to the realities of solar farms and correct design practices. The main difference is the supporting structure used and the cable layout. Therefore, the simulation was made based on the Polish reputable mounting structure manufacturer – Corab and its product WS-004M structure with a 25° tilt.

ECONOMIC ANALYSIS ASSUMPTIONS

The economic analysis was carried out for two types of installation: the designed floating PV system and a ground-mounted PV system corresponding with parameters and main components to the FPV 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 would operate is the auction mechanism preceded by an auction conducted by the Energy Regulatory Office.

According to the Polish Renewable Energy Sources Act (RES Act), the period of support for producers participating in the auction system is 15 years [19]. After this period, energy will be sold on market terms. This analysis covered a financially secure period from the investor's perspective - 15 years. After this period, the capitalization of the company was calculated in the form of the residual value of fixed assets. All values given in the analysis are net prices (excluding VAT).

Floating photovoltaic systems have not enjoyed great popularity in Poland so far. There is only one operating pilot plant. Many administrative and financial issues are not solved yet. Thus, it was necessary to make a few assumptions. They mainly concerned the duration of the project, the method of settling revenues, the project's discount rate, building permit or environmental decisions. The outcome of the renewable energy sources (RES) auction (basket < 1MW) held in the first half of 2020 in Poland was adopted as the auction prices for the project's economic analysis.

All the values included in the capital expenditure statement (CAPEX) used in 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. It turned out to be a big obstacle to list the price of a 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 providing floating solutions were extremely helpful. Thanks to their commitment and experience, it was possible to evaluate both missing values. 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).

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. The uncertainty over floating solar farms 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.

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.

Other operational costs included in the analysis are costs related to: depreciation of assets, control of the performance of a system, insurance, electric maintenance, security, equipment repair, land maintenance.

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 to the Energy Regulatory Office. 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).

A company must be established for the purpose of billing. It is assumed that a limited liability company would be founded which sales revenues will not exceed EUR 2 million. Then it qualifies in Poland for the status of a "small taxpayer" and the effective income tax falls from the standard 19% to 9%.

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%.

RESULTS AND DISCUSSION

TECHNICAL ANALYSIS

By analyzing Sankey diagrams of both simulations, which is a final product of a PVsyst report, 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°. On the other hand, 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 inverters is as follows: FPV system - 934 MWh and GMPV system - 973 MWh.

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% [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 dominated 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.

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.

ECONOMIC ANALYSIS

The economic analysis was performed in Excel software. The calculations included all elements of financial statements - a balance of assets and liabilities, profit and loss account, and cash flow statement. The auction price and investor's equity were considered as a variable. The project indicators were Net Present Value (NPV) and Internal Rate of Return (IRR).

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. The Table 2 shows values adopted for the analysis with the indicators, while graph in Fig. 3 cumulative cash flows compared to the investor’s equity. However, in the first years of the system operation, the instalments 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.

The situation is different for a ground-mounted farm. 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.

However, the positive NPV indicator for the FPV project was achieved for the highest auction price (73 EUR/MWh). The break-even point was achieved in the 11th year of operation for the FPV project. Nevertheless, it is still not feasible for an investor to cover operational expenditures during the first years. Instalments were too high compared to the incomes.

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 67 EUR/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.

Table 2. General assumptions and financial indicators (FPV) 67 EUR/MWh

General information		**Financial indicators**	
Auction price:	67 EUR/MWh	*Project NPV:*	- 45,888
Capacity installed:	983.04 kWp	*NPVR:*	-0.28
Annual energy yield:	932.8 MWh	*IRR:*	4.81%
CAPEX:	759,631 EUR		
Operational costs:	64,915 EUR		
Residual value:	101,614 EUR		
Long term loan:	607,704 EUR		

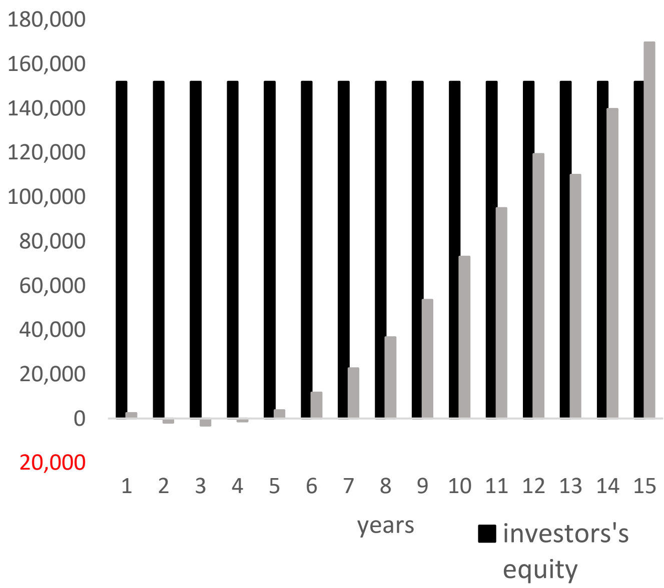

Fig. 3. Graph of cash flow/investor’s equity (FPV) 67 EUR/MWh

CONCLUSIONS

The paper 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 and assess solar floating technology in Polish conditions, 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 challenge for the project implementation on the selected reservoir is that the water is drained once a year. The floating structure lying at the bottom of the reservoir may make maintenance (cleaning and repairing) impossible. The paper did not consider the influence of harsh humid conditions on the components. There is insufficient scientific evidence on how high humidity and a corrosive environment affect the long-term operation of an FPV system. This issue was mitigated by considering appropriately certificated components only.

Considerations about the intensified heat exchange proofed to be exaggerated – at least in Poland. The thermal gain of 0.9 pp over the GMPV system was easily lost by a more suitable tilt. The FPV system was limited to the existing fixed-tilt 12° floating structure. It seems that lower latitudes may gain more from floating PV, due to higher temperature and lower optimal tilt. The result of the performance analysis is 932.8 MWh for the FPV system and 971.4 MWh for the GMPV system (first year).

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. They are all required before getting involved in the auction mechanism, 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.

The results of the economic analysis of the floating system were not satisfactory from the investor's point of view. According to the predictions, the higher CAPEX was supposed to be neutralized by the increase in energy yield. In turn, the energy yield was lower compared to the conventional system. The initial cost of the FPV system is estimated at EUR 760,000 with EUR 590,000 of the GMPV system. Considering the average price from the last auction of projects up to 1 MW and a 20% investor's contribution the project is not able to maintain liquidity – installments exceed incomes in the first years of the system operation.

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. It should be expected that along with the improvement of technology and the growing number of producers on the market, the price will decrease. 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.

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