Technical and technoeconomic analysis of Floating Photovoltaics on Pumped-Storage Hydropower dams

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***Abstract*— As the world is transitioning away from fossil fuels and towards intermittent renewables, there is a growing need to drive down costs of energy storage and increase the efficiency of renewable technologies through innovation. This study evaluates the benefits of placing Floating Photovoltaics on top of Pumped Hydro-Storage dams, in terms of economic and technical advantages. Specifically, two Reservoirs were selected in the region of Amfylochia in Greece and compared by placing a total FPV capacity equal to 1 – 30% of the total surface area. The PV PERC Mono DBP 400 flat plate was selected and installed on pure plastic floating pontoons with 0 degree tilting and a 180° Azimuth. Using established electrical formulas, it was derived that water has a cooling effect on the PV arrays, decreasing the cell temperatures by 6°C and improving their power output efficiency and energy production by 2,19% amounting to a 44,35 MWh reduction in a year. Moreover, the as FPV blocks direct insolation on the water, it has a positive effect on the evaporation, reducing it by 95%. Looking at the technoeconomic metrics the LCOE of LPV was derived at 33,32 Euros/ MWh compared to FPV at 39,53 Euros/ MWh. The FPV performed worse in all financial metrics including ROI, Payback period, NPV and IRR due to the higher capital costs of FPV. However, a sensitivity analysis indicated that at the same Capex, FPV has a higher energy production and that installing it at a location with a higher insolation and temperature, will result to an increased power output efficiency of 4,16%. In conclusion, this report identifies that this hybrid model is still not economically beneficial, due to the higher capital costs of FPV, indicating the need for further research and development to drop down costs.**

Keywords: Floating Photovoltaics, Pumped Hydro Storage, Renewable Energy, Hybrid Energy Systems

I. INTRODUCTION

The effects of Global Warming have been very noticeable over the last years. Extreme weather conditions such as storms, earthquakes, floods and high and low temperatures have been exacerbated. Thus, countries are starting to take practical actions to lower their emissions and adopt greener solutions and habits. Specifically, initiatives like the COP25 and the climate bill will be increasing significant investments in renewable energy installations, which are slowly capturing a bigger share of electricity production. However, their problem of intermittency is still substantial and constant energy supplies still dominate most of the production, which is captured by fossil fuels. The recent war with Russia has cut huge amounts of that constant natural gas supply to Europe, indicating once again the importance of dispatchable power. Now countries are trying to explore solutions of energy storage that will allow them to keep a high renewable energy capacity and store any excess amounts, to fill the gap of fossil fuels. This effort requires innovative solutions in the field of renewables and existing storage applications. Two areas that can be improved are solar PV and energy storage technologies that could cover the challenge of dispatchability and intermittency. The scope of this report focuses on the current drawbacks of Photovoltaic panels and pumped-storage hydroelectricity, as well as the mutual benefits arisen when combining the two in the form of floating photovoltaics. Moreover, a technoeconomic analysis of the most important investment metrics in the short and long term are evaluated.

II. LITERATURE REVIEW

A Floating Solar Photovoltaic system refers to the action of placing photovoltaics on top of bodies of water to float. It differs with conventional PV's due to the need of a floatation system and an anchoring and evacuation plan. The floating system can have several forms such as: Pure, Metallic, Membrane or other, with different materials and costs of each. The anchoring system is responsible for keeping the system still and at the same position. The most common types of anchors are:

- Bottom anchoring: Anchor on seabed.
- Bank anchoring: Anchor on ground above the sea water.
- Piles: Piles are buried on the seawater and then the system is anchored on those piles.

Placing panels on the water can cause an efficiency increase. In 2021, a study conducted by Mohamad Al-Widyan et al. [1], evaluated the effects of FPV on their energy output. The study compared an in-land and a dam reservoir PV farm and found a 11% increase in efficiency of floating PV, due to the cooling effect on the panels. This can lead to a better performance over long term in contrast to higher temperature cells that get their performance reduced over a long period of time. However, this study only evaluated the technical benefits of FPV.

Floating photovoltaic costs differ significantly from conventional photovoltaics in CAPEX and OPEX. A study conducted by NREL 2021 [2], assessed and compared the system costs between FPV and PV of a 10 MW plant. It was found that FPV is more expensive mainly due to the structural costs of the floating equipment required, at 1,03 dollars/Watt for the ground mount PV and 1,29 dollars/Watt for floating PV. However, at larger scale farms of more than 50 MW, the cost drops significantly to 1,05 dollars/ Watt. Regarding Operations and Maintenance, FPV has a lower cost by 2.5 dollars/ W reaching a total of 15,5 dollars/ kW year for O&M, as the lifetime is increased due to better cooling and lower temperature stress on the PV cells. However, this study does not evaluate the economic benefits arisen by the reduced evaporation of water which could result to significant savings for a PHS. Converting these costs to euros we get €0.95/ W for ground mount PV and €1,19/ W for floating PV. Leonardo Micheli et al. 2021 [3] conducted a study on the cost competitiveness of FPV in reservoirs in Spain, concluding that module temperature is a key factor in determining the maximum allowed CAPEX of FPV. Also, high future electricity is likely to lower the CAPEX of FVP and become cost completive against LPV. However, the study addresses only Spain whereas this report will evaluate the Greece as the selected location.

When looking at the challenges PHS faces, evaporation is one of the biggest. Covering the surface of the water with objects can significantly reduce it. A study conducted by Lewis W.Farrar et al. [4], evaluated the evaporation benefits of placing FPV on a reservoir in Jordan. The study found that 42% of water (12.700 m^3) was saved by covering with FPV compared to an uncovered reservoir of 300 kW. The report also conducted an economic analysis, estimating a cost saving of €1.360 per year. However, the study used Jordan as the selected location and this report will evaluate a European country.

FPV has a secondary advantage of limiting the formation and growth of algae and improving the water quality of the reservoir. A study conducted by Haas J. et al. [5] and colleagues addressed the ecological impact of FPV on hydropower reservoirs. The study concluded that the optimal shading trade-off between ecology and costs should be between 40 – 60%. Low coverages would result to little effect. Higher coverages would avoid algae blooms and very high coverages could harm the natural food web in the ecosystem. These findings are significant since algae produces toxins that can make people and animal sick and affect the environment. Luayao Liu et al. 2019 [6] evaluated the befits of integrating FPV in PHS plants. The study found that system sizing is an important issue for the hybrid system and that FPV helps cover the electricity load in daytime and pump-up water during excess generation hours, to maintain water balance. However, the study did not evaluate the generation improvement of water cooling on the solar cells.

The contribution of this thesis is to provide a clear understanding of the technical and economic relationship of FPV on PHS. Specifically, to conclude whether FPV is beneficial regarding the energy output of both systems, as well as a detailed analysis of the costs and revenues. The value of this study will provide a basis for further investment developments that will require the specific characteristics of this system. The study will consider a reservoir installed in a European country with significant adequate throughout the year.

III. TECHNICAL ANALYSIS

In this section detailed calculations were used to find the energy efficiency increase and evaporation losses reduction, due to placing FPV on a selected PHS dam. The data used in this report was accessed from literature review and online datasets. All calculations were conducted based on established technical and technoeconomic metric formulas. This report uses euros as the reference currency as Greece is part of the European Union. The currency exchange of 0,92 euros per dollar has been used as per 4/1/2023 [7]. This thesis uses "." for thousands and "," for decimal points.

The selected location was the area of Amfilochia in Greece. The location was selected due to relatively high solar insolation, yearly average temperatures above 10°C, a medium yearly precipitation and evaporation and the availability of various locations for hydro storage plants. Moreover, a planned project for the construction of a PHS plant makes it an appropriate study location. The location is shown in figure 1 below.

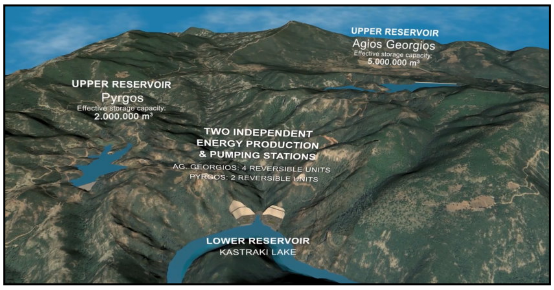


Fig. 1. Reservoir location [16]

Two upper reservoirs were identified with the lower reservoir being the Kastraki lake. The characteristics of the two upper reservoirs are depicted in the Figure 1 above.

This section identifies a potential FPV capacity to be installed in the upper reservoirs outlined previously. Only a coverage of 1 - 30% will be evaluated for each dam, by solar panels. Since the dams have a large surface area, the study for a coverage of 100% would result to significant capital expenditures, which is not a feasible solution. For every square meter of water surface, 88 Watts of FPV can be installed [8]. Thus, for reservoirs A and B the total potential installed capacities are depicted in Tables I and II below.

TABLE I
RESERVOIR A

Reservoir A		
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**
1	7.900	695,2
2,5	19.750	1.738
5	39.500	3.476
7,5	59.250	5.214
10	79.000	6.952

TABLE III
RESERVOIR B

Reservoir B		
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**
1	3.100	273
2,5	7.750	682
5	15.500	1.364
7,5	23.250	2.046
10	31.000	2.728

Regarding the characteristics of the panels, an existing flat plate generic model was used. Specifically, the PERC Mono DBP 400 [9]. High temperatures reduce the efficiency of PV cells. Specifically, as the temperature decreases the open-circuit voltage decreases as well. In addition, the short-circuit current increases slightly due to the bandgap energy decreasing but is typically negligible. The relationship of these two values is shown in the equation 1 below:

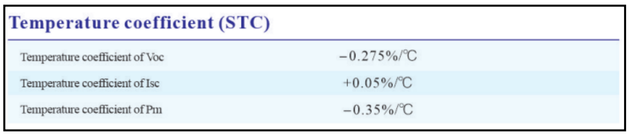
$$\boxed{P = I \times V = I_{SC} \times V_{OC}} \; (1)$$

The effect temperatures on the panels were considered to calculate the performance improvement of the array. Firstly, the temperature of the PV cell will be calculated using the equation 2 below:

$$\boxed{T_{Cell} = T_{air} + \frac{NOCT - 20}{80} \times S \; (2)}$$

For an average yearly sunlight exposure of 2756 hours, the air temperature is 18°C and the average temperature of the cell is 37°C. Considering the temperature coefficients shown in Table III.

TABLE IIII
RESERVOIR A



Temperature coefficient (STC)	
Temperature coefficient of Voc	−0.275%/℃
Temperature coefficient of Isc	+0.05%/℃
Temperature coefficient of Pm	−0.35%/℃

For the cell temperature calculated, the temperature difference from STC is **12**°C . Since the temperature coefficient for the power is -**0,35%**/°C then the power losses due to temperature are **4,2%.** Thus, the actual power output of the PV module will drop, as well as the yield ratio. The power drops at **397,57** Watts and the yield ratio at **2,036**. On the other hand, using the same process but placing the panels on the water the cooling effect causes the new Cell temperature to be 31°C. The new temperature difference from STC 6°C. The power losses amount to **-2,1%** and the actual power output at **406,285 Watts**. The new yield ratio is **0,20806**. The detailed calculations can be found in the Annex. Table IV shows the performance improvement.

TABLE IV
PERFORMANCE IMPROVEMENT

Performance improvement	
Efficiency (%)	+ 2,19
Energy (MWh)- At 1% coverage	+ 44,35

An average price of **€0,068/ kWh** is assumed to be the selling price that the selected system will use when selling to the grid. For simplicity reasons it was assumed that this price is fixed, and the amount of energy produced has already been sold at the futures market to mitigate cost risks from fluctuating prices. Thus, the energy improvement of 2,19% equals a revenue increase of 2,19%, which amounts up to **4 million €** depending on the coverage.

Moreover, FPV helps with reduced evaporation of water. The evaporation rate of the two reservoirs was calculated using the Penman formula, as indicated below in the equation 3. This evaporation rate is calculated for a body of water at the selected location with no coverage.

$$\boxed{E_0 = \frac{700 \times \frac{T_m}{100 - A} + \frac{15}{T - T_d}}{80 - T} \; (3)}$$

To find the dew point temperature, a psychometric chart was used at 18 °and 95% humidity. Thus, the reservoirs lose -570,91 mm of water per year. Table V below, converts this loss to the equivalent volume loss by multiplying by the surface area of each reservoir.

TABLE V
RESERVOIR VOLUME LOSS

Performance improvement	
Reservoir A	Reservoir B
- 450.956 m^3	- 176.958 m^3

By considering the cost of PHS at 186,65 €/ MWh [10] and the energy production of a hydro plant the following cost for the total area of the dam are lost due to evaporation, as depicted in table VI.

TABLE VI
ENERGY PER CUBIC METER

Reservoir B		
Value	**Reservoir A**	**Reservoir B**
Volume loss (m^3)	-450.956	-176.958
E/V (kWh/ m^3)	0,119	0,120
Cost (€ /kWh)	0,187	0,187
Loss (€ /year)	10.000	3.974

However, covering a body of surface with panels will block 95% of light, with 5% still evaporated from sunlight penetrating through the structure by reflection and heat.

IV. TECHNOECONOMIC ANALYSIS

To perform the technoeconomic analysis of the two proposed solar panel systems a percentage coverage of 5% of Reservoir A will be used as a base case for simplification purposes. The specifications of the components are the same as mentioned in the sections earlier. Table VII below shows the derived results.

TABLE VII
TECHNOECONOMIC RESULTS

Metric	LPV	FPV
LCOE (€ /kWh)	33,32	39,53
ROI (%)	215	172
Payback period (Years)	6,37	7,88
NPV (Million €)	4,21	3,44
IRR (%)	15	12

V. DISCUSSION

The data analysis conducted previously is based on the location selection of Amfylochia in Greece. All data regarding the dam were extracted from online sources. After evaluating the solar irradiance in the area and the weather conditions, they were sufficient for the placement of solar photovoltaics. Thus, an appropriate solar panel model was used (PERC Mono DBP 400). A 0-degree tilting was set, to simplify calculations.

Using excel, detailed calculations were made to find the performance improvement of the solar panels. Specifically, the Temperature of the cell was found at 37°C , by taking the average temperature of the location throughout the year. This temperature does not consider the cooling effect and is above the ambient temperature of 25°C . For this reason, the open-circuit voltage of the PV drops and the power efficiency reduces.by 4,2%. However, when considering the heat transfer losses due to the water contact with the array, there was an improvement of the power output at a reduction of only 2,1%, increasing the net efficiency by 2,1%. A 6°C temperature drop at the back-surface of the array, results to a reduced temperature of the cell at 31°C . This results to an energy production reduction of 2,19%, due to the temperature coefficients of the panel. This amounts to an extra energy production of 44,35 MWh in a year.

However, it should be noted that the selected location is in the west-northern part of Greece and has a relatively low average temperature throughout the year of just 18°C . This results to a lower cell temperature and just a small power efficiency drops due to heat. Nevertheless, the cooling coming from water still improves the PV performance. Thus, this study concludes that water has a positive impact in lowering cell temperatures and increasing the open-circuit voltage and thus the power of a solar panel.

Regarding the evaporation of water, it was derived that the evaporation reduction is 95% of the surface area of the FPV installed. However, based on the types of floating structures used, evaporation is affected due to different properties of conductive materials and thus convection, conduction and radiation heat transfers.

The principle of economies of scale is particularly relevant in the context of solar energy installations, as the cost per unit of electricity generated tends to decrease as the capacity of the installation increases. This is reflected in the lower capital expenditures (CAPEX) per watt of solar energy generated for larger installations. However, it is important to note that the costs of photovoltaic installations can vary depending on the type of technology used, with floating photovoltaics generally being more expensive than land-based installations. The OPEX for FPV systems can be brought to the same value as conventional land based photovoltaic systems, arising at O&M costs of **16,56 € per kilowatt per year**. Therefore, the advantages of FPV systems over conventional photovoltaic systems in terms of space utilization, reduced land requirements, and lower environmental impact could potentially offset the higher maintenance costs and make them an economically viable option for renewable energy generation.

The technoeconomic analysis conducted indicated that LPV was favourable in all metrics. This was due to the increased CAPEX of FPV due to the additional structural requirements. At the same time the energy efficiency was not significant to cover those extra costs and thus resulting in a least favourable investment option. In section 6, a sensitivity analysis was conducted to evaluate two indicators.

VI. SENSITIVITY ANALYSIS

Scenario 1 assumes the same Capex costs for FPV as for LPV. This scenario is used to evaluate the benefits of FPV once enough research and development has been done that will drive capital costs down, as depicted in table VIII.

TABLE VIII
SCENARIO 1

Metric	LPV	FPV
LCOE (€/kWh)	33,32	32,60
ROI (%)	215	222
Payback period (Years)	6,37	6,22
NPV (Million €)	4,21	4,40

Once the CAPEX is brought down to the level of conventional PV costs, FPV has a clear advantage as a financial investment. As seen in table 8 above, it outperforms LPV in all metrics and would be preferred from an investment firm.

In Scenario 2, the location is changed with a location that has higher temperatures, insolation and the availability for PHS dams. This will depict whether FPV has a better performance in hotter climates as shown in the calculations performed earlier in the report. Choosing the Spanish island El

Herro with higher temperatures and irradiation and less precipitation. The efficiency of the system was improved from **2,19%** to **4,16%** in the new location. Given the higher insolation this equalled an increase energy production of 100,7 MWh per year by FPV

While the financial metrics of the project are much higher in this location, the difference in efficiency increase of 1,97% from the two locations is not enough to make FPV more attractive than LPV even in higher insolation and temperature locations. The most important metric to look is the LCOE which reaches a cost of 32,41 Euros/ MWh compared to 27,85 Euros/ MWh for LPV at that location. However, it is worth to note that the difference between the LCOE's drops from 6,21 to 4,57 Euros/ MWh between the two locations, indicating a clear advantage of placing FPV in hotter climates with less precipitation.

VII. LIMITATIONS

Several limitations are still found in the study and should be addressed in future work. Those include that fixed cost prices of spot market were considered but those differ day by day. An average energy production yearly was used but the weather is unpredictable and varies year by year. CAPEX and OPEX for some power capacities were interpolated due to the lack of data. Average temperature and precipitation causing average evaporation data were used instead of daily. The PHS spot market price assumed only at highest price whereas the price differs along the day or season. The efficiency of a PHS plant was taken as a worldwide average, whereas it differs plant by plant and country by country. The reduction of algae effect of water on the wall of a PHS plant due to placing a FPV were not considered and could have a high reduction in the costs, making it economically attractive

VIII. CONCLUSION

In conclusion, this thesis shows that FPV causes a power efficiency improvement of 2,2% due to water cooling and a **5%** reduction in the water evaporation of the area covered. However, when looking at a technoeconomic analysis, FPV performs worse than LPV due to the higher CAPEX, indicating the need for research and development in the field to lower initial capital costs. The sensitivity analysis indicated that at the same CAPEX FPV is a favorable investment option and at a hotter climate the power efficiency is improved further at **4,16%**, indicating that such technology is better used in warmer locations.

This thesis is an original study that considered several benefits at a rea life PHS plant and conducted a technical and technoeconomic evaluation. However, as such a study has not been previously conducted, it should only be treated as a basis of key areas of development for FPV and for future work on the topic. Several limitations are subject to this master's thesis that would need to be addressed in further research work. It is proposed that future work should consider the effect of algae formation and the benefits of placing FPV regarding algae. Moreover, using measured values rather than yearly average would tremendously increase the accuracy of the results and give a more precise understanding of the true costs behind floating photovoltaics. This should specifically be done in the O&M costs and conducting a research/ survey analysis to find the costs in a specific plant.

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