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

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Declaration

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

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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

Abstract

No processo de transição dos combustíveis fósseis para as energias renováveis intermitentes, há uma necessidade crescente de diminuir os custos do armazenamento de energia e aumentar a eficiência das tecnologias renováveis através da inovação. Nesta dissertação avaliam-se os benefícios da colocação de sistemas fotovoltaicos flutuantes (FPV) nas albufeiras de centrais hidroelétricas com bombagem, em termos de vantagens económicas e técnicas. Especificamente, foram selecionados dois reservatórios na região de Amfylochia, na Grécia e comparados para uma capacidade fotovoltaica total igual a 1 – 30% da área de superfície total. Para o modelo fotovoltaico, a solução PERC Mono DBP 400 foi selecionada e instalada em pontões flutuantes de plástico puro com inclinação de 0º e azimute de 180º. Com recurso aos modelos elétricos, concluiu-se que a água tem um efeito de arrefecimento nos painéis fotovoltaicos, diminuindo as temperaturas das células em 6°C e melhorando a sua eficiência energética e a produção de energia em 2,19%, o que equivale a uma redução de 44,35 MWh num ano. Além disso, como o FPV bloqueia a exposição solar direta sobre a água, tem um efeito positivo sobre a evaporação, reduzindo-a em 95%. Analisando as métricas tecno-económicas, o LCOE da LPV foi calculado em 33,32 Euros/ MWh derivado de FPV a 39,53 Euros/ MWh. O FPV teve um pior desempenho em todas as métricas financeiras, incluindo o ROI, VAL e TIR devido aos custos de capital mais elevados do FPV. No entanto, uma análise de sensibilidade indicou que, com o mesmo Capex, a FPV tem uma maior produção de energia e que a sua instalação num local com maior exposição solar e temperatura, o que resultará num aumento da eficiência energética de 4,16%. Em conclusão, esta dissertação identifica que este modelo híbrido ainda não é economicamente vantajoso, devido aos custos de capital mais elevados da FPV, indicando a necessidade de mais investigação e desenvolvimento para reduzir os mesmos.

Palavras-chave: Painéis fotovoltaicos flutuantes, armazenamento hidroelétrico por bombagem, energias renováveis, sistemas híbridos de energia

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Abbreviations

Acronym	Meaning
CAPEX	Capital Expenditure
DNI	Direct Normal Irradiance
DSO	Distribution System Operator
FPV	Floating photovoltaics
HENEX	Hellenic Energy Exchange
IRR	Internal Rate of Return
LPV	Land based photovoltaics
LCOE	Levelized Cost Of Energy
NPV	Net Present Value
OPEX	Operational Expenditure
O&M	Operations & Maintenance
PV	Photovoltaic
PHS	Pumped Hydro Storage
RAE	Regulatory Authority for Energy
R&D	Research and Development
ROI	Return on Investment
SA	Sensitivity analysis
TSO	Transmission System Operator

1.0 Introduction

1.1 Problem origin

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 more 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 the majority of 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. One area that can be improved is solar PV, which captures around 10% of the European electricity market [1]. Finding ways to improve efficiencies could increase production capacities. Moreover, regarding storage technologies, pumped-storage hydroelectricity is the most common solution capturing 97% of European storage [2]. Thus, technological improvements will have a tremendous effect on the ongoing efforts mentioned. However, to be able to rapidly scale such solutions, the economic viability and total costs of ownership must also be considered.

1.2 PV drawbacks

Solar PV installations suffer from several drawbacks that lower their efficiencies, power and energy outputs and cause disruptions to their normal operation.

One of the most important factors to take into account is the relationship of heat and solar panel efficiency. Specifically, as the temperature of a panel increases, its output current increases exponentially causing the voltage output to reduce linearly. Thus, extreme heat and temperatures can reduce a solar panel's production of power. The maximum power temperature coefficient indicates the losses for every °C increased above 25°C, as depicted in Figure 1 below [3]. The open circuit voltage and maximum power output reduce significantly after 25 °

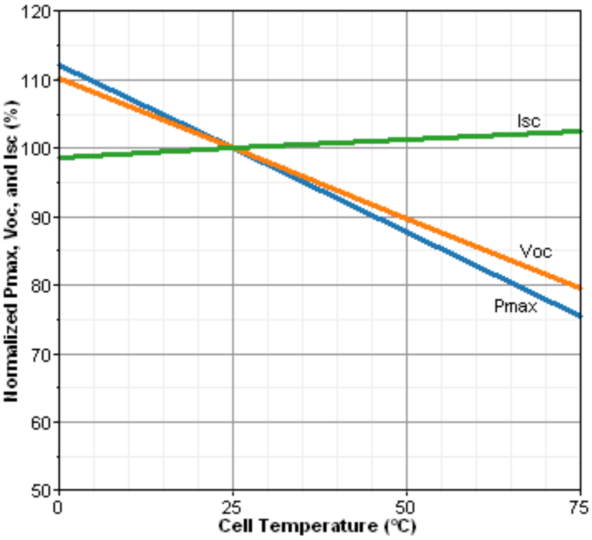


Figure 1: Cell temperature losses [3]

Another common problem of solar production is the intermittency of sun. Specifically, for most European countries the sun is up for an average of 7-8 hours per day in a year. During that time however, the energy consumption tends to drop as most people don't consume as much due to working and not being home. This creates the so-called problem of the duck curve as shown in Figure 2 below [4]. Grids that have a lot of solar capacity can lead to an overgeneration of power, during hours of sun since the electricity demand drops at those hours and vice vera during the night. Adding more solar capacity exacerbates this problem. The only solution is to couple the excess generation with storage applications so as not to waste that energy.

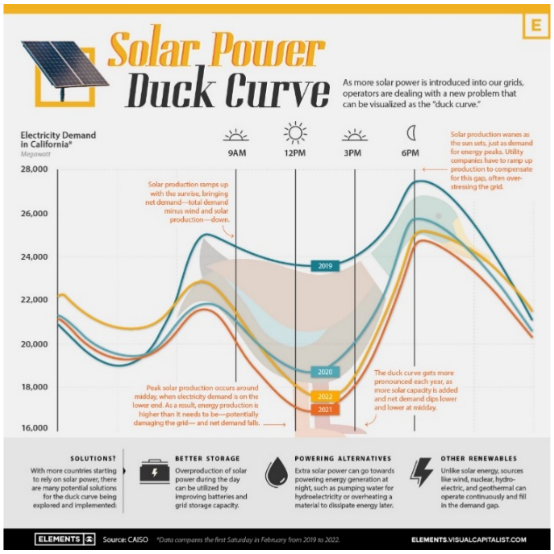


Figure 2: Duck curve [4]

Another issue that PV owners might face is the danger of theft. As large farms are usually located in remote areas, they are in danger of being stolen if not properly secured.

Another upcoming problem is the social opposition of renewables. Some people argue that solar PV can be aesthetically displeasing to natural landscapes.

Lastly, installing large solar farms requires huge areas of real estate which can be hard to find, expensive to acquire and environmentally unfriendly.

1.3 Pumped-storage hydroelectricity drawbacks

Pumped-storage hydroelectricity is a very mature technology based on the provision of 2 lakes, separated at a high-altitude difference, as depicted in figure 3 below. Nevertheless, there are still drawbacks to the use of such storage. Figure 3 depicts a sketch of a PHS plant.

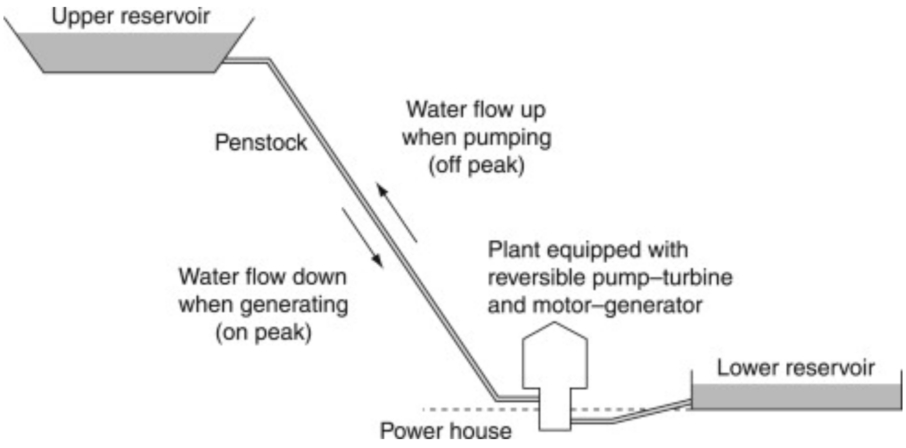


Figure 3: PHS Sketch [39]

The most common problem is the amount of water lost to due evaporation from the surface of the water. This amount is proportional to the total water stored in the dam and is more sever for shallow dams. The evaporation loss could be up to 50% of the total storage volume in some cases [5]. Evaporation is related to the surface area of the water, the depth and shape of a dam, as well as the surrounding topography and ecosystem. This issue is critical for countries that experience high temperatures and heat.

Pumped-storage has very limited availability, as it can only be installed in specific topographic areas. Large elevation differences at the smallest possible distance between two bodies of water are required for a prospective plant to be built.

Pumped-storage plants require significantly high capital costs to build. Due to its low energy density, a large volume of water must be stored to make PHS plants viable for storage. Thus, extensive construction costs and equipment can spike up costs.

1.4 Floating Photovoltaics on reservoirs

A new innovation has been introduced lately, of placing floating photovoltaics on top of reservoirs. This hybrid system provides mutual benefits to both systems, however with several disadvantages as shown in Table 1 below.

Table 1: Pros and Cons of FPV

Advantages	**Disadvantages**
Reduced surface water evaporation	High Capital costs
Increased power output of PV due to lower Temperatures and cooling of water	High Operational costs
No land requirement	Electrical safety of building PV on water
Reduced risk of theft of equipment	Underdeveloped concept and no study of long-term environmental impacts
Reduced algae formation on water and improved water quality	Lack of permits and regulation procedures

1.5 Innovation

All renewable energy solutions face drawbacks and even the most mature technologies such as the ones mentioned earlier, could be potentially improved. Innovative solutions are being studied every day by large institutions, universities and companies, while investment and funding is being increased by governments and initiatives. Innovation is essential for the decarbonization of our grid, industry and economy.

1.6 Scope of report

The scope of this report focuses on a technical analysis of several drawbacks of Photovoltaic panels and pumped-storage hydroelectricity, as well as the mutual benefits arisen when combining the two. Moreover, the financial costs of PV's, PHS and hybrid FPV's plants are analyzed, while assessing the most important financial investment metrics in the short and long term. This report focuses on the following thesis:

"Evaluation of technical and technoeconomic mutual benefits of placing floating photovoltaics on pumped-storage hydroelectric dams."

1.7 Objectives

- Conducting a technical analysis of the drawback of Pumped Hydro-Storage and PV by conducting a literature review.
- Evaluating the technical benefits of FPV as a technology by conducting a thorough literature review.
- Undertaking an economic analysis that underline the costs of PV and PHS and how those costs increase using FPV
- Conducting a technical analysis of the benefits of placing Floating Photovoltaics on the efficiency of the cells as well as the water conservation of the dam.
- Developing a technoeconomic analysis of a hypothetical investment opportunity of installing FPV's
- Comparing results between two different dam locations with different sizes and characteristics.
- Identifying limitations and variables by conducting a sensitivity analysis and changing different parameters to observer the behavior of the final results.

1.8 Procedures and methods to be used

This report is based on the attainment of information from the web, articles and publications and not on the acquisition of raw data through practical experiments. Thus, for the technical analysis, the use of electrical formulas for power and energy in combination with acquired data will be used. For the economic analysis, the use of formulas from common metrics will be used, while reported economic figures will be extracted online. To perform the above calculations an Excel file will be used to speed up complex formulas and have a common data base. This will also allow the use of iteration procedures and optimizations of the system. **This thesis uses "." for thousands and "," for decimal points.**

1.9 Structure of document

The structure of the document is based on 4 sections. Section 1 is the introduction of the report, introducing basic information about the subject of this study, the scope and research question and procedures used. Section 2 is the literature review that evaluates current solutions in the field and compares them with the intended work of this study. Section 3 is the main body, which contains technical and economic calculations to evaluate the benefits of the proposed hybrid system, as well as a sensitivity analysis. Section 4 is the conclusion of the document, concluding the main points arisen by this investigation.

2. Literature review

This section will discuss current studies of floating photovoltaics, regarding the technology available on the industry and their drawbacks and benefits. Moreover, an evaluation of current reports on hybrid FPV- PHS systems will be conducted, focusing on the technical and economic assessments available. This comparison will give a clear picture of the current state of this technology and the differentiation of this report compared to existing ones.

2.1 Floating photovoltaics

As mentioned in the introduction section, photovoltaic faces several challenges in the field. However, by placing them on water, some of those drawbacks can be improved or even eliminated. A Floating Solar Photovoltaic (FPV) system refers to the action of placing photovoltaics on top of bodies of water to float, as depicted in Figure 4 below [6].

Figure 4: FPV

This system is very similar to conventional PV plants, but differs due to the need of a floatation system (floats), an anchoring and an evacuation plan. The floating system can have the form of 4 different types [7]:

1. **Pure**

In this system, the panels are placed above the floating structure. However, it is important to accurately measure the maximum tilt angle, to achieve the highest possible production. This is required to compensate for the extra costs arisen by using floating structures and anchors.

2. **Metallic**

Metallic systems are usually made of steel structures supported by a floating system, where the panels are also placed on. Such systems can offer a better cooling due to steel's thermal conductivity. In turn this can also improve the energy production of the system but can increase costs since steel is expensive.

3. Membrane

Membrane systems are floating membranes on water, in direct contact with panels that rest on them. This causes lower loads to the membrane since no extra material is required. The thickness of the membrane can be up to 1mm thick, allowing for a better thermal contact with panels, contributing positively to the heat dissipation. Figure 5 below [8], depicts Ocean Sun's membrane floating PV system, placed on the Philippines

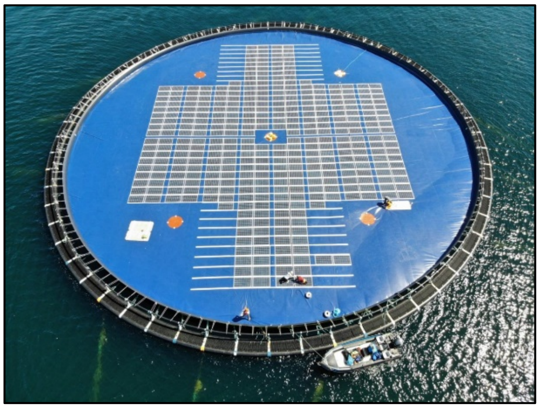


Figure 5: Ocean sun membrane [8]

4. Other

Other floating devices consist of alternative materials like iron and concrete but lack development and implementation.

The **anchoring system** is responsible for keeping the system still and at the same position. A topographical study of the water bed is required called a bathymetry, to analyze the depth and surroundings of the water. However, the system should have some degree of freedom, as the water level of lakes and dams can vary greatly depending on the month of the year. The most common types of anchors are detailed below and in Figure 6 [7].

1. <u>Bottom anchoring:</u> Anchor on seabed.
2. <u>Bank anchoring:</u> Anchor on ground above the sea water.
3. <u>Piles:</u> Piles are buried on the seawater and then the system is anchored on those piles.

Each of these types have advantages and disadvantages based on the location they are installed in.

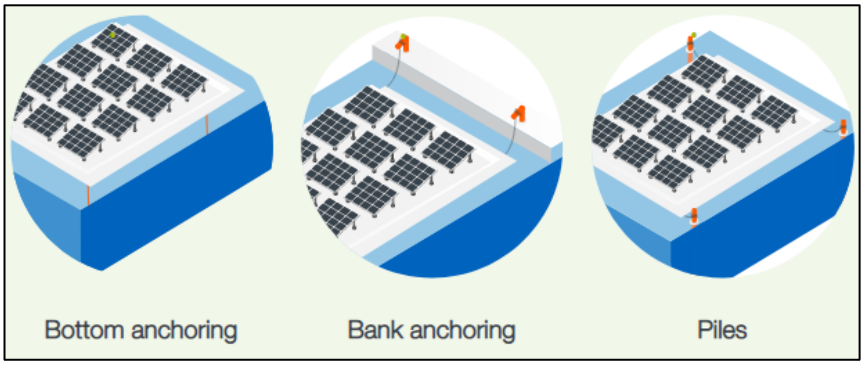


Figure 6: Types of anchors [7]

In 2021, a study conducted by Mohamad Al-Widyan et al. [9], 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. Even though this is an emerging technology, several plants have already been installed as depicted in Table 2 below [10].

Table 2: Existing FPV's

Floating Solar Farm	Capacity	Location
Saemangeum floating solar energy project	2,10GW	Yellow Sea, Saemangeum, South Korea
Omkareshwar Dam floating solar farm	600MW	Narmada river in Khandwa district of Madhya Pradesh, India
Hangzhou Fengling Electricity Science Technology’s solar farm	320MW	Cixi, Zhejiang Province, China
Three Gorges New Energy’s floating solar farm	150MW	Huainan City, Anhui Province, China
Cirata Reservoir floating photovoltaic (PV) power project	145MW	West Java province, United Arab Emirates
NTPC Kayamkulam solar project	105MW	RGCCPP Kayamkulam, Kerala, India
NTPC Ramagundam solar power plant	100MW	Peddapalli district, Telangana, India
CECEP’s floating solar project	70MW	Bengbu, in the province of Anhui, China
Sembcorp’s Tuas floating solar project	60MW	Tengeh Reservoir in Tuas, South Korea
Hapcheon Dam floating PV power plant	41MW	South Gyeongsang Province, South Korea

Most existing plants are installed in lakes and bodies of water and less in reservoirs. However, there is an increased trend and investment interest in FPV placement on dam reservoirs of gravity batteries. A study conducted by the National USA Renewable Energy Laboratory in 2019 [11], assessed the technical potential of FPV, as seen in Figure 7 below.

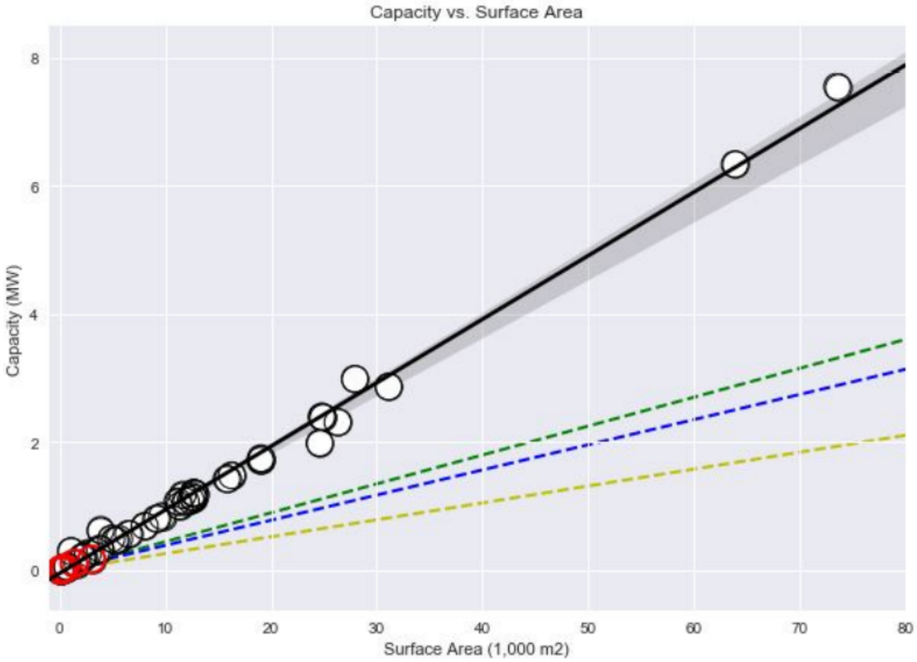


Figure 7: Capacity vs Surface area [11]

The red and black hollow dots represent current FPV projects. The solid black line gives a linear regression, while the rest of the dashed lines are average land-based trends installations. This figure indicates the great potential of large FPV farms, in bodies of water that are currently available and could provide a significant energy generation. Specifically, the global floating solar panel market is expected to reach 180,21 million euros in 2030; that is a significant increase from the current 35,59 million euros [12].

Floating photovoltaic costs differ significantly from conventional photovoltaics placed in-land, for the reasons stated previously. Extra costs are attributed to the enhancement of PV's when placed on water, as listed below:

- More secure support structures, commonly made of High-Density Polyethylene (HDPE) and need of anchoring.
- Water proof and marine grade wiring.
- Extra hydrodynamic and bathymetry surveys for site preparation
- Additional external loading factors such as waves, water currents and water level variations.
- Different tilt angles required

The listed additional requirements of FPV's can increase CAPEX and OPEX costs significantly. A study conducted by NREL 2021 (15), assessed and compared the system costs between FPV and PV of a 10 MW plant. Figure 9 below breaks down the cost differences of ground mount PV and FPV. 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 actually 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.

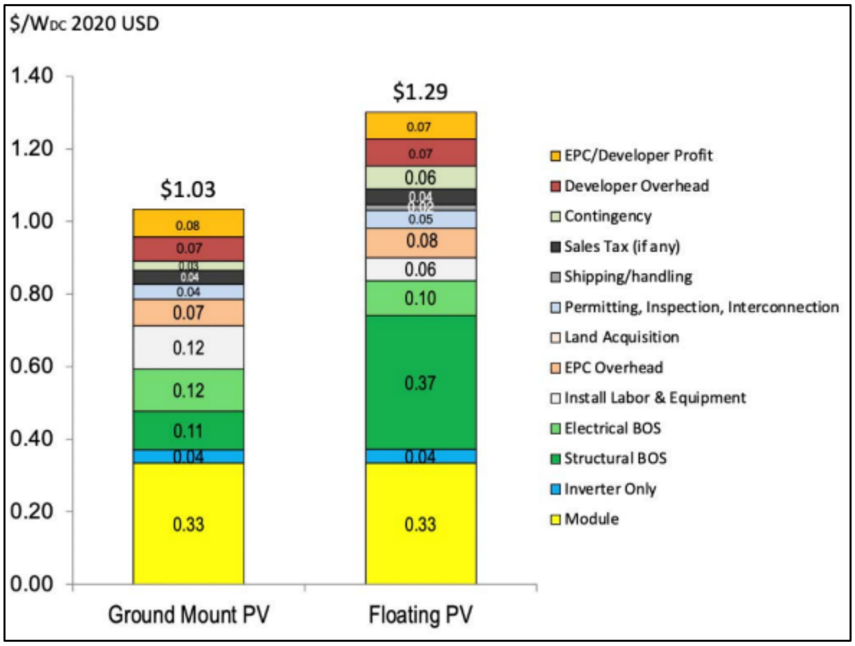


Figure 8: PV vs FPV costs [15]

Leonardo Micheli et al. 2021 [25] 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.

2.2 Hybrid Pumped Storage Hydropower with Floating Photovoltaics

As discussed previously in the Introduction, evaporation is the biggest challenge dams face. Thus, covering the surface of the water with objects can significantly reduce it. A study conducted by Lewis W.Farrar et al. [13], 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, as depicted in Figure 8. A study conducted by Haas J. et al. [14] 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.

Figure 9: Algae formation [40]

Luayao Liu et al. 2019 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 also 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.

2.3 Contribution

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.

3. Technical analysis

This section describes the system specifications that were selected including the location and solar panel. Moreover, geographical potential is presented in terms of solar irradiation and precipitation. Then the costs are revenues associated with the system are conducted and financial metrics are analyzed.

3.1 Methodology

The data used in this report was accessed from literature review and online datasets. All calculations were conducted on the basis of established technical and economic 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 [26].

3.2 Location selection

This study will evaluate the benefits of placing FPV on a reservoir in a European country. Greece has been chosen due to the high renewable penetration in the total share of the country's electricity generation. Specifically, it ranks 7th in combined wind and solar generation of the total share. This indicates a huge potential of sun in the country. Figure 10 shows the solar insolation in Greece. Moreover, Greece has a feasible hydropower potential of 20.000 GWh with many PHS projects in the pipeline. The reservoir that is going to be evaluated in this report is the project of Agios Georgios and Pyrgos in Amfilochia, which has been selected from the E.U as a Project of Common Interest. The project has completed all the technical studies and permits and is awaiting investment to be constructed. This study will provide information as to whether FPV implementation will help reduce the investment required or the LCOE, as well as the energy production.

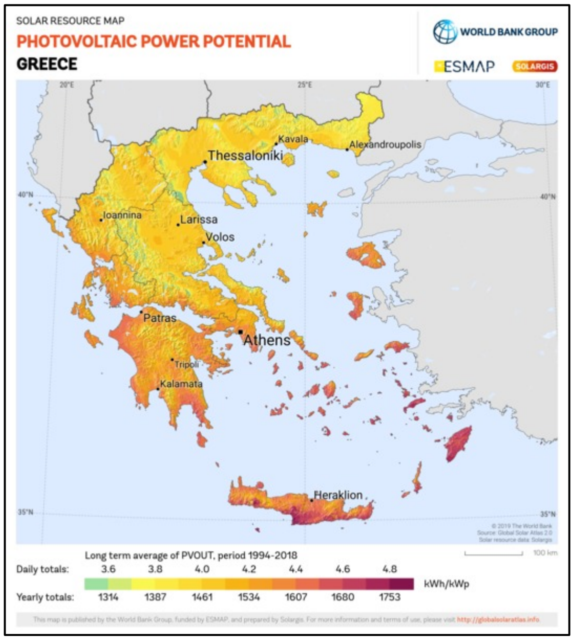


Figure 10: Solar insolation in Greece [41]

This location was selected for several reasons:

1. Relatively high solar insolation
2. Yearly temperatures above 10°C
3. Medium yearly precipitation and evaporation
4. Availability of various locations for hydro storage plants

The reasons stated above, allow the implementation of the proposed hybrid system to be beneficial. Insolation allows for adequate energy production, temperatures for the effect of cooling to increase PV cell efficiencies, medium precipitation and evaporation for dam water levels to benefit and geography for topographical feasibility.

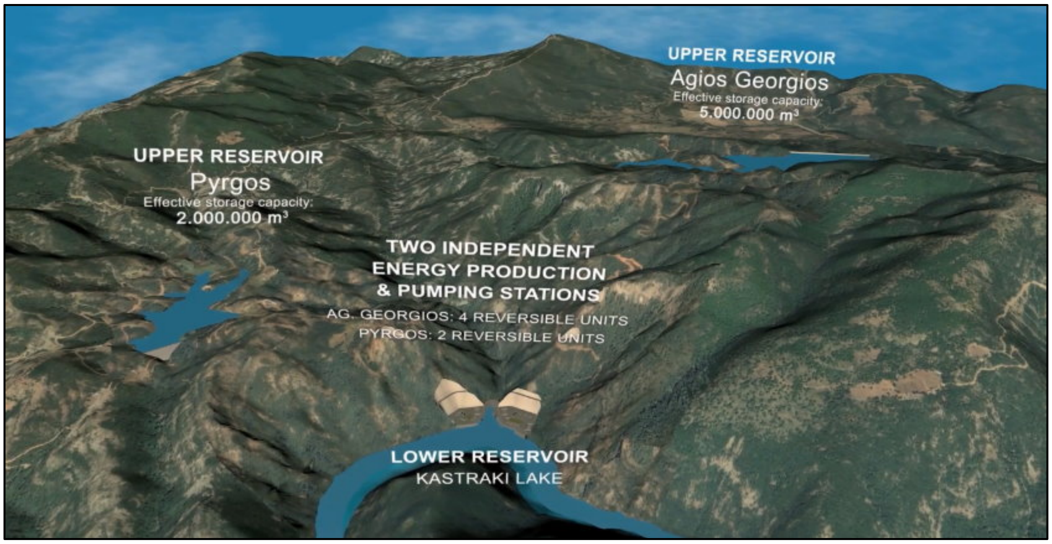


Figure 11: Reservoir location [16]

Two upper reservoirs have been identified with the lower reservoir being the Kastraki lake. The characteristics of the two upper reservoirs are depicted in the Figure 11 above and Tables 3 and 4 below:

Table 3: Reservoir A

Upper reservoir Agios Georgios (A)	
Total Reservoir Volume	$6{,}72 \times 10^6 m^3$
Effective volume	$5{,}08 \times 10^6 m^3$
Height	55,30 m
Surface area	0,79 km^2
Dam body volume	620.000 m^3
Flow rate (Pump)	176,39 $\frac{m^3}{s}$
Flow rate (Generator)	235,19 $\frac{m^3}{s}$
Gate shaft gross head	242,35 m
Length tunnel	2.037 m
4 Francis pump-turbine units	
Flow rate	58,80 $\frac{m^3}{s}$
Power	464 MW

Table 4: Reservoir B [17]

Upper reservoir Pyrgos (B)	
Total Reservoir Volume (m^3)	$2{,}42\ \times 10^6\ m^3$
Effective volume	$2{,}01\ \times 10^6\ m^3$
Height	56 m
Surface area	0,31 km^2
Dam body volume	160.000 m^3
Flow rate (Pump)	69,79 $\frac{m^3}{s}$
Flow rate (Generator)	93,06 $\frac{m^3}{s}$
Gate shaft gross head	289,35 m
Length tunnel	863m
2 Francis pump-turbine units	
Flow rate	46,53 $\frac{m^3}{s}$
Power	220 MW

Agios Georgios is a dam with more volume, a higher number of turbines as well as a longer length, however with a lower head. Thus, it has a bigger power capacity of 464 MW and will require significantly more investments. This study will evaluate the placement of FPV on both reservoirs and identify the pros and cons of each.

The projected investment exceeds €500 million and will create other opportunities for the local economy as well:

- More than 960 new jobs during construction and operation will be created
- The nearby road network will be improved
- Access to the area of farming facilities, agriculture, forest management and protection
- Touristic improvement of area and growth of alternative tourist attractions

In an effort to verify the total costs of the project, a brief cost analysis was conducted. The cost of an ATB Class 3 PHS is 2.214 €/ kW installed [27] Adapted to the selected system the total costs are:

CAPEX (€/ kW)	Total cost (Million €)
2.214	697

The costs calculated are significantly higher by 64,60% than what has been projected. One factor might be due to the fact that the reported cost is just a ballpark number. Moreover, NREL costs are extracted from studies conducted in the USA where costs might differ from Europe. Lastly, given the large investment requirement and complexity of such as project, cost estimation tends to overshoot while in the construction phase.

3.3 PV system selection

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.

Reservoir A

For every square meter of water surface, 88 Watts of FPV can be installed [18]. The reason behind the significantly lower wattage per m^2 installation capability, is due to the larger area required from the floating structures when tilting the panel and placing electrical circuits. Thus, for reservoirs A and B the total potential installed capacities are depicted in Tables 5 and 6 below.

Table 5: 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
20	158.000	13.904
30	237.000	20.856

Table 6: Reservoir B

Reservoir B		
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**
1	3.100	272,8
2,5	7.750	682
5	15.500	1.364
7,5	23.250	2.046
10	31.000	2.728
20	62.000	5.456
30	93.000	8.184

Regarding the characteristics of the panels, an existing flat plate generic model will be used. Specifically, the PERC Mono DBP 400 [19]. Table 7 below shows the specifications of this module.

Table 7: PV model

Specification	Value
Type	Monocrystalline cell (108 cells)
Power output range	400 - 415 Wp
Maximum efficiency	21,25%
Open circuit voltage	37,54 V
Short circuit current	13,52 A
Frame	Anodized aluminum alloy
Module weight	24 kg
NOCT	45 +- 2 °C
Lifetime	25 years

Based on the floating capacity per surface area mentioned previously, the number of panels installed for each reservoir are shown in Table 8 below.

Table 8: No of panels

No of panels	
Reservoir A	**Reservoir B**
1.738	682
4.345	1.705
8.690	3.410
13.035	5.115
17.380	6.820
34.760	13.640
52.140	20.460

3.3.1 CAPEX

Given that the selected dam has a huge surface area, the costs of installing FPV should be analyzed. CAPEX costs are capital expenditure costs, meaning all costs (Materials, operations, supply chain, etc.) required to install a system that happen only once. The costs compared to a land-based system (LPV) will also be conducted, to compare total costs. NREL's (15) projections were used for powers of 2, 5, 10 and 20 MW. The larger the capacity the smaller the costs, as the costs benefit from economies of scale, depicted in table 9. The study assesses monocrystalline cells of a slightly lower efficiency of 1.35%, thus costs are assumed to be the same for both types of cells.

Table 9: Capex costs for LPV & FPV

PV Type	Power (MW)	Costs (€/ Watt)
LPV	2	1,23
FPV		1,55
LPV	5	1,07
FPV		1,34
LPV	**10**	**0,95**
FPV		**1,19**
LPV	20	0,77
FPV		0,97

Linear interpolation was used to adapt costs to the study's scenarios. For any system size less than 2 MW, the same costs as for 2 MW were assumed to not over project costs, due to missing data below that capacity as indicated in table 10 and 11. Equation 1 shows the linear interpolation formula:

$$y = y_1 + (x - x_1) \times \frac{y_2 - y_1}{x_2 - x_1} \text{ (1)}$$

Table 10: Linear interpolation of CAPEX for Reservoir A

Reservoir A					
		LPV		FPV	
Coverage	**FPV Capacity (MW)**	**Capex (€/ W)**	**Total costs (Million €))**	**Capex (€/ W)**	**Total costs (Million €)**
0,01	0,695	1,23	0,86	1,55	1,07
0,025	1,74	1,23	2,14	1,55	2,69
0,05	3,48	1,15	4,01	1,45	5,03
0,075	5,21	1,07	5,56	1,34	6,97
0,10	6,95	1,02	7,12	1,28	8,91
0,20	13,90	0,88	12,22	1,10	15,30
0,30	20,86	0,77	16,09	0,97	20,15

Table 11: Linear interpolation of CAPEX for Reservoir B

Reservoir B					
		LPV		FPV	
Coverage	**FPV Capacity (MW)**	**Capex (€/W)**	**Total costs (Million €))**	**Capex (€/W)**	**Total costs (Million €)**
0,01	0,273	1,23	0,34	1,55	0,42
0,025	0,68	1,23	0,84	1,55	1,05
0,05	1,36	1,23	1,68	1,55	2,11
0,075	2,05	1,23	2,52	1,54	3,16
0,10	2,73	1,19	3,26	1,50	4,08
0,20	5,46	1,06	5,79	1,33	7,25
0,30	8,18	0,99	8,13	1,24	10,18

Figure 12 below depicts the relationship between total costs and installed capacity for PV. It is clear that as the PV coverage of the total dam is increased, the costs are also increased. However, the cost per capacity is decreased since larger projects benefit from larger quantity orders and less equivalent labor hours and equipment used. The costs shown in figure 12, follow an inversely exponential line, with LPV having increased lower costs for higher capacities.

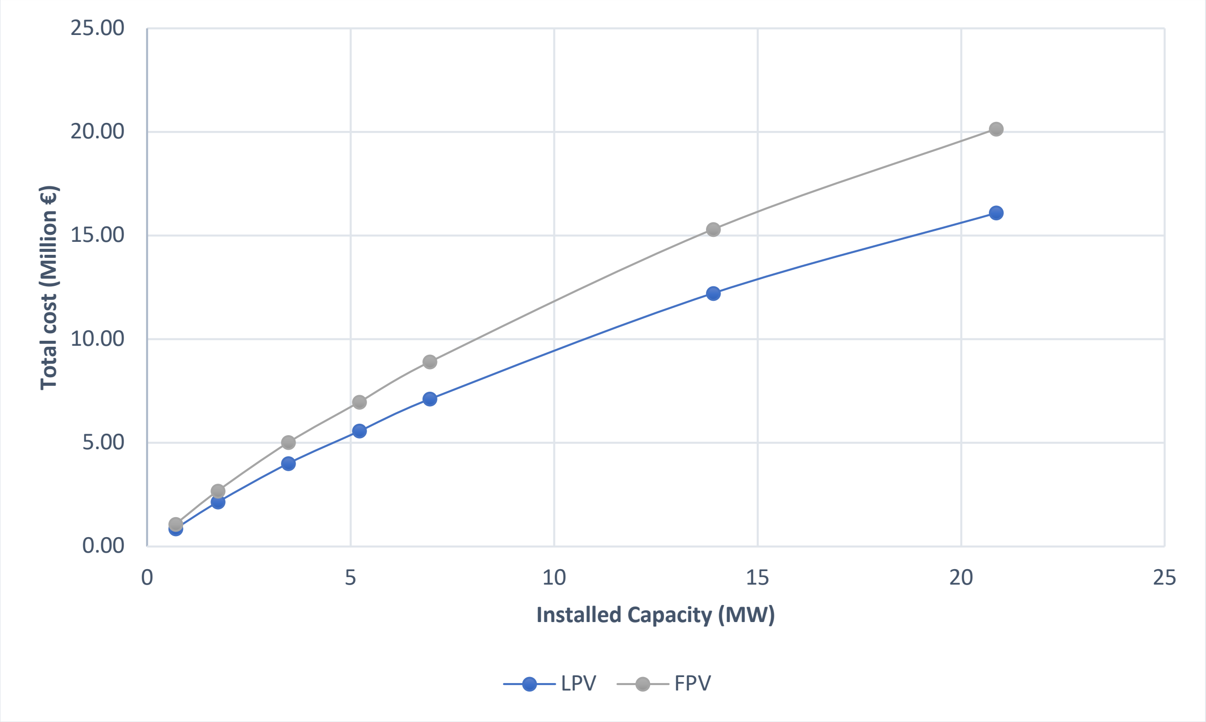


Figure 12: Total cost per installed capacity

3.3.2 OPEX

OPEX costs are operation and maintenance costs that occur periodically as the system needs to operate and be kept at an adequate level for optimal performance. Operation and maintenance costs for the selected Ground-Mounted PV system are calculated at **16,56 €/ kW year** [15]. O&M costs for PV can be accounted for different operations and repairs as listed:

- Plant operations & administration
- Module Cleaning
- Vegetation management
- Preventative maintenance
- Corrective maintenance
- Inverter and peripheral replacements

For FPV O&M costs, several installers claim that they are lower due to the lack of vegetation and fencing of sites, resulting to savings. However, other installers claim that FPV has increased costs due to the use of boats to access floating systems away from the shore, as well as divers required to operate anchoring and mooring placed underwater. Moreover, land leasing costs are not accounted for since they are already part of the dam costs. Thus, it is assumed that FPV costs are also at **16,56 €/ kW yearly.** Calculated for the two scenarios, the total OPEX costs throughout the lifetime of the system are shown in table 12.

Table 12: OPEX costs

	Reservoir A		Reservoir B	
Coverage	**FPV Capacity (MW)**	**OPEX (Million €/ year)**	**FPV Capacity (MW)**	**OPEX (Million €/year)**
0,01	0,70	0,012	0,27	0,005
0,025	1,74	0,029	0,68	0,011
0,05	3,48	0,058	1,36	0,023
0,075	5,21	0,086	2,05	0,034
0,1	6,95	0,115	2,73	0,045
0,2	13,90	0,230	5,46	0,090
0,3	20,86	0,345	8,18	0,136

3.4 Irradiation

The total irradiation and PV power generation at the selected location was extracted from the Global Solar Atlas, using the coordinates of the reservoirs (*38.806728°, 21.364131°*) [20]. Table 13 below shows the solar irradiation data and optimal positioning and Table 14 the monthly irradiation averages:

Table 13: Solar irradiation

Specific photovoltaic power output	PV OUT_specific	1.510,5	kWh/kWp year
Direct normal irradiation	DNI	1.677,1	kWh/m² year
Global horizontal irradiation	GHI	1.664	kWh/m² year
Diffuse horizontal irradiation	DIF	637,1	kWh/m² year
Global tilted irradiation at optimum angle	GTI_opta	1.887,7	kWh/m² year
Air temperature	TEMP	17,8	°C
Optimum tilt of PV modules	OPTA	31	°
Terrain elevation	ELE	142	m

Table 14: Average monthly irradiation

Month	**DNI kWh/m²**
Jan	97
Feb	97,6
Mar	124,9
Apr	127,3
May	161,1
Jun	201,9
Jul	224,9
Aug	201,1
Sep	149,7
Oct	128,8
Nov	95,5
Dec	84,9
Yearly	1.694,7

The selected location has adequate sunlight throughout the year, which indicates the financial upside of installing solar panels.

3.5 Electricity Markets in Greece

The electricity market of Greece is described below, to understand how price mechanisms work. The current electricity market in Greece is regulated by the Greek Regulatory Authority for Energy (RAE). The RAE is responsible for the overseeing of the energy market and for licensing activities related to electricity generation, such as the construction of new power plants. The market is divided into two main segments [28]:

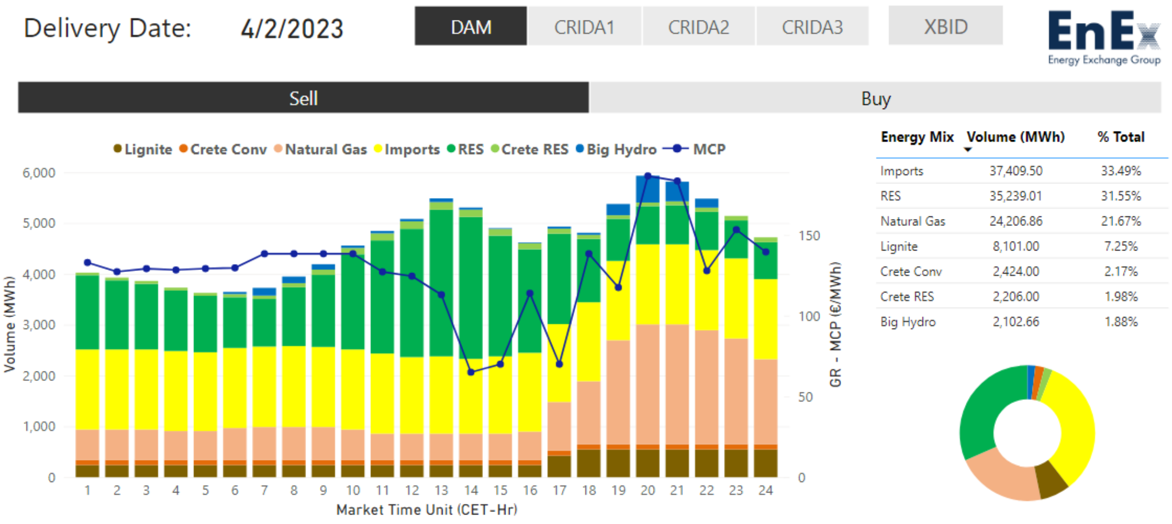
1. **The Wholesale market**

   This market consists of several players. Firstly, producers generate electricity and sell it to the transmission system operators (TSO). TSO's are then responsible for transmitting that electricity along the grid and to the distribution system operators (DSO). In turn, the DSO's scope includes successfully distributing that electricity to end users and consumers. An auction system is placed where producers can submit bids to sell their electricity to the TSO, who in turn selects the lowest cost bids until the volume required to cover the demand is satisfied. The Hellenic Energy Exchange (HENEX) is the operator of this market and is responsible for all trading.

2. **The Retail market**

   This market is where consumers purchase electricity from either the regulated electricity supplier or from a competitive supplier. The regulated electricity supplier is accountable for providing electricity to any end user that does chose to buy electricity from a competitive supplier. The retail market in Greece is liberalized, meaning that consumers can purchase electricity from any competitive supplier they want. These suppliers differ in pricing and contract options providing a large range of selections.

The overall market operates on several time frames such as the futures, which participants can buy large amounts of electricity for a given time in the future at a locked price. This guarantees no price fluctuations or future consumption. Another time frame is the day-ahead basis, which means that electricity for the next day is traded on the day before. In this time frame, a marginal cost market is used, which means that the price is based on the marginal cost of the last producing unit of electricity required to meet the demand. This is usually set by fossil fuels such as natural gas plants that are bought to cover the remaining demand required at the highest price and all other producers receive the price at which that source is bought. This gives an incentive to all producers to increase their efficiencies of operation and lower production costs, encouraging more cost effective and greener technologies like solar and wind. Figure 13 below depicts the wholesale market prices and volumes at the 2nd of March in 2023 [28].



Energy Mix	Volume (MWh)	% Total
Imports	37,409.50	33.49%
RES	35,239.01	31.55%
Natural Gas	24,206.86	21.67%
Lignite	8,101.00	7.25%
Crete Conv	2,424.00	2.17%
Crete RES	2,206.00	1.98%
Big Hydro	2,102.66	1.88%

Figure 13: Wholesale electricity prices [28]

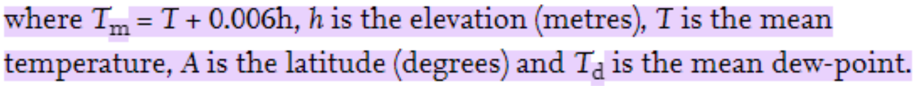
In 2021, the average price that photovoltaic electricity was sold at was **€ 0,068/ kWh or** as reported by HELAPCO [29] **,** so this value will be used in the report to estimate revenues.

3.6 Evaporation and precipitation

As mentioned previously, dams are subject to water evaporation due to heat and sunlight hitting water and causing it to evaporate and lose water. Nevertheless, when it is raining some of that evaporated water can be replenished and thus a cycle is kept to refill the dams naturally. In this section the net water loss resulting from – evaporation and precipitation.

The evaporation rate of the two reservoirs was calculated using the Penman formula [21], as indicated below in Equation 2. This evaporation rate is calculated for a body of water at the selected location with no coverage.

$$E_0 = \frac{700\ T_m/(100-A)+15(T-T_d)}{(80-T)}(\text{ mm day}^{-1}) \tag{2}$$



where $T_m = T + 0.006h$, h is the elevation (metres), T is the mean temperature, A is the latitude (degrees) and T_d is the mean dew-point.

The elevation and mean temperature were found using the solar atlas.

- *H = 142m*
- *A = 38,806728°*
- *T = 17,8 °C*

To find the dew point temperature, a psychometric chart of figure 14 was used at 18 degrees and 95% humidity [22].

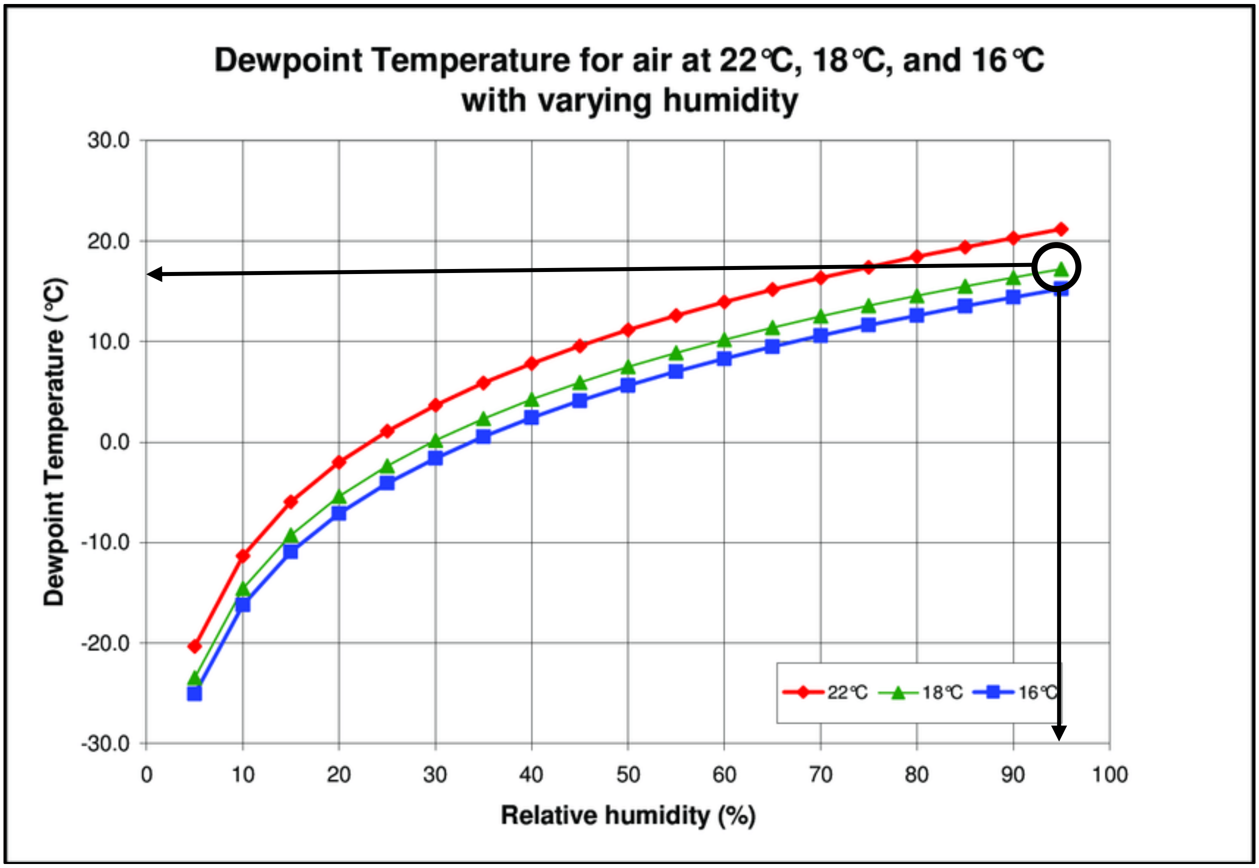


Figure 14: Dewpoint temperature [22]

Using a humidity of 95% and a temperature of 18At the temperature of 18 °C we are able to find the dewpoint temperature at 16,5 °C.

Thus, using Equation 2, the average evaporation is -3,744 mm per day throughout a year. In a year this amounts to -1.366,56 mm. The precipitation for the province of Aitiolocarnania was extracted using a climate portal [23] and is +795,65 mm per year.

Summing the negative evaporation and positive precipitation, the total water lost from a reservoir at the selected location is expressed in Equation 3:

$$\boldsymbol{Net\ loss = 795,65 - 1366,56 = -570,91\ mm\ per\ year}\ \textbf{(3)}$$

Thus, the reservoirs lose -570,91 mm of water per year. Table 15 below, converts this loss to the equivalent volume loss by multiplying by the surface area of each reservoir.

Table 15: Reservoir volume loss

Reservoir A	**Reservoir B**
- 450.956 $\boldsymbol{m^3}$	- 176.958 m^3

It should be noted that the values derived are average values and will differ in real time as increased or decreased precipitation as well as high or low temperatures will cause different final results. However, the average derived value is significant and unsustainable meaning that the net loss is negative. This underlines the issue of increased temperatures and global warming leading to water shortages that also affect pumped storage lakes.

3.6.1 Evaporation Costs

As described in section 4.5, a net loss of water due to higher evaporation than precipitation leads to a significant amount of water being lost. However, this loss water equals high costs for a hydro storage dam that depends on the availability of water to pump, store and release energy. This can in turn lead to higher prices that pumped hydro plants sell energy at, affecting the national electricity market prices. An average estimation of the cost due to this evaporation is calculated below. The methodology is outlined in several steps:

1. Pumped Hydro Storage is used to store energy during hours of excess supply and later discharge it during hours of less supply. For this reason, it is assumed that PHS electricity is sold in the day ahead market due to its high flexibility and dispatchability. As mentioned earlier, Greece's spot market is based on a marginal market and thus all generators will sell energy at the price set by the last generator covering the remaining demand. As PHS is an energy storage carrier, it has the flexibility to sell its energy at the highest price due to the high demand of dispatchability. Figure 15 below shows the pumped hydro cost in the spot market in Greece for April 2023.

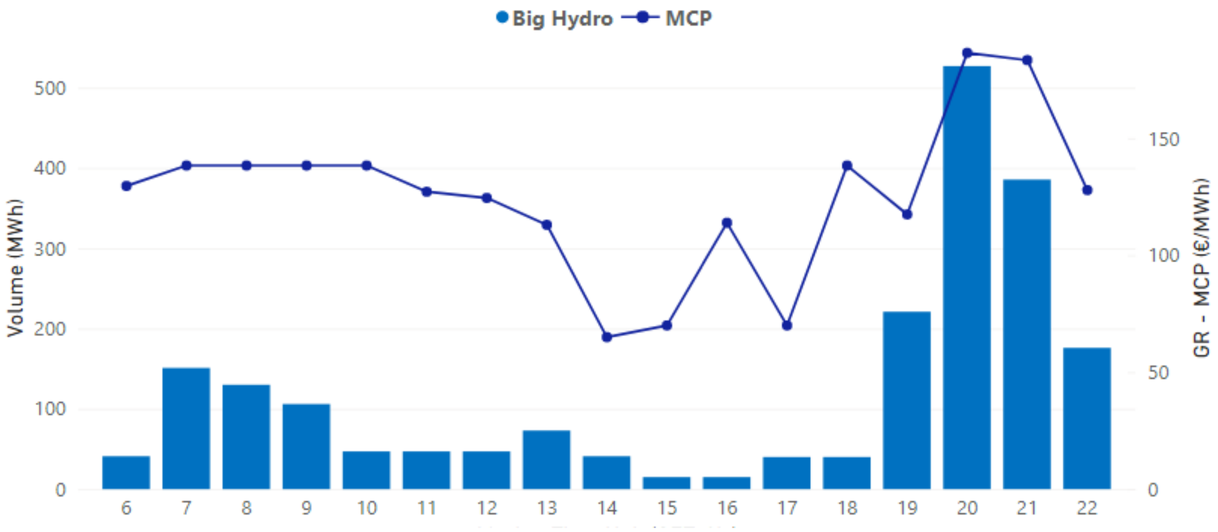


Figure 15: Hydro storage prices [28]

The highest price at 20:00 of **186,65 €/ MWh** [28], is used for the calculations, as it covers the period of the highest demand, which will generate the largest amount of electricity during that hour to leverage high prices.

2. The potential energy of a reservoir is $E = m \times g \times h\ [Joules]$. This is used to calculate the amount of energy that will be generated when the PHS plant is in a turbine mode and water flows from the upper reservoir to the lower. To convert joules into kWh, a division by $3{,}6 \times 10^6$ is required.
3. The average roundtrip efficiency of PHS worldwide is 70-85%, thus an average efficiency of $n = 80\%$ [27] is used. Roundtrip efficiency takes into account the energy lost during pumping and generating and provides a better accuracy of the total losses. However, it should be noted that efficiencies depend on several conditions such as equipment use and topography and will differ heavily in each power plant.
4. To calculate the energy per cubic meter we express mass in terms of volume using $Mass = \frac{Density}{Volume}$, using the density of water. Water's density changes with temperature and will lower for higher temperatures. Figure 16 below indicates the relationship between the density of water and temperature. As outdoor temperatures around the year are 17,8 °C, water temperatures will range between 0-25°C. An average density of $\rho = 998 \frac{kg}{m^3}$ is used [30].

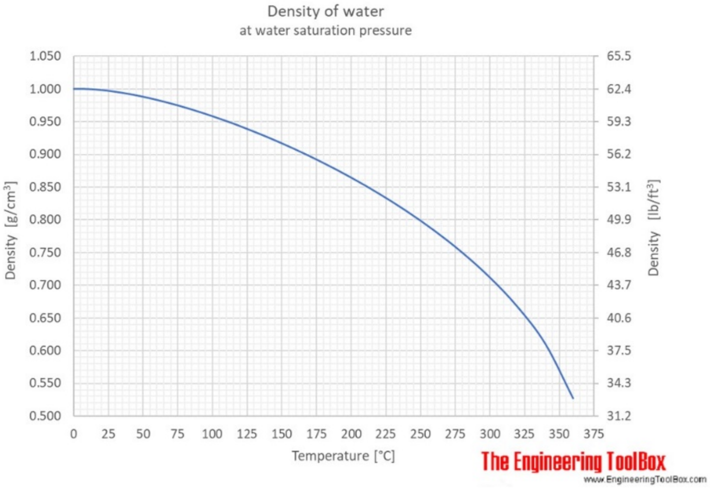


Figure 16: Density and temperature of water

5. Expressing the mass in terms of volume and rewriting the equation in terms of energy per volume, as well as taking into account the roundtrip efficiency we derive $\frac{E}{V} = \rho \times g \times h \times n\ [\frac{Joules}{m^3}]$.
6. Reservoir's A height at 55,3m and Reservoir's B height at 56m.

Table 16 below shows the theoretical energy per cubic meter for PHS, based on the methodology outlined above.

Table 16: Energy per cubic meter

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

The total losses only due to evaporation of water lead to €10.000 per year for Reservoir A and €3.974 for Reservoir B. Even though these costs might seem low compared to the total costs, when summed up during the total lifetime of a PHS plant which is 100 years [31] for the dam construction, they amount to € 1 Million of present value costs. It should be noted that this cost was derived as an approximation of total evaporation costs translated for a PHS plant and should not be used as a reference number for cost model but rather as an order of magnitude.

3.7 Floating structure selection

The floating structure selected are pure plastic floating pontoons. Plastic pontoons are typically made with high density polyethylene or polypropylene. They have several advantages such as durability and resistance to corrosion and degradation caused by salt water. Also, they are lightweight and easy to install and maintain.

The pontoons will be anchored with banks for stabilization and pointed towards the equator. Several types of bank anchoring exist:

- Fluke anchors
- Mushroom anchors
- Plow anchors

An azimuth of 180 degrees will be used and no tilting for the PV panels. Figure 17 shows an example of a tilting FPV.

Figure 17: FPV tilting example

- Such structure allows for any size of panel arrays to be installed
- Only a few metal parts are used, avoiding corrosion due to water
- The platform can withstand small movements in the water
- Cost effective

3.8 Data analysis

3.8.1 Energy production increase

As mentioned previously, 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 Equation 4 below:

$$P = I \times V = I_{SC} \times V_{OC} \quad (4)$$

Thus, it is clear that if the open-circuit voltage drops, then the power output of the cell will also decrease. Figure 18 below, depicts how these two values behave at different temperature and how the power output is affected.

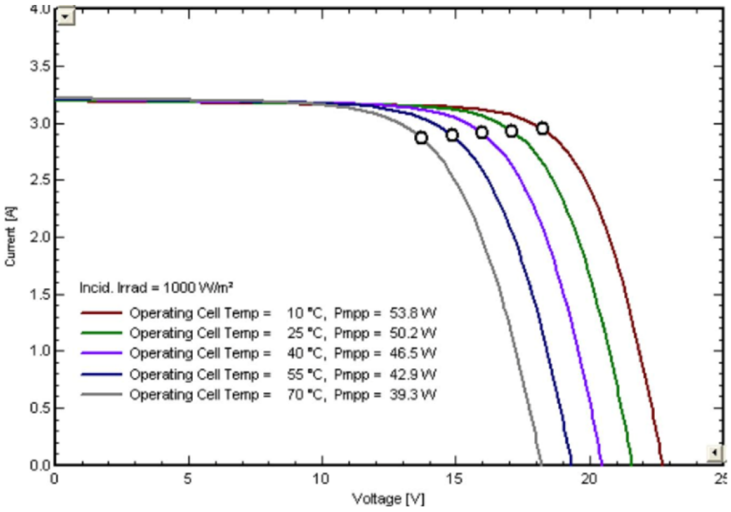


Figure 18: Voltage vs current [23]

PV Energy production at ambient temperature

To calculate the energy produced without the cooling effect at the selected location, several formulas, data and assumptions were used and taken by the PV manufacturer leaflet.

1. Maximum efficiency of PV at 21,25%
2. Nominal Operation Cell Temperature at 45 +- 2 °C
3. Power output at 415 Watts
4. Temperature at Standard Test Conditions at 25 °C
5. Energy calculated using Equation 5: $E = A \times r \times H \times PR$ (5)

A: Total solar panel area (m^2)	*H:* Annual average solar irradiation
R: Solar panel yield	*PR:* Performance ratio

6. For the performance ratio, the following assumptions were taken:
    a. Inverter losses = 5%
    b. DC cable losses = 1,5%
    c. AC cable losses = 1,5%
    d. Losses at weak radiation = 5%
    e. Losses due to dust = 2%
    f. Shading losses = 10%
    g. This sums to a PR = 0,75

Table 17 below shows the energy output for the two reservoirs using the assumptions mentioned previously.

Table 17: Energy output

Reservoir A			
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**	**Energy (GWh)**
1	7.900	695,2	2,11
2,5	19.750	1.738	5,28
5	39.500	3.476	10,56
7,5	59.250	5.214	15,84
10	79.000	6.952	21,12
20	158.000	13.904	42,24
30	237.000	20.856	63,35
Reservoir B			
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**	**Energy (GWh)**
1	3.100	272,8	0,83
2,5	7.750	682	2,07
5	15.500	1.364	4,14
7,5	23.250	2.046	6,21
10	31.000	2.728	8,29
20	62.000	5.456	16,57
30	93.000	8.184	24,86

PV Energy production without cooling effect

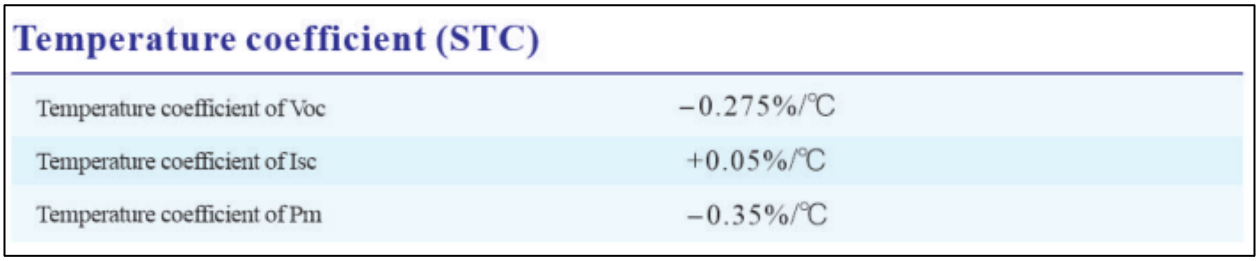
Now the effect of cooling on the panels will be taken into account to calculate the performance improvement of the array. Firstly, the temperature of the PV cell will be calculated using Equation 6:

$$T_{Cell} = T_{air} + \frac{NOCT - 20}{80} \times S \ (6)$$

Tcell: Cell temperature	*NOCT:* Nominal Operating Cell Temperature
Tair: Air temperature	*S:* insolation

For an average yearly sunlight exposure of 2756 hours, the air temperature is 18oC and the average temperature of the cell is **37C.** Taking into account the temperature coefficients shown in Table 18.

Table 18: Temperature coefficients [19]



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 before, 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**. The detailed calculations can be found in the Annex. The new energy calculations for that temperature drop are shown in Table 19 below:

Table 19: Energy production

Reservoir A			
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**	**Energy (GWh)**
1	7.900	695,2	2,023137468
2,5	19.750	1.738	5,05784367
5	39.500	3.476	10,11568734
7,5	59.250	5.214	15,17353101
10	79.000	6.952	20,23137468
20	158.000	13.904	40,46274936
30	237.000	20.856	60,69412404
Reservoir B			
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**	**Energy (GWh)**
1	3.100	272.8	0,793889386
2,5	7.750	682	1,984723465
5	15.500	1.364	3,969446931
7,5	23.250	2.046	5,954170396
10	31.000	2.728	7,938893861
20	62.000	5.456	15,87778772
30	93.000	8.184	23,81668158

PV Energy production with cooling effect

Now taking into account the cooling of the panels from the water of the lake, there is a drop in the temperature of the cells. Depending on the type of contact of the floating structure with water, different cooling will be applied. For this study, there is no direct contact of the array with water but directly with the floating structure. Thus, convective, conductive and radiation heat losses are taken into account. In this study, the numerical temperature is extracted from a report conducted by the Norwegian University of Life Sciences. Specifically, a 6 $°C$ drop at the back-surface of the modules is assumed [24].

Using the same methodology as without the cooling effect, the new Cell temperature will be $\mathbf{31°C}$. The new temperature difference from STC $\mathbf{6°C}$. 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. The new energy calculations for that temperature drop are shown in Table 20 below:

Table 20: New energy production

Reservoir A			
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**	**Energy (GWh)**
1	7.900	695,2	2,07
2,5	19.750	1.738	5,17
5	39.500	3.476	10,34
7,5	59.250	5.214	15,50
10	79.000	6.952	20,67
20	158.000	13.904	41,35
30	237.000	20.856	62,02
Reservoir B			
Coverage (%)	**Surface area (m^2)**	**FPV Capacity (kW)**	**Energy (GWh)**
1	3.100	272,8	0,81
2,5	7.750	682	2,03
5	15.500	1.364	4,06
7,5	23.250	2.046	6,08
10	31.000	2.728	8,11
20	62.000	5.456	16,22
30	93.000	8.184	24,34

The power losses improve by 2,1 % compared with no cooling. It is clear that the energy produced is improved if the cooling of the PV cells is taken into account. Specifically, the performance improvements are depicted in Table 21 below:

Table 21: Performance improvement

Performance Improvement	
Efficiency (%)	+ 2,192
Energy (MWh)- At 1% coverage	+ 44,348

3.8.1.2 Revenue increase

The improvement in energy production due to the efficiency gains by the cooling effect, will also lead to higher revenues. Having the PV system specifications selected, as well as the irradiation data, we can calculate the revenues associated with selling the generated electricity to the grid

As described in Section 4.4, 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 is 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. As found earlier, the energy improvement of 2,19% equals a revenue increase of 2,19%.

Table 22 below shows the yearly revenues from the selected installed capacities, for the two reservoirs assuming land-based PVs at a cell temperature of $37°C$.

Table 22: Yearly revenues

Reservoir A		
Coverage	**FPV Capacity (kW)**	**Revenue (Million €)**
1	695	0,138
2,5	1.738	0,344
5	3.476	0,688
7,5	5.214	1,032
10	6.952	1,376
20	13.904	2,751
30	20.856	4,127
Reservoir B		
Coverage	**FPV Capacity**	**Revenue (Million €)**
1	273	0,054
2,5	6.82	0,135
5	1.364	0,270
7,5	2.046	0,405
10	2.728	0,540
20	5.456	1,080
30	8.184	1,620

Table 23 depicts the increased revenues resulting from the FPV cooling effects.

Table 23: Revenues from cooling effect

Reservoir A		
Coverage	**FPV Capacity (kW)**	**Revenue (Million €)**
1	695	0,141
2,5	1.738	0,351
5	3.476	0,703
7,5	5.214	1,054
10	6.952	1,406
20	13.904	2,812
30	20.856	4,218
Reservoir B		
Coverage	**FPV Capacity**	**Revenue (Million €)**
1	273	0,055
2,5	682	0,138
5	1.364	0,276
7,5	2.046	0,414
10	2.728	0,552
20	5.456	1,103
30	8.184	1,655

Table 24, below shows the total increased revenues.

Table 24: Increased revenues

	Reservoir A	**Reservoir B**
Coverage	**Δ revenue (Thousand €)**	
1	3,0	1,2
2,5	7,5	3,0
5	15,1	5,9
7,5	22,6	8,9
10	30,2	11,8
20	60,3	23,7
30	90,5	35,5

There is a noticeable revenue increase due to the cooling effect of several thousand euros. It should be noted that selecting a location with higher temperatures would result to a higher efficiency improvement and thus higher revenues. There is a clear benefit to solar panel generation which leads additional revenue for the solar farm owners.

3.8.2 Evaporation reduction

To calculate the evaporation reduction by placing FPV on the dam, the covered surface area has to be taken into account. Moreover, it is assumed that from the covered surface area, 5% is still evaporated from sunlight penetrating through the structure by reflection and heat. Thus, the total potential reduction compared to the evaporation without any FPV, for the two reservoirs is indicated in Table 25 below.

Table 25: Evaporation reduction

Reservoir A		
PV Coverage (%)	**Evaporation avoidance (m^3)**	**Evaporation reduction (%)**
1	-4.114,56	-0,91
2,5	-10.286,4	-2,28
5	-20.572,8	-4,56
7,5	-30.859,2	-6,84
10	-41.145,6	-9,12
20	-82.291,3	-18,25
30	-123.437	-27,37
Reservoir B		
PV Coverage (%)	**Evaporation avoidance (m^3)**	**Evaporation reduction (%)**
1	-1.614,58	-0,91
2,5	-4.036,44	-2,28
5	-8.072,88	-4,56
7,5	-12.109,3	-6,84
10	-16.145,8	-9,12
20	-32.291,5	-18,25
30	-48.437,3	-27,37

Pumped Hydro storage plants use water for power generation and are relying on a consistent supply of water around the clock. Thus, when water is lost due to evaporation or leakages, the amount of energy that can be generated decreases, resulting to lower revenues gained by the plant. Moreover, losing significant amounts of water reduced the reliability of a hydro storage plant which is its main advantage. Losing an adequate amount of water below the set threshold may even shut down a plant completely to prevent damage to equipment. Taking into account local wildlife, losing water may have a negative impact on local biodiversity such as reduced water flows impacting aquatic habitats or availability of water for irrigation.

The evaporation reduction achieved by the proposed FPV is translated into increased revenues below.

To calculate the energy generated by a hydro storage dam equation 7 is used:

$$E = \frac{(\rho \times V \times g \times H)}{3{,}6 \times 10^{6}} \quad (7)$$

- E: Energy [kWh]
- P: Density
- V: Volume [m3]
- G: Gravitational acceleration
- H: Head height [m]

Calculating the energy per volume gained for the two reservoirs we get:

- Reservoir A: 0,1188 kWh/ m3
- Reservoir B: 0,1203 kWh/m3

Table 26 below shows the total cost avoided by due to the evaporation reduction benefit.

Table 26: Total avoided costs

Reservoir A		
Coverage (%)	Energy equivalent (kWh)	Cost (€)
1	-489	-91
2.5	-1222	-228
5	-2444	-456
7.5	-3666	-684
10	-4888	-912
20	-9777	-1825
30	-14665	-2737
Reservoir B		
Coverage (%)	Energy equivalent (kWh)	Cost (€)
1	-192	-36
2.5	-480	-90
5	-959	-179
7.5	-1439	-269
10	-1918	-358
20	-3837	-716
30	-5755	-1074

The benefit in terms of revenue is not significant but still positive at a magnitude of thousands of euros. In a better context, over the lifetime of the plant which is 100 years, the total costs avoided can range from 9 – 107 thousand euros, depending on the solar coverage of the dam.

4.0 Financial analysis

Section 5 contains a detailed financial analysis of the proposed system. Specifically, this part analyses the LCOE of LPV and FPV as well as several investment indicators such as the Return On Investment, Net Present Value, Payback Period and the Internal Rate of Return. Taxes have not been taken into consideration in this study and it should be noted that the financial metric calculated below are likely to differ and be closer to estimates given by studies, once taxes have been added.

4.1 LCOE

To calculate the levelized cost of energy for 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.

To calculate the LCOE equation 8 is used:

$$LCOE = \frac{\sum \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}} \quad (8)$$

It: Initial cost of investment/ CAPEX

- LPV: 4,36 Million euros
- FPV: 5,46 Million euros

Mt: Maintenance and operational expenditures/ OPEX

- LPV=FPV= 0,057Million euros
- The solar panels selected have a total lifetime of 25 years.

Ft: Fuel

- No fuel is used for solar panels

Et: Sum of all generated energy

- LPV: 253 GWh
- FPV: 258 GWh

R: Discount rate

The discount rate is a key factor in the development of renewable projects such as solar. It is used to calculate the present value of future cash flows generated by the project and to evaluate the financial feasibility of the investment proposal. In Greece, the discount rate can vary regarding several factors such as the risk profile, the cost of capital and the market conditions. As a rule of thumb discount rates tend to be between 7 – 10% [32] for projects. However, latest market trends show that the average discount rate in Europe dropped to 5,5% [33] in 2018. Given the climate targets set by the European Union, the European Investment Bank has started providing financial aid for the development of renewable energy projects. The EIB uses a benchmark discount rate around 5-7% depending on the risk of the project. As solar is a relatively safe investment with a projected energy production that can be accurately predicted, a discount rate of **5,5%** is used in this report. It is assumed that a relatively large company with a large equity and low debt is funding this project, so it can ask for a low discount rate.

The LCOE derived is shown in the table 27 below:

Table 27: LCOE

Type of PV	**LPV**	**FPV**
LCOE (Euros/ MWh)	**33,32**	**39,53**

The LCOE calculated is lower for LPV than FPV, due to the higher upfront cost of the floating photovoltaics. The energy increase of the FPV isn't enough to compensate for the price increase due to the additional structural requirements. When looking at the industry, the average LCOE for solar in 2021 was 32,11 Euros/ MWh which is in line with the LCOE calculated in this report. It is worth to note that 32,11 euros/ MWh is an average estimate and the LCOE of solar differs country by country. Higher solar insolation and labor and material costs will have a substantial effect on the final LCOE. The higher cost by 6 euros/ MWh is significant and will require substantial R&D as well as subsidies from governments and the European Union, to bring capital costs down and become competitive with land based solar. It is worth to note that 2023 was the only year in which solar PV's LCOE increase compared to the previous year at 54,70 euros per MWh [34]. This could have resulted due to several reasons:

- <u>Changes in policies and regulations:</u> Government policies and regulations have a significant impact on the financials of an investment such as changes to tax credits, increasing the costs of solar development and thus a higher LCOE.
- <u>Increase in equipment costs:</u> Even though the cost of equipment has been going down in the past years due to economies of scale, a very large demand for solar has caused disruptions in the material supply chains; Such as a shortage of raw materials like silicon. This shortage may have resulted to higher prices for the raw materials PV cells are made from.

- Rising interest rates: As inflation has significantly increased in the years following the COVID – 19 pandemic, governments are trying to reduce it to tackle high prices via increasing interest rates. However, increased interest rates cause the cost of borrowing money to increase. Developers are now facing higher costs to get debt financing that can lead to a higher LCOE.
- Infrastructure costs: As substantial infrastructure is required to connect remote solar farms with the grid, the cost of this infrastructure may have increased as well. This raises the overall capital expenditure needed for projects
- Labor costs: Inflation has caused higher costs and salaries have also increased, this results to higher CAPEX as well as operational and maintenance costs throughout the year that can cause higher LCOE.

4.2 Return On Investment

Return On Investment is a financial metric that is used commonly to evaluate the profitability of an investment. It measures the net gain or loss from an investment to the initial cost. Equation 9 below was used to calculate the ROI.

$$ROI\ (\%) = \frac{Final\ investment - Initial\ investment}{Initial\ investment} \times 100\ (9)$$

It is an important metric as it helps to identify which investment can return a large profit compared to other options. Typically, solar investments have a ROI of 10% [35] as they are considered a relatively safe investment option with a guaranteed return. Solar insolation can easily be predicted in the coming months and tends to be of the same magnitude between years. Table 28 shows the detailed ROI values derived.

Table 28: ROI values

	LPV	FPV
Cost of investment (Euros)	5.452.361	6.465.427
Energy (kWh)	10.115.687	10.337.430
Energy cost (Euros per kWh)	0,068	0,068
Time period (Years)	25	25
Final value of investment (€)	17.196.668	17.573.631
ROI (%)	**215**	**172**

The return on investment calculated for LPV is **215%** and for FPV is **172%.** Again, the ROI is lower for FPV due to the higher investment required, even though the energy produced is larger. However, this ROI has been calculated using a fixed cost at which solar electricity is sold at 0,068 Euros/ kWh. It is likely that electricity prices can spike up or lower depending on the geopolitical state of countries and Europe. Some of the causes that can cause this happen include the following:

- Policies and regulations: States can impose policies and regulations related to energy production and consumption which can affect electric prices. Some countries tend to subsidize energy production which leads to lower energy prices to consumers. Moreover, countries that impost strict environmental regulations such as imposing taxes on carbon emissions may cause higher prices of energy due to the cost of mandatory compliance.
- International trade: Countries that rely heavily on imports of specific fuels likes natural gas energy production, might have higher electricity prices if those sources become more expensive due to tariffs or trade restrictions.
- Resource availability: Limited resources and shortages such as natural gas will cause prices to increase while the demand for them remains the same.
- Political instability: Political unrest can disrupt energy production or distribution, causing prices to rise. Examples such as the Russian – Ukraine war has led to sanctions imposed by the European Union and Russia limiting its supply of natural gas to Europe, causing prices to increase significantly in all European states.

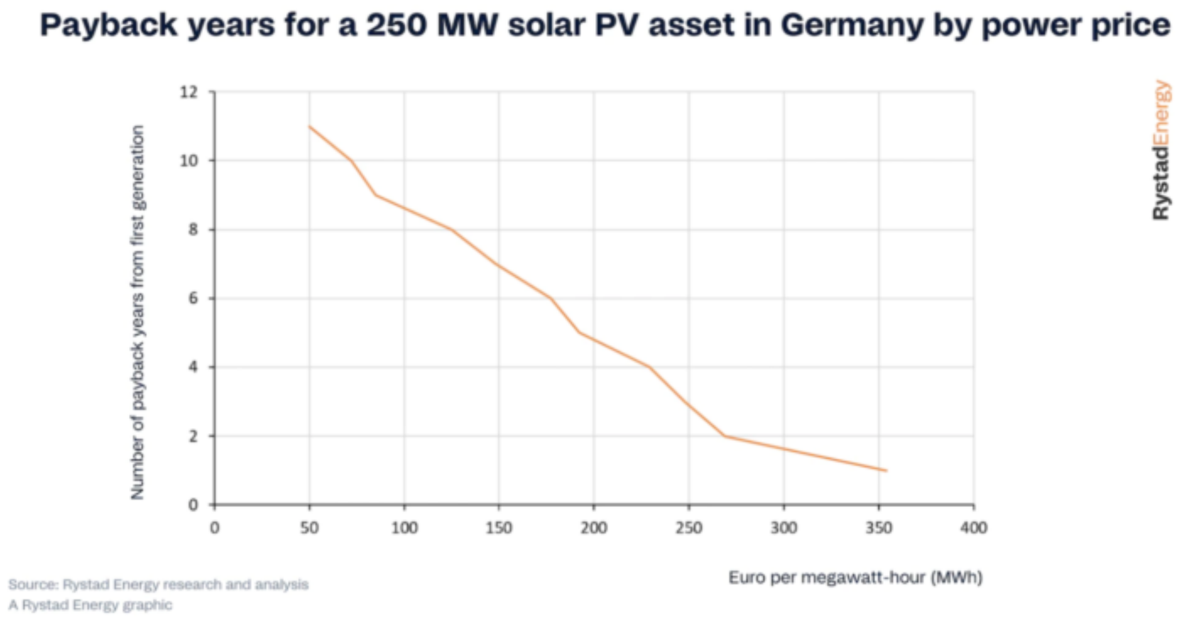
However, it's important to note that ROI is just one of many metrics used to evaluate investment performance. Other metrics have to be taken intro consideration to evaluate an appropriate investment. These include the payback period, internal rate of return and net present value that provide a more comprehensive view of an investment's performance.

4.3 Payback period

The payback period is a metric used to evaluate the time required for an investment to recoup its initial cost back. Projects with shorter payback periods are considered more desirable as it allows to reinvest capital in other projects sooner. Equation 10 is used to calculate the payback period.

$$Payback\ period = \frac{Investment\ costs}{Annual\ cash\ flows}\ (10)$$

The payback periods were calculated at 6,37 and 7,88 years for LPV and FPV respectively. The average payback period of solar investments is between 6-10 years depending on the location and prices that electricity is paid at. However, the payback period can significantly decrease as a solar farm increase in size due bringing down costs. A study conducted in 2022, found that solar systems installed in Germany could achieve payback times of less than a year, as indicated in figure 19 below. At 0,068 euros/kWh a payback period of around 10 years would be achieved, for a larger solar park of 250 MW. However, given that Greece has a much higher solar irradiation than Germany, the payback period would be lowered due to the higher capacity factor. Moreover, it is worth to note that taxes haven't been applied and if they were taken into account, the payback period would be higher, as depicted in figure 19 below.



Source: Rystad Energy research and analysis
A Rystad Energy graphic

Figure 19: Payback period for solar [36]

However, the payback period does not consider the time value of money and does not take into account the fact that money received in the future has a lower value than in the present due to inflation and the higher cost of goods.

4.4 Net Present Value

The Net Present Value is a metric used to evaluate the profitability of an investment in terms of present value. The future cash flows as well as the initial cost of investment are taken into account when calculating the NPV. This is a valuable metric as the same amount of money in the future compared to today has a lower value since the costs of goods increase with years. The NPV was calculated using equation 11 below:

$$Net\ Present\ Value = \sum_{t=0}^{n} \frac{Cash\ Flow_n}{(1+r)^n}\ (11)$$

The Net Present Value for LPV was calculated at €4,21 Million and for FPV at €3,44 Million considering a lifetime value of the project of 25 years. For both cases the project achieves a positive NPV indicating the feasibility of solar investments. However, LPV once again outperforms FPV due to the higher costs.

4.5 Internal Rate of Return

The Internal Rate of Return is a metric that determines whether an investment is likely to generate a return that exceeds the cost of capital. If the IRR is higher than the cost of capital, it indicates that the investment will be profitable. The IRR was calculated using equation 12 below:

$$Net\ Present\ Value = \sum_{t=0}^{n} \frac{Cash\ Flow_n}{(1+IRR)^n} = 0\ (12)$$

The IRR gives the maximum discount rate needed to achieve a NPV of 0. It was calculated that LPV required an IRR of 15% and LPV of 12%.FPV would need a lower discount to achieve a positive NPV. Moreover, this IRR gives the compounded rate of return of the total investment.

4.6 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 take into account 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 taking into account 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 using the Penman formula and taking into account the annual precipitation as well. For reservoir A and B, the annual evaporation is 450.956 m^3 and 176.958 m^3 of water respectively. The effect of the FPV on the evaporation was then calculated for the different scenarios of coverage. It was assumed that the total coverage of the panels protected the whole surface area of water under them, except 5% that was evaporated from heat and reflection of sunbeams. Thus, 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.

Regarding the two reservoirs, since Reservoir A has a higher volume and surface area than Reservoir B, there is a noticeably higher energy production, as well as evaporation reduction, when placing FPV. For higher surface area coverages, the PV capacity increases and in turn the energy production. However, a higher capital expenditure is required. Thus, developers should weigh the initial capital availability of an investment and the long-term operational expenditure reduction, to assess the optional FPV capacity installment.

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. This is due to the additional costs associated with designing and constructing a floating platform that can withstand the harsh marine environment. As a result, the CAPEX for floating photovoltaics was derived between 0,97 euros per watt and 1,55 euros per watt, compared to a range of 0,77 euros per watt to 1,23 euros per watt for land-based photovoltaics. Despite the higher costs of floating photovoltaics, they offer unique advantages such as being able to utilize underutilized bodies of water and reducing land-use conflicts.

Operational expenditure (OPEX) is an essential component of any solar power project, and it includes the expenses incurred during the operational phase of the project. In the case of floating photovoltaics (FPV), the higher maintenance costs are due to the need to use boats to access farms and the requirement of divers to operate anchoring and mooring systems. However, the lack of vegetation and fencing site maintenance in FPV systems lead to lower costs. The overall impact of these factors is that the OPEX costs for FPV systems can be brought to the same value as conventional land based photovoltaic systems, arising at O&M costs of **16,56 euros 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 price of electricity in the spot market is an important factor in determining the economic viability of any solar power project. Based on the 2021 prices of solar, it has been assumed that electricity generated from FPV and LPV is sold at a rate of 0,068 euros per kilowatt-hour in the spot market. This assumption takes into account the competitiveness of solar energy in the current market, as well as the relative costs of producing electricity from conventional sources. With the global shift towards renewable energy sources and the growing demand for sustainable energy, the prices of solar energy are expected to continue to decline, making it even more competitive in the spot market. This, in turn, could lead to increased adoption of FPV systems as a reliable and cost-effective source of renewable energy generation.

One of the significant advantages of using (FPV) is the reduction of water loss through evaporation, which results in more energy available for generation and increased revenue. At the selected location, evaporation costs were estimated to be between 3974 - 10000 euros per year, based on a price of PHS of 186,65 euros per megawatt-hour as mentioned in section 4.7.1. However, by placing an FPV system, up to 18,25% of the evaporation costs can be avoided per year. This reduction in water loss not only translates into cost savings but also has positive environmental implications, as it helps to conserve water resources. Furthermore, with the growing focus on sustainability and the need for responsible water management practices, the use of FPV systems could become increasingly attractive to investors, further increasing revenue opportunities in the renewable energy sector.

In the financial analysis of the base case scenario for 5% LPV coverage of reservoir A, the levelized cost of energy (LCOE) was calculated to be **33,32** euros per megawatt-hour (MWh) for LPV and **39,53** euros per MWh for FPV. The LCOE for LPV was found to be very close to the reported LCOE of 32.11 euros per MWh in 2021. This indicates that LPV technology is a competitive option for generating solar power. However, FPV still requires further research and development to reduce capital expenditure costs and lower the LCOE. Additionally, it is worth noting that in countries with higher temperatures, FPV might be more cost-competitive due to increased efficiency and lower maintenance costs. The sensitivity analysis in the report evaluates this possibility and provides further insight into the economic viability of FPV systems in different climates. Overall, the financial metrics calculated in the analysis provide a comprehensive understanding of the economic feasibility of using floating photovoltaics for renewable energy generation in reservoirs.

The return on investment was calculated to be **215%** for LPV and **172%** for FPV. This indicates that both LPV and FPV systems have the potential to generate significant returns for investors, with LPV performing slightly better in terms of ROI. The payback period, the time it takes for the initial investment to be recouped, is an important factor in determining the ROI. After the payback period is reached, all electricity generated comes at only the expense of operation and maintenance (O&M) costs. This means that the solar power generated by the systems becomes increasingly profitable over time and can provide a stable source of income for investors.

The payback period for LPV and FPV systems was calculated at 6,37 and 7,88 years, respectively. These payback periods are within the average range for solar energy, which typically falls between 6 to 10 years, depending on the location. It is worth noting that larger solar farms could potentially bring down the payback period, as economies of scale may allow for lower installation costs and greater efficiency in power generation. Overall, the estimated payback periods for LPV and FPV indicate that these systems have the potential to provide attractive returns for investors, while also contributing to the expansion of renewable energy infrastructure and reducing carbon emissions.

The net present value was calculated at 4,210 million euros and 3,441 million euros for LPV and FPV systems, respectively. The positive NPV values indicate that both LPV and FPV have the potential to generate significant profits in today's value of money. NPV is a measure of the present value of the future cash inflows and outflows from an investment, discounted to the present day using a predetermined rate. The high NPV values for LPV and FPV systems further support their potential as attractive investment opportunities for investors seeking to invest in renewable energy infrastructure. The internal rate of return was calculated at 15% and 12% for LPV and FPV systems, respectively. These IRR values suggest that both LPV and FPV systems have the potential to generate returns that are higher than the discount rate used in the analysis. In the case study, a discount rate of 5.5% was assumed, which is a common rate used in renewable energy project financing. The fact that both LPV and FPV systems have IRRs that exceed the discount rate suggests that they have the potential to generate positive NPV values even if the discount rate is increased.

Taking into account all financial metrics for each type of photovoltaics, it is clear that LPV outperforms FPV in each metric and is currently the preferred option regarding financial investment decisions. However, this report has taken several assumptions and is subject to limitations that could alter results significantly. Those limitations are addressed in section 5.7 below. Moreover, changing the location of the installed PV will have tremendous effects on energy generation, temperatures and evaporation as well as costs that would alter the final results of this report. Overall, FPV still requires significant R&D to bring costs down and make it a standard investment option.

4.7 Sensitivity analysis

In this section a sensitivity analysis is conducted to evaluate how different factors affect the performance of a floating photovoltaic. Two scenarios were analyzed regarding the energy and cost of the floating photovoltaics.

4.7.1 Scenario 1

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 29.

Table 29: Scenario 1

Metric	LPV	FPV
LCOE (Euros per Mwh)	33,32	32,60
ROI (%)	215	222
Payback period (Years)	6,37	6,22
NPV (Million euros)	4,21	4,40
IRR (%)	15	16

It is clear that 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 29 above, it outperforms LPV in all metrics and would be preferred from an investment firm.

4.7.2 Scenario 2

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.

The island of El Hierro in Spain was selected due to proximity to the equator that will give high solar irradiation throughout the year. Moreover, the island has already built a hydro storage dam with a power capacity of 11,5 MW connected to the sea at a lower level. Moreover, the minimal rainfall in the island makes it a perfect case study to evaluate the benefits of FPV in such climates [37]. Figure 20 shows El Hierro on the map.

Figure 20: El Hierro on the map [37]

Table 30 below shows the key geoclimatic differences between the two locations.

Table 30: Geoclimatic differences

Value	Base case	Sensitivity analysis – Scenario 2
Irradiation (kWh/m^2)	1.677	2.051
Temperature air (°C)	20,6	18
Precipitation (mm/ year) [38]	795,65	325

The differences indicated in table 30 above will alter the results in terms of energy production and water loss, between LPV and FPV systems. After changing the new inputs, the following results were derived. The efficiency of the system was improved from 2,19% to **4,16%** in the new location. Given the higher insolation this equaled an increase energy production of **100,7 MWh** per year by FPV. Table 31 shows an overview of the financial metrics.

Table 31: Financial metrics

Metric	FPV (Greece)	FPV (Spain)
LCOE (Euros per Mwh)	39,53	32,41
ROI (%)	171,8	231
Payback period (Years)	7,88	6,28
NPV (Million euros)	3,44	5,40
IRR (%)	12	15

While it is clear that 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.**

4.8 Limitations

As mentioned earlier in the report several limitations are found in this study and outlined below.

Fixed cost prices of spot market

It was assumed that the price at which solar electricity is sold is fixed and will not change throughout the years. Even though this is in line with future markets in which electricity contracts are set with specific time frames and prices, the costs assumed where extracted from the spot market and are likely to vary in a futures market scenario.

Average energy production yearly

All calculations are based on the assumption of the yearly average production calculated via the solar insolation in 2023. However, weather effects and conditions are likely to affect this energy production causing costs and revenues to differ under a real scenario.

CAPEX and OPEX interpolation costs

Capex and Opex costs were extracted from literature review. However, reported costs were given for specific power capacities and linear interpolation was performed to find costs at the scenarios of this report. It is likely that those interpolated values might slightly differ in reality as they might not be linearly related.

Average temperature and precipitation causing average evaporation

By assuming an average temperature and precipitation an average yearly evaporation is derived. However, different weather conditions and temperatures will likely differ under a daily scenario throughout the year.

PHS spot market price assumed only at highest price

When calculating evaporation costs, the highest price of the spot market was used as a price to sell PHS energy, since PHS tends to be sold as the last generator due to its flexibility and dispatchability. However, this is heavily dependent on the current renewable generation and fossil energy availability that could alter the price at which PHS is sold at

Efficiency of PHS plant is taken as a worldwide average

The efficiency of the PHS plant was assumed to be equal to the worldwide average. However, efficiencies differ from location to location and weather conditions.

Algae effect not considered

The formation of algae and the reduction of their formation due to placing FPV was not considered for complexity reasons. However, Algae growth in hydro storage dams can increase operating expenses for several reasons. Firstly, algae can block waterways and clog intake structures, reducing the water flow and efficiency of the dam. This can lead to reduced power output and the need for costly maintenance and cleaning. Secondly, algae can increase water treatment costs. Secondly, algae can cause damage to mechanical equipment such as pumps, valves, and screens, leading to increased maintenance costs and downtime. Lastly, if the algae bloom becomes severe, it can cause an increase in the concentration of dissolved oxygen in the water, which can lead to corrosion of metal components in the dam. This can lead to costly repairs and replacements of the affected components. Floating photovoltaics (FPV) can help reduce the growth of algae in hydro storage dams. The shading effect of FPV systems on the water surface can reduce the amount of sunlight that reaches the water, which in turn can reduce the growth of algae. Algae require sunlight to grow and multiply, and by blocking some of the sunlight, the growth of algae can be controlled. Additionally, the floating structure of FPV systems can create a stable environment that is less conducive to the formation of algae colonies.

5 Conclusion

In conclusion, the objective of this report was to assess the mutual technical and financial benefits of the installation of FPV on hydro storage dams. Two advantages were identified through the use of several calculations using Excel. Firstly, the efficiency of the PV power output increased by **2,2%** due to the cooling effect from the water in contact with the array. This caused the cell temperature to drop by **6 C**, causing the open-circuit voltage to increase and in turn increase the power and energy output. Secondly, installing FPV on a body of water covers that surface area from sun exposure. This led to a **5%** reduction in the water evaporation of that area. The selected location had a relatively low average annual temperature and thus only a small efficiency improvement was derived. Looking at the financial metrics, the FPV performed worse than LPV due to the higher capital costs. Specifically, the LCOE of LPV was derived at **33,32 Euros/ MWh** compared to FPV at **39,53 Euros/ MWh**. Moreover, FPV performed worse in all metrics including the ROI, Payback period, NPV and IRR. This indicates the need for more research and development to be implemented in FPV so that capital costs can be reduced. Furthermore, a sensitivity analysis was conducted to evaluate two scenarios. Scenario 1 assumed the same capital costs for FPV as for LPV, resulting to a lower LCOE and indicating that once capital costs are brought down FPV has a clear advantage as an investment option. Scenario 2 evaluated how choosing a location with higher insolation and temperatures and lower precipitation will affect the performance of an FPV. Choosing the island of El Hierro increased the energy efficiency by **4,16%** compared to 2,19% for the base case of Greece.

This thesis provides a detailed study of the combined technical and technoeconomic benefits of FPV on a PHS dam at a selected location. 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 could bring more transparent results.

References

[1] SolarFeeds Editorial Team (2022) Solar Power Statistics in Europe 2021, SolarFeeds Magazine. Available at: https://www.solarfeeds.com/mag/solar-power-statistics-in-europe-2021/ (Accessed: December 4, 2022).

[2] IHA (2020) Pumped storage hydropower has 'crucial role' in Europe's energy strategy. Available at: https://www.hydropower.org/news/pumped-storage-hydropower-has-e2-80-98crucial-role-e2-80-99-in-europe-e2-80-99s-energy-strategy#:~:text="With%20an%20efficiency%20degree%20of,EU%27s%20current%20energy%20storage%20facilities (Accessed: December 4, 2022).

[3] (2021) Homer pro user manual. Available at: https://www.homerenergy.com/products/pro/docs/ (Accessed: December 4, 2022).

[4] Wallach, O. (2022) The solar power duck curve explained, Elements by Visual Capitalist. Available at: https://elements.visualcapitalist.com/the-solar-power-duck-curve-explained/ (Accessed: December 5, 2022).

[5] Farm water calculator: Additional information (2020) Water Calculator. Available at: https://calculator.agriculture.vic.gov.au/fwcalc/information/determining-the-evaporative-loss-from-a-farm-dam#:~:text=The%20amount%20of%20water%20lost%20due%20to%20evaporation%20from%20the,the%20dams%20total%20storage%20volume (Accessed: December 5, 2022).

[6] State, local, and tribal governments (2021) NREL.gov. Available at: https://www.nrel.gov/state-local-tribal/ (Accessed: December 6, 2022).

[7] Floating photovoltaic solar energy (2021) Iberdrola. Available at: https://www.iberdrola.com/innovation/floating-photovoltaic (Accessed: December 6, 2022).

[8] Bellini, E. (2020) Floating PV learning from Aquaculture Industry, pv magazine International. Available at: https://www.pv-magazine.com/2020/03/23/floating-pv-learning-from-aquaculture-industry/) (Accessed: December 6, 2022).

[9] Al-Widyan, M., Khasawneh, M. and Abu-Dalo, M. (2021) 'Potential of floating photovoltaic technology and their effects on energy output, water quality and supply in Jordan', Energies, 14(24), p. 8417. doi:10.3390/en14248417.

[10] Sami (2021) Floating solar panels, Dynamic SLR. Available at: https://www.dynamicslr.com/floating-solar-panels/) (Accessed: December 6, 2022).

[11] Spencer, R.S., Jordan Macknick, Alexandra Aznar, Adam Warren, and Matthew O. Reese (2018) 'Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States', Environmental Science & Technology, 53(3), pp. 1680–1689. doi:10.1021/acs.est.8b04735.

[12] Floating solar panels market size, Share & Trends Analysis Report by product (tracking, stationary), by region (Asia Pacific, North America, Europe, Middle East & Africa) and segment forecasts, 2022-2030 (no date) Research and Markets - Market Research Reports - Welcome. Available at: https://www.researchandmarkets.com/reports/4076512/floating-solar-panels-market-size-share-and?utm_source=BW&utm_medium=PressRelease&utm_code=kmbxc9&utm_campaign=1727991%2B-%2BGlobal%2BFloating%2BSolar%2BPanels%2BMarket%2B%282022%2Bto%2B2030%29%2B-%2BSize%2C%2BShare%2B%26%2BTrends%2BAnalysis%2BReport%2B&utm_exec=jamu273prd (Accessed: December 7, 2022).

[13] Lewis W.Farrara, Abu Bakr, S.Bahaja, Patrick Jamesa, Arif Anwarab, Nafn Amdarc, (2022) 'Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study jordan', Energy Conversion and Management, 260, p. 115598. doi:10.1016/j.enconman.2022.115598.

[14] Haas, J, Khalighi, J., Chen, P. J., De La Fuente, A, Nowak, W. (2018) Save the lake! floating solar photovoltaic to avoid algae blooms?, NASA/ADS. Available at: https://ui.adsabs.harvard.edu/abs/2018AGUFM.H13R2020H/abstract (Accessed: December 7, 2022).

[15] Ramasamy, V. (2021) Floating photovoltaic system cost benchmark: Q1 2021 ... - NREL, NREL. Available at: https://www.nrel.gov/docs/fy22osti/80695.pdf (Accessed: December 7, 2022).

[16] Todorović, I. (2021) Terna to start building 730 MW pumped storage hydropower plant in October, Balkan Green Energy News. Available at: https://balkangreenenergynews.com/terna-to-start-building-730-mw-pumped-storage-hydropower-plant-in-october/ (Accessed: December 7, 2022).

[17] Hydro-pumped storage of Agios Georgios and Pyrgos, municipality of amfilochia, Greece: Σοφιός ΑΕ: Σύμβουλοι Μηχανικοί (2022) Σοφιός ΑΕ | Σύμβουλοι Μηχανικοί | Υδραυλικά και γεωτεχνικά έργα, φράγματα, υδροηλεκτρικά, αποχετεύσεις. Available at: https://www.sofios.gr/en/projects/meletes-antlisotamiefsis-agios-geo/ (Accessed: December 8, 2022).

[18] Floating solar pannels (2022) edp.com. Available at: https://www.edp.com/en/innovation/floating-solar-pannels (Accessed: December 8, 2022).

[19] Perc Mono DBP400 (2022) Rinxin Solar. Available at: https://www.rixinsolar.com.cn/product/perc-mono-dbp400/ (Accessed: December 8, 2022).

[20] Solargis (2022) Global solar atlas. Available at: https://globalsolaratlas.info/detail?c=38.806728%2C21.364131%2C11&s=38.806728%2C21.364131&m=site%29. (Accessed: December 9, 2022).

[21] Linacre, E.T. (1977) 'A simple formula for estimating evaporation rates in various climates, using temperature data alone', Agricultural Meteorology, 18(6), pp. 409–424. doi:10.1016/0002-1571(77)90007-3.

[22] Zoom Earth (2022) Relative humidity forecast map, Zoom Earth. Available at: https://zoom.earth/maps/humidity/ (Accessed: December 10, 2022).

[23] Fesharaki, V.J., Dehghani, M. and Fesharaki, J.J. (1970) Figure 2 from the effect of temperature on photovoltaic cell efficiency: Semantic scholar, Figure 2 from The Effect of Temperature on Photovoltaic Cell Efficiency | Semantic Scholar. Available at: https://www.semanticscholar.org/paper/The-Effect-of-Temperature-on-Photovoltaic-Cell-Fesharaki-Dehghani/4eb139ee8e2cc5d722b14ced834f35a8183b1188/figure/1 (Accessed: December 11, 2022).

[24] Olsen, E. (2018) Study on the Cooling Effect for Floating PV Modules in Thermal Contact with Water and the Potential for Modelling Floating PV, Brage NMBU. Available at: https://nmbu.brage.unit.no/ (Accessed: December 12, 2022).

[25] Spencer, R.S., Jordan Macknick, Alexandra Aznar, Adam Warren and Matthew O. Reese (2018) 'Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States', Environmental Science & Technology, 53(3), pp. 1680–1689. doi:10.1021/acs.est.8b04735.

[26] *USD/EUR Currency Exchange Rate & News* (2023) *Google Finance*. Available at: https://www.google.com/finance/quote/USD-EUR?sa=X&ved=2ahUKEwjx-6_m64j-AhWdcfEDHRvrBa4QmY0JegQIBxAd (Accessed: 02 May 2023).

[27] *Pumped Storage Hydropower* (2022) *ATB - NREL*. Available at: https://atb.nrel.gov/electricity/2022/pumped_storage_hydropower (Accessed: 03 May 2023).

[28] *Navigation* (2022) *EnExGroup*. Available at: https://www.enexgroup.gr/energy-markets (Accessed: 03 May 2023).

[29] *Global market outlook – HELAPCO(2022)*. Available at: https://helapco.gr/pdf/GMO_2017.pdf (Accessed: 14 May 2023).

[30] *Water - density, specific weight and thermal expansion coefficients Engineering ToolBox*. Available at: https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html (Accessed: 04 May 2023).

[31] *Pumped Hydro Storage Pumped Storage | GE Renewable Energy*. Available at: https://www.ge.com/renewableenergy/hydro-power/hydro-pumped-storage (Accessed: 05 May 2023).

[32] University of Galgary *Discounting*, *Discounting - Energy Education*. Available at: https://energyeducation.ca/encyclopedia/Discounting#:~:text=Discount%20Rate%20and%20LCOE%20of,of%20LCOE%20in%20the%20future. (Accessed: 19 April 2023).

[33] Freyman, T. (2019) *What are the appropriate discount rates for valuing renewable energy projects?*, *LinkedIn*. Available at: https://www.linkedin.com/pulse/what-appropriate-discount-rates-valuing-renewable-energy-freyman-1e/ (Accessed: 20 April 2023).

[34] Lazard (2023) *2023 levelized cost of energy+*, *https://www.lazard.com*. Available at: https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/ (Accessed: 01 May 2023).

[35] Brock, M. (2023) *Solar panel roi: Are solar panels worth it?*, *Solar Panel ROI: Are Solar Panels Worth It? | Quicken Loans*. Available at: https://www.quickenloans.com/learn/solar-panel-roi#:~:text=What%20Is%20The%20Average%20Solar,your%20specific%20solar%20panel%20setup. (Accessed: 02 May 2023).

[36] *Energy costs 2020 - pv-magazine.com* (2020) *pv-magazine*. Available at: https://www.pv-magazine.com/wp-content/uploads/2020/02/ESE2020-final.pdf (Accessed: 02 May 2023).

[37] Blázquez-Bermejo, Z., Julio Hernández-Afonso (2020) 'Heart transplantation in a distant island population: Accessibility and outcomes in patients from the Canary Islands transplanted in Madrid', Transplantation, 104(2), pp. 223–226. doi:10.1097/tp.0000000000002929.

[38] Travel guide (2020) *The climate of the Canary Islands: When to go to the canary*, *Travel Guide*. Available at: https://www.travelguide-en.org/canary-islands-climate/#:~:text=In%20all%20the%20Canary%20Islands,months%20between%20December%20and%20February. (Accessed: 05 May 2023).

[39] Pumped-storage hydroelectricity (no date) Pumped-Storage Hydroelectricity - an overview | ScienceDirect Topics. Available at: https://www.sciencedirect.com/topics/engineering/pumped-storage-hydroelectricity (Accessed: 02 May 2023).

[40] Arnot, J. (2021) How & why does algae grow in a water storage tank?, How & Why Does Algae Grow in a Water Storage Tank? Available at: https://blog.enduraplas.com/water-storage-rain-harvesting/how-why-does-algae-grow-in-a-water-storage-tank (Accessed: 20 May 2023).

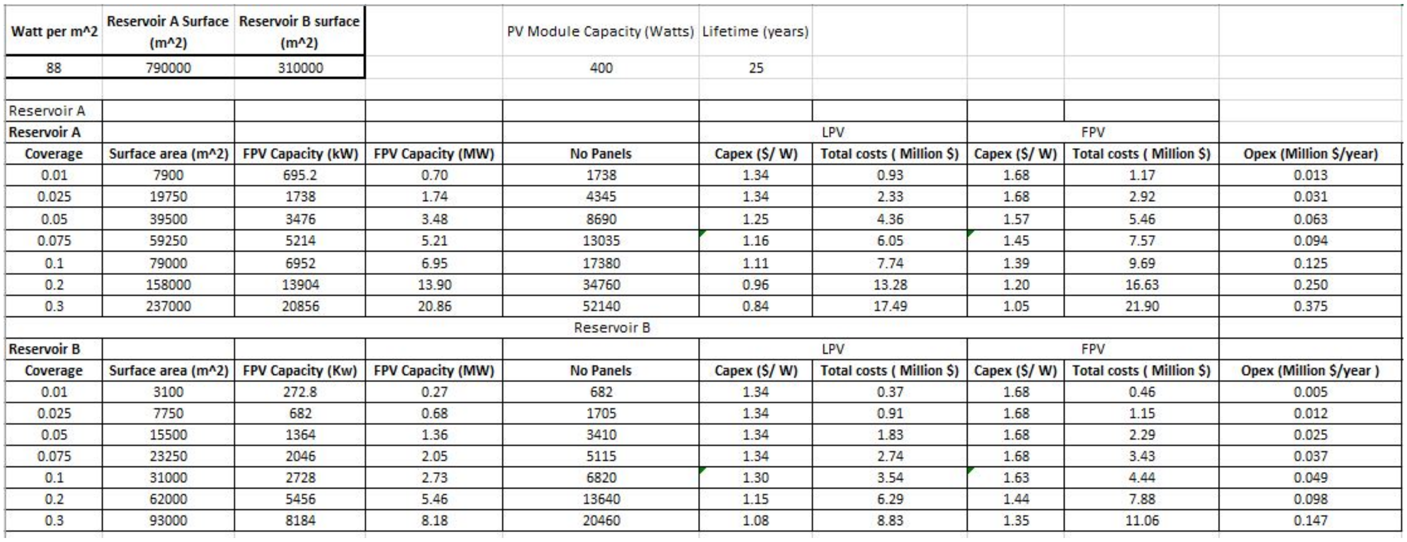
[41] Solar resource maps of Greece (2023) Solargis. Available at: https://solargis.com/maps-and-gis-data/download/greece (Accessed: 2023).

[42] Luyao Liu, Qinxing Wang, Haiyang Lin, Hailong Li,Qie Sun and Ronald Wennersten. (2017) 'Power generation efficiency and prospects of Floating Photovoltaic Systems', Energy Procedia, 105, pp. 1136–1142. doi:10.1016/j.egypro.2017.03.483.

[43] Goncalves, S. and Pereira, M. (2022) Portugal set to start up Europe's largest floating solar park, World Economic Forum. Available at: https://www.weforum.org/agenda/2022/05/portugal-europe-floating-solar-farm-renewable-energy/ (Accessed: 10 July 2023).

Annex

A1 - Costs FPV



Watt per m^2	Reservoir A Surface (m^2)	Reservoir B surface (m^2)	PV Module Capacity (Watts)	Lifetime (years)
88	790000	310000	400	25

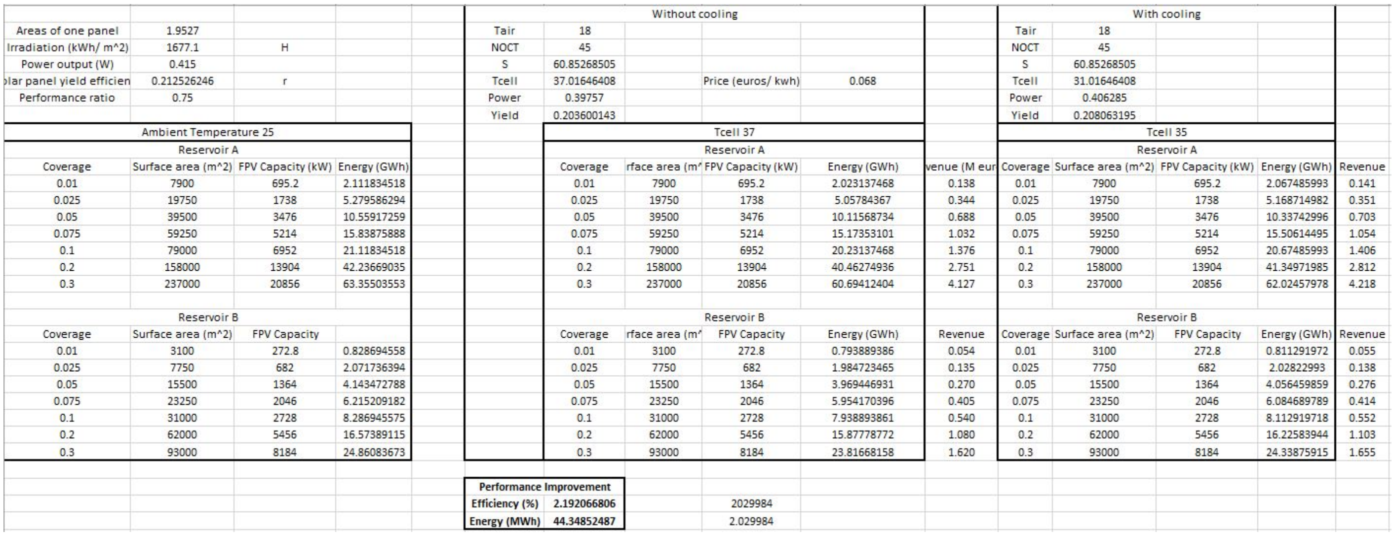
Reservoir A

Reservoir A					LPV		FPV		
Coverage	Surface area (m^2)	FPV Capacity (kW)	FPV Capacity (MW)	No Panels	Capex ($/ W)	Total costs (Million $)	Capex ($/ W)	Total costs (Million $)	Opex (Million $/year)
0.01	7900	695.2	0.70	1738	1.34	0.93	1.68	1.17	0.013
0.025	19750	1738	1.74	4345	1.34	2.33	1.68	2.92	0.031
0.05	39500	3476	3.48	8690	1.25	4.36	1.57	5.46	0.063
0.075	59250	5214	5.21	13035	1.16	6.05	1.45	7.57	0.094
0.1	79000	6952	6.95	17380	1.11	7.74	1.39	9.69	0.125
0.2	158000	13904	13.90	34760	0.96	13.28	1.20	16.63	0.250
0.3	237000	20856	20.86	52140	0.84	17.49	1.05	21.90	0.375

Reservoir B

Reservoir B					LPV		FPV		
Coverage	Surface area (m^2)	FPV Capacity (Kw)	FPV Capacity (MW)	No Panels	Capex ($/ W)	Total costs (Million $)	Capex ($/ W)	Total costs (Million $)	Opex (Million $/year)
0.01	3100	272.8	0.27	682	1.34	0.37	1.68	0.46	0.005
0.025	7750	682	0.68	1705	1.34	0.91	1.68	1.15	0.012
0.05	15500	1364	1.36	3410	1.34	1.83	1.68	2.29	0.025
0.075	23250	2046	2.05	5115	1.34	2.74	1.68	3.43	0.037
0.1	31000	2728	2.73	6820	1.30	3.54	1.63	4.44	0.049
0.2	62000	5456	5.46	13640	1.15	6.29	1.44	7.88	0.098
0.3	93000	8184	8.18	20460	1.08	8.83	1.35	11.06	0.147

A2 – Energy production



Areas of one panel	1.9527	
Irradiation (kWh/ m^2)	1677.1	H
Power output (W)	0.415	
olar panel yield efficien	0.212526246	r
Performance ratio	0.75	

Without cooling

Tair	18		
NOCT	45		
S	60.85268505		
Tcell	37.01646408	Price (euros/ kwh)	0.068
Power	0.39757		
Yield	0.203600143		

With cooling

Tair	18
NOCT	45
S	60.85268505
Tcell	31.01646408
Power	0.406285
Yield	0.208063195

Ambient Temperature 25

Reservoir A

Coverage	Surface area (m^2)	FPV Capacity (kW)	Energy (GWh)
0.01	7900	695.2	2.111834518
0.025	19750	1738	5.279586294
0.05	39500	3476	10.55917259
0.075	59250	5214	15.83875888
0.1	79000	6952	21.11834518
0.2	158000	13904	42.23669035
0.3	237000	20856	63.35503553

Reservoir B

Coverage	Surface area (m^2)	FPV Capacity	
0.01	3100	272.8	0.828694558
0.025	7750	682	2.071736394
0.05	15500	1364	4.143472788
0.075	23250	2046	6.215209182
0.1	31000	2728	8.286945575
0.2	62000	5456	16.57389115
0.3	93000	8184	24.86083673

Tcell 37

Reservoir A

Coverage	rface area (m^	FPV Capacity (kW)	Energy (GWh)	venue (M eur
0.01	7900	695.2	2.023137468	0.138
0.025	19750	1738	5.05784367	0.344
0.05	39500	3476	10.11568734	0.688
0.075	59250	5214	15.17353101	1.032
0.1	79000	6952	20.23137468	1.376
0.2	158000	13904	40.46274936	2.751
0.3	237000	20856	60.69412404	4.127

Reservoir B

Coverage	rface area (m^	FPV Capacity	Energy (GWh)	Revenue
0.01	3100	272.8	0.793889386	0.054
0.025	7750	682	1.984723465	0.135
0.05	15500	1364	3.969446931	0.270
0.075	23250	2046	5.954170396	0.405
0.1	31000	2728	7.938893861	0.540
0.2	62000	5456	15.87778772	1.080
0.3	93000	8184	23.81668158	1.620

Tcell 35

Reservoir A

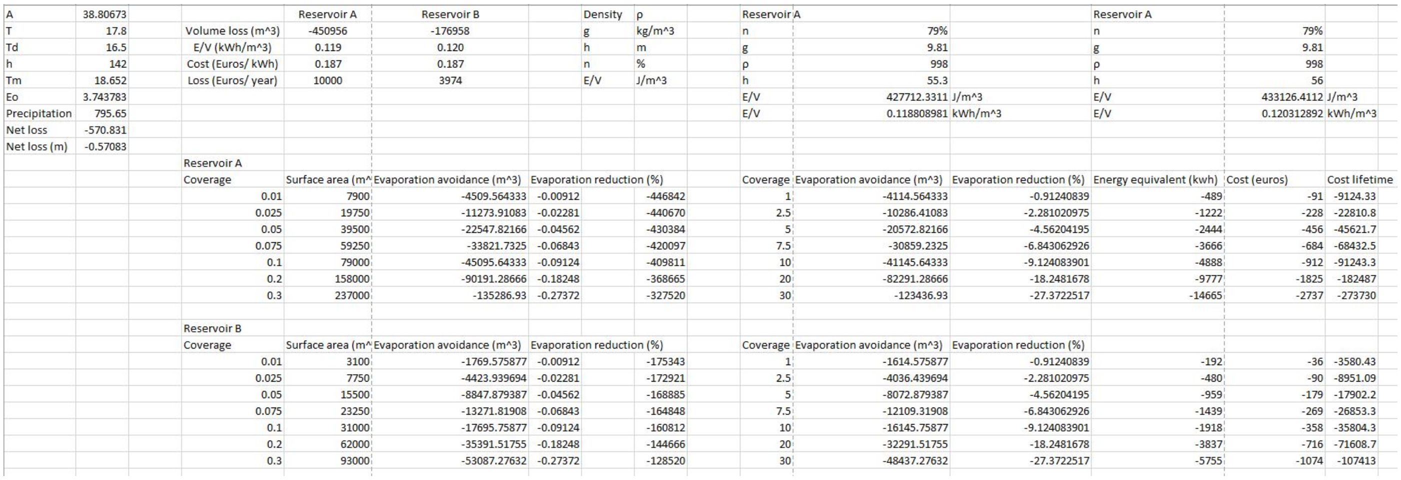
Coverage	Surface area (m^2)	FPV Capacity (kW)	Energy (GWh)	Revenue
0.01	7900	695.2	2.067485993	0.141
0.025	19750	1738	5.168714982	0.351
0.05	39500	3476	10.33742996	0.703
0.075	59250	5214	15.50614495	1.054
0.1	79000	6952	20.67485993	1.406
0.2	158000	13904	41.34971985	2.812
0.3	237000	20856	62.02457978	4.218

Reservoir B

Coverage	Surface area (m^2)	FPV Capacity	Energy (GWh)	Revenue
0.01	3100	272.8	0.811291972	0.055
0.025	7750	682	2.02822993	0.138
0.05	15500	1364	4.056459859	0.276
0.075	23250	2046	6.084689789	0.414
0.1	31000	2728	8.112919718	0.552
0.2	62000	5456	16.22583944	1.103
0.3	93000	8184	24.33875915	1.655

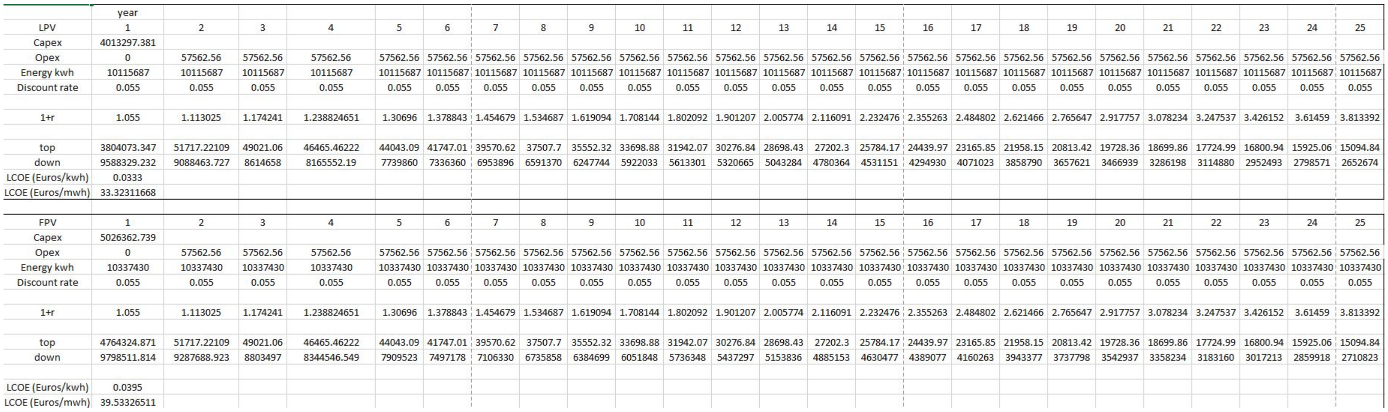
Performance Improvement			
Efficiency (%)	**2.192066806**		2029984
Energy (MWh)	**44.34852487**		2.029984

A3 – Evaporation



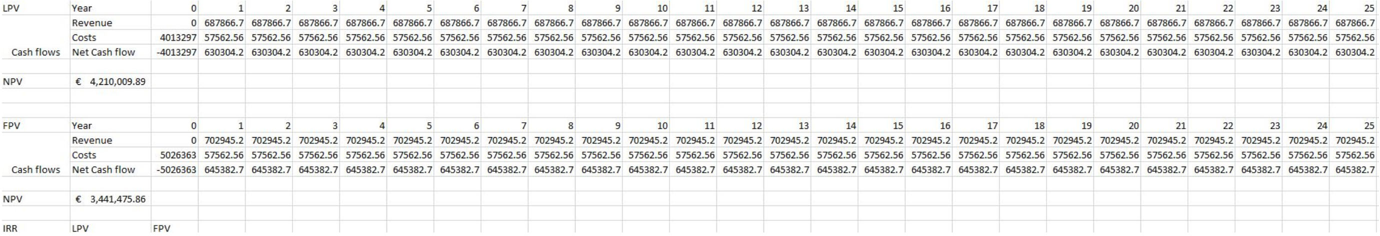
A	38.80673			Reservoir A	Reservoir B		Density	ρ		Reservoir A			Reservoir A		
T	17.8		Volume loss (m^3)	-450956	-176958		g	kg/m^3		n	79%		n	79%	
Td	16.5		E/V (kWh/m^3)	0.119	0.120		h	m		g	9.81		g	9.81	
h	142		Cost (Euros/ kWh)	0.187	0.187		n	%		ρ	998		ρ	998	
Tm	18.652		Loss (Euros/ year)	10000	3974		E/V	J/m^3		h	55.3		h	56	
Eo	3.743783									E/V	427712.3311	J/m^3	E/V	433126.4112	J/m^3
Precipitation	795.65									E/V	0.118808981	kWh/m^3	E/V	0.120312892	kWh/m^3
Net loss	-570.831														
Net loss (m)	-0.57083														
			Reservoir A												
			Coverage	Surface area (m^	Evaporation avoidance (m^3)	Evaporation reduction (%)				Coverage	Evaporation avoidance (m^3)	Evaporation reduction (%)	Energy equivalent (kwh)	Cost (euros)	Cost lifetime
			0.01	7900	-4509.564333	-0.00912		-446842		1	-4114.564333	-0.91240839	-489	-91	-9124.33
			0.025	19750	-11273.91083	-0.02281		-440670		2.5	-10286.41083	-2.281020975	-1222	-228	-22810.8
			0.05	39500	-22547.82166	-0.04562		-430384		5	-20572.82166	-4.56204195	-2444	-456	-45621.7
			0.075	59250	-33821.7325	-0.06843		-420097		7.5	-30859.2325	-6.843062926	-3666	-684	-68432.5
			0.1	79000	-45095.64333	-0.09124		-409811		10	-41145.64333	-9.124083901	-4888	-912	-91243.3
			0.2	158000	-90191.28666	-0.18248		-368665		20	-82291.28666	-18.2481678	-9777	-1825	-182487
			0.3	237000	-135286.93	-0.27372		-327520		30	-123436.93	-27.3722517	-14665	-2737	-273730
			Reservoir B												
			Coverage	Surface area (m^	Evaporation avoidance (m^3)	Evaporation reduction (%)				Coverage	Evaporation avoidance (m^3)	Evaporation reduction (%)			
			0.01	3100	-1769.575877	-0.00912		-175343		1	-1614.575877	-0.91240839	-192	-36	-3580.43
			0.025	7750	-4423.939694	-0.02281		-172921		2.5	-4036.439694	-2.281020975	-480	-90	-8951.09
			0.05	15500	-8847.879387	-0.04562		-168885		5	-8072.879387	-4.56204195	-959	-179	-17902.2
			0.075	23250	-13271.81908	-0.06843		-164848		7.5	-12109.31908	-6.843062926	-1439	-269	-26853.3
			0.1	31000	-17695.75877	-0.09124		-160812		10	-16145.75877	-9.124083901	-1918	-358	-35804.3
			0.2	62000	-35391.51755	-0.18248		-144666		20	-32291.51755	-18.2481678	-3837	-716	-71608.7
			0.3	93000	-53087.27632	-0.27372		-128520		30	-48437.27632	-27.3722517	-5755	-1074	-107413

A4 – LCOE



	year																								
LPV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Capex	4013297.381																								
Opex	0	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56
Energy kwh	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687	10115687
Discount rate	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055
1+r	1.055	1.113025	1.174241	1.238824651	1.30696	1.378843	1.454679	1.534687	1.619094	1.708144	1.802092	1.901207	2.005774	2.116091	2.232476	2.355263	2.484802	2.621466	2.765647	2.917757	3.078234	3.247537	3.426152	3.61459	3.813392
top	3804073.347	51717.22109	49021.06	46465.46222	44043.09	41747.01	39570.62	37507.7	35552.32	33698.88	31942.07	30276.84	28698.43	27202.3	25784.17	24439.97	23165.85	21958.15	20813.42	19728.36	18699.86	17724.99	16800.94	15925.06	15094.84
down	9588329.232	9088463.727	8614658	8165552.19	7739860	7336360	6953896	6591370	6247744	5922033	5613301	5320665	5043284	4780364	4531151	4294930	4071023	3858790	3657621	3466939	3286198	3114880	2952493	2798571	2652674
LCOE (Euros/kwh)	0.0333																								
LCOE (Euros/mwh)	33.32311668																								
FPV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Capex	5026362.739																								
Opex	0	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56
Energy kwh	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430	10337430
Discount rate	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055
1+r	1.055	1.113025	1.174241	1.238824651	1.30696	1.378843	1.454679	1.534687	1.619094	1.708144	1.802092	1.901207	2.005774	2.116091	2.232476	2.355263	2.484802	2.621466	2.765647	2.917757	3.078234	3.247537	3.426152	3.61459	3.813392
top	4764324.871	51717.22109	49021.06	46465.46222	44043.09	41747.01	39570.62	37507.7	35552.32	33698.88	31942.07	30276.84	28698.43	27202.3	25784.17	24439.97	23165.85	21958.15	20813.42	19728.36	18699.86	17724.99	16800.94	15925.06	15094.84
down	9798511.814	9287688.923	8803497	8344546.549	7909523	7497178	7106330	6735858	6384699	6051848	5736348	5437297	5153836	4885153	4630477	4389077	4160263	3943377	3737798	3542937	3358234	3183160	3017213	2859918	2710823
LCOE (Euros/kwh)	0.0395																								
LCOE (Euros/mwh)	39.53326511																								

A5 – NPV



LPV	Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Revenue	0	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7	687866.7
	Costs	4013297	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56
Cash flows	Net Cash flow	-4013297	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2	630304.2
NPV	€ 4,210,009.89																										
FPV	Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Revenue	0	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2	702945.2
	Costs	5026363	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56	57562.56
Cash flows	Net Cash flow	-5026363	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7	645382.7
NPV	€ 3,441,475.86																										
IRR	LPV	FPV																									