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# Economic comparison of floating photovoltaic systems with tracking systems and active cooling in a Mediterranean water basin

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ABSTRACT

Floating Photovoltaic (FPV) modules are installed on water surface to reduce land use. This original solution, potentially deployable on hydropower and aquaculture basins as well, can benefit of enhanced cooling due to the proximity to water. Thanks to this natural effect, FPV modules can work at higher operating efficiencies than ground-based (GPV) modules. However, because of the relatively young age, FPV still requires higher installation costs than GPV. This study investigates the economic competitiveness of GPV and FPV in terms of energy performance and total costs. Different PV system solutions are economically evaluated on the basis of three key figures, namely the capital costs (CAPEX), the operation and maintenance costs (OPEX) and the power generation costs (LCOE). An economic ranking is created based on the comparative analysis of these three key figures.

The crucial point in the proposed economic model is that the revenues resulting from the reduced evaporations are considered as well. Every year, indeed, a significant volume of water can be preserved thanks to the shading effect of FPV modules. This water can be used for various purposes, increasing the overall revenues of the FPV system. In addition, the present LCOE calculations also take into account the performance enhancements that could be achieved through the installation of active cooling systems.

In light of the expected economy of scale, a sensitivity analysis of the LCOE is carried out to account potential reductions in the capital cost of FPVs. This is done by analyzing the energy and economic performance of various FPV designs on a water basin in Southern Italy. The results demonstrate that, reducing the CAPEX of the FPV by 30 %, a nearly 20 % reduction in LCOE can be obtained compared to the reference GPV system.

## Introduction

The most widespread way of using solar energy for electrical power generation is through photovoltaic (PV) systems (Kumar et al., 2020). PV is among the renewable energy solutions that can significantly contribute to the world's sustainable energy needs (Victoria et al., 2021). The number of PV installations worldwide is rapidly increasing, as result of the sharp decline in costs (https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf, 2023), of the raising electricity demand and of the fossil fuel depletion. In early 2022, PV reached a capacity of 1 TW worldwide (SolarPower Europe, 2023). However, utility-scale photovoltaic systems have a potentially significant land use problem, as large areas are required for their installation, leading to potential conflicts with other activities, such as agriculture (Kumar et al., 2021). This problem can be solved by floating photovoltaics (FPV). In this configuration, PV modules are deployed on water surfaces, such as lakes or hydropower basins (Cazzaniga et al., 2019).

FPV systems have attracted attention from both a research and market perspective thanks to the advantages associated with their installation, namely space savings; cooling effect of the water microclimate on the modules; improved water quality by reduced photosynthesis and algae growth; 4 to 7 % higher energy production (depending on the season and geographical location) compared to fixed photovoltaic systems installed on the ground (Tina et al., 2021a). In addition, FPV contributions to the sustainable development are not limited to the sole generation of green energy. For example, as aforementioned, installing PV modules on water will reduce the land competition with agriculture,

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which could otherwise cause an increase in food prices. In addition, it has been shown that the presence of FPV modules on water can mitigate some of the effects of climate change on lakes' temperature and stratification (Exley, Armstrong, et al., 2021). Overall, a recent work based on a systematic review and a stakeholder survey highlighted that FPV could have an impact on nine of the U.N. sustainable development goals (SDGs), including SDG2 on zero hunger, SDG11 on sustainable cities and communities and SDG13 on climate action (Exley et al., 2021).

Since the first installation in 2007, FPV capacity has rapidly grown according to the trend shown in Fig. 1. The global capacity has more than doubled in just two years, going from to 1.1 GWp in 2018 (World Bank Group et al., 2018) to 2.6 GWp in 2020 (Haugwitz, 2020). Nowadays, FPV represents about 0.4 % of the global PV capacity, a small percentage that however has been also rapidly rising over the past years. Both the FPV capacity and its share in the PV market are expected to continue increasing in the future. The capacity could go up to 13 GWp in 2025 (Deloitte, 2022) and, in a medium growth scenario, could reach more than 20 GWp by 2030 (DNV, 2023).

FPV has a significant global capacity potential and can substantially contribute to the clean energy transition. Indeed, according to a report published by the World Bank (World Bank Group et al., 2018), covering just 1 % of the freshwater man-made reservoirs' surface worldwide would increase the FPV capacity by 404 GW. It should be also noted that a quarter of this capacity could be installed just in Africa. This continent is characterized by an extremely high solar potential, and, at the same time, suffers of frequent and severe draughts. A solution like FPV would therefore provide a significant double benefit to this region, as the shading induced by the PV modules on the basins could also reduce evaporation, making more water available for other purposes. For example, the results of a recent investigation (Gonzalez Sanchez et al., 2021) showed that covering less than 1 % of the African hydropower reservoirs would increase the electricity generation by 58 % and save 743 $m^3$/year of water. This hybridization would also lower the installation costs of the system, as FPV could make use of the existing grid connection and electrical infrastructures, reducing the upfront costs.

The deployment of FPV in Africa is already at an early stage, but because of the aforementioned potentials and benefits, FPV is already being considered as a practical and viable energy solution also in that continent. For example, a pre-feasibility study is being conducted to install FPV modules on a hydroelectric power plant in Mozambique and the first Kenyan FPV system is currently being designed (https://www.pv-magazine.com/2022/01/05/mozambiques-first-floating-solar-project/, 2023). Because of the likely effects of economy of scale, one can expect even more power plants to be deployed in the African continents as the global capacity increases and, therefore, the installation cost drops.

Given the significant interest and the rapidly growing number of installations, a variety of FPV configurations are already available in the market. So far, most of the large-scale floating PV systems have been mounted at fixed tilt angles. In addition, they are commonly installed at inclinations of 15° or less (World Bank Group et al., 2018) in order to minimize the wind load. The use of trackers can maximize the incident radiation and the FPV energy conversion, and therefore enhance its cost-competitiveness. However, the lack of a solid base and the floating conditions can make both the installation and the operation of FPV tracking systems difficult (Cazzaniga et al., 2018). Because of these challenges, only a limited number of studies, so far, has focused on tracked FPV. Existing and potential tracking designs and challenges for FPV were reviewed and discussed in Cazzaniga et al. (2018) and Rosa-Clot and Tina (2020a). In 2014, Choi et al. (2014) presented the design of tracking mechanisms and algorithms for a commercial 100 kW FPV under development in Korea. A dual axis tracker prototype for FPV was designed and fabricated by Natarajan et al. (2019), but no information on the actual performance were provided. The authors of Gurfude and Kulkarni (2019) modelled various FPV configurations over an Indian lake. They estimated energy generation increases of 18 to 21 % and of 25 to 30 % for 1-axis and 2-axis tracking, respectively, compared to fixed FPV.

Pilot and commercial FPV systems with tracking mechanisms have been deployed at least since 2011 (Thurston, 2012). A few-year data collection campaign showed that the tracking system increased the energy yield by 24 % compared to the expectations, consuming only 1 % of the photogenerated energy (Rosa-Clot & Tina, 2020a). A 4 MWp tracked concentrator FPV plant was installed in 2015 in a wastewater treatment basin in Australia (Vorrath, 2015). FPV plants with tracking systems were reported as under construction in 2019 in the Netherlands (Bellini, 2019) and in 2020 in France (Rollet, 2020). However, despite these examples, the analysis of the economic costs and benefits of these systems has still to be improved (Rollet, 2020). So far, only one techno-economic assessment of tracked FPV has been presented (Campana et al., 2019). The work, authored by Campana et al. (2019), focused on a FPV system installed on a shrimp farm in Thailand. The researchers found that, despite the higher installation costs, tracked FPV systems can achieve the same cost of the electricity as fixed FPV, thanks to the higher yields.

As aforementioned, the use of trackers has been, on some occasions, coupled with the installation of reflectors to develop concentrator FPV systems. However, while the tracking precision required for concentrator PV might be difficult to obtain on a floating platform, the use of reflectors can still be beneficial for bifacial FPV applications. Bifacial

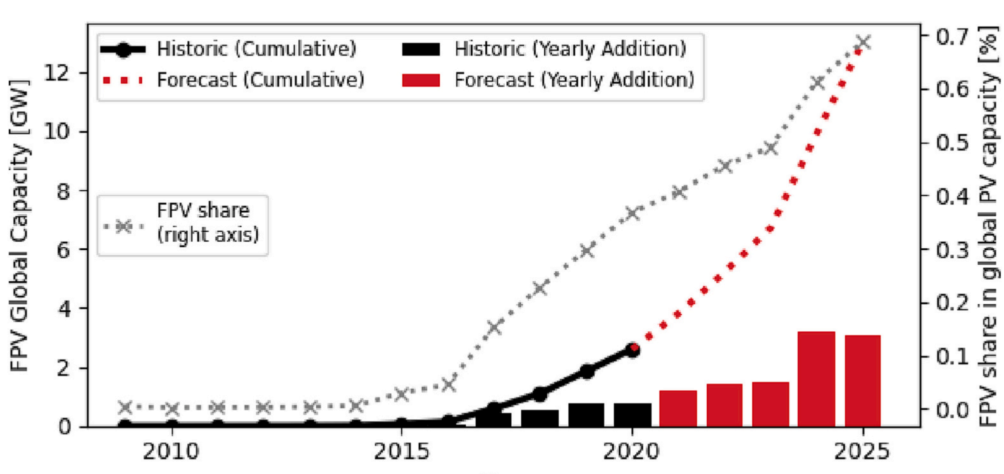


**Fig. 1.** Left axis: global installed floating PV (FPV) capacity (Haugwitz, 2020; Where Sun Meets Water, 2019) and forecast (Deloitte, 2022). Right axis: Share of floating PV in global PV capacity (BP p.l.c, 2021; SolarPower Europe, 2021).

modules are able to convert light arriving on both the front and the rear surfaces and are expected to represent more than 50 % of the modules' market share by 2030 (VDMA, 2021). However, they have been typically considered not beneficial for FPV applications (Saini et al., 2023), because of the low albedo of water compared to ground. The installations of reflectors on the floaters would raise the albedo, improving therefore the yields of FPV systems, especially in presence of bifacial modules. Tina et al. (2021a) showed that, with an albedo of 0.2, the yield of bifacial modules on water would be 13.5 % greater than that of monofacial ones. Ziar et al. (2021) found the best performance, among various tested FPV configurations, when reflectors were coupled with horizontal tracking. Moreover, it must be considered that the use of reflectors and of floats made of light-coloured materials could provide a double benefit. In addition to the reflected light increasing the energy conversion, the presence of the floats actually reduces evaporation (Peters & Nobre, 2022), making more water available for other uses.

From an energy perspective, it should be noted that, as PV cells are approaching the maximum theoretical electrical efficiency, the use of active cooling systems in PV installations is also gaining attention. Any solar cell, indeed, increases its efficiency as its temperature lowers. For this reason, solutions such as water pipes can use a small fraction of energy to cool down the PV modules and return positive energy gains. Despite this potential, the use of active cooling systems in FPV has been limitedly investigated in literature, under the assumption that the natural cooling due to the presence of water would be sufficient. In reality, some evidence has emerged showing that the temperature of FPV is not always necessarily lower than that of land-based systems, as it will change depending on the system's design (Dörenkämper et al., 2021) and on the basin's characteristics (Peters & Nobre, 2022).

The impact of bad weather on floating systems has also to be taken into consideration when the system is designed, in particular regarding the mooring system and the reciprocal connection of the units that comprise the floating system (Kaymak & Şahin, 2022). The wrong evaluation of the extreme weather conditions (especially of the wind speed) and, subsequently, the incorrect design and sizing of the FPV system can lead to catastrophic consequences (https://www.pv-magazine.com/2019/09/09/japans-largest-floating-pv-plant-catches-fire-after-typhoon-faxai-impact/, 2023; https://www.pv-magazine.com/2022/03/01/akuo-speaks-out-on-recent-fire-accident-at-its-17mw-floating-pv-plant-in-france/, 2023).

Such considerations could be applied also to tracked FPV. However, the one and two axis trackers can place the modules horizontally in case of strong winds, significantly limiting the load.

Surely, another source of stress is the action of waves (Lee et al., 2022), but in this study we are not considering offshore installations where the waves can have very important height and so impact a lot the design and the cost of the floating structure (Song et al., 2023). However, even when lakes or large basis are considered, the mechanical design of floating structure has to be carefully sized with respect to wave and wind stress loads, also by means of experimental tests on the field, as the one reported in Kaymak and Şahin (2021).

There are a few real scale experiences only of FPVs with vertical tracking system (Kim et al., 2016), but no evidence about the impact of extreme weather on them.

Bird dropping is another problem to consider in the design and performance evaluation in general for the PV systems and in particular for FPV.

Different studies conducted on land-based installations have indeed reported lower soiling losses for steeper tilt angles (Sarver et al., 2013). In addition, tracked modules can be expected to experience less soiling compared to fixed modules (Safieh et al., 2020; Sayyah et al., 2014). However, as aforementioned, limited literature is available for field FPV systems. Anyway, it is interesting to cite (Ziar et al., 2021), where the experimental data have been reported on the electrical energy produced by the different bifacial photovoltaic floating design solutions (fixed, horizontal tracking, with and without reflectors). In this research, it has been observed that the birds' presence has a severe effect on floating PV performance in the short term, and that FPV modules should be kept tilted and at a high elevation from water. These reduce the birds' presence effects. Active bird control techniques are also recommended in that work. Although this is a specific case, we can infer that tracked modules can be less impacted by bird dropping, as they can move and assume high tilt angle also during the night. Of course, the high tilt angle can create problems in case of high-speed wind.

In light of the current PV trends and of the dynamic FPV market, the present study assesses the economic viability of various FPV designs. In particular, systems with and without tracking mechanisms are compared, taking into account the use of both monofacial and bifacial modules. Overall, nine FPV configurations are analysed, providing useful information to designers and installers. In addition, the costs and benefits of an active cooling system are also evaluated. All these FPV configurations are compared with a conventional fixed monofacial system for a more comprehensive analysis. To get the most realistic results, the model takes into account input data sourced from the literature and from the actual field installations.

The analysis is not limited to the electrical performance of FPV, as mainly done in previous literature, but it also takes into account the water evaporation savings. As aforementioned, indeed, the preserved water can be of significant value in arid high-insolation regions, where this resource is not abundant. The unevaporated water can be used for other purposes and can return to FPV owners variable economic revenues, depending on the application. For example, it can be used for irrigation, and therefore sold at the water price, or it can be employed for hydroelectricity generation, and therefore converted in energy and indirectly sold at electricity price. In this light, the present work provides a first assessment of the additional revenues due to water evaporation savings taking into account the two aforementioned scenarios.

The analysis is conducted by modelling comparing the energy and economic performance of different FPV designs on a water basin in Sicily, Southern Italy. This is done so that actual data can be used in the analysis and realistic results can be presented. The model is indeed provided with input data sourced either from the literature or from the interaction with stakeholders. This makes it possible to generate and compare reliable results for the different technologies. However, this also means that the quantitative results will have to be adjusted to the site-specific conditions of any new location where the investigation is repeated. Despite that, the results of this analysis can still be of interest, as they provide a first insight on the potential and the viability of various FPV configurations. In addition, it has to be highlighted that the chosen site is in Sicily, a large island in the centre of Mediterranean Sea, whose conditions, especially in terms of irradiance and ambient temperature, are those typical of the Mediterranean climate. For this reason, the results of this FPV comparative study could be considered representative for a number of countries overlooking the Mediterranean. Moreover, it should be highlighted that, similarly to the present study, valuable previous works in the FPV literature have also reported site-specific results, which have however contributed increasing the knowledge on this still relatively unexplored topic. For example, the authors of Boduch et al. (2022) reported information on the economic viability of FPV in Poland. The authors of Peters and Nobre (2022) raised doubts on the better heat transfer characteristics of FPV compared to land-based installations, by looking at a single site in Cambodia. The authors of Kjeldstad et al. (2021) investigated the different thermal mechanisms of FPV in enclosed water basins and in open seas by studying a single installation in Norway. As for these previous studies, the results of the present work could still be of value in different locations and conditions, as they discuss the performance of different floating PV solutions, even if the exact economic figures would change with time and from location to location.

The results of the analysis show the cost of electricity of the various FPV configurations and can contribute to the development of novel FPV solutions, identifying the potential tracking and enhanced efficiency designs that can lower the costs of this technology. In addition, they can guide designers in the selection of the most appropriate configuration, depending on the available fundings and the desired energy output. Also, they provide a first estimate of the economic value of FPV water savings, which have been often neglected in the literature. These have however also a wider, not-only-economical, value, which makes this analysis of interest also for policymakers. They can, indeed, find in this work techno-economic data on a key technology for sustainable development, and therefore make more-informed decisions on potential initiatives and directives to favour and/or regulate its deployment. The same model employed in this study could also be applied in the future to other locations, so that the results could be adjusted to the specific conditions of each site. In addition, it could be adapted to any new potential FPV design that will be presented in the market, to evaluate its profitability and its costs and benefits.

This work is structured as follows. In the second chapter, the methodology leading to the results is presented. In particular, the steps to determine the energetic results of the different systems investigated are listed. The analytics used for the LCOE estimation of GPV and FPV systems based on CAPEX, OPEX and yields resulting from the evaporation reduction induced by the FPV shading are also described. The third chapter shows the results obtained on the basis of some initial hypotheses, namely the choice of the site and consequently the producibility of the plant, the percentage of water surface occupied by the FPV system, the cooling effect, and the revenues deriving from the failure evaporation. In the fourth and last chapter the main results and the conclusions are summarized.

## Methodologic approach

This section describes the methodology used for comparing the economic performance of the various FPV designs considered in this study. As detailed in the following subsections, the performance of the FPV systems were modelled using energy parameters sourced from previous literature and from actual installations of collaborators. The analysis is based on the evaluation of three key figures, namely the cost of capital (CAPEX), the cost of operation and maintenance (OPEX) and the cost of electricity (LCOE).

The key point in the present economic model proposal for FPV plants is to take into account the revenues generated from the water evaporation savings. In addition, the LCOE costs are calculated taking into account the increase in energy efficiency due to active cooling with water. In addition, because of the uncertainty about the capital costs of FPVs, a sensitivity analysis of the LCOE is also performed.

### *Data on locations and photovoltaic systems*

The simulation is conducted considering the characteristic conditions in Anapo (37°06′57.9″N 15°08′20.8″E), a mid-latitude basin in Sicily, Southern Italy. The energy production is estimated using the PVsyst model, implemented in MATLAB environment and is based on experimental data (modules temperature and power) (Tina et al., 2021a; Tina et al., 2021b). A constant albedo of 10 % is assumed in the simulations. This is the average value among those proposed in the literature (https://www.pv-magazine.com/2022/03/01/akuo-speaks-out-on-recent-fire-accident-at-its-17mw-floating-pv-plant-in-france/, 2023; Kaymak & Şahin, 2022). The simulation does not consider the impact of waves on the energy yield. Indeed, FPV systems are mostly installed on in-land water basins, where waves are limited.

The LCOE is calculated for the following design and installation solutions (they are denoted in the following list by the acronyms in brackets):

- Fixed PV Monofacial (FXPVm), (this solution represents the base case for the comparative economic analysis)
- Bifacial fixed PV system (FXPVb)
- Horizontal Axis Tracker PV Monofacial (HATPVm)
- Horizontal axis tracker PV bifacial (HATPVb)
- Vertical axis Tracker PV Monofacial (VATPVm)
- Two axes Tracker PV Monofacial (2AXTPVm)

Four geometrical parameters are considered to model the PV arrays, namely the tilt angle ($\gamma_{Mm/b}$ (°)), the pitch distance ($d_r$), the length of a PV module (L) and the azimuth angle (Φ). The latter one is considered 0° if oriented along the North-South axis and 90° if oriented along the East-West axis. The effects of the height of the bifacial modules from ground or water surface is neglected. This is motivated by the fact that it is crucial to install FPV in a low position to reduce the effects of wind forces.

The graphical representation of the variables is reproduced in the scheme shown in Fig. 2. The values assigned to each variable depending on the geometric configuration of the system are shown in Table 1.

### *Temperature of PV modules*

The temperature of the modules is estimated using equation Eq. (1). This model has been chosen according to the experimental analysis performed in Tina et al. (2021a).

$$T_{pv} = T_{amb} + \frac{\alpha_{pv}\, G_{fr}(1-\eta_{STC})}{U_0 + U_1 w_v} \tag{1}$$

$U_0$ and $U_1$ are fit variables describing the impact of irradiance and wind speed, respectively, on the thermal balance of a PV module. Higher values mean that more heat is exchanged with the environment. Therefore, the higher the values, the lower the modules' operating temperatures and the efficiencies. In this work, the quantity $U_0$ and $U_1$ are chosen according to the values shown in Table 2. These have been sourced from a recent work (Tina et al., 2021a), where the performance of bifacial and monofacial FPV modules were experimentally compared.

### *CAPEX*

In this study the CAPEX values of the different plant solutions will be considered, obtained from economic offers received by companies that operate in the field of FPV and methodology for distribution of costs adopted in Rosa-Clot and Tina (2020b). They are slightly lower than the minimum cost values reported in https://www.woodmac.com/reports/power-markets-floating-solar-landscape-2021-476537/ (2023). This reflects the current situation as the reference is from 2021, when the first FPV systems were still being born. As is well known, the cost trend tends to decrease as the technology becomes mature.

The raw materials and consequently the plants, over the last few years have costs that fluctuate considerably over time and are linked to the political-economic situations of the various countries (see pandemic situation and war in Ukraine). To take into account this aspect and the uncertainty of the FPV costs due to the lack of maturity of the technology, a sensitivity analysis of the LCOE has been carried out which takes into account the variation of the CAPEX.

A variable called ΔCAPEX is introduced which is used to relate the variation of LCOE as a function of the reduction in CAPEX. Therefore, ΔCAPEX is defined as follows:

$$\Delta CAPEX = 100(1-K) \tag{2}$$

where K is a coefficient between 1 and 0.7 and takes into account the reduction of CAPEX from 0 to 30 %.

The evaluation of the CAPEX refers to the system solutions with the configuration shown in Table 1.

In the cost analysis, an increase in CAPEX for the cooling system will be considered based on the data provided by the companies that have built the active water-cooling systems with electric pumps, for the experimental plants monitored at the Enel Innovation Lab laboratories of Catania (Tina et al., 2021a; Tina et al., 2021b).

However, it should be highlighted that FPV is still at an early stage of

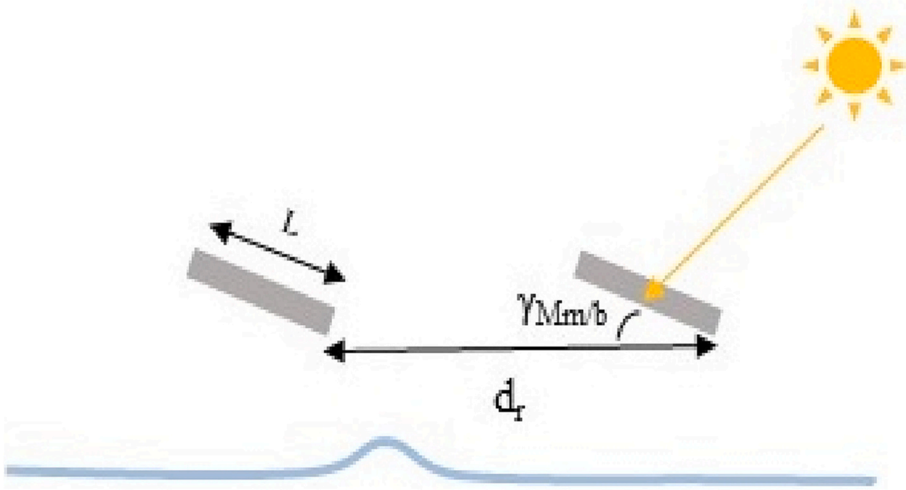


**Fig. 2.** Geometric variables of Ground and Floating PV systems.

**Table 1**
Geometrical characteristics of the modelled PV power plants.

| | |
|---|---|
| FXPV | |
| $\gamma_{Mm/b}$ (°) | 25 |
| $d_r/L$ | 2.1 |
| Φ (°) | 0 |
| FXGFPVm | |
| $\gamma_{Mm}$ (°) | 10 |
| $d_r/L$ | – |
| Φ(°) | ±90 |
| HATPV | |
| $\gamma_{Mm/b}$ (°) | ±50 |
| $d_r/L$ | 2.1 |
| Φ (°) | 0–90 |
| VATPV | |
| $\gamma_{Mm/b}$ (°) | 25 |
| $d_r/L$ | 2.1 |
| Φ (°) | ±120 |
| 2AXTPV | |
| $\gamma_{Mm/b}$ (°) | 0–50 |
| $d_r/L$ | 2.1 |
| Φ (°) | ±120 |

**Table 2**
Thermal characteristics of the modelled PV power plants, sourced from Tina et al. (2021a).

| | Monofacial FPV | Bifacial FPV | Monofacial GPV | Bifacial GPV |
|---|---|---|---|---|
| $U_0$ [W/(m$^2$·K)] | 31.92 | 35.22 | 25 | 29.5 |
| $U_1$ [W·s/(m$^3$·K)] | 1.5 | 1.5 | 1.2 | 1.2 |

development. This means that the supply chain is not yet fully established, and the technologies have not reached the maturity level required for the economy of scale to kick in. For these reason, one can expect the CAPEX of FPV to lower in future, as technological improvements are identified first and pass from prototypes to utility-scale plants then. In addition, a reduction of CAPEX can be obtained as the size of the plants gets larger. Indeed, the largest FPV system to date has a capacity of 320 MW (PV-magazine, 2022), while the largest GPV system currently in operation reaches 2.2 GW. A report published by NREL showed that CAPEX for a 50 MW FPV system is about 60 % compared to a 2 MW FPV power plant (Ramasamy & Margolis, 2021). Therefore, giving the dynamic nature of such a young market, a sensitivity analysis has also been carried out to evaluate the variability of the results as the CAPEX change.

The conventional fixed GPV system (FXPV) will be used as a reference to compare the cost differences of the various FPV designs.

*OPEX*

Different scenarios will be considered for modelling the OPEX. In the first scenario, the maintenance required by the cooling system is modelled to increase the OPEX. In the second and third scenarios, another factor is introduced, i.e. the revenues deriving from non-evaporated water. As mentioned above, these can be due to:

- water sold for irrigation ($REV_{IRR}$).
- water fed into the turbine of a hydroelectric power plant ($REV_{HPP}$).

The reduction in water evaporation rates is modelled by taking into account the findings of Bontempo Scavo et al. (2020). In that work, Bontempo Scavo et al. (2020) shared numerical evaporative models for different floating geometries. Subsequently, the volume of water because of the lower evaporation due to the shading from the module was calculated as follows:

$$Vol = \eta_{cover} E_{free} S \tag{3}$$

where:

- $\eta_{cover}$ is the efficiency of the covering with FPV, defined as the ability of the FPV system to reduce evaporation;
- $E_{free}$ is evaporation of free water surfaces [m];
- S is the surface covered by the FPV system [m$^2$].

In one scenario, the saved water is modelled to be sold as is for water irrigation. In this case, the revenues, $Rev_{IRR}$ [$], made from the sale are calculated as follows:

$$Rev_{IRR} = Vol^{*} c_{w-irr} \tag{4}$$

where:

- $c_{w\text{-}irr}$ is the price of water for irrigation [$/m$^3$];
- Vol is the volume of the water non-evaporated [m$^3$].

In the other scenario, the water is fed into the turbine for hydroelectricity production. In this caser the additional revenues for the HPP plant, $Rev_{HPP}$ [$], are calculated as follows:

$$Rev_{HPP} = EE^* c_{el.en} \tag{5}$$

where:

- $c_{el.en}$ is the price [$/kWh] of the sold electricity;
- EE [kWh] is the energy produced by HPP.

The energy produced by the turbine, EE [kWh], is calculated as follows:

$$EE_{HPP} = P_{HPP}{}^* t \tag{6}$$

where t is the time spent by the turbine to convert the amount of non-evaporated water into electrical energy. $P_{HPP}$ [kW] is the power produced by the hydroelectric power plant and is calculated as follows:

$$P_{HPP} = 9.81^* Q^* h^* \eta \tag{7}$$

where Q is the flow rate of the turbine in [m$^3$/s], h is the head in [m] and η is the efficiency of the turbine.

With the method described above the OPEX, expressed in [$/kW], of each plant are calculated in the case of revenues obtained from the water sold for irrigation, as follows:

$$OPEX_{TOT\ IRR} = OPEX_{BASE} + OPEX_{COOL} - Rev_{IRR} \tag{8}$$

where $OPEX_{BASE}$ is the OPEX value provided by the system installer, $OPEX_{COOL}$ are the costs related to the operation and maintenance of the active cooling system, and, as described above, $Rev_{IRR}$ are the revenues from the sale of non-evaporated water.

With the method described above, the OPEX of each plant are calculated in the case of revenues due to water converted into electricity by the HPP plant, as follows:

$$OPEX_{TOT\ HPP} = OPEX_{BASE} + OPEX_{COOL} - Rev_{HPP} \tag{9}$$

The $OPEX_{COOL}$ value are obtained as follows:

$$OPEX_{COOL} = OPEX_{COOL\ MAINT} + \left(P_{w\ pump}{}^* Price_{el}{}^* t_{wpump}\right) \tag{10}$$

where $P_{w\ pump}$ is the power of the pump, $Price_{el}$ is the price per kWh of the electricity consumed by the pump, $t_{w\ pump}$ is the operating time of the pump and $OPEX_{COOL\ MAINT}$ is the OPEX due to maintenance of cooling system.

From the experience acquired during the monitoring of the cooling system of the FPV experimental plant of the ENEL Innovation Hub and Lab in Catania (IT), it can be assumed that the pump can be activated on average for 3.5 h per day during the six hottest months of the year (Tina et al., 2021b). As it is necessary to clean the filters and sprinklers of the cooling system due to the excessive turbidity of the water, an additional cost for maintenance will be considered.

As for the revenues for irrigation, they are a function of the selling price of water, so a sensitivity analysis of the revenues will be carried out in relation to the unit cost of water.

As for the revenues from the sale of energy, they depend on the electricity market and vary from day to day and month to month. Furthermore, since the energy produced depends on other variables such as the prevalence of the HPP plant that changes from plant to plant, it is necessary to make a sensitivity analysis of the revenues according to the prevalence but also the cost of selling electricity.

*LCOE*

Starting from the hypotheses of costs and producibility of the plants, the LCOE will be calculated for each technology (mono, bifacial, fixed and tracking). Through a sensitivity analysis, the competitiveness of FPV systems with respect to ground-based reference systems will be assessed, evaluating the benefits due to the reduction of evaporation and the increase in energy yield.

The LCOE expresses the cost of producing each kWh over the lifetime of an energy system. It is often employed to compare different energy technologies. The lower its value, the more cost-competitive the energy source. In this work, the LCOE calculations are based on the model presented by NREL in Short et al. (1995). The calculation formula is as follows:

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electrical\ energy\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{11}$$

where:

- $\boldsymbol{CAPEX_t}$ [$/kW] is investment expenditures in the year t
- $\boldsymbol{OPEX_t}$ [$/kW] is operations and maintenance expenditures in the year t
- $\boldsymbol{E_t}$ [kWh] is electrical energy generated in the year t
- $\boldsymbol{r}$ is discount rate
- $\boldsymbol{n}$ is expected lifetime of system

The LCOE of each plant will be calculated in absolute value. At the same time, the LCOE differences between the innovative FPV solutions and the GPV reference solution will be also provided for comparative purposes. These are expressed as ΔLCOE, calculated as follows:

$$\Delta LCOE = 100\frac{LCOE_{FPV} - LCOE_{FXGPVm}}{LCOE_{FXGPVm}} \tag{12}$$

A positive ΔLCOE value indicates that the FPV system is more costly (and therefore not competitive) respect to reference GPV system and vice versa.

To evaluate the competitiveness of the various systems examined with respect to the fixed monofacial ground reference system, a sensitivity analysis of the LCOE will be carried out as a function of the CAPEX variation for the different solutions and scenarios considering:

- reduction from 0 to 30 % of the CAPEX in active cooling conditions of the modules;
- reduction from 0 to 30 % of the CAPEX in conditions of active cooling of the modules and revenues deriving from the sale of additional energy produced by HPP with the saved non-evaporated water;
- reduction from 0 to 30 % of the CAPEX in conditions of active cooling of the modules and revenues from the sale of non-evaporated water, for irrigation.

The following formula is used to reduce the CAPEX of different plant solution:

$$CAPEX_{Reduced} = K\ CAPEX \tag{13}$$

where K is a coefficient between 1 and 0.7 and takes into account the reduction of CAPEX from 0 to 30 %.

## Results

This paragraph will show the comparison of the LCOE for the various plant solutions studied and demonstrate its competitiveness.

*Assumptions*

Before showing the results, it is necessary to make some clarifications and assumptions that we report below:

- The values of equivalent hours, Y, considered in the LCOE calculations for each single technology are shown in Table 3 and have been calculated in the paragraph of energy performance analysis. These values are based on the results of an experimental analysis that results are reported in Tina et al. (2021a) and in Tina et al. (2021b).
- The used CAPEX values are shown in Table 4 and deriving from offers of stackeolders working in the field of installing FPV systems. They are slightly lower than the minimum cost values reported in https://www.woodmac.com/reports/power-markets-floating-solar-landscape-2021-476537/ (2023). This reflects the current situation as the reference is from 2021, when the first FPV systems were still being born. As is well known, the cost trend tends to decrease as the technology becomes mature.
- The used OPEX values are Table 6. The reference values deriving from offers of stackeolders working in the field of installing FPV systems.
- The cost of the active water-cooling system is $CAPEX_{COOL}$ = 20 \$/kWp. This value deriving from the experience of experimental FPV that the authors manage.
- Discount rate r = 3 % based on the analysis of https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf (2023);
- Plant life n = 30 years. This value is the mean of maximum and minimum reported by NREL in https://www.nrel.gov/analysis/tech-footprint.html (2023) and in Ndzibah et al. (2021). Morehover the lifetime of PV panels is 30 years as reported in https://www.pv-magazine.com/2022/11/08/most-new-solar-panels-retain-80-production-after-30-years/ (2023).
- The increase in energy due to active cooling is 9.5 % for monofacial and 9.7 % for bifacial modules consistently as reported in Tina et al. (2021b).
- The occupied water surface is 180,000 $m^2$ that correspond to a 50 % of occupied area of Anapo Dam. The percentage of covering is suggested in Muñoz-Cerón et al. (2023).
- The occupied surface area per 1 MW is equal to 10,000 $m^2$ (Pouran et al., 2022). A system of 18 MW size is considered.
- The annual evaporation for free water surface for Sicily is $E_{free}$ = 1742 mm. This value is coherent with results of Bontempo Scavo et al. (2020).
- The percentage of water surface covered by the modules is $x = 50$ %.
- The coverage efficiency considering the type of floats is 73 %. This value is coherent with results of Bontempo Scavo et al. (2020). The annual evaporation per MW of water surface covered by the system is $E_{FPVd}$ = 470.34 mm. The water saved is 1271.66 mm.
- The efficiency of the HPP plant is equal to $\eta = 0.9$
- The head of the HPP plant is equal to h = 500 m

**Table 3**
Equivalent hours, $Y_{eq}$, values for different PV power plant solutions in Anapo Dam (Sicily).

| PV systems | $Y_{eq}$ [h] | $\Delta Y_{eq}$ [%] |
|---|---|---|
| FXGPVm | 1736.6 | – |
| FXFPVm | 1818.5 | 4.724 |
| FXFPVb | 1863.2 | 7.30 |
| HATFPVm (E-W) | 1928.9 | 11.10 |
| HATFPVb (E-W) | 1982.8 | 14.18 |
| HATFPVm (N-S) | 2056.9 | 18.44 |
| HATFPVb (N-S) | 2110.5 | 21.53 |
| VATFPVm | 2172.2 | 25.08 |
| 2AXTFPVm | 2515.1 | 44.83 |

**Table 4**
CAPEX for different FPV plants for a peak power of 1 MW.

| | CAPEX (\$/kW) | CAPEX + $CAPEX_{COOL}$ (\$/kW) |
|---|---|---|
| FXGPVm | 899.6 | – |
| FXFPVm | 984.0 | 1004.0 |
| FXFPVb | 1012.2 | 1032.2 |
| HATFPVm (E-W) | 1230.0 | 1250.0 |
| HATFPVb (E-W) | 1266.9 | 1286.9 |
| HATFPVm (N-S) | 1230.0 | 1250.0 |
| HATFPVb (N-S) | 1266.9 | 1286.9 |
| VATFPVm | 1394.3 | 1414.3 |
| 2AXTFPVm | 1935.7 | 1955.7 |

- The selling price of water for irrigation is 0.15 \$/$m^3$ (Regione Siciliana, 2021)
- The selling price of the electricity produced by the HPP plant is 90 \$/MWh (https://www.mercatoelettrico.org/it/, 2023).
- The LCOE sensitivity analysis takes into account a CAPEX variation ranging from 0 to 30 %.

Table 3 shows the summary of Y for different power plant in Anapo Dam (Sicily) (Tina & Bontempo Scavo, 2022). Because of the cooling effect of water, FPV systems return more equivalent hours than GPV, thanks to the higher yields. In particular, the same fixed monofacial installation moved from land to water increases the performance by almost 5 %. An additional 2.5 % enhancement could be achieved if monofacial modules are replaced with bifacial modules. More improvements are possible, as expected, if trackers are mounted. In this simulation, the best performance among single axis trackers is returned by a vertical axis configuration. In this case, equivalent hours would be 20 % more than those registered by a fixed configuration. This is 12 % more than the worst performing single axis design, i.e. the horizontal single axis tracker parallel mounted on E-W configuration. It is also higher than any bifacial horizontal-axis tracker configuration. However, if a two-axis tracker is employed, the equivalent hours could be increased by almost 40 % and 16 % compared to a fixed and single vertical axis configuration, respectively.

*CAPEX*

Clearly the addition of trackers has non-negligible costs. These affect both the capital and the maintenance expenditures. A summary of the CAPEX costs per kW for 1 MW FPV plant in Anapo Dam (Sicily) is reported in Table 4. Moreover, the last column of the table shows the increased CAPEX due the addition of the cooling system. All the data shown in Table 4 were obtained using the methodology of Tina and Bontempo Scavo (2022).

Installing a PV system on water is still more expensive than on land. As aforementioned, this is not surprising, given the early stage of development and the limited installed capacity of FPV compared to GPV. In 2020, FPV had the same capacity that GPV achieved in the early 2000s. For this reason, one can expect capital costs in the order of 10 % higher for floating installation compared to land-based systems. Using bifacial modules instead of monofacial ones and mounting a tracker system could further increase the costs by up to 3 %. However, trackers have the greater impact on the CAPEX. Indeed, compared to the fixed FPV configuration, horizontal trackers can raise the expenditure by 20 %–30 %, whereas vertical trackers might go as high as 40 %. Using a double axis tracker almost double the CAPEX compared to fixed FPV configurations. Last, the addition of an active cooling system increases the capital cost by 1 % to 2 %.

*Revenues*

Based on the above methodology and assumptions, it is possible to calculate the revenues from the sale of water for irrigation and from the sale of electricity produced by the HPP plant.

The revenues from irrigation directly depend on the selling price of water. Therefore, according to the assumptions, a sensitivity analysis of the revenues can be carried out in relation to the cost of water sold for irrigation. Table 5 shows the variation in revenues from irrigation for three water price scenarios. In an intermediate condition, in which the cost of water is 0.15 $/m$^3$, the revenues are equal to $Rev_{IRR} = 1.90$ $/kWp/y.

If the saved water is used for hydro-energy production, the revenues have to be calculated from the electricity prices. Electricity in Europe is mostly sold in so-called spot-markets, where it is subject to a bid-based competition. The final price is set depending on the demand and on the offered prices. This means that the electricity market price varies every hour and from day to day and month to month. In addition, also the hydro-energy production varies. Indeed, the water-to-energy conversion rate depends on a number of factors, such as the head of the HPP system, which changes from plant to plant. For all these reasons, a sensitivity analysis of the revenues is presented based on both various values of head and electricity selling prices. The results are shown in Fig. 3, which reports the revenues in relation to the head (h) for the different electricity price scenarios ($Price_{el}$). In an intermediate situation ($Price_{el} = 90$ $/MWh and h = 500 m), revenues ($Rev_{HPP}$) as high as 1.40 $/kW can be obtained. This will increase while the head of the HPP plant and the electricity prices raise.

### OPEX

Table 6 shows the OPEX in the baseline and in the additional configurations. These include the scenario in which the water is sold for irrigation and the one in which it is sold in the form of energy produced by the HPP plant. Note that these values are calculated on the basis of the following revenues:

- $Rev_{IRR} = 1.90$ $/kW.
- $Rev_{HPP} = 1.40$ $/kW.

Assuming that the pump is activated for an average of 3.5 h per day for six months of the year, the $OPEX_{COOL}$ value can be obtained as follows.

$$\text{Pump operation equal to}: t_{w\ pump} = 30\ (\text{days})3.5\ (\text{hours per day})6\ (\text{months}) = 630\ \text{h}.$$

Taking as an example the cooling system of the above mentioned FPV plant of the Enel Innovation Lab in Passo Martino (CT), it can be said that a pump with an absorption of 0.25 kWh is sufficient for cooling a 5 kWp FPV system. This translates into an energy consumption of 0.05 kWh/kWp.

Assuming a cost of electricity equal to $Price_{el} = 0.09$\$/kWh and a cost for maintenance of 1.8 $/kW: $OPEX_{COOL} = \left(630\,h\,0.05\frac{kW}{kWp}0.09\frac{\$}{kWh}\right) + 1.8\,\frac{\$}{kW} = 4.63\,\$/kWp$ is obtained. Therefore, $OPEX_{COOL} = 4.63$ $/kWp.

In Table 6 there is summary of OPEX values in relation to the adopted plant solution. To provide a visual insight of such values compared to the fixed ground PV solution a histogram is shown in Fig. 4. Fixed configurations have minimal costs, as limited maintenance is required, and no power is needed to operate. OPEX are higher if trackers are mounted as they consume energy to move the system and they are also likely to require some regular and exceptional maintenance. The OPEX increases range in between 10 and 20 % compared to a fixed configuration and raise with the number of degrees of freedom. However, as aforementioned, also the energy yield increases with trackers, and is higher if two-axis trackers are employed.

Similarly, also the installation of a cooling system increases the OPEX costs but, at the same time, when activated, it increases the performance of the modules. It also reduces the effect of degradation and therefore increases the useful life of the system.

In summary, the following operating costs are shown in Table 6:

- $\mathbf{OPEX_{BASE}}$. Additional costs (i.e. due to cooling) are not considered;
- $\mathbf{OPEX_{BASE} + OPEX_{COOL}}$. The basic costs are considered to which the costs necessary to maintain the cooling system active and functioning are added.
- $\mathbf{OPEX_{TOT\ IRR} = OPEX_{BASE} + OPEX_{COOL}\text{-}Rev_{IRR}}$. The basic costs are considered to which the costs necessary to maintain the cooling system active and functioning are added and, the revenues due to the sale of water (saved due to lack of evaporation) are subtracted from these costs for irrigation use.
- $\mathbf{OPEX_{TOT\ HPP} = OPEX_{BASE} + OPEX_{COOL}\text{-}Rev_{HPP}}$. The basic costs are considered to which the costs necessary to maintain the cooling system active and functioning are added and, the revenues due to the production of electricity with the water saved due to the lack of evaporation are subtracted from these costs.

### LCOE

As described earlier, the most performing configurations (bifacial modules, trackers, cooling) have higher capital and/or operation & maintenance cost. However, the cost-competitivity of each solution has to be weighted taking into account also the energy yield improvements. This can be done through an analysis of the LCOE, whose results are shown in Table 7, calculated on the basis of the previous hypotheses. To provide a visual insight of such values compared to the fixed ground PV solution a histogram is shown in Fig. 5.

Moving the same fixed system from land to water is found to always bring an economic benefit. The same can be said for bifacial modules, which, despite the higher installation costs, lead to higher energy gains and therefore lower costs of electricity. On the other hand, using trackers and active cooling systems is not always cost-competitive compared to the reference system on the ground. In particular, only the horizontal N-S trackers are found to lower the FPV LCOE and only if coupled with active cooling. Any other configuration returns higher LCOEs. The same results are true if additional profits from the preserved water are considered. These are indeed found to lower the LCOE by 1 to 2 % depending on the configuration and the water usage. However, this reduction is not sufficient to make horizontal E-W, vertical and two-axis trackers cost-competitive with the baseline fixed land-based installation.

Nonetheless, these findings should not discourage since, as previously mentioned, the FPV systems are still a recent technology and, in the future, there will be a drastic reduction in costs in particular for innovative solutions such as tracking systems. Under this premise, it is worth seeing what happens when the CAPEX is reduced. For this, a sensitivity analysis of the LCOE will be developed and presented in the following section.

### Sensitivity of LCOE

In just a decade, GPV has seen his capital expenditure drop by more than 80 % (IRENA, 2022). This was due to a significant reduction in module's cost but was also contributed by the lowering balance-of-system costs. As already mentioned, with the improvement of the FPV technology in the future, a reduction of costs can be foreseen also for this type of installations. Some elements, such as floaters, are indeed specific to floating systems, and will benefit of the growing deployment of FPV.

**Table 5**
Revenue of irrigation in relation to price of water.

| | | | |
|---|---|---|---|
| $Price_{wIRR}$ ($/m$^3$) | 0.05 | 0.15 | 0.25 |
| $Rev_{IRR}$ ($/kWp) | 0.63 | 1.90 | 3.17 |

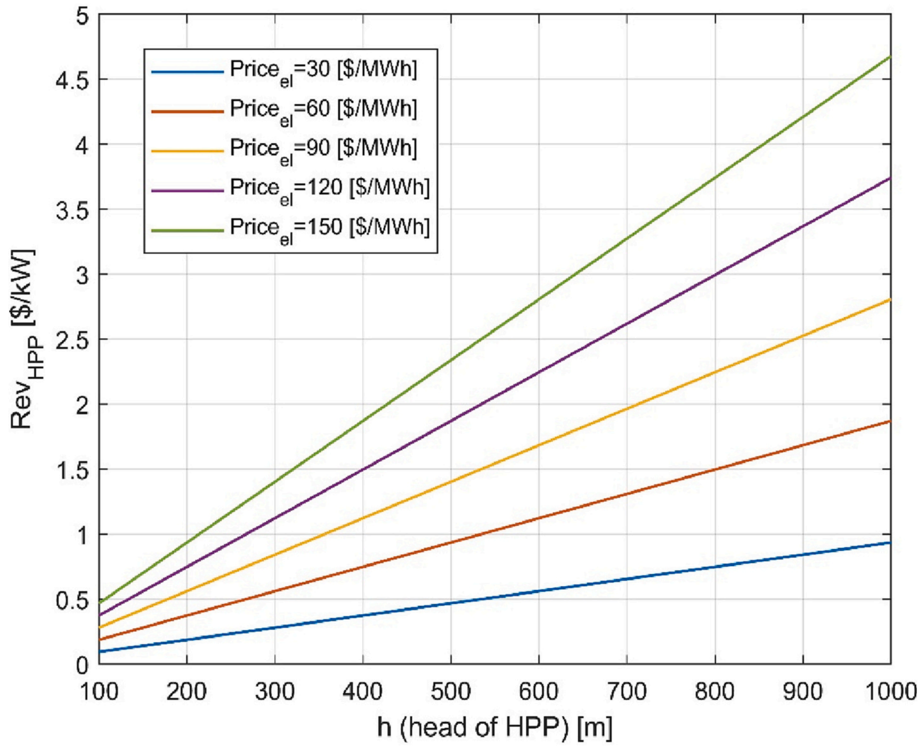


**Fig. 3.** Revenues in relation to h for the different electricity costs.

**Table 6**
OPEX of GPV/FPV plants.

| PV systems | $OPEX_{BASE}$ ($/kW) | $OPEX_{BASE}$+$OPEX_{COOL}$ ($/kW) | $OPEX_{TOT\ IRR}$ ($/kW) | $OPEX_{TOT\ HPP}$ ($/kW) |
|---|---|---|---|---|
| FXGPVm | 51.64 | – | – | – |
| FXFPVm | 51.64 | 56.27 | 54.36 | 54.86 |
| FXFPVb | 52.15 | 56.78 | 54.88 | 55.38 |
| HATFPVm (E-W) | 56.80 | 61.43 | 59.52 | 60.03 |
| HATFPVb (E-W) | 57.32 | 61.95 | 60.04 | 60.54 |
| HATFPVm (N-S) | 56.80 | 61.43 | 59.52 | 60.03 |
| HATFPVb (N-S) | 57.32 | 61.95 | 60.04 | 60.54 |
| VATFPVm | 59.38 | 64.01 | 62.10 | 62.61 |
| 2AXTFPVm | 61.96 | 66.59 | 64.69 | 65.19 |

For this reason, this paragraph presents a sensitivity analysis of the LCOE as function of the CAPEX reduction.

Fig. 6 shows the relative LCOE reduction for the various FPV

**Table 7**
LCOE of F/GPV plants. In bold the LCOE values lower than the reference.

| (cent$/kWh) | $LCOE_{BASE}$ | $LCOE_{COOL}$ | $LCOE_{COOL+RevHPP}$ | $LCOE_{COOL+RevIRR}$ |
|---|---|---|---|---|
| FXGPVm | 5.62 | – | – | – |
| FXFPVm | **5.60** | **5.40** | **5.33** | **5.30** |
| FXFPVb | **5.57** | **5.36** | **5.30** | **5.27** |
| HATFPVm (E-W) | 6.20 | 5.93 | 5.86 | 5.84 |
| HATFPVb (E-W) | 6.15 | 5.87 | 5.80 | 5.78 |
| HATFPVm (N-S) | 5.81 | **5.56** | **5.50** | **5.47** |
| HATFPVb (N-S) | 5.78 | **5.51** | **5.45** | **5.43** |
| VATFPVm | 6.01 | 5.72 | 5.67 | 5.64 |
| 2AXTFPVm | 6.39 | 6.04 | 5.99 | 5.97 |

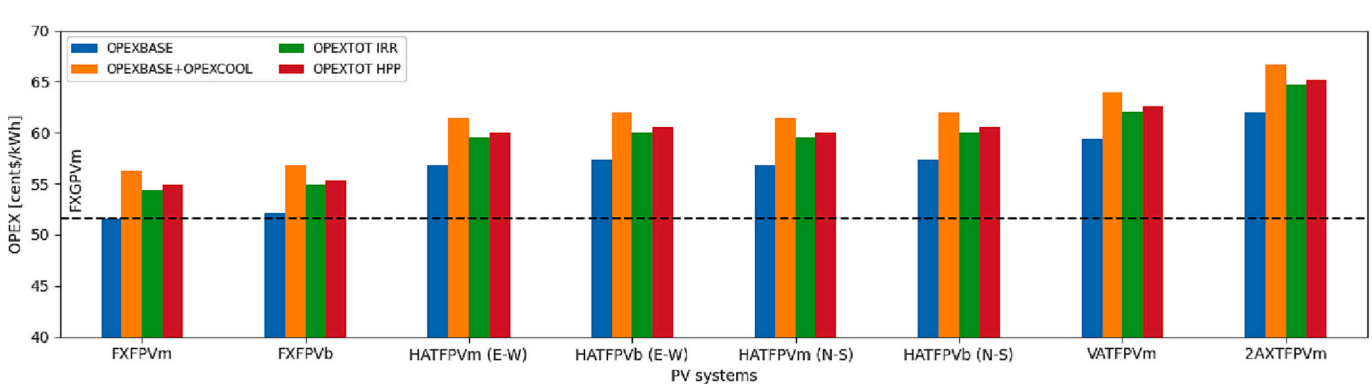


**Fig. 4.** OPEX values of different floating PV solutions compared to the GPV OPEX (dashed black line).

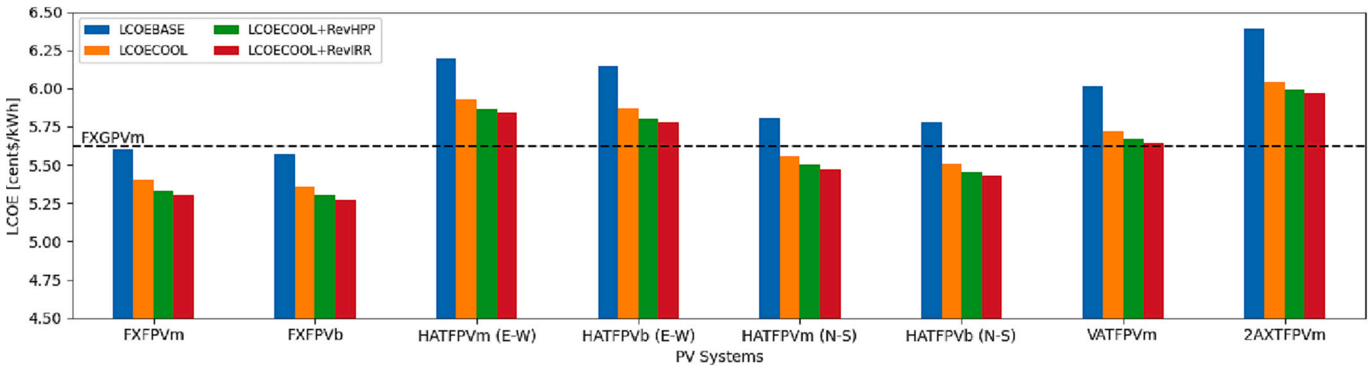


**Fig. 5.** LCOE values of different floating PV solutions compared to the GPV OPEX (dashed black line).

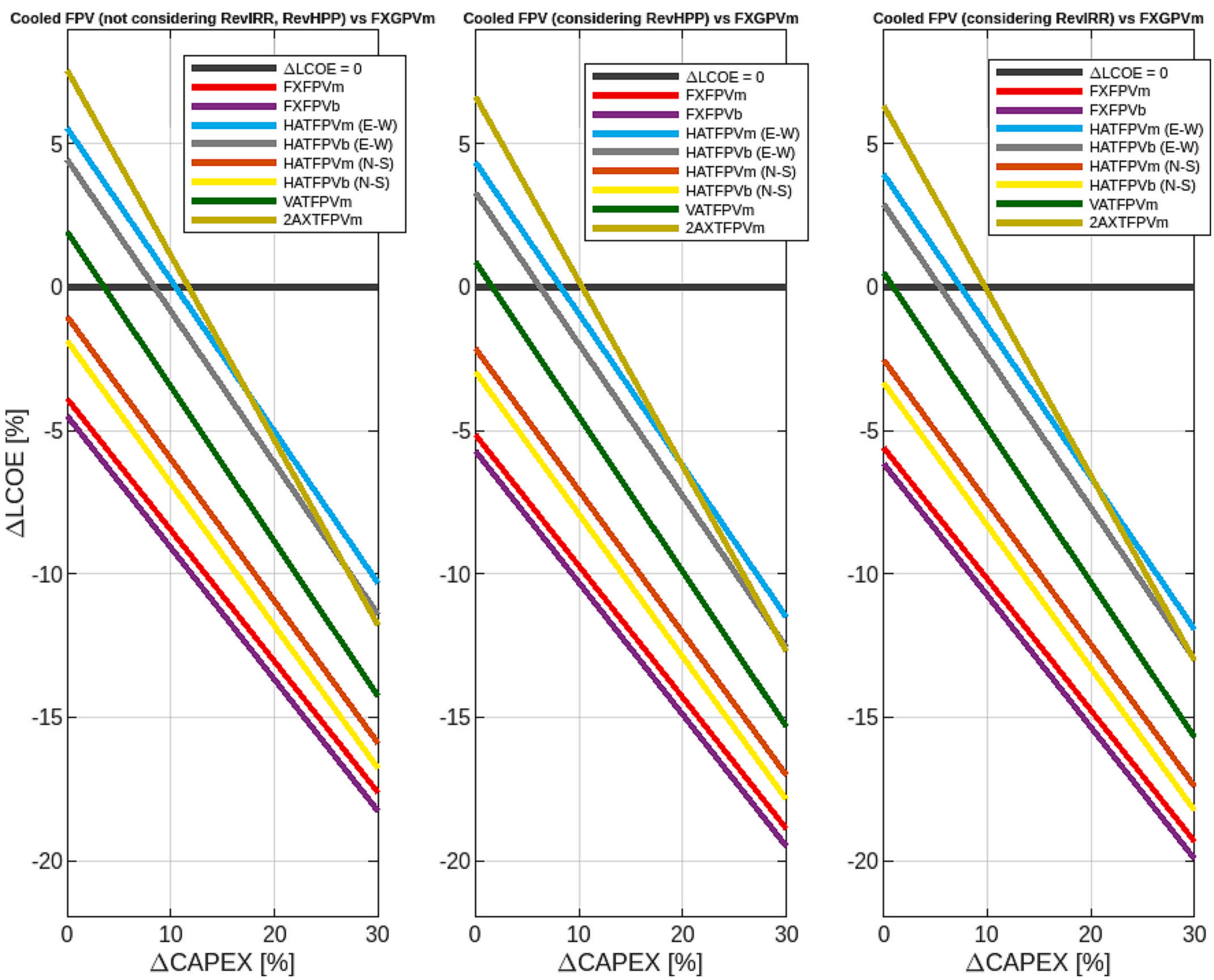


**Fig. 6.** ΔLCOE in function to ΔCAPEX.

configurations compared to the reference system. As it can be seen, the ΔCAPEX lines have approximate slopes of 0.8. This means that each percentage point of reduction in CAPEX return a 0.8 % reduction in LCOE. A significantly steeper slope is found for the two-axis configuration. In this case, indeed, because of the disproportion between additional costs and yield improvement, every reduction in CAPEX returns an even higher reduction in LCOE. Under certain conditions of CAPEX reduction, this configuration can become more competitive than single E-W axis configuration.

In addition, it should be noted that for CAPEX reductions of at least 12 %, all the floating configurations become more cost-competitive than the reference fixed-tilt GPV system. Table 8 shows the decrease of CAPEX of FPVs with cooling to have the same LCOE of a FXGPVmin (ΔLCOE = 0) for three cooling scenarios analysed.

**Table 8**
Decrease of CAPEX of FPVs with cooling to have ΔLCOE = 0.

| Scenario | ΔCAPEX(ΔLCOE = 0) | | |
|---|---|---|---|
| | Cooling | Cooling and $Rev_{HPP}$ | Cooling and $Rev_{IRR}$ |
| FXFPVm | 0 | 0 | 0 |
| FXFPVb | 0 | 0 | 0 |
| HATFPVm (E-W) | 10.5 | 8 | 7 |
| HATFPVb (E-W) | 8 | 6 | 5 |
| HATFPVm (N-S) | 0 | 0 | 0 |
| HATFPVb (N-S) | 0 | 0 | 0 |
| VATFPVm | 3.5 | 2 | 1 |
| 2AXTFPVm | 12 | 10.5 | 10 |

Table 9 shows the minimum and maximum ΔLCOE values obtainable by comparing the ground system with the FPV system in the following scenarios:

- increase in energy yield due to the active cooling of the modules
- increase in energy yield due to the active cooling of the modules and revenues from the sale of additional energy produced with the saved non-evaporated water.
- increase in energy yield due to the active cooling of the modules and revenues from the sale of non-evaporated water (for irrigation).

It can be concluded that the most competitive system in terms of the lowest achievable LCOE value is FXFPVb. In this case, indeed, a 19.9 % reduction in LCOE is obtained compared to the reference if the CAPEX is lowered by 30 %. This means that, if the CAPEX were reduced by 30 % in the future, the cost of electricity of the FXFPVb system will be 19.9 % less than the FXGPVm system. This demonstrates the added value that active cooling and non-evaporated water can bring to the floating system.

### Markets volatility and impact on the economics of FPVs

An economic analysis of the floating PV and the comparison with land-based PV installation requires a not simple analysis that involves also the basic material price fluctuations. These, however, have been significant, especially in the last 2 years. As an example, the plot in Fig. 7 shows the average worldwide cost of a ton of steel in the last 10 years. The price rose from 1344 $/ton at the end of 2015 to 6012 $ in October 21 and is now at an average price slightly below 4000 $.

Extraordinarily strong fluctuations are experienced also by the price of oil, which directly affects the cost of HDPE (High Density Poly-Ethylene) pipes. In addition, the price of oil influences also photovoltaic module industry, which is also affected by other factors. For example, the supply chain crisis that followed the initial COVID-19 outbreak has led to the first increase in module prices (33–35 cents per Watt) after ten years of continuous price reduction (from 1 $ per Watt to 20–25 cents). The latest IRENA report on the renewable power generation costs attributes this unexpected trend to the higher material costs and to the lower availability, associated also to a rise in energy and food prices, worsened by the Ukrainian war and the labour market issues (IRENA, 2022).

**Table 9**
Minimum/maximum ΔLCOE for different FPV.

| Scenario | Cooling | | Cooling and $Rev_{HPP}$ | | Cooling and $Rev_{IRR}$ | |
|---|---|---|---|---|---|---|
| | ΔLCOE | | | | | |
| PV systems | Min | max | min | max | Min | Max |
| FXFPVm | −17.6 | −3.9 | −18.9 | −5.1 | −19.3 | −5.6 |
| FXFPVb | −18.3 | −4.5 | −19.5 | −5.7 | −19.9 | −6.2 |
| HATFPVm (E-W) | −10.3 | 5.5 | −11.5 | 4.4 | −11.9 | 3.9 |
| HATFPVb (E-W) | −11.4 | 4.5 | −12.6 | 3.3 | −13.0 | 2.9 |
| HATFPVm (N-S) | −15.9 | −1.0 | −17.0 | −2.1 | −17.4 | −2.5 |
| HATFPVb (N-S) | −16.8 | −1.9 | −17.9 | −2.9 | −18.2 | −3.3 |
| VATFPVm | −14.3 | 1.9 | −15.3 | 0.9 | −15.7 | 0.5 |
| 2AXTFPVm | −11.8 | 7.6 | −12.7 | 6.7 | −13.0 | 6.3 |

Taking modules sold in Europe as a reference, these developments meant that the price of crystalline solar PV modules increased between 4 % and 7 % in 2021 compared to 2020.

Some of these factors clearly influenced also the natural gas market. The fluctuations of natural gas price have been the most extreme, and have directly affected the kWh energy cost. Prices in Europe rose from 20 €/MWh to more than 300 €/MWh in summer 2022. Prices have now lowered to 120€ per MWh (see Fig. 8). It is worth reminding that, thanks to the rule of 3, this implies a cost of electric energy produced with natural gas of 360 € per MWh or 36 cents per kWh.

From the point of view of the PV revenues, also the variability of the day-ahead prices should be considered. It is indeed evident that the current energy crisis, aggravated by the war in Ukraine and the aforementioned consequent impact on natural gas market, has determined an unprecedented increase of the selling price of electrical energy.

The profile of the electricity prices in the European electricity spot markets can be seen in Fig. 9. Following the COVID-19 outbreak, several EU countries enforced lockdown measures, which decreased the electrical energy demand. The sudden unbalance between offer and demand led to severe price drops (Halbrügge et al., 2021). Since the end of the first lockdown, however, electricity prices have increased to unprecedented values, higher than 200 €/MWh (Boduch et al., 2022).

It should be noted that European countries are considering many actions to fight such volatility. In addition, a recent analysis has suggested that price might come back to historical values by 2025 or earlier (Schmitt, n.d.). For these two reasons, the current high prices were not considered in the present economic analysis.

It should be highlighted that the economic conditions vary also from country to country. A more in-depth analysis of the spatial variability of economic conditions on FPV cost-competitiveness has been presented in Micheli et al. (2022). However, the results reported in this paper could still be used, in different locations and conditions, as a comparative economic analysis of different floating PV solutions. However, the presented economic figures of each solution should be careful checked at the time when the investment has to be done.

The grey area in Fig. 9 includes all the prices in the various European countries.

### Conclusions

The present work investigates the cost competitiveness of different FPV configurations installed on a water basin in Southern Italy. This analysis considers various factors in addition to the improved efficiency that floating installations experience because of the cooling effect of water. Indeed, the use of a water based active cooling system and of a tracker could further boost the energy yields of these systems. Moreover, the shading produced by the FPV modules limits the water evaporation from the basins, potentially leading to additional profits. The non-evaporated water, indeed, can return revenues greater than 3 $/kWp if sold for irrigation and greater than 4 $/kWp if employed to generate hydroelectricity.

Considering only the effect of cooling, FXFPVm/b, HATFPVm/b (N-S) systems are competitive without any reduction in CAPEX. HATFPVm (E-W) and HATFPVb (E-W) become competitive when the CAPEX is lowered by at least 10.5 % and 8 % respectively. The VATFPVm system becomes competitive starting from a CAPEX reduction equal to 3.5 % and the 2AXTFPVm system from a CAPEX reduction of 12 %.

If the effect of cooling and the revenues $Rev_{HPP}$ are considered, FXFPVm/b and HATFPVm/b (N-S) systems are competitive without any reduction in CAPEX. HATFPVm (E-W) becomes competitive starting from a reduction in CAPEX equal to 8 % and HATFPVb (E-W) 6 %. The VATFPVm system becomes competitive starting from a CAPEX reduction equal to 2 % and 2AXTFPVm 10.5 %.


**Fig. 7.** Steel price in the last 10 years.

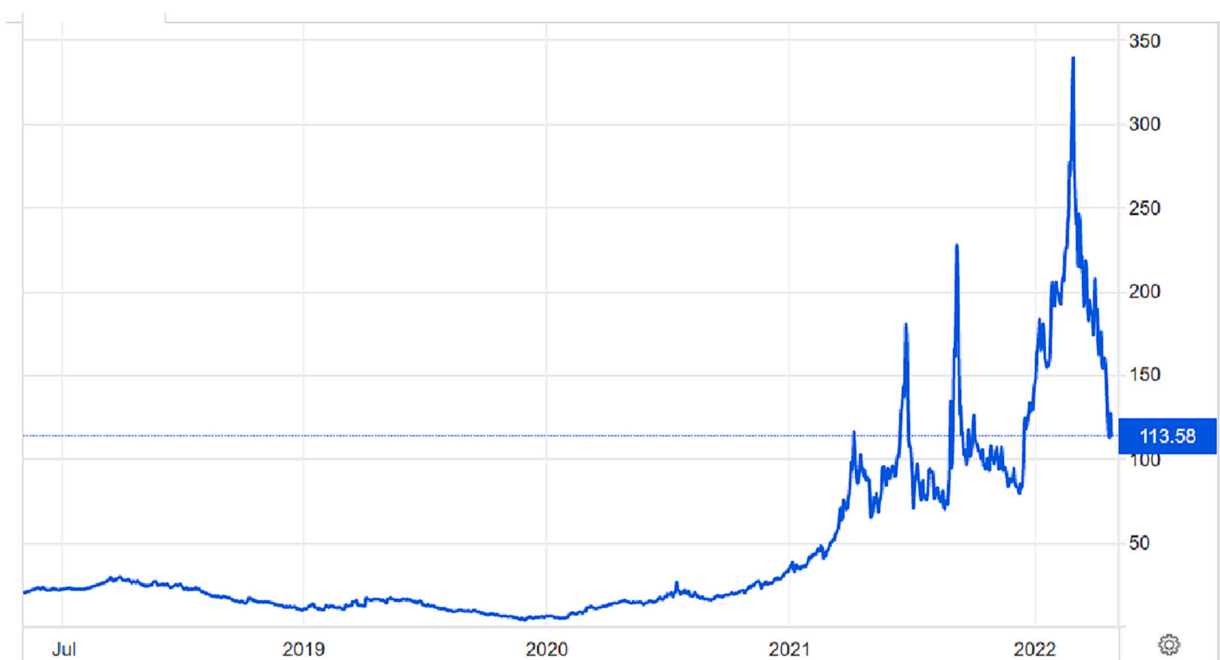


**Fig. 8.** Natural gas cost in € per MWh in the last five years.

Considering the effect of cooling and revenues $Rev_{IRR}$, FXFPVm/b and HATFPVm/b (N-S) systems are competitive without any reduction in CAPEX. HATFPVm (E-W) becomes competitive starting from a reduction in CAPEX equal to 7 % and HATFPVb (E-W) 5 %. The VATFPVm system becomes competitive starting from a CAPEX reduction equal to 1 % and 2AXTFPVm 10 %.

It can be concluded that the most cost competitive system at the given location is FXFPVb. In this configuration, a reduction in LCOE is obtained compared to the reference design equal to −19.9 %, by reducing the CAPEX of 30 %. This means that the cost of electricity produced by the FXFPVb system, if the CAPEX were to be reduced by 30 % in the future, will cost 19.9 % less than the FXGPVm system for the reasons that are reiterated below.

Future work should corroborate the results, extending the analysis to additional locations in order to evaluate the cost-competitiveness of the various configurations in different environmental and economic conditions.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

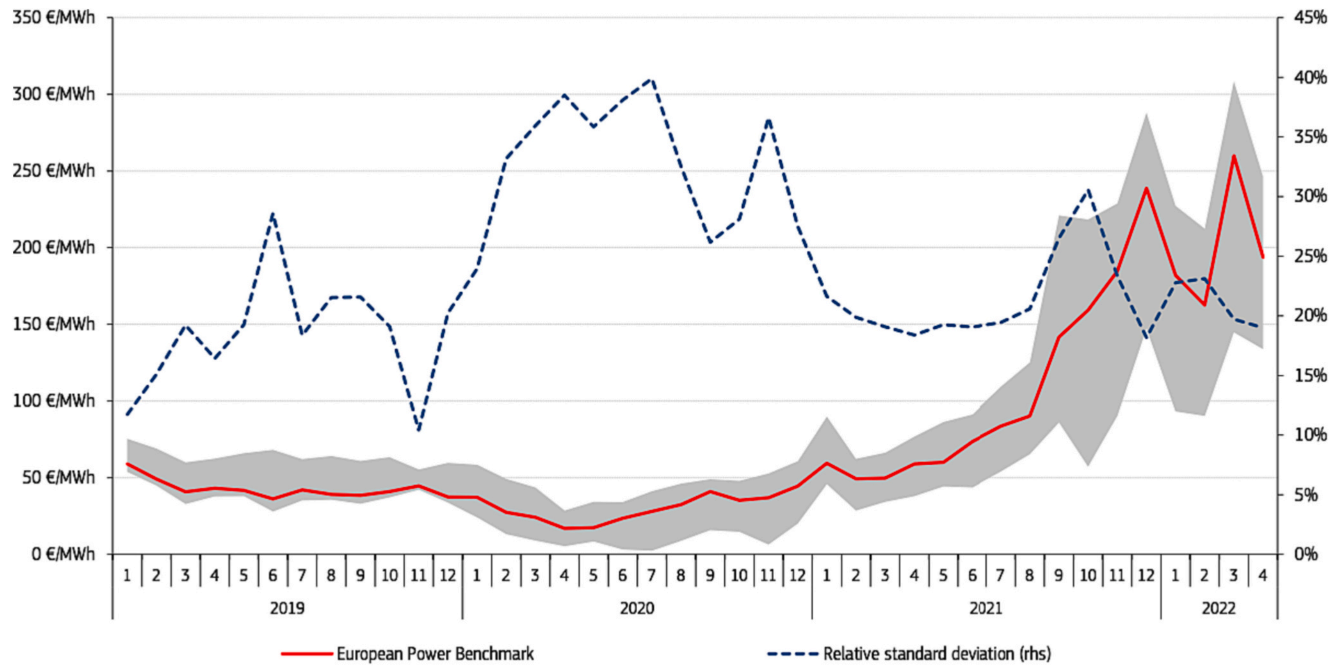


**Fig. 9.** Evolution of wholesale electricity market in Europe.
Source: Platts European power exchange.

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