Economic viability assessment of floating photovoltaic energy

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Abstract

Solar photovoltaic is one of the most well-established forms of renewable energy, currently showing signs of a significant level of maturity. Its production prices in 2016 reached for the first time the level of those of onshore wind, and, in most countries, are permanently lower than those of conventional energies. Furthermore, there is evidence that, in the next ten years, the global weighted average installed cost of utility-scale solar photovoltaics (PV) could fall by around 60%.

As it is a very modular technology, systems may range from very small scales up to utility-scale power generation facilities, allowing for a wide scope of applications.

The exhaustion of global terrestrial resources and the need to avoid the occupation of large farmlands with ground-based solar plants has encouraged the search for alternative solutions. Such is the case of floating photovoltaic energy systems, which recently started attracting the attention of both the research community and utilities. Until a few years ago, this type of solution, which has the potential to improve PV systems efficiency while, at the same time, addressing the space usage issues, was hardly regarded as economically viable.

The work consists in a breakdown of solar photovoltaic technology and economics, in the study of economic viability of different floating PV configurations, and in a simulation of a floating PV system on a Portuguese dam. For this purpose, a simulation model has been designed to compute the levelized cost of energy and to carry on sensitivity analyses on the most cost-influencing aspects of the power plant.

Keywords: Floating photovoltaics, FPV, Renewable Energy, Sustainability

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1. Introduction

In the next years, solar photovoltaic is expected to keep on its path toward higher competitiveness, driven by continued technological improvements, competitive pressures and economies of scale. For many reasons, such as conventional ground-mounted PV's high land-use and efficiency gains due to the proximity of the water, in the last few years both privates and public entities have been looking at floating photovoltaics (FPV) as an interesting solution.

Floating photovoltaic is already a reality for small size water tanks and artificial lakes, where environmental conditions are favorable, which means that there is no need of mooring lines to the bottom of the basin and cheap mounting structures can be used. Here, the slightly higher capital costs, mainly due to the floating mounting structures, and operational and maintenance costs, which have to be done by boat, are balanced by the efficiency gain principally resulting from the lower working temperature. In fact, it has been demonstrated that PV models installed on floating structure work at lower temperatures, resulting in higher efficiencies. Efficiency gains are around 10% for modules installed on plastic floating structures or pontoons, and may be even higher if the modules are submerged.

Different is the case of installations on dams, where capital costs rise considerably due to the tougher environmental conditions, requiring more resistant structures and mooring lines, preliminary environmental surveys (compulsory when installing a power plant in a delicate natural environment such a lake), and the higher distance among the components of the system (namely between the floating plant and the electrical plant), which increases cabling capital costs as well as losses during operation. On the other hand, installations on dams could take advantage of some savings related to the presence of the hydropower plant, e.g. by using its transmission line, offices, boat/ROV for O&M procedures, measurement and monitoring system. Another important advantage of installations on dams, still to be exhaustively investigated, is the possibility of coupling PV and hydroelectric energy sources. This could represent a good local solution for the renewable energy integration issue, creating a multi-energy-sources plant, much more reliable and predictable than renewables on their own. The objective of this work is the development of a simulation of a FPV plant on a Portuguese dam, done with a simulation model that has been designed for the purpose. It results in a LCOE estimation around 240 €/MWh for medium size PV plants floating on dams (~260kWp), which is still a very high value, if compared to both conventional energy sources and renewable energies. Many factors are expected to reduce the cost of energy, among them economy of scale is the most important.

2. Photovoltaic Technology

Solar photovoltaics (PV) is today one of the most widely deployed solar electric technologies in the world. Solar cells operate near ambient temperature, with no moving parts, and they enable generation at any scale: a 10-square-meter (m2) PV array is in theory no less efficient per unit area than a 10-square-kilometer (km2) array.

A solar PV array consists of one or more electrically connected PV modules, each containing many individual solar cells, integrated with balance-of-system (BoS) hardware components, such as combiner boxes, inverters, transformers, racking, wiring and enclosures. In a grid-connected system, combiners, inverters, and transformers convert the low-voltage direct current (DC) output of many individual PV modules into high-voltage alternating current (AC) power that is fed into the grid.

The operation of a PV cell is described by its characteristic curve (Figure 1), whose main parameters are:

- **Short Circuit Current (I_{SC})** – This is the maximum current that the cell can provide, and it occurs when the cells is short circuited. Unlike other small-scale electricity generating systems PV cells are not harmed by being shorted out.
- **Open circuit Current (V_{OC})** – This is the maximum voltage that exists between the cells terminals and is obtained when there is no load connected across them.
- **Maximum Power Point (P_{Max})** – The point on the I-V curve at which maximum power is being produced by the cell. P_{Max} occurs on the 'knee' of the I-V curve.

Photovoltaic output power is affected by temperature and incident irradiation. PV module short circuit current (*Isc*) is linearly proportional to the irradiation, while open circuit voltage (*Voc*) depends on temperature.

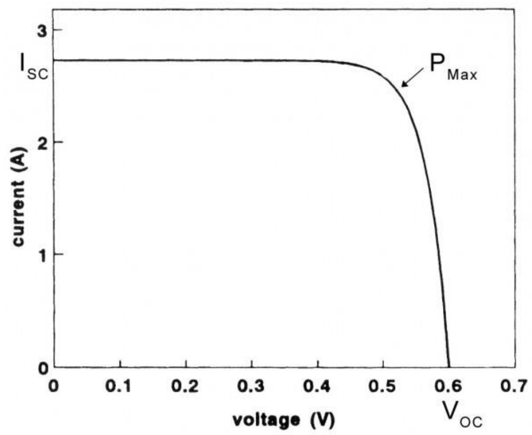

Figure 1: characteristic curve of a PV cell

Solar cell technologies are typically named according to their primary light-absorbing material. Crystalline silicon (c-Si) solar cells constituted approximately 90% of global module production capacity in 2014 and are the most mature of all PV technologies. C-Si solar cells are divided into two categories: single-crystalline (sc-Si) and multicrystalline (mc-Si), with respective market shares of approximately 35% and 55% in 2014 [4]. The remaining 10% of the modules production capacity is covered by the so-called thin-film cells, which can be produced with different materials. Among them, the most well-established in the market are cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and hydrogenated amorphous silicon (a-Si:H), and present better specific light-absorption, which permits the production of thick and light cells, but low average efficiencies (in the range of 12%–15%, compared to 15%–21% for c-Si).

Although solar PV technology is already mature and competitive with most energy sources, both renewable and conventional, it is plausible to expect a further innovation under various aspects:

- Power conversion efficiency (% or W/m2)
- Low material usage (g/m3 or g/W)
- Low manufacturing complexity and cost

No single PV technology today excels in all these three technical characteristics. A detailed comparison aomong technologies suggests some general observations: 1) c-Si and conventional thin-film are the only two technologies deployed in large-scale; 2) record efficiencies for modules are way lower than those of lab cells; 3) thin-film technology uses between 10 and 1000 times less material than c-Si, reducing cell weight per unit area and increasing power output per unit weight; 4) all PV technologies on the market today have been under development for at least three decades.

3. Photovoltaic Economics

The cumulative World's installed solar PV power capacity increased by 29% per year in the period 2000-2015, reaching 229 GW by the end of 2015 [8]. At the end of 2016 it was already around 320 GW, with a global PV electricity power consumption of 333 TWh (around 1.3% of the planet electricity consumption) [10]. In only 5 years, from 2010 to 2015, the total global PV capacity increased over 450% from less than 41 GW. Looking back 10 years, solar photovoltaics' development has been even more impressive - from 5 GW of total commissioned PV capacity at the end of 2005 the market has grown 45 times in just one decade.

The costs related to a photovoltaic power plant are usually divided in two main categories: Capital Expenditures (CAPEX) and Operational Expenditures (OPEX).

3.1 CAPEX

The costs of installation associated to a traditional photovoltaic power plant – either rooftop or ground-mounted – are generally divided in three categories: BoS (Balance of the System), modules and inverter costs.

Balance of the System

Balance of System costs are the most complicated to address, as they include a wide range of different components, from hardware to management costs. Usually they are divided in three broad categories: hardware, installation costs, and soft costs. These may be further decomposed in sub-categories. Hardware costs include cabling, racking and mounting structure, safety and security system, grid connection, and monitoring system. Installation costs are all the costs directly associated to the installation of the system, mechanical and electrical installation and supervision of the construction. Soft costs are all the costs related to design of the system, financing costs, permits, support policies. Estimations of BoS costs for the most developed PV markets range from ~500 USD/kW for China and Germany to over 1600 USD/kW for Japan.

Module costs

Solar photovoltaics modules have high learning rates (between 18% and 22%) and very rapid deployment. In the last 4 years (from 2012 to 2016) there was an average 40% growth in cumulative installed capacity every year [9]. This resulted in PV module prices declining by around 80% between the end of 2009 and the end of 2015. At the end of 2015, the weighted average country level price of a module ranged from 0.52 USD/W in India and China to 0.72 USD/W in Japan.

Inverter costs

The three main inverter categories used in PV power plants are micro-inverters (capacity in the range of module's power), string inverters (capacity up to 100kW) and central inverters (capacity >100kW). The most used are central inverters, especially in utility-scale systems. Recently string inverters are gaining interest, but still remain much less used and only in smaller systems, like rooftop plants. Micro-inverters may find favor for some utility-scale plants in the future, as they have certain advantages, but they are likely to only make a marginal contribution in the utility-scale sector in the next years. Typical average values on global markets (without Chinese market that have much lower prices) are: ~0.14 USD/W for central inverter; ~0.18 USD/W for string inverters; -0.38 USD/W for micro-inverters.

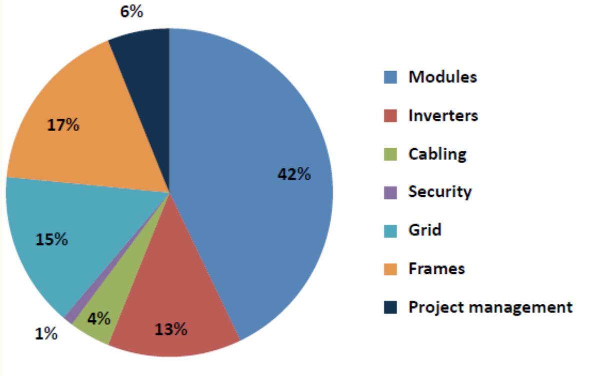

Figure 2: average breaksown of CAPEX shares for a ground-mounted PV project

Figure 2 shows average shares of capital expenditures for global more mature markets. Modules and inverters cover respectively 42% and 13% of the total CAPEX, while Balance of System is responsible for the remaining 45%.

3.2 OPEX

The operational expenditure (OPEX) of PV systems consists mainly of operation and maintenance (O&M) costs, because there are no fuel costs related to PV electricity generation. The need for O&M can be very different depending on the system size and type. Historical OPEX data from different countries vary greatly and it is difficult to find a consensus opinion. In the past, many European countries had a very high feed-in tariff (FIT) which allowed high margins in both the system CAPEX and OPEX; this is the reason why some reports have quoted very high OPEX. Over the years, the FITs have been reduced and even terminated in many countries, which has increased the competition and reduced OPEX. **C. Breyner et al. [12]** (2015) set to 20 €/kW/year for plants from residential-scale up to 1 MW ground-mounted systems, and 15 €/kW/year for multi-watts ground-mounted systems. Similar values are reported by NREL in February 2017 [24]. After analyzing a wide range of data from U.S. plants, namely from 0 USD/kW/year to 110 USD/kW/year, it reports average values of 20 USD/kW/year for residential plants and 16.7 USD/kW/year for utility-scale plants. Another way to express O&M costs is per unit of energy generated, **A. Luque et al. [5]** (2011) indicate as a common energy basis rule of thumb for larger grid-tied PV systems that the O&M costs run in the range of 1-3 USD cents per kWh of energy generated. Off-grid systems are typically more expensive than grid-tied systems to operate and maintain on a relative basis due to the additional components such as batteries.

3.3 LCOE and future trends

In 2015, prices of solar power supply reached record-low levels. The most remarkable contract awarded was for a 100 MW tender in Dubai (UAE) in early 2015. A record-low 58.4 USD/MWh bid lead the Dubai Energy and Water Authority (DEWA) to double the original size of the project to 200 MW. In the meantime, several lower bids were awarded in different regions and countries, often without financial incentives. Another milestone was the 48 USD/MWh in Peru in early 2016, as well as the 36 USD/MWh in Mexico, but everything was beaten by the 29.9 USD/MWh price offered in the third round of the Dubai tender. These costs are clearly site-dependent, meaning that they are much lower than global average costs, which are around 67 USD/MWh.

In general, total system costs for utility-scale PV are expected to decrease from around 1.8 USD/W in 2015 to 0.8 USD/W in 2025, a reduction of 57% in 10 years. The majority of the decrease in the costs is expected to come from lower BoS costs. Cost reductions from modules in the future will contribute less than in the past to total installed cost reduction potentials, even with very rapid growth in solar PV deployment. Globally, the bulk of the global average total PV system cost reduction opportunities in the next decade will therefore come from continuous BoS cost reductions. The share of BoS costs between 2009 and 2015 increased from 37% to 60%. In the same period, module costs declined more rapidly than BoS costs and contributed around 68% of the total cost reduction. For the period of 2015 to 2025, previsions see this trend being inverted, with modules contributing about a quarter of the reduction potential.

4. Floating installations

Examples of PV arrays mounted on floating structures have been proposed and already constructed all over the world. The advantages of this kind of solution are numerous.

The first is related to the increasing demand of energy in the agricultural industry as a consequence of the modernization plans carried out in the last decades. Although water efficiency has improved in the agricultural section due to the installation of more efficient irrigation systems, electrical power demand has increased substantially. The whole energetic system (and market) has drastically changed in the last years/decades. While a few decades ago the main preoccupation was that electricity could reach everybody, today due to many factors, such as the awareness about GHG emissions from fossil fuels, the fear of dangers related to nuclear power, the relentlessly decreasing availability of carbon, and the increasing need/wish of energetic independence, the community is looking at renewable energies as the new era energy source. Among these reasons, the run toward energetic independence, together with the land-use problem, have been the most relevant incentive for the development of floating photovoltaic systems. The possibility to install photovoltaic systems floating on irrigation tanks could mean for farmers, who wouldn't have land to dedicate to a PV system, to achieve the energy independence, or at least to cover part of their increasing power demand.

Another advantage that a floating installation on an irrigation tank would have, especially in hot and highly insulated areas, is the water evaporation rate in these agricultural reservoirs. Studies have been carried on in Spain, Turkey and Australia to estimate the water losses. Bengoechea et al. [25] estimated that in Almeria (south of Spain) water losses due to evaporation amounted to 17%. Martinez et al. [9] estimated water losses of 60 hm3 for the Segura Basin (Murcia, Spain), which means more than 8% of the available water supply for irrigation purposes. Craig et al. [10] suggested that evaporation phenomena in agricultural reservoirs in Queensland (Australia) were the cause of a total water loss of 1000 hm3, i.e. about 40 percent of its total storage capacity. Gökbulak et al. [11] made similar studies from lakes and dams in Turkey and estimated potential water savings of more than 20%. Covering all the surface of the water basin decreases temperature and sunlight, hence the water evaporation. The decrease in temperature and sunlight on the bed of the reservoir discourages also the growth of algae.

4.1 Technical differences

Floating PV power plants have several differences from traditional PV systems, both roof-top and ground-mounted. These are represented by floating structure, mooring system, eventual floating sub-stations and under-water cabling, all of them depending on the nature of the water basin where the plant is installed.

Floating structures

From a state-of-the-art study of floating installations, four main types of structures have been recognized:

- Plane unique, composed of cubic (or similar) buoys forming a floating base, on whose top one can locate the PV modules;
- Modular, each supporting a PV panel;
- Tlited resistant, typically composed of plastic buoys, on whose top is a metallic structure supporting the panels with a tilt angle;
- Semi-submerged, composed of or modules directly put into the water (usually thin-film) or floating structures where between the modules and the water there is only a thin layer od conducting material (like aluminium).

Table 1: comparison of types of mounting structures

Structure	Efficiency Gain	Tilt Angle	Applications
Modular	~10%	Yes	Irrigation tanks, small lakes
Plane Unique	~10%	No	Irrigation tanks, small lakes
Semi-submerged rigid	~10%	No	Irrigation tanks, small lakes
Submerged panel	5% - 12%	No	All
Metallic	~10%	Yes	All

Mooring and others

The mooring system is the component of a floating photovoltaic power plant that depends most on the nature of the water basin where it is installed. It can be just a tying system to the margins, as it is the case of irrigation tanks, which don't present any environmental disturbing component, such as waves and sensible variations of the water level. On the other extreme, it can be as complex as a mooring system for a plant in open sea, or even more complex, due to the huge water depth variations of dams' lakes. Dams' lakes are the most challenging location also for other reasons: the lake's bed could be very steep, since dams are typically situated in mountain valleys where a river flows, so the plant must be located in the middle of the lake, in order not to touch the sides of the valley when the water level goes down. Furthermore, if the structures have a tilt angle, the orientation of the system must remain constant, namely true south for installations in Europe. The orientation of the valley/lake hardly is north-south or east-west, so the mooring lines could have very different lengths and characteristics.

Being in the middle of the lake also means longer under-water cabling. A common configuration for big installations is to use a floating sub-station (or more, depending on the dimensions of the plant) with the inverter(s) on it. The use of floating sub-stations allows all the DC umbilical cabling, i.e. connecting the PV arrays among them and to the inverters, remaining outside the water. This means that it is possible to use normal PV cables, instead of under-water cables. In case there is more than one inverter, AC cables exiting the inverters would be connected on one of the sub-stations into one big cable going to the grid. This has to be an under-water cable – it would be impossible to take it outside the water, because of the dimensions of the lake and of eventual navigation paths in the lake.

Designing both mooring system and under-water cable connection to the lake margin, several parameters must be taken into account: the distance of the system from the margin, the steepness of the valley's sides, the lake's maximum bathymetry variation, the composition of the lake bed.

4.2 Economic differences

Also economics for this kind of plants strongly depends on the dimensions and characteristics of the water basin where it is installed. Namely, if the water basin is a little artificial lake/irrigation tank, the only differences from a traditional ground-mounted plant are basically the costs of the floating structures, while if it is installed on big lakes, it presents a wide range of additional costs that could turn it into non-convenient. Following are listed the main differences in economics between the two technologies, divided in the two categories of capital expenditures and operational expenditures.

CAPEX

CAPEX are the costs that vary the most from ground-mounted to floating PV plants. Main differences are in:

- **Preliminary surveys**, namely such as solar irradiation measurement, bathymetry and lake bed surveys, wind and wave survey, grid connection studies, eventual naval traffic survey and environmental impact assessments (EIA). They are assumed essential for a proper system optimization of installation on big lakes, and are estimated by confidential sources in the range 20-70 k€ per study.
- **Floating components**, namely module's mounting strutures and sub-stations for inverters and cable connections. Costs vary with the type of structures, Confidential sources report prices around 100 €/panel for the Ciel et Terre modular structure, 200 €/panel for rigid structure projected for hard environmental conditions (waves up to 1m high and wind up to 20 knots), while for unique structures the Italian company Otto proposes a model with prices ranging from 140 to 160 €/panel. For the semi-submerged structure cost can be estimated around 50 €/panel, while for submerged thin-film panels the only cost would be that of the floaters under the modules – in order to minimize the layer of water on the panel – and wouldn't be higher than 10-20 €/panel. No literature has been found for floating sub-stations, reasonable costs vary between 200 and 700 € each, depending on dimensions and needed resistance to environmental factors.
- **Mooring system**, A confidential source gave an average price of 60 €/panel for a rigid structure based plant, for the Alto de Rabagão dam in Portugal. This is one of the biggest dams in Europe, and presents very hard conditions, such as bathymetry variations up to 50 m, winds up to 20 knots and waves up to 1 m height.
- **Cabling**. The entire DC system is equal to that of a ground-mounted PV plant. On the contrary, the AC cable, in particular for plants installed on dam's lakes, must be water-resistant, which increases sensibly its costs, both because of the costs itself of the under-water cable and for the installation that requires much more time and an expensive equipment. Grid connection should not be necessary for installations on dams, as it is available that of the turbines – this would represent a saving compared with a classic ground-mounted plant – while for installations on private lakes/tanks costs for grid connection must be incurred as in ground-mounted systems.
- **Installation**, which is assumed to be more expensive than for ground-mounted system. Installation is expected to last 2-5 days. Usually the system is mounted on the lake's shore and gradually put into the water. Once the structure ensemble is completed it can be located in its working site and fixed to the mooring lines by boat. For installations in dams, cables location typically needs a ROV, as they must be positioned under the lake bed, while in little lakes can just lay on the lake bed, or even be taken out of the water in case the floating structure cover almost the great majority of the basin's surface. Eventual purchase of boats/ROV (remotely operated vehicle) would take part of CAPEX costs, but, especially in case of installations on dams, they could already be available. If not, a typical price for a ROV is around 120 k€.

Typical CAPEX costs of large-scale ground-mounted PV systems have been compared with estimated values for an installation on a small lake, resulting in an increase of only 4%, basically due to the mounting structures. CAPEX costs for installations on dams are exhaustively studied in the last chapter, through the simulation model.

OPEX

Maintenance procedures required by photovoltaic systems in little lakes are the same as for traditional ground-mounted plants, with the difference that here they must be done by boat. However, costs could not differ so much, since typically in large-scale ground-mounted this kind of operations are made with the use of machines designed for this scope. The cost of these machines could be even higher than that of a boat, with the advantage of having onsite water to clean the modules. So, for installations in little lakes OPEX costs can be considered almost equal to those of ground-mounted systems.

What makes the OPEX rise in floating installations on dams are the mooring line system and the under-water cables, whose operational maintenance requires a control with a ROV with a frequency of about twice per year, as well as monitoring of power output in case of coupling with the turbine. Plausible values for OPEX costs for floating installation on dams are double of the ground-mounted OPEX costs.

5. Feasibility Analysis of installations on dams

As previously seen, most of the floating PV have been installed on water reservoirs of small dimensions. If we move our attention to installations on dam's lakes, we need to take into account several more variables during the design of the system, among which the most relevant are the bathymetry variation, the incident waves and the wind. Dam's lakes are usually considerably bigger than irrigation reservoirs: they can have non-negligible fetch, hence, high wind can generate waves capable of damaging the floaters. In addition, the highly inconstant turbine's water flow contributes to make the variations of the lake's bathymetry unforeseeable, making harder (and more expensive) the mooring lines design. Another big disadvantage can be the shadowing effect of the mountains surrounding the lake, or of the dam itself, which could represent a relevant production loss. This is one of the main reasons why the floating structure should be located in the middle of the lake, instead of close to the shore, which would significantly facilitate the mooring system of the plant. Another reason is related to the water depth variations: if the structure was moored close to a shore, it could touch the side of the valley and be damaged when the water level reaches its minimum levels. Furthermore, as dams are usually situated in mountainous areas, there could be complications related to the wind blowing on the structure. All these are key factors that increase the cost of the system and could represent the difference between a convenient project and a non-convenient one.

On the other hand, PV on a dam's lake has several unique benefits, in particular a large and unused space and the presence of a grid transmission line already in place, as well as environmental and other kind of surveys probably already assessed for the previous construction of the dam and easy licensing due to the existing power plant. Depending on many variables, there is also the possibility to couple the photovoltaic and hydropower technologies in order for the PV to work as a 'virtual storage system'. For the total system's economics, these benefits could represent a fundamental saving, contributing to reduce its cost of energy, which is inevitably higher than that of large-scale ground-mounted PV plants, as it is further explained.

5.1 Environmental challenges

Dams can present hard environmental conditions for floating structures. Since dams can be located in very different environments, their conditions are strongly site-related, reason why environmental surveys are fundamental in the project development phase of a floating photovoltaic system. The main challenges that a project developer must take into account are listed below:

- **Wind** in Portuguese lakes can reach 20 knots of velocity. It could damage the system in two different ways, directly with its pressure on the system, especially if the modules are tilted, and creating big waves. The wind blowing on the structure requires stronger supporting structures for the panels and tougher mooring lines due to its continuous force applied in one direction.
- **Waves** generated by the wind can reach 1 meter height, depending on the length of the lake and the direction of the wind related to that of the lake (fetch). When wind is blowing in the lake's longitudinal direction and the lake itself is some kilometers long – as most of the dam's lakes are, particularly in Portugal – it could generate high waves. The incident waves, in the long-term, could seriously damage the junctures between structures, due to the relative movements of one structure to the other.
- **Current** is another relevant factor, especially in long lakes. When the turbine is generating it could reach up to 5 m/s of velocity, and could represents a danger for mooring lines, pushing the structure out of its proper position. Currents in lakes also depend on the characteristics of the lake itself, such as its shape, length and steepness of the shores and vary considerably with the measuring spot. Higher currents are measured in the very proximity of the dam.
- **Water depth variations** are probably the most critical factors for mooring lines costs. Dams lakes can have up to 5 meters daily and to 50 meters yearly variations in the water depth. The daily variations are due to the turbine's flow and cannot be precisely foreseen, since water flow in the turbine depends on several variables, mainly on energy demand. Yearly variations are usually gradual and easily foreseeable.

All these factors strongly rest on the lake characteristics, mainly its shape, its dimensions, the steepness and morphology of its shores and of the lake bed, as well as on the hydropower plant characteristics, such as height of the dam, number and section of the turbines, which determine their average water flows.

Preliminary surveys are essential to properly design the floating system in order to optimize costs and performance and minimize operations and maintenance interventions during the plants' lifetime.

5.2 Model construction

The model is organized in various sheets, each assessing a structural/economic/financial aspect of the plant. In the following lines it is explained how the model has been structured and the main assumptions made for the simulation.

Key elements of the model:

- Regarding the **power plant location** and relative energy resource, the Portuguese territory has been divided in nine main areas, each associated to the solar irradiation of the main city in the area.
- **Values of irradiation** are from RETScreen's database [30], which for Portugal is based on NASA's values. The project developer can choose the **tilt angle**, which impacts the total solar irradiation on the surface. The azimuth angle is assumed to be constant and equal to the optimum value, which is 0° (true south), because it is assumed that a floating structure in the middle of a lake can be freely oriented. Also, as mentioned in paragraph 2.4, the influence of little variations of module's orientation on the annual energy output is negligible.
- For the design of the **photovoltaic system**, it has been chosen to use as support an open-source software, PVsyst, which optimizes the whole system to work at the maximum power point, giving as an output all the operating parameters necessary for the dimensioning of the rest of the power plant. These are, for example, the optimal number of modules connected in series per string, which determines the DC voltage, and of strings connected in parallel, determining the DC current, the panel's efficiency and surface area among the others. PVsyst also allows to choose the inverters and the cabling system, computing electrical losses. Finally, it provides the Maximum Power point working conditions, namely current and voltage, which are used for the cabling optimization.
- System's **losses** are addressed in a specific sheet, and include cabling losses, in both DC and AC circuits, shading and weak irradiation losses, inverter losses, temperature losses and losses due to external factors covering the modules (snow, dust…).
- The project developer can choose between two types of **floating mounting structures**, the modular and the rigid structure (both well described in paragraph 3.2), because these are the only two that have already been tested in lacustrine environments, with waves and currents. In case there are no structures available, the model includes a tool to estimate the cost of construction of floating structures, based on simple shapes and raw material costs. The PV panels disposition on the rigid structures is arbitrary, and doesn't really affect neither the energy production nor the costs of installation. While for module structures, the disposition is completely arbitrary and depends on the electrical connection among modules.
- **CAPEX and OPEX** sheets list all the costs divided in categories.
  - For CAPEX, categories are: project development, which includes project management costs, preliminary surveys and legal and financial expenses; system manufacturing, including all the main components of the system, from PV modules to mooring lines; electrical connection equipment, including all cabling (DC and AC) and sub-stations; assembly, installation and commissioning; monitoring and miscellaneous equipment.
  - For OPEX are: management and administrative costs; annual monitoring and maintenance; onsite replacement and works; major replacement and works onshore; contingencies.

Once determined all the costs and the technical characteristics of the plant, the model is able to predict the annual energy generation, hence to compute the expected cost of energy, with the formula previously described.

5.2 Simulation and results

The chosen location for the simulation is Alqueva dam, near Évora, a city in central-south Portugal. This is one of the most highly insolated areas of Europe, having an average annual solar irradiation on horizontal plane of 1.84 MWh/m^2 (data from RETScreen software). The lake has a large part in front of the dam where the plant can be located and a dockside where boats are parked. It is assumed that the administration of the hydropower central already owns a boat for dam maintenance and monitoring, which could be used for installing and monitoring the FPV plant. The base-case is a 262 kW, similar to the first floating PV system that EDP (Energia de Portugal) installed in the Alto Rabagão dam in November 2016. Panels are mounted on rigid structures, because the lake is long and tight, hence significant waves can be generated. The system is designed to have a tilt angle of 20°, which is a good compromise between the optimum tilt angle (higher than 30°) and a good price for the mounting structure.

The simulation plant is composed of 1008 260W poly-crystalline Yingli modules. They are installed on 36 rigid structures, which means 28 modules per structure. The photovoltaic circuit is organized in 72 strings, each composed of 14 modules in series. Every structure has 2 strings installed on it, organized in 3 rows, two rows of nine modules and one of ten modules. The total surface of each structure is approximately 93 m^2. The system uses 8 string inverters with 30kW of capacity, each connected to 9 strings. The system is designed to have a floating sub-station per inverter. Only one sub-station has the connection to the under-water cable that connects the floating plant to the shore. It is a sort of star configuration, where all the strings are connected through their inverters to a central sub-station, from which a unique under-water cable links the system to the grid. For simplicity it has been avoided the presence of a transformer, it is assumed that the transformer of the hydropower turbine can be used.

The mooring system is composed of 8 lines and associated anchors. No information has been found on the lake bed nor on water depth variations of the lake. The lake bed has been assumed composed of 70% rock and 30% mud, with water level variations of around 30 m. From cartography valuations the steepness of the lake bed has been assumed low (<10 degs), so deadweight anchors, i.e. the cheapest anchors and the easiest to install, can be used. The space in front of the dam is 800 m long and 700 m ca., so the system is thought to be placed at a distance of around 200 m from the dam. The under-water cable doesn't go directly to the dam, but to an on-shore substation at a distance of 100 m from the dam. From this sub-station to the electrical central of the hydropower plant, a distance of 150 m have been estimated.

The simulation results in an energy production of 455.7 MWh/year and a capacity factor of 19.8%. The value of LCOE is 23.88 cUSD/kWh, i.e. 238.8 USD/MWh, which is relevantly higher than both land-based renewable and conventional energies. It is composed of 82% of CAPEX costs and of 18% of OPEX costs.

CAPEX

As expected CAPEX costs represent the major part of the LCOE, and are divided as follows:

- 28% Project development
- 50% System manufacturing
- 8% Electrical connection equipment
- 11% Assembly, installation and commissioning
- 3% Monitoring equipment

Project development has a high cost due to the preliminary surveys that have been considered necessary for an installation on a dam. Namely it has been assumed a cost of 20 k€ for a lake bed survey, 50 k€ for environmental and climate (wind and wave) surveys, 50 k€ for a real resource data assessment, 100 k€ for EIA (environmental impact assessment) and grid connection studies. In case all these preliminary studies had already been available – e.g. previously done for the construction of the dam – the value of project development costs would drastically go down. Other development costs are for insurance, project management and construction supervision costs, which together are assumed to have a cost around 5% of the construction costs (40 k€ ca.). Avoiding preliminary surveys, project development costs would reduce from 28% to 5% of the total CAPEX.

Mounting structures have sensibly higher values (more than double) because, as already explained, the use of rigid structures has been assumed necessary. The value of Power conditioning units and inverters costs is almost half of those of ground-mounted systems, because it has been assumed to be only the cost of the inverters (no batteries are considered). Grid connection costs have a similar value to that of ground-mounted, which means that the advantage of having a transmission line is balanced by the higher cost of the electrical grid in lacustrine locations (floating sub-stations for the inverters, under-water cables…). Also Civil and general works have much higher values than for ground-mounted, because of the higher difficulties of installations on water.

OPEX

OPEX costs are divided as follows:

- 69% Management and administrative costs
- 12% Annual monitoring and maintenance
- 17% Onsite replacement and works
- 3% Major replacements and works on-shore.

It is assumed a frequency of 6 onsite visual inspection and module cleaning per year, 4 technical periodic maintenance (mainly for structures and inverters) per year and 2 under-water visual inspections with ROV per year.

OPEX total costs are 4.26 cUSD/kWh, almost double of estimations for ground-mounted, while CAPEX total costs are 19.15 cUSD/kWh, which is much higher than average values for ground-mounted.

Sensitivity Analyses have been performed on the parameters with higher influence on the LCOE value: the system total capacity, the modules cost, the cost of the floating mounting structures, the plant location.

As largely expected, growing system installed capacity results in a decrease of cost of energy. For utility-scale (multi-megawatts) plants, LCOE almost reaches values comparable with those of conventional energy sources, such as conventional combustion turbines (10.9 cUSD/kWh) and biomass (10.2 cUSD/kWh).

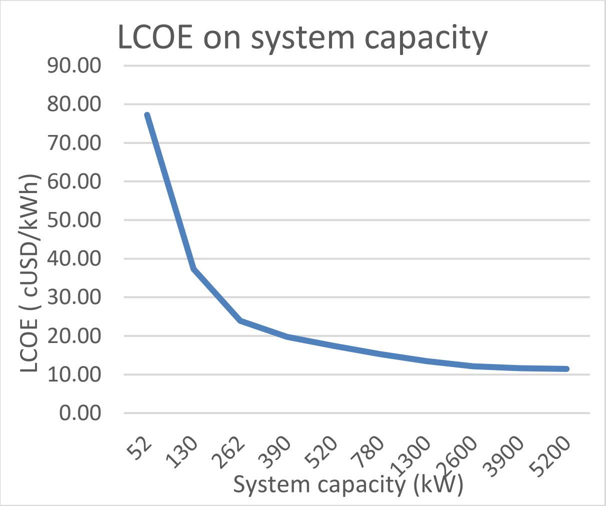

Figure 3: LCOE, (expressed in cUSD/kWh) on total system capacity (in kW)

Another parameter that strongly influences the LCOE is the **floating structures cost.** The choice between modular and tilted resistant structures, which are the only two considered in the model, with a fixed number of modules (1008), gives a difference of 11% on the value of LCOE.

Table 2: influence of the choice of the structure on LCOE

Structure	Modular	Rigid
LCOE (cUSD/kWh)	21.46	23.88

Since the number of floating structures directly depends on the system capacity, i.e. grows with the number of modules, the cost of the structure gains greater influence on the cost of energy with growing total installed capacity. In a 5.2 MW system, which would have 20’000 modules, the choice of modular instead of rigid structures would reduce the cost of energy of about 20%.

Location is also a fundamental parameter when designing a PV system, both for ground-mounted and for floating systems. A sensitivity analysis performed on the 9 portuguese locations considered in the model confirmed that Évora is in one of the zones with higher solar irradiation in Portugal.

6. Conclusions

The sensitivity analyses carried on with the model highlighted the important role played by the system capacity on the total cost of energy, which showed an almost-exponential decreasing trend for growing capacities, reaching values similar to those of conventional technologies for multi-Watts scale plants. In fact, for capacities higher than 2 MW LCOE stabilizes around 12 cUSD/kWh for systems mounted on rigid structures, and under 10 cUSD/kWh for systems installed on modular structures. These values are comparable to LCOEs of conventional combustion turbines (10.9 cUSD/kWh) and biomass (10.2 cUSD/kWh) plants. Sensitivity analyses have been carried on also on the choice of the mounting structures, between modular and rigid ones, which shows a variation growing up to 20% of the LCOE for a 5 MW plant. Finally, the location has shown a considerable weight on the cost of energy, confirming that Alqueva dam is an optimal choice due to the high level of insulation.

Recommendations for future work

The research undertaken within this work is only the basic backbone and there are other considerations which will need to be taken into account. Firstly, the simulation model reliability is to be verified with experimental values from a real floating system. In fact, it is based on numerous assumptions, due to lack of material available on the issue. Secondly, a thorough investigation should be conducted on all the electrical connection possibilities, including the opportunity of coupling solar PV with hydropower energy productions.

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