COVERING RESERVOIRS WITH A SYSTEM OF FLOATING SOLAR PANELS: TECHNICAL AND FINANCIAL ANALYSIS

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Abstract

This paper presents a technical and financial analysis of a new floating photovoltaic cover (FPC) system for reservoirs. After the conceptual design phase, technical and financial analyses of the system were carried out focusing on the key power and structural factors. A pilot plant consisting of a 20 kWn prototype covering 350 m2 was then installed in a reservoir in Agost (Alicante, Spain). The successful performance of the prototype led to a full-scale installation of 1,458 PV panels supported on 750 pontoons, covering an area of 4,490 m2, which is now generating clean energy at a nominal power of 300 kWn and significantly reduces water evaporation from the reservoir.

***Keywords**: reservoirs, floating covers, water and power efficiency.*

1. Introduction

The practice of covering irrigation reservoirs to minimise evaporation losses is still relatively little used, although as water is becoming an ever scarcer resource, interest in these systems is expected to grow in the future. The different techniques available for this purpose can be divided into three main groups: (i) chemical, (ii) physical, (iii) biological, (iv) construction and exploitation, and (v) mechanical (Craig et al., 2005). Of these, the last, involving fixed or floating mechanical and structural systems is the most important (Martinez Alvarez et al., 2009). These techniques can reduce evaporation of water from reservoirs by around 80%, besides which, by shielding the water from solar radiation they reduce photosynthesis and weed growth, thus improving water quality. Based on the numerous studies on the subject that have been published, it can therefore be said that such methods provide more efficient irrigation systems (DNRM, 2003).

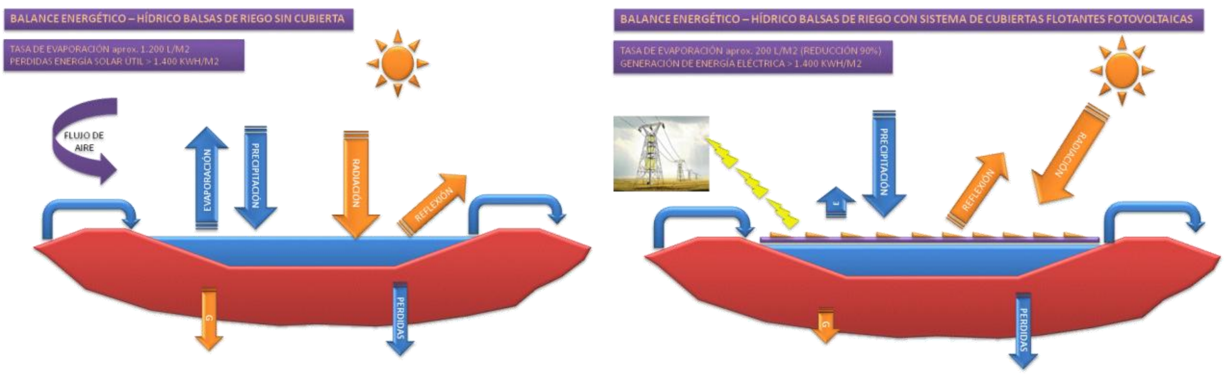
Another aspect to be considered is the fact that electricity consumption of many of these irrigation systems has increased considerably due to modernization plans, so that at the present time power costs form a high proportion of the running costs of many farmers' irrigation associations. According to Corominas (2008) the transformation of the traditional irrigation methods to pressurized systems, which has been going on since 1950, has reduced water consumption per hectare by 23% while power consumption has risen by 670%. This is a clear indication that any action plans for irrigation must be focused on improving both water and energy efficiency.

The aim of this work is therefore to achieve the technical and experimental development of a modular floating photovoltaic cover for irrigation reservoirs, with the multiple advantages and benefits of increasing synergy and enhancing the sustainability of the agricultural sector.

2. Method: Conceptual design

The main objective of the floating photovoltaic cover (FPC) is to improve the water-power balance in irrigation reservoirs, as seen in Figure 1. The surface is covered by a set of floating modules that intercept solar radiation to generate power and are joined together by articulated couplings (Redón, 2011). It can also be seen that the basic needs of the system are based on ensuring its structural integrity in accordance with the reservoir's characteristics while producing the maximum possible amount of electricity. The following section deals with the basic factors that define the geometric and structural configuration of the photovoltaic deck.

Figure 1: Power balance: a) Uncovered reservoir b) Floating Photovoltaic Cover System



2.1 Design factors: Photovoltaic system

In order to meet the plant's solar and power requirements, the following factors were considered:

- Inclination and orientation of the modules to make the most efficient use of radiation. When installing the permanent photovoltaic modules on the floating deck, both inclination and optimal southern orientation were considered for each specific situation.

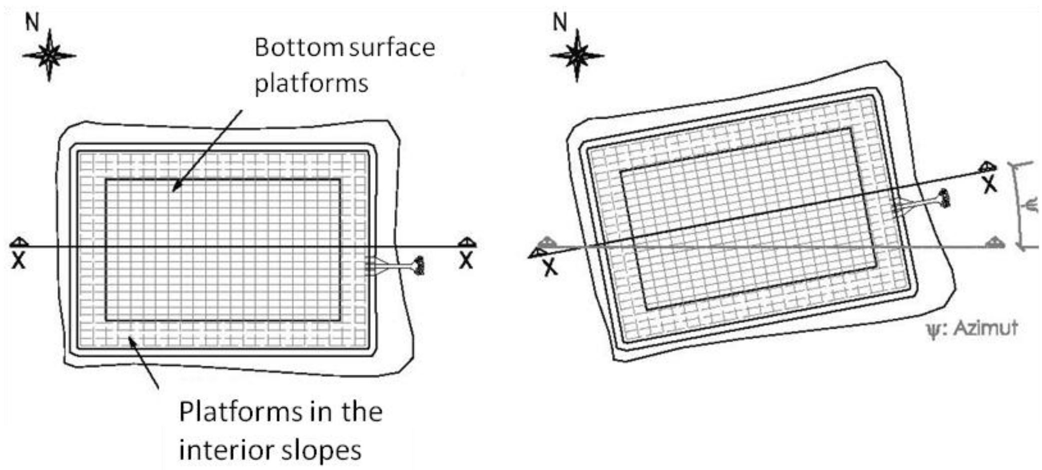
- Dimensions of solar panels: basic geometry of 1.65 m long by 1.00 m wide was adopted.
- Inter-panel separation to reduce shaded areas to a minimum: this was calculated according to the latitude of the site and was increased with higher inclinations.
- Layout of servicing and maintenance walkways was planned to facilitate operation of the photovoltaic plant.

2.2 Design factors: Installation on the reservoir

Placing a floating deck on the surface of a reservoir to act as a support for photovoltaic modules, besides complying with the electrical requirements, must also take into account the operational and design characteristics of the reservoir as a water storage and supply system. The following items were analysed:

- Geometry and characteristics of the reservoir: the reservoirs are irregular in shape due to their adaptation to the topography of the zone. Also, their principal alignments may or may not be optimal for maximum energy production as regards their degree of alignment with the cardinal points (Figure 2).

Figure 2: Orientation of the principal axes of a reservoir.



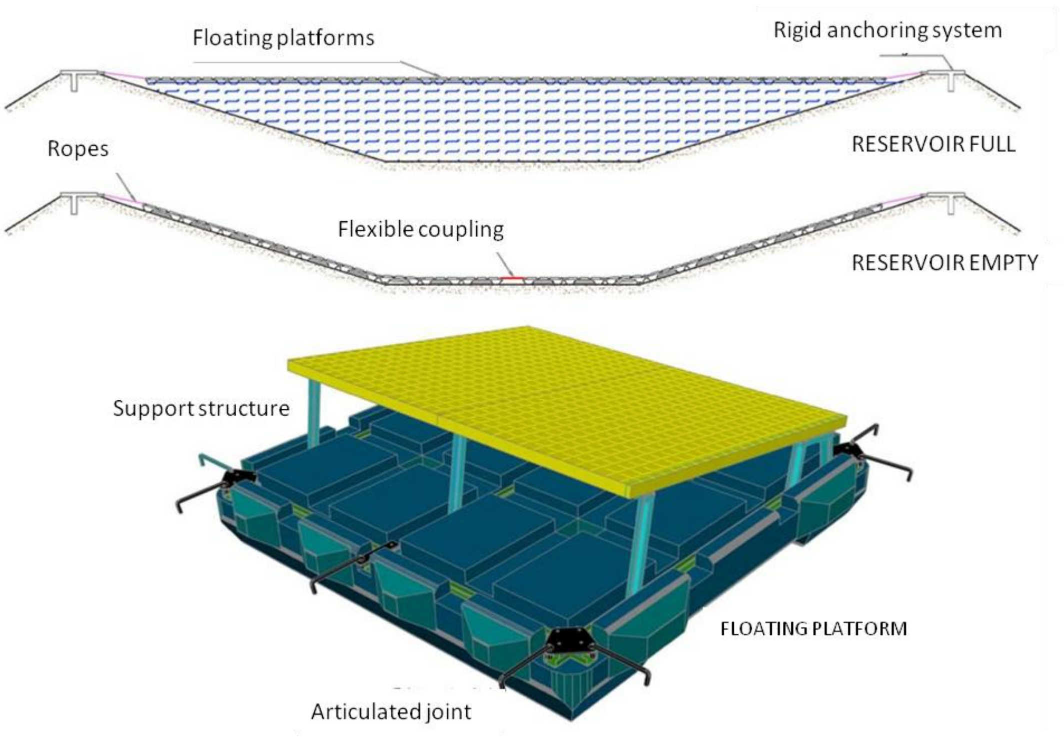
- Types and materials of floating platforms: floating modules must offer dimensional and mechanical versatility to allow the system to be adaptable to different conditions of the sloping reservoir floors. The floating units are therefore symmetrical and measure 2.35 x 2.35 m.
- Inclination of photovoltaic panels (α): the angle of elevation of the solar modules has a strong influence on the action of the wind on the cover.

2.3 Elements forming the FPC

From the structural point of view, the system consists of the following principal elements (Figure 3):

- Floating platform (pontoons): these elements guarantee the buoyancy and stability of the electricity-generating system. They are made from MDPE by rotational moulding and each supports two PV panels.
- PV module support structure: this consists of UF and CF cold-formed metal frames which must be able to withstand the weight of the PV modules and transmit wind forces across the pontoons to the anchoring system at the perimeter.
- Articulated metal couplings between pontoons: these consist of metal chains or cables linking the pontoons together, allowing vertical displacements so that the deck can adapt to concave reservoir profiles.

Figure 3: Components of an FPC.



- Flexible couplings: these allow the pontoons to move in relation to one another so that the system can adapt to different water levels. They consist of rubber or MDPE straps that are allowed to stretch until confined by the rigid polyester or nylon ropes that come into action when the maximum displacement has been reached.
- Ropes: these are polyester and nylon nautical ropes used to tie the outside modules of the floating cover to the sides of the reservoir.
- Rigid anchoring system: this anchors the floating cover and transmits horizontal forces to the sides of the reservoir. It consists of a series of reinforced concrete piles that resist lateral forces using the passive pressure of the surrounding ground.

3.- Results

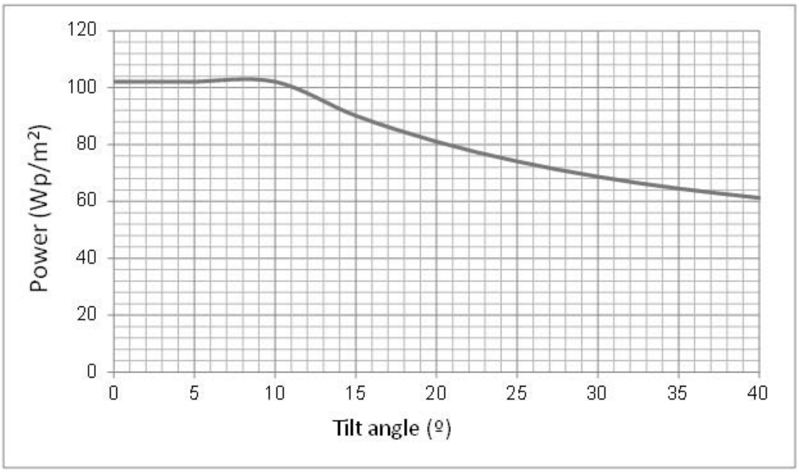
3.1. Analysis of all design factors.

Electrical efficiency per cover surface unit can be determined from the dimensions of the floating module and the electrical design factors of the photovoltaic plant. In this way, and in accordance with the angle of inclination, the floating deck will be characterized by:

- For $\alpha \leq 10º$: an unbroken grid of floating units covering the complete reservoir surface.
- For $\alpha > 10º$: an incomplete grid of floating units that do not cover the entire reservoir surface. The distance between the rows of pontoons increases with the angle of inclination.

If a standard maximum power of 240 Wp is adopted for monocrystalline silicon PV panels, Figure 4 shows the evolution of the installed power per surface unit of an FPC. As the area of each floating module is increased (dimensions of panels according to inclination + shaded area + service walkway), the power density of the generating plant is below the maximum produced between 0 and 10º.

Figure 4: Power density according to angle of inclination.



In Spain PV power generation can be estimated for different latitudes (36º,38º,40º) at different angles of inclination and orientation from the radiation data provided by the European Commission's Photovoltaic Geographic Information System (PVGIS). Given the maximum power of the solar panel (240Wp), PV production values can be calculated for specific installations.

Figure 5: Power generation according to angle of inclination of an FPC.
a) Optimal southern orientation. b) 20º deviation

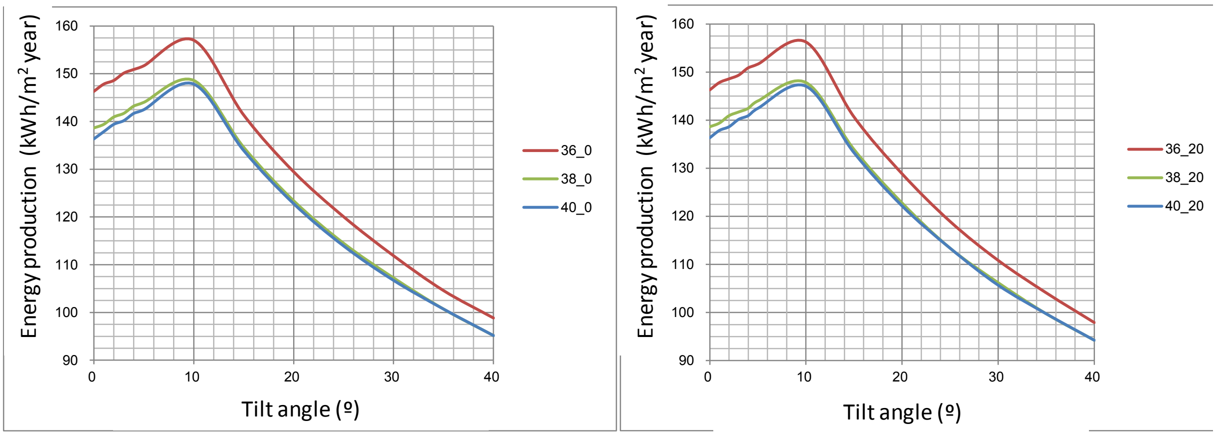
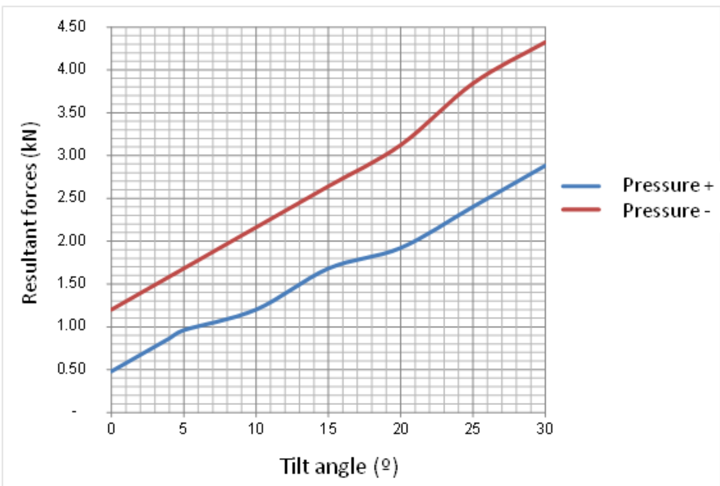


Figure 5 gives the power produced per surface unit according to angle of inclination for the optimal southern orientation (Fig.5a) and for a 20º deviation from the optimal (Fig.5b). It can be seen that even though the maximum benefit is not obtained from the solar radiation of individual units, the denser distribution possible with lower panel inclinations (≤10º), regardless of orientation, increases the power generated per surface unit and at the same time the complete reservoir surface can be covered. In the same way, maximizing the surface covered at angles of less than or equal to 10º keeps water evaporation to a minimum.

From the structural perspective, the angle of elevation of the solar panels has a strong influence on the wind forces exerted on the cover. The increase in wind pressure and suction forces on a PV module according to angle of inclination can be calculated from the European wind action standards (EN 1991-1-14), as seen in Figure 6.

Figure 6: Wind loads on a PV module according to angle of inclination.



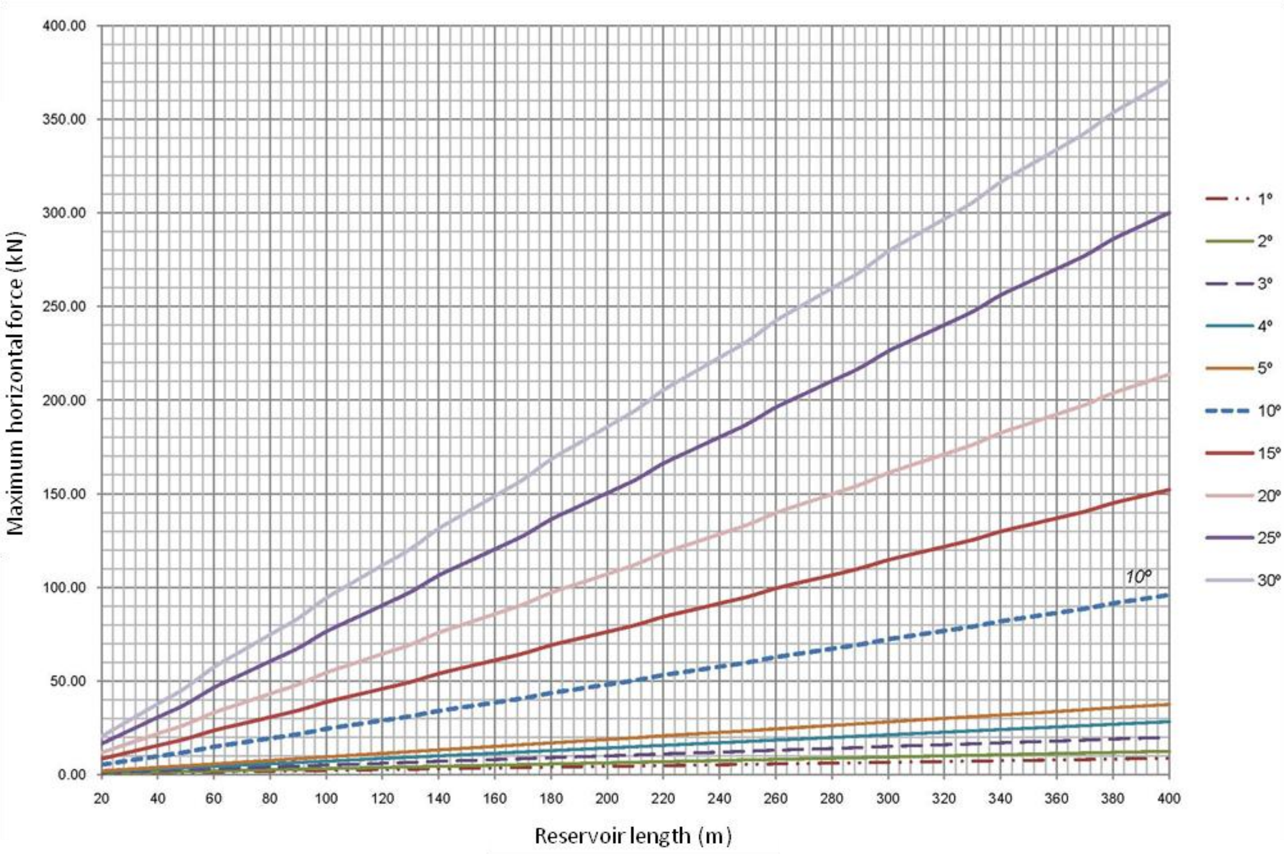
The vertical wind component is balanced by sustentation forces. The horizontal component exerts strong pressure on the cover that is absorbed by the reinforced concrete piles. Figure 7 gives the loads produced by horizontal wind forces on an FPC in reservoirs up to 400 m long and with sides between 5 and 20 m high.

From Figure 7 it can be seen that the horizontal forces resisted by the pontoon couplings vary widely according to panel elevations. Mechanical and structural dimensioning of the

FPC can be calculated from these lateral forces. From the structural perspective, a force of 125 kN is considered the maximum load the system can stand, mainly due to the limitations of the deck anchorage.

For the standard mechanical characteristics of the sides of the reservoir into which the piles are driven, the pile dimensions obtained range from 1.50 and 4.00 m long and diameters between 0.25 and 0.55 m. The geometry of the piles is in proportion to the size of the reservoir in question. The height of the reservoir bank is usually in proportion to reservoir size, from 5 m high in small reservoirs to 15-20 m in larger ones.

Figure 7: Maximum horizontal forces according to reservoir size.



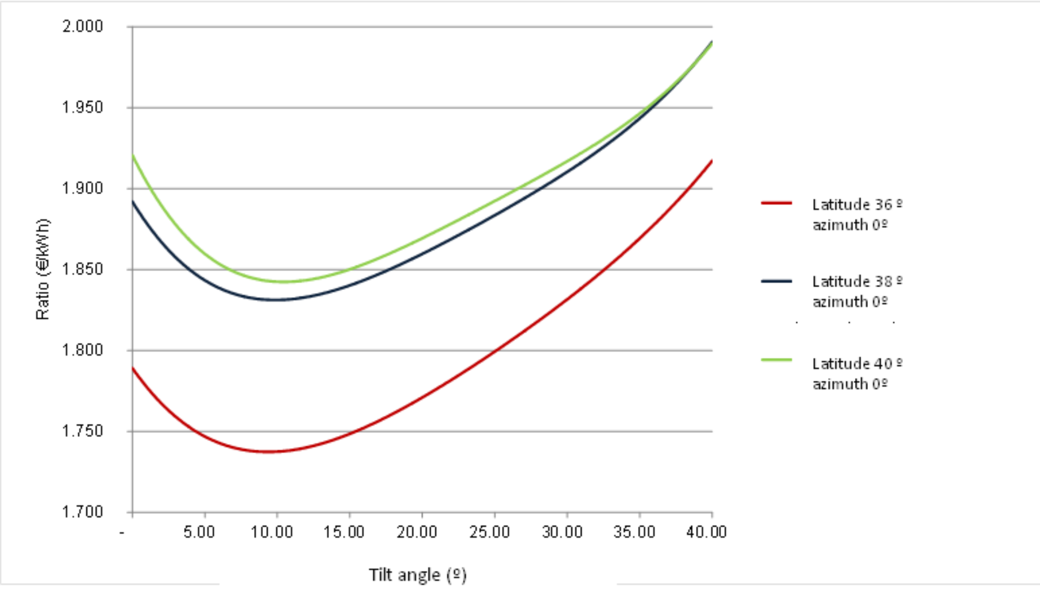
3.1. Financial analysis.

The above-described design factors together with the structural dimensions of the system can be used to estimate the cost of the FPC according to angle of inclination as shown in Table 1. Figure 8 shows a graph of the relationship between investment costs and electricity production (€/kWh), in which it can be seen that an angle of 10º gives the best return on investment for the latitudes under study and a southern orientation. In cases in which the azimuth deviates from the optimal southern orientation, a 10º angle also gives the best return on investment.

Table 1. System cost according to angle of inclination.

TILT ANGLE	-	**1,00**	**2,00**	**3,00**	**4,00**	**5,00**	**10,00**	15,00	20,00	25,00	30,00	35,00	40,00
COST ESTIMATION. COVER													
FLOATING PLATFORM	195,00	195,00	195,00	195,00	195,00	195,00	195,00	195,00	195,00	195,00	195,00	195,00	195,00
STRUCTURE	55,00	60,00	65,00	65,00	70,00	70,00	95,00	95,00	95,00	95,00	95,00	95,00	95,00
PLATFORMS TRANSPORT	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00
TENSORS	8,00	8,00	10,00	10,00	10,00	10,00	15,00	15,00	15,00	15,00	15,00	15,00	15,00
SCREWS AND RIVETS	2,00	2,00	2,00	2,00	2,00	2,00	2,70	2,70	2,70	2,70	2,70	2,70	2,70
ASSEMBLY	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00
TOTAL PLATAFORM	285,00	290,00	297,00	297,00	302,00	302,00	332,70	332,70	332,70	332,70	332,70	332,70	332,70
TOTAL PLATAFORM €/m^2	**51,61**	**52,51**	**53,78**	**53,78**	**54,69**	**54,69**	**60,24**	**60,24**	**60,24**	**60,24**	**60,24**	**60,24**	**60,24**
POWER (Wp/m^2)	**102,13**	**102,13**	**102,13**	**102,13**	**102,13**	**102,13**	**102,13**	**90,18**	**81,04**	**74,10**	**68,74**	**64,56**	**61,30**
TOTAL €/Wp	**0,51**	**0,51**	**0,53**	**0,53**	**0,54**	**0,54**	**0,59**	**0,67**	**0,74**	**0,81**	**0,88**	**0,93**	**0,98**
COST ESTIMATION. FOUNDATIONS AND ELASTIC JOINTS													
ELASTIC JOINTS	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06
PILOT FOUNDATION	0,03	0,03	0,04	0,04	0,04	0,04	0,06	0,06	0,08	0,08	0,08	0,09	0,09
TOTAL FOUNDATIONS + ELASTIC JOINTS €/Wp	**0,10**	**0,10**	**0,10**	**0,10**	**0,10**	**0,10**	**0,12**	**0,12**	**0,14**	**0,14**	**0,14**	**0,15**	**0,15**
TOTAL SYSTEM €/Wp	**0,61**	**0,61**	**0,63**	**0,63**	**0,64**	**0,64**	**0,71**	**0,79**	**0,88**	**0,95**	**1,02**	**1,08**	**1,13**
INVERTERS	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,19
PHOTOVOLTAIC PANELS	1,40	1,40	1,40	1,40	1,40	1,40	1,40	1,40	1,40	1,40	1,40	1,40	1,40
WIRING	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18
MONITORING	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
SECURITY SYSTEM	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
CIVIL WORKS (earthworks, fencing)	-	-	-	-	-	-	-	-	-	-	-	-	-
ENGINEERING	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
HEALTH AND SAFETY ON SITE	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
QUALITY CONTROL	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
HIGH VOLTAGE													
Others	1,96	1,96	1,96	1,96	1,96	1,96	1,96	1,96	1,96	1,96	1,96	1,96	1,96
Total (€/Wp)	**2,56**	**2,57**	**2,58**	**2,58**	**2,59**	**2,59**	**2,67**	**2,74**	**2,84**	**2,91**	**2,97**	**3,04**	**3,09**
Total (€/m^2)	**261,55**	**262,45**	**263,72**	**263,72**	**264,63**	**264,63**	**272,23**	**247,42**	**230,08**	**215,54**	**204,30**	**196,18**	**189,31**

Figura 8: FPC investment/production ratio.



3.2 Prototype

A full-scale prototype (1:1) of the FPC was built in a test installation over an irrigation reservoir in Agost (Alicante, Spain). The area covered was 350 m^2, corresponding to 20 kWn of maximum installed power, as shown in Figure 9.

After its completion in March 2010 up to the present time, the structural and operational performance of the prototype has proved to be highly satisfactory. Throughout this period and for every reservoir filling-emptying cycle the FPC has been able to adapt itself appropriately to the varying water levels of the cycle.

Figure 9: FPC prototype: a) Aerial view; b) Side view.

a)

b)

3.3 Complete covering of the reservoir surface

The favourable results obtained from the pilot plant encouraged us to go ahead with covering the total reservoir surface with 1458 PV panels supported on 750 pontoons, covering an area of 4490 m^2. Figure 10 shows a photo taken during the installation and another in Figure 11 gives a view of the completed project.

Figure 10: Assembly of the panels.

Figure 11: The reservoir completely covered by PV panels.

The electricity-generating plant has a nominal capacity of 300 kWn, which gives an annual production of 475000 kWh/year of renewable energy, which is fed directly into the supply network. The saving in water from covering the reservoir and reducing evaporation is 5000 m^3, or 25% of the reservoir's storage capacity.

4. Conclusions

The study of the combined factors involved in the design of a solar panel electricity-generating plant, together with the operating factors implicit in its being located on the surface of an irrigation reservoir, have shown that the basic module should be composed of symmetrical pontoons measuring 2.35 x 2.35 m^2 supporting two photovoltaic panels on their upper surface. From the technical and financial analyses based on the angle of inclination of the solar panels it was concluded that the optimal angle of panel inclination is 10º.

The study also specifies the characteristics of the components that together make up a continuous floating platform over the entire surface of reservoirs of up to 400 m long and with sidewalls up to 20 m high. Maximum electrical power generation is also specified for a given reservoir surface area for the range of latitude in the Iberian Peninsula, thus achieving the maximum efficiency in both water and energy resources per surface unit.

After the technical study, a proof-of-concept prototype was constructed on the *El Negret* reservoir which was found to give satisfactory results. Finally, we were sufficiently encouraged by the success of the prototype to proceed with the construction of a floating platform over the entire surface of the reservoir to generate 475000 kWh/year of renewable energy while at the same time achieving an annual saving of 5000 m^3 of water, equivalent to 25% of the reservoir's storage capacity.

To conclude, we believe there is great potential for the installation of floating solar panel electricity generating plants in order to improve the water and energy balances in arid and semi-arid zones with limited water resources, as is the case of the zones near to the Spanish eastern Mediterranean coastline.

5. Acknowledgements

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