A NEW PHOTOVOLTAIC FLOATING COVER SYSTEM FOR WATER RESERVOIRS

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Abstract

This paper describes a new photovoltaic floating cover system for water reservoirs developed jointly by the company CELEMIN ENERGY and the Universidad Politécnica de Valencia. The system consists of polyethylene floating modules which, with the use of tension producing elements and elastic fasteners, are able to adapt to varying reservoir water levels.

A full-scale plant located near Alicante (Spain) was built in an agriculture reservoir to study the behaviour of the system. The top of the reservoir has a surface area of 4700 m^2 but only 7% of such area has been covered with the fixed solar system.

The system also minimizes evaporation losses from water reservoirs.

Keywords: Photovoltaic floating cover, water reservoirs, evaporation water losses

1. INTRODUCTION

Nowadays, farmers' income is strongly affected by the electricity costs. High production costs, small farm size, competitive international markets and the water deficit are the main causes that characterize the difficult situation of the Spanish agriculture.

The demand for energy is to increase in the agriculture industry as a consequence of the greater use of the water resources and the modernization plans carried out in the last decades. The installation of more efficient irrigation systems has led to water savings; however, power consumption has grown because of increasing pumping needs and filter operations. So, although water efficiency has improved in the agriculture sector, electric power demand has increased substantially. Upward revisions of the electricity rates and uncertain future scenarios adversely affect the price of water.

The solutions to these problems come not only from setting special electricity rates for irrigation but also from improving the energy and water efficiency of the irrigation systems. Renewable energy sources emerge as a way to counter-balance such situations.

The new irrigation plans involve the transformation of traditional systems into pressurized systems. In most cases, this modernization has demanded the construction of water reservoirs. Among the different storage systems available, earth reservoirs waterproofed with geomembranes are the most widely used solution.

In arid and semi-arid climates, water stored in reservoirs would be better managed if evaporation losses from the water surface were reduced.

In this sense, Bengoechea et al. [1] studied the water evaporation rate in agricultural water reservoirs in the south of Spain (Almeria) and estimated that water losses by evaporation in farms amounted to 17 percent. Martinez et al. [2] estimated water losses of 60 hm^3 for the Segura Basin (Murcia, Spain), which means more than 8% of the available water supply for irrigation purposes. Craig et al. [3] suggested that evaporation phenomena in agricultural reservoirs in Queensland (Australia) were the cause of a total water loss of 1,000 hm^3, i.e. about 40 percent of its total storage capacity. Gökbulak et al. [4] made similar studies from lakes and dams in Turkey and estimated potential water savings of more than 20%.

The above results highlight that the evaporative losses from water storages at both the farm and the regional scales can be large. Thereby, the assessment of such losses and the development of evaporation mitigation techniques is crucial for preserving the limited water resources [5, 6, 7].

In the last decades, several evaporation control products were developed to control evaporation losses from water reservoirs [8]. These products range from floating covers, modular covers, shade structures, chemical monolayer covers and biological and design methods. Craig et al. [3] highlighted the good performance of mechanical methods, either floating systems or suspended shade structures. The evaporation reduction achieved with such systems is around 80%.

Moreover the use of floating covers provides other benefits like:

- lower filtering costs (by controlling sunlight and water temperature),
- much longer duration of the geomembranes,
- reduced silt accumulation.

But there is a lack of technical studies about cover systems for irrigation reservoirs. Although in Spain a standard for reservoir covers has been recently published [9], its scope is for systems based on geomembranes (not on floating ones) and it focuses on the execution process, not on system design.

However, latest trends show an increasing interest for developing membrane and spatial structures to minimise water evaporation [10, 11].

The Photovoltaic Floating Cover System (PFCS) described in this paper is the synergic response to the issues mentioned above and is highly innovative in today’s agriculture sustainability. On the one hand, an evaporation mitigation technology is applied into agricultural water reservoirs. On the other hand, the production of clean energy is envisaged as a means of balance the electricity costs either exporting the electricity back to the grid or enabling to generate power for self-consumption [12].

The solution consists of a continuous platform placed above the water level by replicating a floating module which acts as the support of the photovoltaic panels. To our knowledge, no detailed studies assessing the performance of a photovoltaic covering system for reservoirs have been published to date. Also, a distinguishing element of the present system is that covers the whole area of the reservoir (bottom surface and upstream slope areas).

2. KEY DESIGN ELEMENTS

The primary purpose of the PFCS is to improve water and power efficiency of agricultural irrigation reservoirs as illustrated in Figure 1. The water surface is covered with a number of floating modules which are joined together by means of pins. Incident solar radiation is used to produce renewable energy. Additionally, properly designed reservoir cover systems prevent fluid loss due to evaporation and by blocking off sunlight they prevent algae bloom.

Figure 1: Water & energy balance: a) Uncovered reservoir. b) Photovoltaic Floating Cover System

The key design factors affecting the performance of the system are:

- Good structural performance of the floating platform as a partially submerged body.
- Good structural behaviour of the reservoir and floating cover as a whole.
- Ability to adapt to varying reservoir water levels and reservoir layouts.
- Meeting the PV installation requirements.
- Minimizing in-situ work during construction and exploitation.

In summary, the primary purpose of the system is to meet the water requirements of the reservoir while maximizing power production.

2.1 Suitability assessment of the reservoir layout

Floating cover systems require site specific planning and design to be successful. Most reservoir designs are irregular in order to better fit land topography. Moreover, both the reservoir's walls and the different design layouts for the internal 3D geometry of the reservoir are highly variable. As a consequence, the geometry of the floating module has to be versatile enough to properly adapt to different internal geometries of the water reservoir.

2.2 Geometry of the floating module

The floating module's geometry was designed taking into account two main issues. First, the dimensions of the module must be adapted to commercial photovoltaic panels. Second, the modules must cover the maximum possible water surface to prevent water evaporation.

The solar issues under analysis were: photovoltaic panel dimensions and tilt angle, number of units to be installed, distance between panel rows to prevent shade effects and access ways to ease operational maintenance.

Several configurations and geometries of the floating module were studied before selecting the design presented in Figure 2, which comprises two 1.6x1.0m / 200 Wp panels and a 0.5m access way.

Figure 2: Layout of the floating module

For the latitude of the field site (Agost, Alicante province, Spain), 30º is the optimal tilt angle for the fix solar panels to maximize energy production. However the shade analysis for the prototype installed in the reservoir named “El Negret”, revealed (Table 1) that lower tilt angles not only provided better electrical performance but also a more regular module geometry. As the tilt angle of the FV array decreases, it is needed a shorter distance between row lines of PV panels to prevent interactive shadows. As a result, a more homogeneous module grid was obtained. Besides, low tilt angles significantly reduced the effects of wind uplift and drifting. Since wind forces play an important role in the structural behaviour of the system, the use of low tilt angles will improve the global performance of the system. Also, Table 1 shows the energy yield obtained from meteorological data and a global performance ratio of 0.75.

Table 1: Number of photovoltaic units and power installed depending on the tilt angle

2.3 Orientation of the photovoltaic panels

The layout shown in Figure 3 illustrates a particular case of a reservoir. First, the main axes of the cover (key directions of the floating modules) were determined taking into consideration the south cardinal and the direction of the reservoir slopes.

Figure 3: Cover configuration for a particular case study

The reservoir shown in Figure 3 has a rather rectangular geometry; moreover, the main longitudinal axes of the reservoir are aligned with the cardinal directions, so the solar panels faced south. However, such configuration will not be suitable for other sites where the slope’s alignment of the reservoir does not fit the south orientation. Therefore, in such cases, the PV panels will be installed with higher deviations from the south direction since the directions of the reservoir slopes will always prevail over power production to achieve a good coupling of the whole platform inside the reservoir. Therefore, the successive rows of PV panels uniformly lean above the slope as the water level of the reservoir decreases without introducing biaxial forces and torsion stresses between modules.

Table 2: Power loss vs. azimuth rotation

As a result, there would be reservoirs where the main alignments of the platforms are no directly orientated to south. However, Table 2 compares the global irradiation expressed in equivalent sun hours of the system for a tilt angle of 10º, latitude of 38º (prototype reservoir conditions) and azimuth rotation between 0 and 60º. As can be seen, azimuth variations are not relevant when using low tilt angles since the losses of irradiation are not significant.

3. DESCRIPTION OF THE SYSTEM

The cover consists of a floating module, sized 2.35 x 2.35 m, which is used as a frame for supporting a grid of units. Each module is joined to its adjacent ones with a metallic pin-anchorage. The platforms are fix-moored on the top of the reservoir.

The system can be applied to any water storage structure not exposed to heavy wave forces (ponds, tanks, reservoirs, lagoons, etc). However, the system described in this paper was designed to be used in agricultural reservoirs.

3.1. Floating modules

The pontoon is the key element of the system. It has to ensure the stability and buoyancy of the system and it is the basis of the photovoltaic plant. As shown in Figure 4, the module was designed to accommodate two standard solar panels with a tilt angle of 10º and a 0.5m access way located behind the upper side of the panels. It is shaped like a boat consisting of two hulls separated by an upper platform. The three main elements form a single square unit of 2.35 m x 2.35 m and a height of 0.40 m. After considering several alternatives, the material selected was medium density polyethylene made by rotomoulding.

Figure 4: Floating module

The two hulls have a trapezoidal section and a draft of 0.2 m. They were placed longitudinally on the bottom of the pontoon. A slack and smooth contact between the module and the reservoir´s geomembrane is needed to ensure excellent resistance to punctures [13]. The bottom of the trapezoidal hulls is thin and with rounded edges.

On the other hand, the technical requirements of the upper side of the pontoon are different from those of the bottom. The platform must resist several design loads, such as dead and live loads and wind uplift and drifting, so that it must be stiffer. The top side of the module consists of several rectangular gutters. As can be seen in Figure 4, these elements divide the platform into smaller units that improve the stiffness and the load bearing capacity of the system.

This configuration enables the installation of the horizontal steel frame which supports the solar panels. Also, the horizontal frame is a linking element that distributes the structural forces among the modules. Some additional gutters are used for the electrical wiring.

Finally, and in order to improve the stiffness and stability of the pontoon, both sides are attached by four vertical hollow cone-shaped columns. Such supports are symmetrically placed on the gutter’s intersection.

On each side of the floating module there is a half-cylinder boss. The horizontal steel frame is placed vertically above the place where the half-cylinders rest.

These elements are built in during the manufacture of the module and their main role is to join adjacent modules and allow for the installation of the grid system. Thanks to this mechanism, the whole platform is able to transmit tension forces by means of the metallic rods, and compression forces through the contact of the plastic half-cylinders.

In this way, downward rotation is controlled on the vertical plane. However, it is free to rotate upwards because the contact between successive half-cylinders tends to separate.

The aforementioned design features provide a better coupling of the system in singular areas of the reservoir such as the bottom and the internal walls.

Point loads on the platform may cause overlapping between adjacent horizontal half-cylinder bosses. To prevent such negative effect, vertical bosses are placed at the ends of the horizontal bosses thus limiting differential settlement.

The floating module described meets the design requirements. It is a safe, hollow and airtight element which can be made by the rotational molding technique.

3.2. Joints between floating modules

As previously mentioned, the cover layout is formed by a grid of modules joined together by means of metallic rods. The mechanism consists of a pinned joint that enables both the transmission of horizontal forces and vertical rotations, and allows the fitting of the cover to the geometry of the reservoir.

3.3. Elastic joints

The elastic joints enable the opening of the cover. In this way, the system can easily adapt to varying reservoir water levels. When the reservoir is empty, the longitudinal slope is longer than the surface of the full reservoir. To solve this problem, a number of elastic joints are placed along the main axes of the reservoir.

In the case of full reservoir, the elastic joints remain closed and the system practically covers the entire water surface. However, when the reservoir is empty, the elastic joints are completely opened and the system covers the internal walls of the reservoir. The grid of modules can adjust to any situation between these two extremes.

The opening mechanism is almost symmetrical to the main longitudinal axis of the reservoir. However, its installation and its mechanical and geometrical design will depend on the particular features of the site.

The modules situated at the outer cover perimeter are rigidly fixed to the top of the reservoir as follows.

3.4. Rigid anchorages

A rigid support along the perimeter of the reservoir is needed to withstand the dead loads acting on the reservoir slopes and the lateral forces caused by wind and waves. The anchorage system designed is made up of a pile foundation, a pile cap and a continuous perimeter floor.

The piles are placed at spaced intervals all around the reservoir's perimeter.

4. DIGITAL AND REAL SCALE PROTOTYPE

During the engineering design phase, several numerical and digital models were developed (further details on reference [12]). After the conceptual design, a real scale prototype was implemented in "El Negret" reservoir (Alicante) in order to check the real performance of the system, assembling process and power characterization.

4.1. Numerical and digital models

The numerical models served to check the structural behaviour, buoyancy, mechanical interferences and energy gain of the system. The next step consisted in determining the engineering specifications of the components for further drawing and design [12].

Conventional methods and computational techniques were used to check the elements of the system. Digital models of the system were also developed as can be seen in Figure 5.

Figure 5: Digital model visualization

The finite element method (FEM) was a key tool used in the design of the floating module. The shape complexity of the module led us to combine Computer Aided Design (CAD) and FEM. The pontoon is made of medium density polyethylene (MDPE). Firstly, Figure 6 shows the four previous models modelled and analysed to withstand the forces of the system. The main loads acting on the system are summarized below: dead loads, photovoltaic panels, maintenance live loads, wind pressure and buoyancy forces.

Figure 6: Previous models of the floating module

Secondly, the specific design issues of rotomoulding together with the mechanical feedback gained with the four previous models enabled the conception of the pontoon consisting on two basic elements (Figure 7): a MDPE floating module and a horizontal steel frame supporting the PV array and loads due to weather conditions. A rigorous analysis of the structural response of the pontoon was carried out with different thicknesses (3-8 mm) to assess the performance of the pontoon [12, 14].

According to plastic design [16, 17], a non-linear structural approach is performed since: i) Plastic materials exhibit a non-linear behaviour even at small strain values. Additionally, time and temperature enhance such effect, ii) MDPE undergoes significant geometric changes under load. So, changing the shape of the structure changes its stiffness. Therefore, the analytical approach must fit the geometric characteristics of the model, iii) The combined analysis of the plastic module and the metallic frame requires the mechanical interaction of two materials with different rheological behaviour.

The thorough parametric study determined a minimum thickness of 4 mm to meet the strength and deformation plastic conditions [18]. Meanwhile, the rigid frame is made from cold-formed steel profiles with UF-60x3 sections.

Figure 7: FEM Modelling (Plastic module + metallic frame)

4.2 Real prototype

Around 7% of the water surface of the reservoir named "El Negret" (Figure 8) was used as a real scale prototype in order to check the behaviour of the system and make the appropriate technical and experimental changes.

The reservoir is located in Agost, a town near Alicante (East of Spain). The earth reservoir was covered with a high density polyethylene (HDPE) geomembrane. The reservoir has a slope section of 2.8 Horizontal/1.00 Vertical, maximum slope height of 5 m and maximum water storage capacity of 20,000 m^3.

The prototype was installed in August 2009 and up to now its global performance has been highly satisfactory. For a peak power of 22.27 kWp the yearly energy yield was 28,349 kWh which corresponds to a performance ratio of 71.45%.

The in-situ performance of the system has served to verify the feasibility of the solution as well as the following issues:

- Buoyancy conditions and free-draft measures under different load conditions.
- Efficient support of the modules on the reservoir slope, particularly at critical design points (vertex lines between planes).
- Mechanical behaviour of the system.
- Testing of different elastic joints in order to properly define load-displacement requirements.
- Cost estimation and assembling process.

Figure 8: Real model

5. ECONOMIC VIABILITY

The experience served to estimate the real cost of the elements of the system. The figures in Table 3 are an illustration of the economic viability of a 100 kWp system.

Table 3: Estimated cost

The cost of the system is about 30 percent higher than that of a conventional grid-connected PV installation.

With the operation costs showed in Table 4, the profitability index obtained is 9.86%.

Table 4: Operation costs

Also a financial evaluation has been carried out considering a loan (10 years, 4.5%) for 80% of the investment, and an inflation index of 3% (Table 5 and Figure 9).

Table 5: Financial evaluation

The Net Present Value (NPV) at 5% is 149,179 € and the Internal Rate of Return (IRR) 12.65%. Although, logically, the system is less profitable than a conventional grid-connected PV installation, it keeps being profitable, even without quantifying the water savings.

Figure 9: Cumulative Net Cash Flows

6. FINAL REMARK

At the time the prototype was developed, the Spanish government guaranteed a revenue of 0.29 Euro/kWh for 25 years, but later on bonus policy was eliminated. However, due to the continuous increase of electricity prices and declining prices of PV modules, the self-consumption is presented as an option increasingly promising for our system. In fact, we are focusign our latest research in this direction, although Spanish law does not regulate yet the self-consumption completely.

6. CONCLUSIONS

The system is technically feasible and economically viable. In the near future, the surface of the reservoir will be totally covered with the floating system. The photovoltaic plant will become a source of income for the reservoir’s owners. Additionally the system will help reduce water losses due to evaporation.

On the other hand, the system also contributes to more sustainable land management practices since a pre-existing water storage structure is used to install a photovoltaic plant instead of having to change the use of agricultural lands.

The Photovoltaic Floating Cover System (PFCS) described in this paper can be an efficient solution to certain agro-energetic policies and issues and to the need for water efficiency tools in the agricultural industry.

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The system described in this text is under patent process [18].

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Table 1: Number of photovoltaic units and power installed depending on the tilt angle

Tilt angle	**Number of floating modules (2 PV panels)**	**Floating module size (Width x length) (m)**	**Peak Power installation (kWp)**	**Peak Power density (Wp/m^2)**	**Energy yield (kWh/m^2 year)**
30º	652	3.40 x 2.00	260.8	55.46	82.49
15º	787	2.20 x 2.55	314.8	65.55	104.27
10º	908	2.20 x 2.20	363.2	74.16	114.89

Table 2: Power loss vs. azimuth rotation

Azimuth rotation	**Peak Sun-Hours (PSH)**	**Losses regarding 0º azimuth**
0º	1,800	-
10º	1,800	0.00%
20º	1,790	-0.56%
30º	1,780	-0.56%
40º	1,770	-0.56%
50º	1,750	-1.13%
60º	1,730	-1.14%

Table 3: Estimated cost

Concept		Cost (€)
Platform		
Pontoons		40755
Pontoons transport		1045
Structure		19855
Tensors		3135
Screws and rivets		564
Assembly		4180
	Total platform	69534
Foundations and elastic joints		
Pilot foundation		7000
Elastic joints		6000
	Total covering	82534
“Conventional” costs		
Inverters		19461
Photovoltaic panels		140000
Wiring		19000
Monitoring		2000
Security		7000
Engineering		8300
Health and safety on site		2000
Quality control		800
	Total	198561
Overheads (15%)		42164
Industrial profit (6%)		16866
Total costs		340126

Table 4: Operation costs

Energy production	135000 kWh
Gross income	39150 €/year (0.29 €/ kWh)
Leasing	1296 €/year
Maintenance	4320 €/year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Revenues from energy sales		39.852	40.743	41.654	42.586	43.432	44.295	45.176	46.074	46.989	47.923	48.876	49.847	50.838	51.848	52.879	53.930	55.002	56.095	57.210	58.347	59.506	60.689	61.895	63.125	64.380
Insurances		1.469	1.513	1.558	1.605	1.653	1.703	1.754	1.807	1.861	1.917	1.974	2.033	2.094	2.157	2.222	2.289	2.357	2.428	2.501	2.576	2.653	2.733	2.815	2.899	2.986
Maintenance		4.320	4.450	4.583	4.721	4.862	5.008	5.158	5.313	5.472	5.637	5.806	5.980	6.159	6.344	6.534	6.730	6.932	7.140	7.355	7.575	7.802	8.036	8.278	8.526	8.782
Leasing		1.296	1.335	1.375	1.416	1.459	1.502	1.547	1.594	1.642	1.691	1.742	1.794	1.848	1.903	1.960	2.019	2.080	2.142	2.206	2.273	2.341	2.411	2.483	2.558	2.635
Gross operating margin		32.767	33.446	34.138	34.844	35.458	36.082	36.716	37.360	38.014	38.679	39.354	40.040	40.736	41.444	42.162	42.892	43.632	44.384	45.148	45.923	46.710	47.509	48.320	49.142	49.978
Depreciation expenses		34.013	34.013	34.013	34.013	34.013	34.013	34.013	34.013	34.013	34.013															
Financial expenses		12.245	11.248	10.207	9.119	7.982	6.793	5.552	4.254	2.898	1.481															
Profit before taxes		-13.490	-11.815	-10.082	-8.287	-6.536	-4.724	-2.848	-906	1.104	3.186	39.354	40.040	40.736	41.444	42.162	42.892	43.632	44.384	45.148	45.923	46.710	47.509	48.320	49.142	49.978
Taxes (25%)		0	0	0	0	0	0	0	0	276	796	9.839	10.010	10.184	10.361	10.541	10.723	10.908	11.096	11.287	11.481	11.678	11.877	12.080	12.286	12.494
Profit after taxes		-13.490	-11.815	-10.082	-8.287	-6.536	-4.724	-2.848	-906	828	2.389	29.516	30.030	30.552	31.083	31.622	32.169	32.724	33.288	33.861	34.442	35.033	35.632	36.240	36.857	37.483
Payment of loan principal		22.143	23.140	24.181	25.269	26.406	27.595	28.836	30.134	31.490	32.907															
Net cash flows	-68.025	-1.621	-942	-250	456	1.070	1.694	2.328	2.972	3.351	3.495	29.516	30.030	30.552	31.083	31.622	32.169	32.724	33.288	33.861	34.442	35.033	35.632	36.240	36.857	37.483
Cumulative Net Cahs Flows	-68.025	-69.646	-70.588	-70.838	-70.382	-69.312	-67.618	-65.290	-62.317	-58.967	-55.472	-25.956	4.074	34.626	65.709	97.330	129.499	162.223	195.511	229.372	263.814	298.847	334.478	370.718	407.575	445.058

Table 5: Financial evaluation