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Design and construction of a test bench to investigate the potential of floating PV systems

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ABSTRACT

Floating photovoltaic systems (FPVSs) are a modern concept for clean energy generation, which combine the existing PV systems with a floating structure. Such a combination enables achieving a higher efficiency of PV modules and a best management of land resources which ensures meeting energy requirements more effectively. In this paper, an experimental investigation of a small-scale FPVS is presented. It is designed and built for research and demonstration purposes as a first attempt to analyze this concept under Moroccan operating conditions. The objective is to analyze and compare the electrical and thermal performances of an FPVS with those of an overland PV system (OPVS) with a similar nominal capacity. To do this, a test bench consisting of FPVS and OPVS and measurement station has been proposed and established. The design and construction aspects of the FPVS, as well as the experimental setup of the entire test bench, are extensively described in this paper. The test results show that the average temperature of the FPV modules, during the test period, was always lower compared to that of the OPV modules with a difference of up to 2.74 °C. This means that FPVS can benefit from the natural cooling effect of water and operate with higher efficiency as compared to OPVS. It was also found that the FPVS generates up to 2.33% more daily energy than the OPVS. Further, an experimental test was also performed in this work to compare the energy production of FPVS under different tilt angles. The test result confirms that the FPVS produces the highest energy when it is installed at the annual optimal tilt angle. Hence, adjusting the PV modules at their optimal tilt angle is recommended as well for FPVSs.

1. Introduction

Recently, photovoltaic (PV) energy, which depends on solar panels to produce electricity, has become one of the world's most popular options for power generation (Motahhir et al., 2020a; International Renewable Energy Agency, 2019). While the PV energy domain is growing rapidly around the world, many countries, especially those with high-density urban sectors, are experiencing space problems (Choudhary and Srivastava, 2019). That is, finding enough space to install more PV panels, which usually needs to be installed on rooftops or overland has become a critical challenge. In addition, due to their low efficiency (Motahhir et al., 2020b; Zanlorenzi et al., 2018), PV systems are subject to intense land requirements (about 10 m^2 for each kW). These problems can be overcome by the implementation of floating photovoltaic systems (FPVSs) on the water bodies with the aim to save the land and use it for agriculture, housing or other purposes. On the other hand, FPVSs give the potential to take advantage of the effect of water for natural cooling of solar panels, which improves their efficiency.

FPVS is a new form of solar electricity generation technology, where PV panels can be installed on a floating structure on bodies of water such as ponds, reservoirs, canals, rivers, etc. The first FPVS was built in 2007 in Aichi, Japan with a capacity of 20 kW for research purpose (Trapani and Redón Santafé, 2015). Since then, different types of FPVSs were installed in France, Italy, Korea, USA, Spain, etc. Sahu et al. reviewed the various FPV projects that have been realized over the years (Sahu et al., 2016). According to the World Bank Report "Where Sun meets Water", the cumulative installed capacity of FPVSs was approximately 1.1 GW_p as of mid-

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2018, the same level reached by the overland PV systems (OPVSs) in 2000 (World Bank Group, 2019). FPVSs have numerous advantages compared to OPVSs, specifically:

- FPVSs do not require any land space, which constitutes a huge economic advantage. They can be installed in unused space on bodies of water, such as hydroelectric dam reservoirs, wastewater treatment ponds, etc (Cazzaniga et al., 2018);
- Floating structures provide shade to the body of water, which reduces water evaporation and therefore maintains the volume of stored water (Qin et al., 2019). Clot et al. reported in their work that FPVSs could reduce water evaporation losses between 15,000 and 25,000 m^3 for each MW_p installed (Rosa-Clot et al., 2017). Overall, it is reported in the literature that water loss using FPVSs can be reduced by 25–70% (Do Sacramento et al., 2015; Sahu et al., 2016);
- The shade that the floating structures produce can help to prevent the growth of algae, thereby improving water quality (Pringle et al., 2017);
- Since the efficiency of a solar panel decreases as the temperatures rise, the bodies of water that host the floating structures can help the solar panels cool down, which means that FPVSs can benefit from the natural cooling effect of water and operate with higher efficiency as compared with OPVSs (Rosa-Clot and Marco Tina, 2020; Song and Choi, 2016). Generally, FPVSs can enhance PV modules efficiency by up to 12% (Ranjbaran et al., 2019);
- The natural reflectivity of the water surface increases the incidence of solar radiation in the PV modules, therefore increasing the PV energy generation (Rosa-Clot et al., 2017).

Based on this background, FPVSs can be considered as a good solution for the land requirements with interesting outcomes for energy production and water saving. Besides the benefits that FPVSs can contribute, they could cause some harmful effects on the aquatic environment because they reduce the penetration of sunlight into bodies of water, which can affect the growth of aquatic animals living below (Pimentel Da Silva and Branco, 2018). In addition, FPVSs have an important limitation; they do not resist strong wind gusts, requiring a very large number of mooring points (especially if they are installed in the sea) so that they remain intact and maintain their angular position (Cazzaniga et al., 2018). However, the installation of FPVSs is increased significantly over the years due to its multiple advantages. Several studies about technologies of FPVSs and their performances have been carried out in the last years. Some studies have mainly focused on the design and operation of certain FPVS, and/or analyzed its economic feasibility (Campana et al., 2019; Ferrer-Gisbert et al., 2013; Kim et al., 2017; Lee et al., 2014). Other works investigated the environmental advantages of FPVSs, such as their potential in saving water by reducing the evaporation losses as well as in improving water quality (Redón Santafé et al., 2014; Santafé et al., 2014). Whereas other studies examined the electrical performance and analyzed the power generation of FPVSs (Campana et al., 2019; Choi, 2014; Liu et al., 2017). Since FPVSs represent one of the hot and modern topics in the field of clean renewable energy, it is very important to perform more research in this context to encourage countries, especially developing ones, to keep abreast of the current development in this field. However, is not easy to conduct such research due to the high cost involved. Most of the existing research papers discuss the kilowatts and megawatts scales of installed PV modules in land and water, which require significant funding, and that is not always available for many researchers mostly in developing countries like Morocco. For this reason, it would be of interest to use a small-scale PV installation based test bench as a preliminary step to conduct the experimental tests and to assess the FPVS potential, which enables large-scale FPVSs research and development and allow for FPVSs to outreach students and researchers. Nevertheless, to the authors' best knowledge, no reference has been found in the literature that presents such a test bench. While an experimental study using an 80 W_p FPVS installed in a pond simulator has been discussed in (Azran Abdul Majid et al., 2014), the entire real system has not been presented in this paper and the proposed design does not completely cover a real test bench of an FPVS. Another experimental study of a small-scale FPVS (250 W_p) installed on an artificial pond has been presented in (Yadav et al., 2017) which analyzes its electrical performance and compares it to that of the OPVS. However, the design of the FPVS and the real fabrication of the experimental setup have not been presented in this paper. Accordingly, the present paper is distinctive as it presents in detail a small-scale FPVS based test bench to investigate the potential of FPVSs comparing to OPVSs. The proposed test bench is comprised of an FPVS and OPVS with a similar nominal capacity and a measurement station including different instruments to measure electrical, thermal, and weather parameters related to these PV systems. Furthermore, this home-made small-scale FPVS is based on simple components and has been constructed in such a way to have the possibility of varying the tilt angle of PV modules. This gives us the opportunity to test the energy production of the FPVS under different tilt angles. Moreover, one should add that there is, until now, no research work that investigates the assessment of FPVSs in Morocco. In fact, Morocco is a north-African country with a huge solar energy potential and is presently investing in several solar energy projects to meet the target of its energy strategy. Implementing FPVSs as a power generation alternative seems to be an interesting opportunity for Morocco because of the following reasons:

- Morocco suffers a lot from the water scarcity (Tekken and Kropp, 2012; "Water strategy in Morocco," 2016), especially in rural areas, the shading resulting from FPVSs can save an amount of water by reducing the evaporation losses in water bodies with further electricity generation benefit;
- Almost all the water spaces in Morocco (such as rivers, lakes, dams) are often surrounded by agricultural lands where there are important proportions of the population. FPV plants can deliver electricity to this population for domestic use or for agricultural purposes without using land for PV installation. Thus, preserving agricultural lands as well as reducing the rate of water evaporation;
- Merging of FPVSs with existing hydroelectric power plants (HPP) in order to increase hydropower generation by reducing water evaporation losses, where FPVSs can be installed on the water surface of HPP reservoirs (dams) (Martínez-Jaramillo et al., 2020). And this can represent a cost-effective strategy since the existing grid connection infrastructure of HPP can be shared with FPVSs.

As such a second objective of this work is to explore, through the developed test bench, the potential of using an FPVS, operating under the climatic conditions of Morocco to assess the possible energy gains that can be reached as compared to the OPVS.

The rest of this paper is structured around three sections. After the introduction, section two presents the proposed test bench, including the design of FPVS, and all the materials used to build it. The third section lists and discusses the experimental results of the FPVS and OPVS, obtained through this test bench. Finally, the main conclusions are drawn and some recommendations for future researches are proposed.

2. Materials and methods

To test the efficiency and the benefits of an FPVS, a critical comparison between its electrical and thermal performances with those of an OPVS is required. For this purpose, a test bench, which consists of FPVS and OPVS and a measurement station, is proposed. Fig. 1 illustrates an overview of the proposed test bench and its targets. The FPVS is installed on the water while OPVS on land. The measurement station is composed of several instruments that are used for measuring the electrical parameters (voltage, current and power), the metrological parameters (ambient and water temperature and solar radiation), and the PV modules temperature, linked to these two PV systems. Then, the test bench is experimentally performed and tested to evaluate the thermal (PV modules temperature) and electrical (efficiency and energy) performances of FPVS comparing with the reference OPVS according to the prevailing metrological conditions during the experimental test. In addition, FPVS is tested under different tilt angles to determine the optimal tilt angle of FPV modules leading to the highest energy production.

2.1. FPV system design

As shown in Fig. 2, the 3D model of the proposed small-scale FPVS (which was designed in CATIA software), is presented to visualize its final form before the real manufacturing. It is composed of a floating unit, supporting systems and four PV panels to generate electricity. The floating unit maintains the metallic structure which retains the PV modules. Polyethylene (PE) cans play the role of floating elements. The floatation level of FPVS can be adjusted by the amount of water in the cans. The supporting structure, which is used for fixing PV panels on the floating unit, is designed in such a way to have the possibility of varying the tilt angle ranging from 0° to more than 50° as shown in Fig. 2. The real configuration of the proposed FPVS, as well as the reference OPVS are presented in Fig. 3. The FPVS was installed on a pond simulator (water PVC basin). At this stage, it is interesting to stress that the final manufactured configuration allowed a high ability for easily floating on the water surface.

2.2. Description and experimental setup of test bench

Fig. 4 depicts the experimental setup of the proposed test bench. The total power of the installed PV array in two systems (FPV and OPV) is 87.5 W at STC (standard test conditions) arranged in two parallel strings where each one is formed by two PV modules serially connected as shown in Fig. 5. The used PV panels have the same electrical characteristics, as presented in Table 1, and the same dimensions (55 cm by 28 cm). The FPV and OPV modules are initially installed at a tilt angle of 30°, which corresponds to the optimal tilt angle leading to the highest annual electricity production in Fez city, Morocco (Allouhi et al., 2019; Hammoumi et al., 2018). In addition, the azimuthal orientation of the PV modules is fixed at 180° to the south. Table 2 presents the main components of the measurement station. The electrical parameter data (V_{oc} and I_{sc}) are recorded manually. The horizontal solar radiation data are saved in the SD card of the pyranometer used. Other parameters are recorded in real-time on MS Excel using an automatic instrument system as can be shown in Fig. 6 (Motahhir et al., 2019). It should be noted here that only one DS18B20 sensor which is connected to the acquisition board (Arduino UNO), for the sake of simplifying the representation. However, in reality, all sensors were connected in parallel and coexist on the same 1-wire bus (A A El Hammoumi et al., 2018). The FPV structure is moored with cables fixed symmetrically in several points on each side of it to halt the free movement of the structure in the water and maintain its position in the southward direction (optimal orientation in Morocco to harness the sun power).

In addition, and as mentioned before, this paper aims to examine the energy production of the FPVS under different tilt angles, ranging from 0° to 30° (optimal tilt angle for Fez city). For a meaningful comparison, the requested test for all tilt angles must

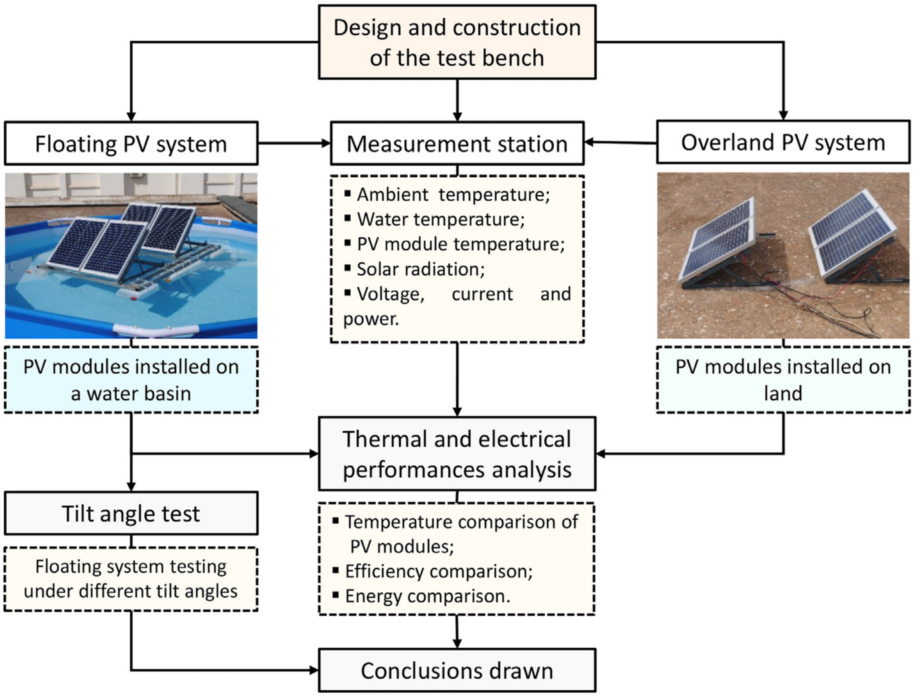


Fig. 1. Overview of the proposed test bench and its targets.

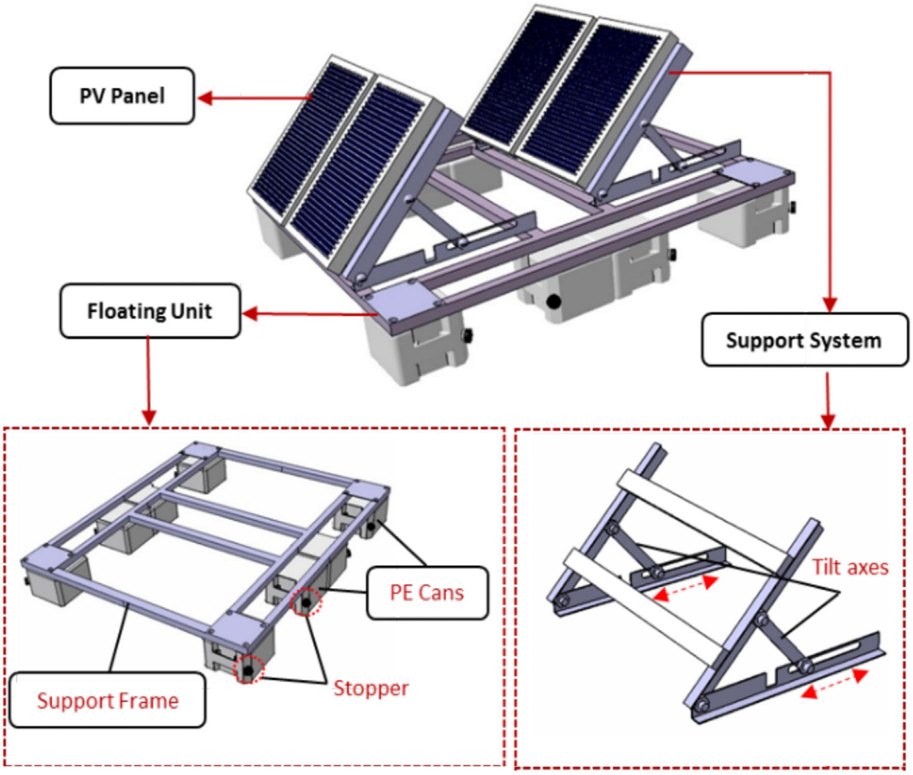


Fig. 2. 3D-design and components of the FPV system.

be carried simultaneously. Thus, a new floating structure that contains four PV strings is constructed. Each PV string is formed by two similar serially connected PV modules and set at a specific tilt angle as shown in Fig. 7.

3. Results and discussion

3.1. Weather data

The experimental tests have been performed over 5 days (hot sunny days): from September 24, 2019 to September 28, 2019 in Fez (lat: 34°01′59″ N, long: 5°00′01″ W, Elev: 1332 ft), Morocco, for a duration of 9 h every day (from 08:30 a.m. to 5:30 p.m.) with a measurement step of 10 min. The weather during this period was almost steady, especially for the incident solar radiation, which exhibits a little variation (as can be seen in Fig. 8 (a)). The maximum solar radiation reached a value of 989 W/m^2 at 1:20 p.m. in day 1, 996 W/m^2 at 1:00 p.m. in day 2, 964 W/m^2 at 12:50 p.m. in day 3, 967 W/m^2 at 1h00 p.m. in day 4, and 971 W/m^2 at 1h00 p.m. in day 5. The minimum daily solar radiation was recorded to 204 W/m^2, 210 W/m^2, 194 W/m^2, 192 W/m^2, and 199 W/m^2, respectively for days 1, 2, 3, 4, and 5; all occurring at about 8:30 a.m. Fig. 8 (b) shows the recorded solar radiation data for day 1 in horizontal (tilt angle of 0°) and inclined (tilt angle of 30°) surface. From this figure, it can be concluded that PV modules set at a tilt angle of 30° (optimal tilt angle in Fez city) have the potential to capture more solar radiation per unit area as compared to a 0° tilt angle; independently of the observation day. The water (T_w) and ambient (T_a) temperatures were as well recorded during the same period. Fig. 8 (c) depicts T_w and T_a recorded in the first day, while Fig. 8 (d) shows the difference between T_w and T_a ($T = T_a – T_w$) during the test period. The deviation between water temperature and ambient temperature can reach or exceed 15 °C, as is the case on day 5. Obviously, in most cases, water temperature is lower than the ambient temperature which is required to create the cooling effect for FPV modules. The minimum and maximum daily ambient temperatures were recorded to be 23 °C and 37,94 °C, respectively for day 1, 23,81 °C and 38,31 °C for day 2, 23,37 °C and 39,81 °C for day 3, 24,31 °C and 39,19 °C for day 4 and to 24,06 °C and 43,25 °C for day 5.

3.2. Thermal behavior of PV modules

In this paper, the thermal behavior of the PV module was studied by measuring both the temperature of the rear and front side of the PV module. This will allow a better estimation of the transient module temperature that will be calculated as the average value. As presented in Table 2, the thermocouple sensors measured the rear side temperature while the front side temperature is measured using ThermaCam. Fig. 9 illustrates the temperature (T_m) of floating and overland PV modules during the test period. It can be seen that during the daytime, the temperature of the FPV module was typically lower than the OPV module. This is mainly attributed to the cooling effect of water resulting from the water surface. Fig. 10 (a) shows the instantaneous temperature between OPV and FPV modules during the test period of day 1, including instantaneous front and rear side temperatures between OPV and FPV modules. Under a solar radiation of 981.43 W/m^2, an ambient temperature of 33.25 °C and a water temperature of 25.69 °C, all at 1:00 p.m., the PV modules reach the highest temperature, i.e. 53.56 °C on the OPVS and 51.19 °C on the FPVS. This implies that the cooling effect of water creates a difference in operating temperature of 2.08 °C between the two systems. In some other cases, this difference may exceed 5 °C. Fig. 10 (b) presents the average deviation of temperature between OPV and FPV modules during the test period, as well as the averages deviation of front and rear side temperatures between OPV and FPV modules. The average

Fig. 3. Real configuration of FPVS and OPVS.

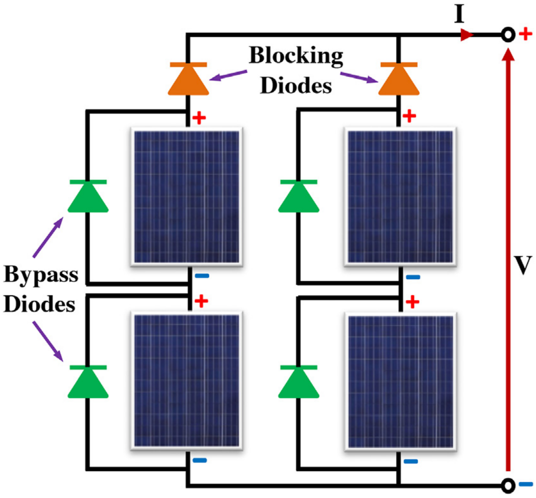


Fig. 5. Solar PV modules connections.

Table 1
Characteristics of the used polycrystalline solar panel at STC.

Characteristic	Value
Maximum power, Pmax	21.9 W
Voltage at Pmax, Vmp	17.8 V
Current at Pmax, Imp	1.23 A
Short-circuit current, Isc	1.17 A
Open-circuit voltage, Voc	21.8 V
Number of cells	36

deviation of temperature between OPV and FPV modules is about 2.74 °C in the first day, 2.44 °C in the second day, 2.84 °C in the third day, 2.24 °C in the fourth day and 2.52 °C in the fifth day. Overall, it was proved that the floating technology has the capability of reducing considerably the temperature of PV modules and as such it is expected that FPVS will produce a higher energy level as compared to the OPVS.

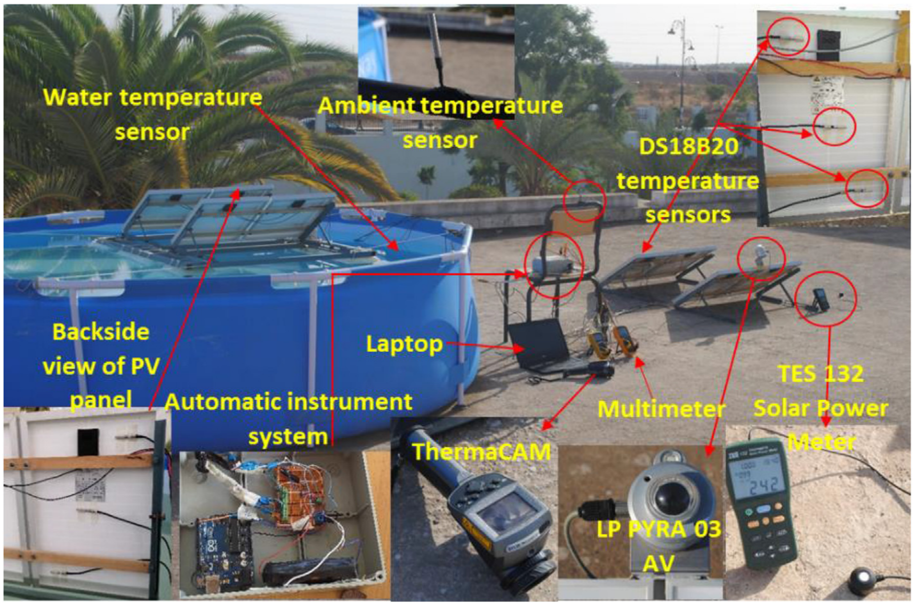


Fig. 4. Experiment setup of the test bench.

Table 2
The main components of the measurement station.

Component	Specifications	Description
FLIR ThermaCAM E4	• Thermal sensitivity: 0.1 °C at 25 °C • Temperature ranges: −20 °C to +250 °C/+250 °C to +900 °C (optional) • Accuracy: ± 2 °C or ± 2% of absolute temperature in °C	It is used to measure the temperature of the front side of the PV module.
LP PYRA 03 AV	• Typical sensitivity: 0..10V (0..2000 W/m^2) • Measuring range: 0–2000 W/m^2 • Power supply: 14–30 V • Output signal: 0..10 V/0..2000 W/m^2 • Operating temperature: 40–80 °C • Response time: <30 s	It is used to measure the inclined solar radiation on the surface of the PV module.
TES 132 Solar Power Meter	• Range: 2000 W/m^2, 634 Btu/(ft2 x h) • Resolution: 0.1 W/m^2,0.1 Btu/(ft2 x h) • Accuracy: Typically within ±10 W/m^2 [±3 Btu/(ft2 x h)] • Sampling Rate: 4 times/sec • Accessories: USB Cable, CD software …	It is used to measure the horizontal solar radiation. It is placed at the ground surface (0° of tilt angle).
DS18B20 sensors (Thermocouples)	• Communicates using 1-Wire bus • Operating voltage: 3V–5V • Temperature Range: −55 to +125 °C • Accuracy: ±0.5 °C • Output Resolution: 9-bit to 12-bit • Unique 64-bit address enables multiplexing • Conversion time: 750 ms at 12-bit	Eight sensors are used, two of which are used to measure the ambient and water temperature, while others to measure the temperature of the rear side of the PV module. The latter is measured via three thermocouples, which were placed diagonally as can be seen in Fig. 4.
Arduino Uno	• Operating Voltage: 5V • Input Voltage (recommended): 7–12V • Digital I/O Pins: 14 (of which 6 provide PWM output) • Analog Input Pins: 6 • Flash Memory: 32 KB • SRAM: 2 KB (ATmega328) • EEPROM: 1 KB (ATmega328) • Clock Speed: 16 MHz	Data acquisition board used to real-time data instrumentation of thermocouples sensors and LP PYRA 03.
Multimeters	ARNOUX CHAUVIN Multimeters	Two multimeters are used for short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) measurement of PV systems.

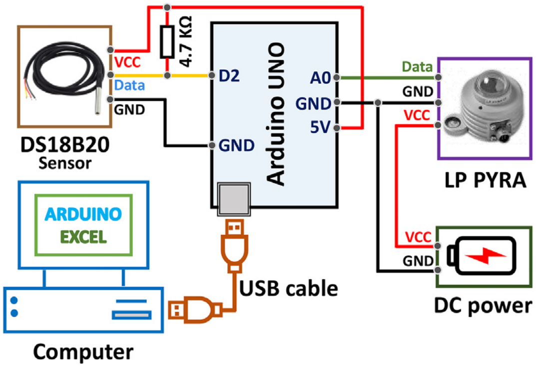


Fig. 6. Circuit diagram of the automatic instrument system.

3.3. Conversion efficiency and energy analysis

The instantaneous DC power (P_{dc}) recorded during the test period is plotted in Fig. 11. It is seen that the power profile for these days is very close to each other resulting mainly from the insignificant deviation in the incident solar radiation. The maximum produced power of FPV and OPV systems were respectively: 82.41 W and 81.30 W in day 1 at 1:30 p.m., 84.22 W at 1:30 p.m. and 82.52 W in day 2 at 1:10 p.m., 79.66 W and 78.35 W in day 3 at 12:50 p.m., 79.68 W and 78.25 W in day 4 at 12:50 p.m., 80.26 W and 78.97 W in day 5 at 1:20 p.m. Fig. 12 presents the open-circuit voltage, short-circuit current and DC power generated from OPV and FPV systems during the test period (day 1). From this figure, it can be seen that there is a high deviation of voltages when compared to those of currents. This is mainly due to the fact that the change of PV module temperature has a stronger influence on the PV voltage, while the PV current is principally affected by solar radiation.

Fig. 7. FPVS under different tilt angles.

For meaningful conclusions about the efficiency benefit resulting from the use of the FPVS against the OPVS, the relative

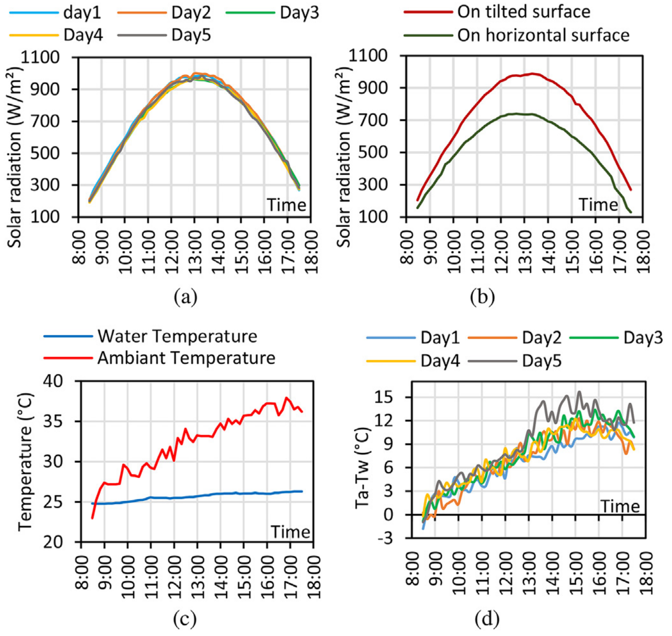


Fig. 8. Weather data. (a) Inclined solar radiation during the test period. (b) Comparison between inclined and horizontal solar radiation in day 1. (c) Deviation between ambient and water temperature during the test period.

efficiency enhancement (REE) was calculated at each time step for each day. Fig. 13 (a) depicts the obtained results for day 1, including the instantaneous conversion efficiency of FPVS and OPVS; the results of other days follow approximately the same pattern. Fig. 13 (b) presents the average REE obtained during the test period. The averages REE obtained were 1.88%, 1.87%, 2.33%, 2.46% and 2.57% respectively for day 1 to day 5, which means that FPVS has benefited from the natural cooling effect of water to operate with a higher efficiency compared to OPVS. It is also expected that the FPVS efficiency will be even greater if it is placed in a large body of water where the airflow is high, resulting in a greater reduction in

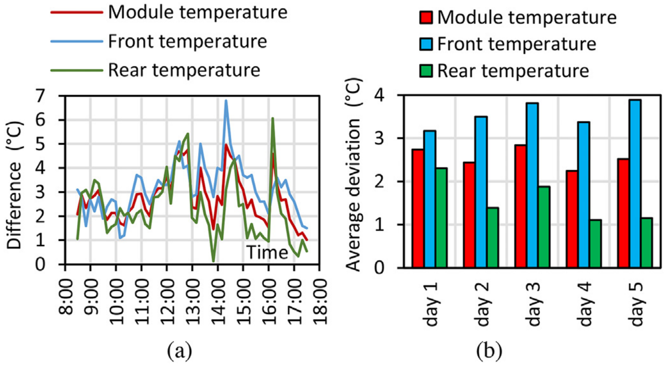
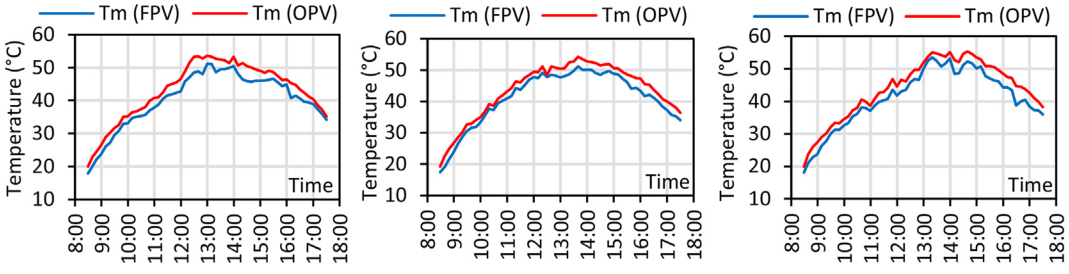


Fig. 10. The instantaneous temperatures between OPV and FPV modules during day 1 (a). The average deviation of temperatures between overland and floating PV modules during the test period.

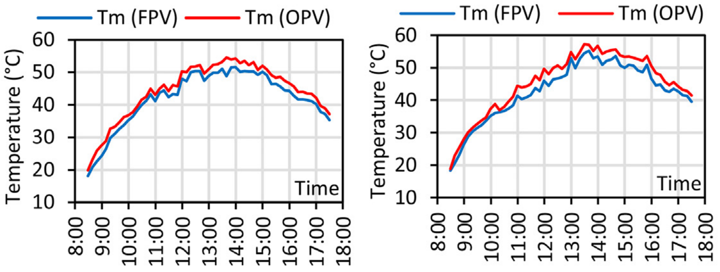
the temperature of PV modules.

Integrating numerically the DC power over the time allows estimating the daily DC energy generated. Fig. 14 presents the produced energy by FPV and OPV systems during the test period. From this figure, it can be noted that the energy production of the FPVS was always greater than the OPVS. For instance, on the first day, the FPVS produced 254.3 Wh, whereas the OPVS produced 544.22 Wh; i.e. FPVS generates 1.85% more energy than the OPVS. The energy generation (energy gain) can be increased up to 2.33% for the fifth day.

As shown in Table 3, the obtained results in this work are compared with some experimental works published in the literature. The table compares different FPVSs according to the following criteria: installed PV power, location of FPV and OPV systems, type of water body, temperature difference between FPV and OPV modules, efficiency gain, and power (or energy) gain. For instance (Azran Abdul Majid et al., 2014), have tested and compared the electrical performance of a 80 W FPVS (installed on a pond simulator in Malysia) with the same capacity OPVS, and indicated that during 2-h of the experiment, the power gain of FPVS was increased by 15.5% (Yadav et al., 2017). have conducted an experimental study

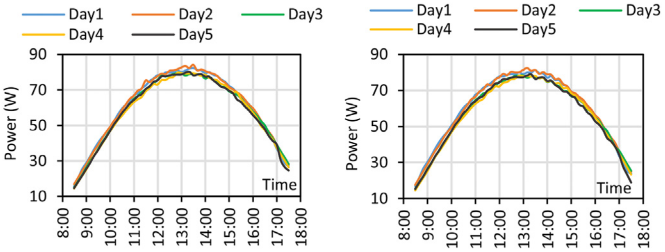


(a). Day 1 (b). Day 2 (c). Day 3



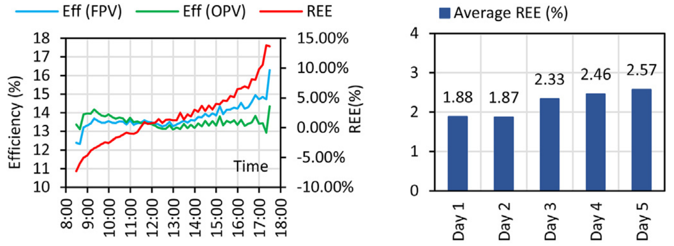
(d). Day 4 (e). Day 5

Fig. 9. Comparison graph of PV modules temperatures during the test period.



(a) (b)

Fig. 11. Power profile for FPV (a) and OPV (b) systems during the test period.



(a) (b)

Fig. 13. Efficiency comparison between OPVS and FPVS, and the relative efficiency enhancement in day 1 (a). Average REE between FPVS and OPVS during the test period (b).

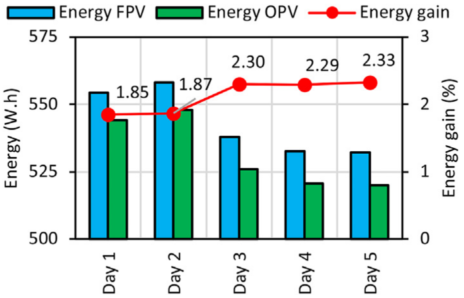


Fig. 14. The produced energy by FPV and OPV systems during the test period.

of a 250 W FPVS (installed on an artificial pond in India), and illustrated that during 9-h of the experiment (in a hot sunny day in the month of June) the efficiency gain of FPVS was greater by 0.79% compared to OPVS. Another experimental study of a 1 MW FPVS (installed in Kaylana lake, Jodhpur city, India) has indicated that compared to the OPVS, FPVS has 2.48% more energy generation yearly with a decrease of 14.56% in the temperature of its PV modules (Mittal et al., 2018). Generally, and as can be shown in Table 3, all FPVSs have marked out by higher performances in comparison with OPVSs. However, it is very difficult to make a real comparison between the presented results in the literature due to the fact that the performances of FPVSs depend on the climatic conditions in which they were operating, type of water bodies in which they were installed, PV panels' technology and efficiency, as well as the duration and conditions of the test. The results obtained in this work are encouraging keeping in mind that the FPVS was installed only in a mini basin without water flow.

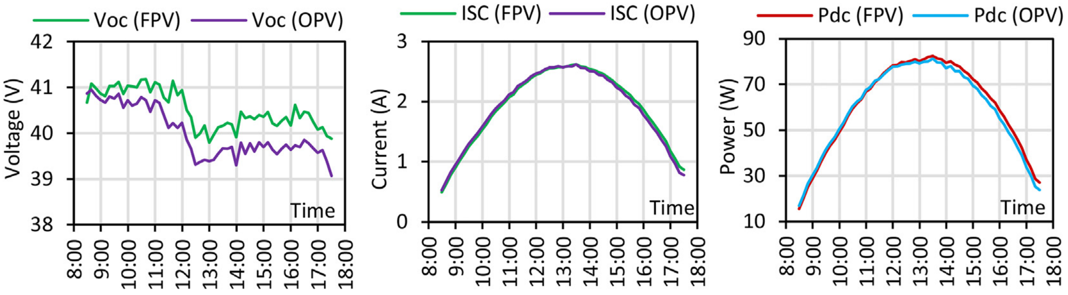
3.4. FPVS under different tilt angle

The results of the experimental test of the FPVS under various tilt angles are depicted in Fig. 15. The experimental test has been performed on a sunny day (October 26, 2019) from 1:00 p.m. to 3:45 p.m.; the average values of ambient and water temperature during the test period were 34 °C and 21° respectively. The instantaneous DC power generated from each string has been recorded at the same time for each measurement step (15 min). It can be clearly seen, from the obtained results, that the highest power production during the test period was obtained from the PV string that is inclined at the optimal tilt angle (30°) while the lowest power has resulted from the PV string that set at 0°. During the test period, the PV string tilted at 30° produced 86.09 Wh, while the PV string set at 0° produced 59.98 Wh, i.e. the PV string set to 30° generates 43.5% more energy than the flat PV string. Despite horizontally placed panels may benefit more from water cooling due to its more closeness to the water surface, they produced the lowest energy. This can be explained by the fact that the effect of optimizing the tilt angle is more pronounced than the cooling effect. As a conclusion, adjusting the PV modules at their optimal tilt angle is recommended as well for FPVSs.

4. Conclusions and perspectives

In this paper, a simple test bench is developed for research and demonstration purposes. It compares energetically the benefits resulting from using FPV panels against land installed PV panels. Several experimental tests have been made, using the developed test bench, to investigate the thermal and electrical behavior or the FPVS, operating in Morocco. The key results of this preliminary research are the following:

(i) Firstly, the proposed small-scale FPV structure shows a high ability to easily float PV panels on the water surface. Such a structure with some minor modifications can be extended to larger capacities by connecting several units.



(a) (b) (c)

Fig. 12. Open-circuit voltage (a), short-circuit current (b) and DC power (c) generated from OPV and FPV systems during the test period in day 1.

Table 3
Comparison between our proposal and some experimental works published in the literature. (NP: not presented).

Publication year, Paper	Installed PV power	Location	Type of water bady	Results (FPVS compared to OPVS)		
				PV modules temperature	Efficiency gain	Power (PG) or energy gain (EG)
Azran Abdul Majid et al. (2014)	80 W	Peninsular Malaysia	Pond simulator	Less than OPVS	NP	15.5% (PG) (2 h of experiment)
.(Yadav et al., 2017)	250 W	MANIT-Bhopal, India	Artificial pond	Less than OPVS	0.79%	NP
Choi (2014)	100 kW (in FPVS) and 1 MW (in OPVS)	Hapcheon, South Korea	Dam (Hapcheon dam)	Less than OPVS	11%	NP
Yoon et al. (2018)	100 kW	Hapcheon, South Korea (FPVS) Sacheon, South Korea (OPVS)	Dam (Hapcheon dam)	Less than OPVS	NP	10.59% (yearly EG)
Mittal et al. (2018)	1 MW	Jodhpur, India	Lake (Kaylana)	Less by 14.56% than OPVS	NP	2.48% (yearly EG)
Proposed	87.5 W	Fez, Morocco	Water PVC basin	Less by 2.24 °C–2.7 °C than OPVS	1.87% –2.57%	1.85%–2.33% (EG)

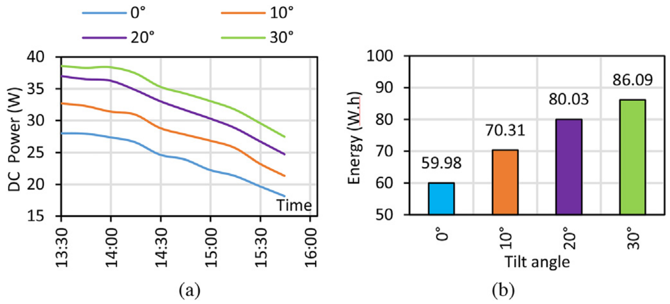


Fig. 15. The instantaneous DC power (a) and the produced energy (b) of FPVS under different tilt angles during the test period.

(ii) During the test period, the average temperature of the FPV modules is always lower than that of the OPV modules with a difference of up to 2.74 °C. These results show that the heat from the surface of the PV panels is transferred to the water basin that acts as a cooling system.
(iii) Due to the cooling effect of water, the energy generation using the FPVS, according to the prevailing metrological conditions during the experimental test, can be increased by up to 2.33% when compared to the reference OPVS.
(iv) FPV modules produce the highest energy when adjusted to the optimal tilt angle. During about 3 h of the test, the FPV modules set to 30° (optimal tilt angle of Fez city) can generate 43.5% more energy unlike if it is set at 0°. Thus, adjusting the PV modules at optimal tilt angle is recommended as well for FPVSs.

Referring to these results and what has been reported in the literature, FPVS is a promising solution to reduce the cost of PV installation in terms of the space required, increasing the PV system efficiency and providing an environmentally friendly technology that saves water and land sources. This technology can provide a great opportunity for Morocco with huge solar radiation, coastal surfaces and many water bodies. On the basis of the findings presented in this paper, the next stage of our research will focus on the following:

(i) Improve the measurement station to make it fully automated.
(ii) Tests will be planned to cover the whole year under a real environment for more general conclusions about the energy gains resulting from the adoption of FPVSs.
(iii) The influence of FPV structures on saving water from evaporation a year should be examined according to the installed capacity of solar parks.
(iv) Perform a detailed financial analysis to prove the economic feasibility of FPVSs as power generation alternatives in Morocco.

Credit author statement

Aboubakr El Hammoumi: Writing - original draft, Writing - review & editing, Formal analysis. **Abdelilah Chalh:** Writng - original draft, Formal analysis. **Amine Allouhi:** Writing - original draft, Writing - review & editing, Formal analysis. **Saad Motahhir:** Writing - review & editing, Formal analysis. **Abdelaziz El Ghzizal:** Writing - review & editing, Formal analysis. **Aziz Derouich:** Writing - review & editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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