Politehnica University of Bucharest
THE DOCTORAL SCHOOL OF
ELECTRICAL ENGINEERING

# INCREASING THE EFFICIENCY OF PHOTOVOLTAIC SYSTEMS USING PLANE CONCENTRATORS AND COOLING SYSTEMS

## DOCTORAL THESIS SUMMARY

*Author*: **Ing. Gabriel C-tin COLȚ**
*Scientific Coordinator*: **Prof. Dr. Ing. Aurelian CRĂCIUNESCU**

BUCHAREST 2020

## Contents

**List of abbreviations**

PFV - photo-voltaic panel;

PFVT - photo-voltaic-thermal panel;

PFVTO - photo-voltaic-thermal panel with mirrors

PFVTO-NS - photo-voltaic-thermal panel with North-South oriented mirrors;

PFVTO-EW - photo-voltaic-thermal panel with East-West oriented mirrors;

MPPT - maximum power point tracking systems;

G - solar radiation;

Ta - atmospheric temperature;

# Chapter 1. Introduction

This chapter presents a short introduction on the photovoltaic systems and the paper content. Among the energy systems based on renewable energy, a special place is occupied by photovoltaic systems. They ensure the conversion of solar energy into electricity and have many advantages over other competing solutions, the associated conversion technology being silent, robust, clean, with low costs of production and maintenance, respectively with low ecological impact. The primary source of energy, represented by solar radiation, is free, practically inexhaustible, without harmful residues or greenhouse gas emissions.

In addition to these advantages, photovoltaic systems are also accompanied by certain specific disadvantages such as: low efficiency, fluctuating character of the useful power due to day-night alternation, respectively winter-summer, important areas occupied by photovoltaic modules, etc.

## Structure of the thesis

The thesis is structured on seven main chapters and begins with a bibliographic study that presents the current stage regarding the studied subject. In the following chapters, the functional parameters of the PhotoVoltaic Panels (PFV) and PhotoVoltaic-Thermal Panels (PFVT) panels are analyzed by numerical modeling, using the Matlab-Simulink-Simscape and Comsol software packages, followed by the implementation, testing, monitoring and comparative analysis of the energy performance of some experimental models of low power PFVT equipped with flat solar concentrators.

The paper ends with a chapter of conclusions, original contributions, future development perspectives, respectively with annexes and references.

## The objectives of the thesis

The present paper aims to analyze various technical solutions to improve the energy efficiency of PFV systems by equipping them with flat solar concentrators (mirrors), respectively with cooling systems, the calculations carried out by numerical modeling being followed by experimental implementations and validations.

# Chapter 2. The current stage regarding the cooling procedures of PFV in order to increase their efficiency.

The cooling process of PFV can be classified into 2 categories depending on the working fluid action:

- Passive cooling systems.
- Active cooling systems.

As part of the passive cooling process, PFV cooling is carried out by:

- The natural air circulation without any other help element;
- The natural air circulation through a radiator mounted on the back of the PFV;

Active cooling systems can be divided according to the cooling agent used as follows:

- Water cooling system;
- Air cooling system;
- Water and air cooling system;

# Chapter 3. Performance analysis of a PFVT using Comsol and Simulink / Simscape

## 3.1 Performance analysis of a PFVT with water cooled radiator using Comsol

In this chapter we analyze the energy performance of a PFVT equipped with dorsal radiator and a forced water cooling system. The considered radiator is of channel type. The analysis is performed using the simulation software COMSOL and SIMULINK.

The physical model of the PFVT with cooling radiator is composed of: PFV, cooling radiator, thermoconductor adhesive layer, connectors between radiator and forced cooling circuit. The radiator attached under the PFV is used to remove as much heat as possible, in order to increase the system efficiency.

*Numerical results*

In Fig. 1.a are shown the continuous and discrete distributions of the cooling water temperature along the radiator channel are presented respectively. There is a difference of 13 °C between the water temperature at the radiator inlet (24 °C) and the water temperature at the radiator outlet (37 °C).

Fig. 1.b presents the temperature distribution on the PFVT surface so that it varies between 46 °C on the top front and 24 °C on the bottom when the water enters the radiator.

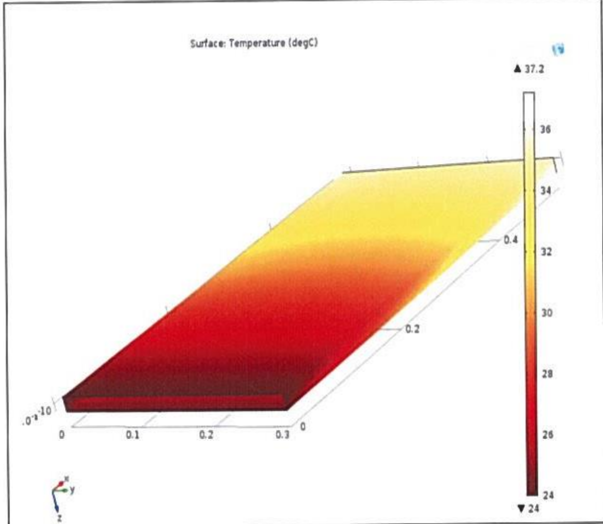


**Fig. 1.a** Continuous distribution of the cooling water temperature along the radiator channel.

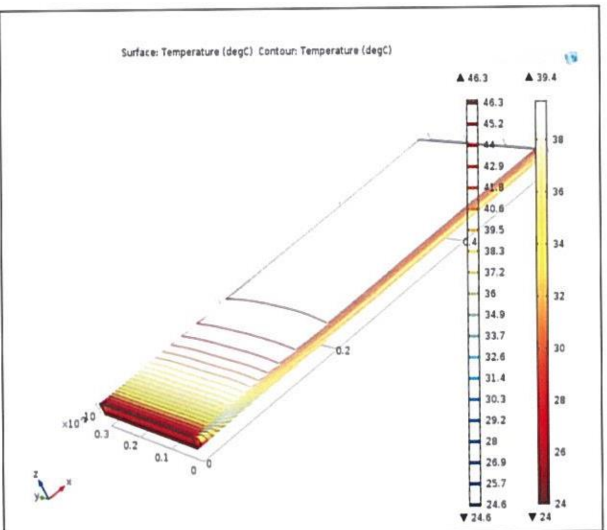


**Fig. 1.b** Temperature distribution on the PFVT surface

Fig. 2 shows the distribution along the PFVT of the electric efficiency of the PV cells, influenced by the variation along the PFVT of the cooling water temperature. It is found that this conversion efficiency decreases with the increase of the cooling water temperature along the flow channel, and hence the temperature of the PV cells.

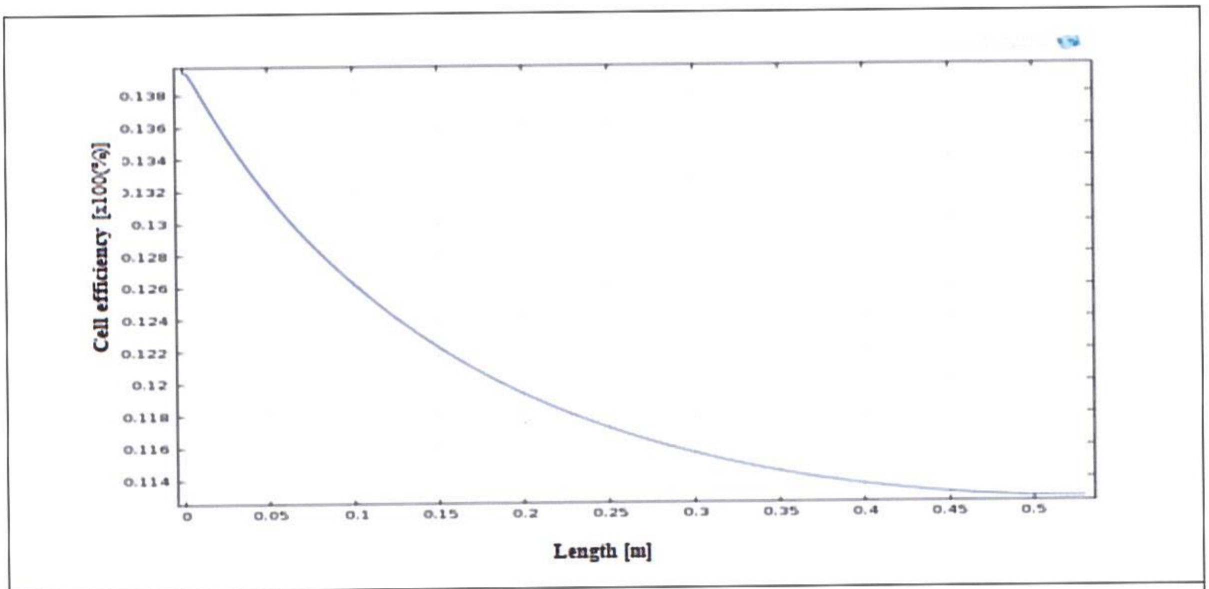


**Fig. 2** Distribution along the PFVT of the electric efficiency

In Fig. 3.a is shown the temperature distribution along PFVT length, for three ambient temperatures: 20 °C, 30 °C and 40°C, under the conditions of a 1000 W/m$^2$ solar irradiation and a cooling water flow of 5 l/min.

In Fig. 3.b is presented the temperature distribution along the PFVT length, for three values of solar irradiance: 600 W/m$^2$, 800 W/m$^2$ and 1000W/m$^2$, under an ambient temperature of 30 °C and a water flow cooling rate of 5l /min.

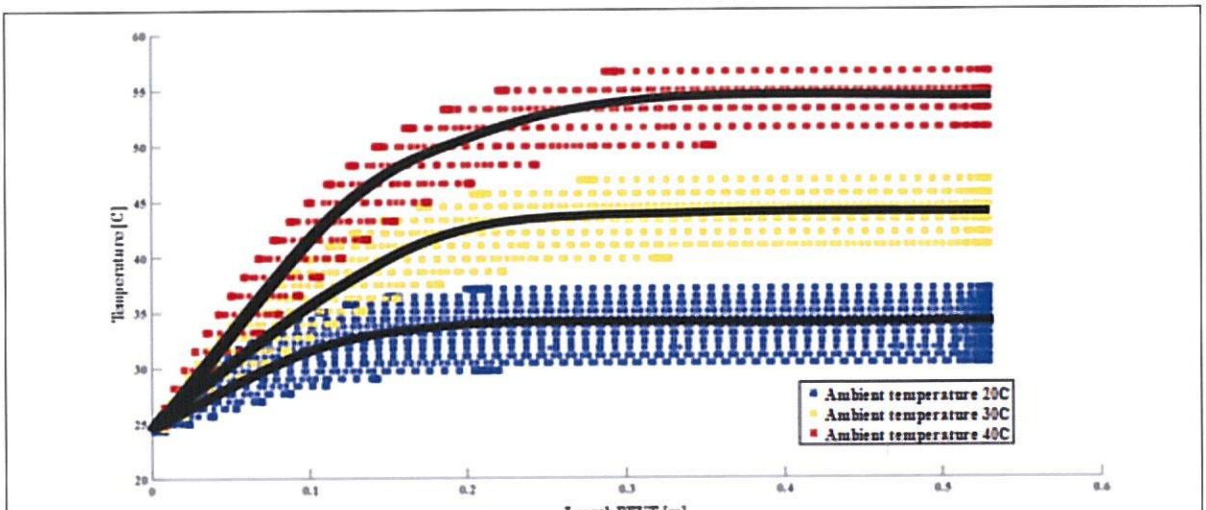


**Fig. 3.a** Temperature distribution along the PFVT length, for different temperature values

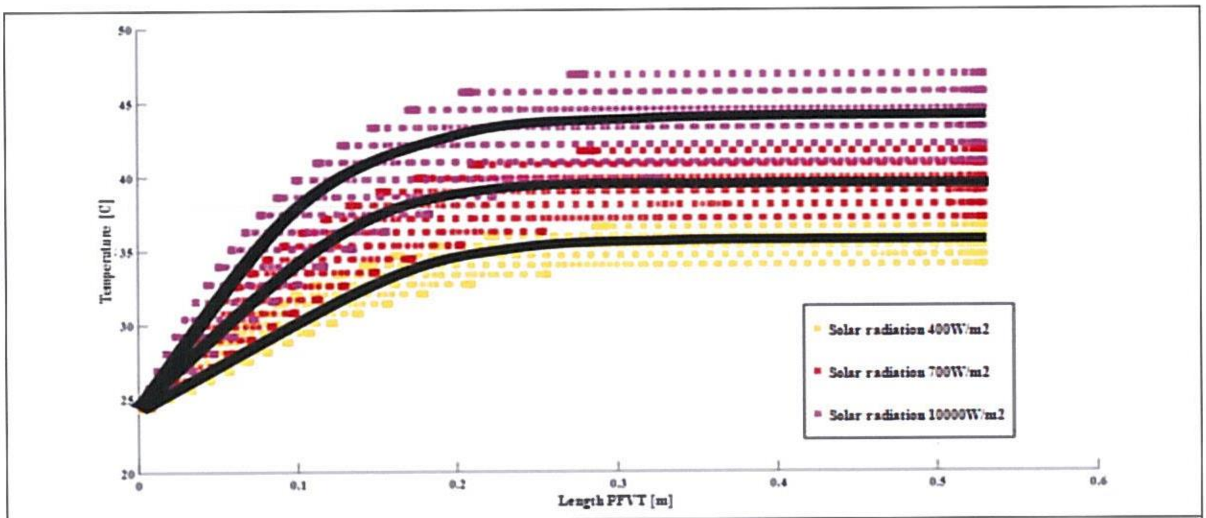


**Fig. 3.b** Temperature distribution along the PFVT length, for different solar irradiance values

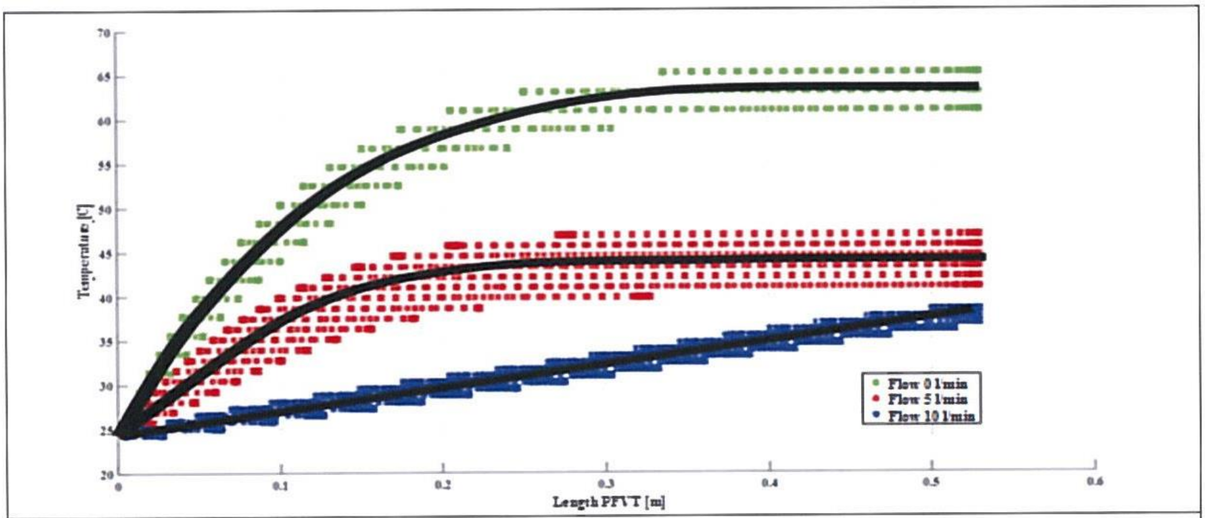


**Fig. 3.c** Temperature distribution along the PFVT length, for different flow rates

Fig. 3.c shows the temperature distribution along the PFVT length, for three values of the cooling water flow rates: 0 l/min, 5 l/min and 10 l/min, under an ambient temperature of 30 °C and a solar irradiance of 1000 W/m$^2$.

### 3.2 Performance analysis of a PFVT using Simulink / Simscape

The numerical model of a PFV can be constructed as a series structure of solar cell blocks. The physical model for the numerical simulations presented in this work is the IS4000 PFV, which is composed of 36 polycrystalline cells connected in series.

The numerical model of this 4x9 matrix panel based on the Simscape "Solar Cell" blocks is shown in Fig. 4.a [1]. Each of the nine rows contains four solar cells connected in series, Fig. 4b.

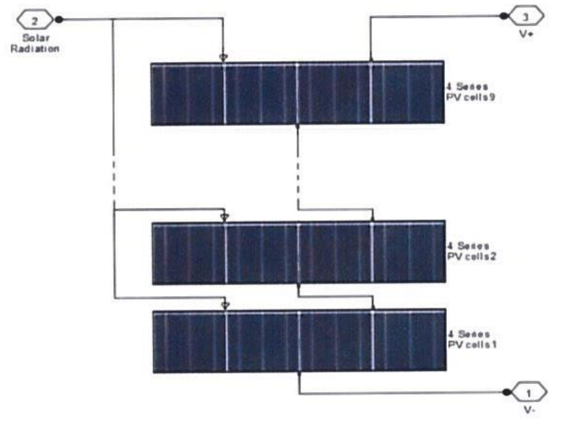


**Fig. 4.a** PFV model 9-lines with 4 solar cells each [1].

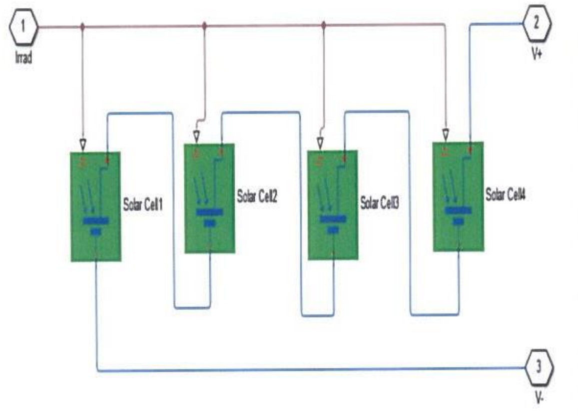


**Fig. 4.b** Details for one of the 9-lines of PFV cells [1].

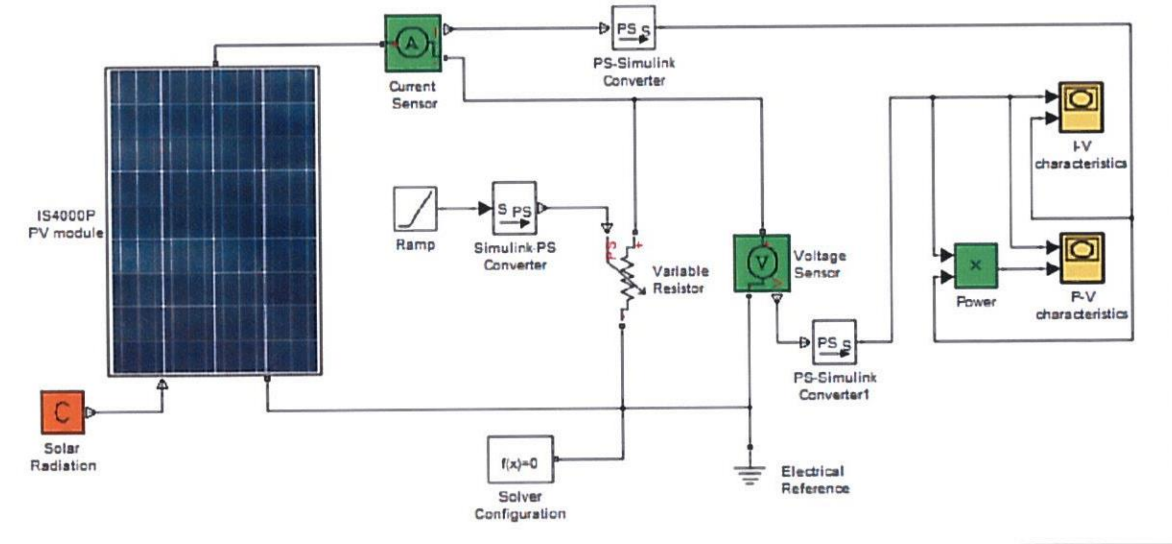


**Fig. 4.c** Diagram used for estimating PFV characteristics [1].

*Experimental results*

In Fig. 5.a the temperature distribution along the PFVT length is presented. This non-uniform heating affects the electric efficiency of PFVT, as shown in fig. 5.b.

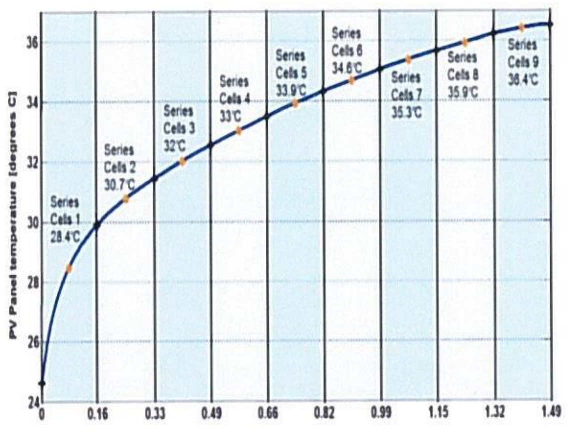


**Fig. 5.a.** Temperature distribution for each of the 9 series cells [1]

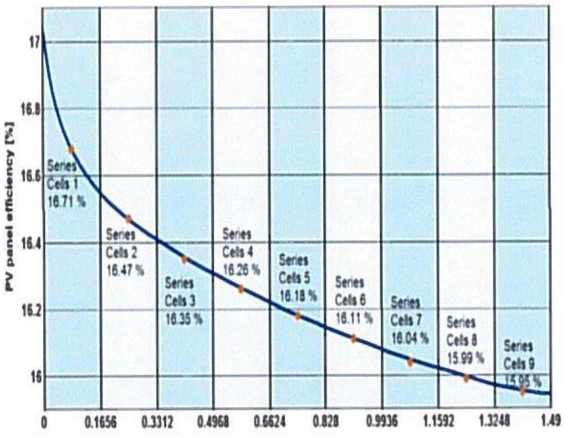


**Fig. 5.b** Efficiency distribution for each of the 9 series cells [1]

The experimental features of PFVT shown in fig. 6.a and 6.b were obtained in the laboratory using a solar simulator. Artificial radiation has a lower intensity, so the short-circuit current and maximum power are considerably lower than the values obtained under real solar radiation conditions.

The numerical results obtained based on the temperature distribution shown in Fig. 5.a are shown in Fig. 6c and 6d. The shapes of the curves are quite similar, the short-circuit current is almost the same, and the maximum power is lower in the simulation than in the experiment (40.5 W vs. 47.5 W). This difference decreases if we use a model with variable parameters for solar cells along PFV (42 W vs. 47.5 W) [1].

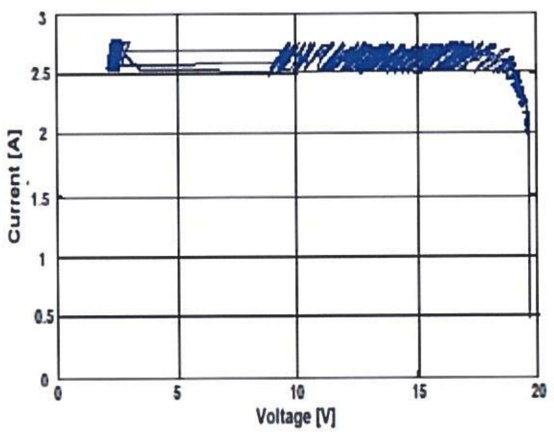


**Fig. 6.a** Experimental I-V characteristics of PFV [1]

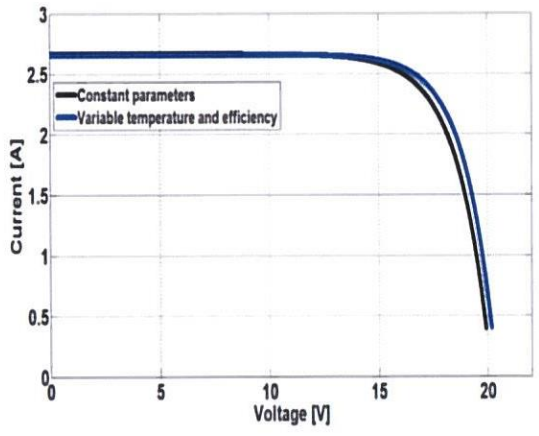


**Fig. 6.b** Simulated I-V characteristics of PFV [1].

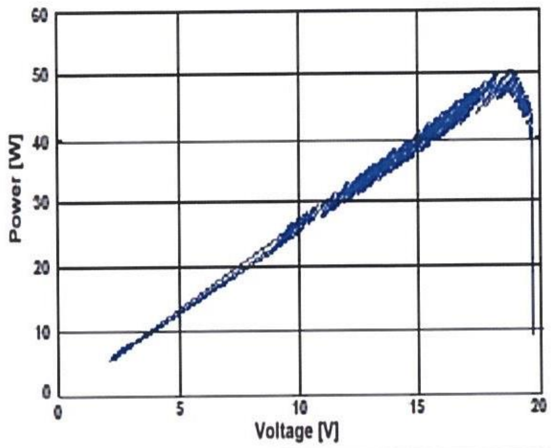


**Fig. 6.c** Experimental P-V characteristics of PFV [1]

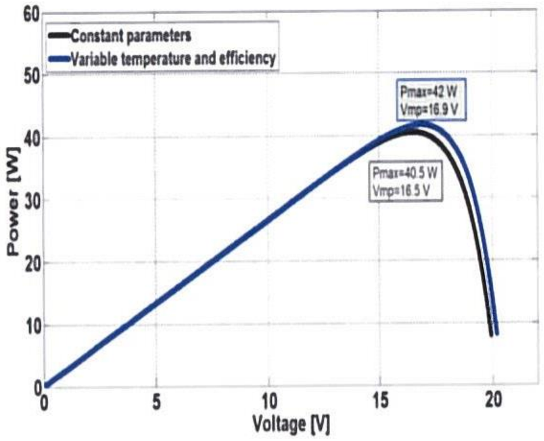


**Fig. 6.d** Simulated P-V characteristics of PFV [1].

## Chapter 4. Experimental model of a PFVT with water cooled radiator with baffles

*How the experimental model works. Water-cooled PFVT using a radiator with baffles.*

The PFVT exposed to the Sun captures the solar radiation and converts it into electricity, the energy being stored into a battery using a charging regulator. Due to the sunlight exposure of the PFVT it is heated and the heat is captured by the radiator which is water-cooled by means of a pump that is intermittently turned-on by a controller. The controller can be programmed so as to turn off or on the power supply for a certain period of time. A voltage dimmer was used to adjust the pump flow rate. The temperature sensors will collect data from the upper surface of the PFVT and from the radiator outlet. The cooling system consists in:

- PFV type YSP-20M
- Aluminum water-cooled radiator with honeycomb structure with the following dimensions: Db = 500 * 270 * 10 mm with wall thickness Gbp = 1mm
- Submersible pump (12 Vdc)
- Battery with rated voltage 12V and capacity of 7Ah
- EPsolar LS2024B battery charger
- Water containers
- Soft data collection “Solar Station Monitor”
- Temperature sensor for PC

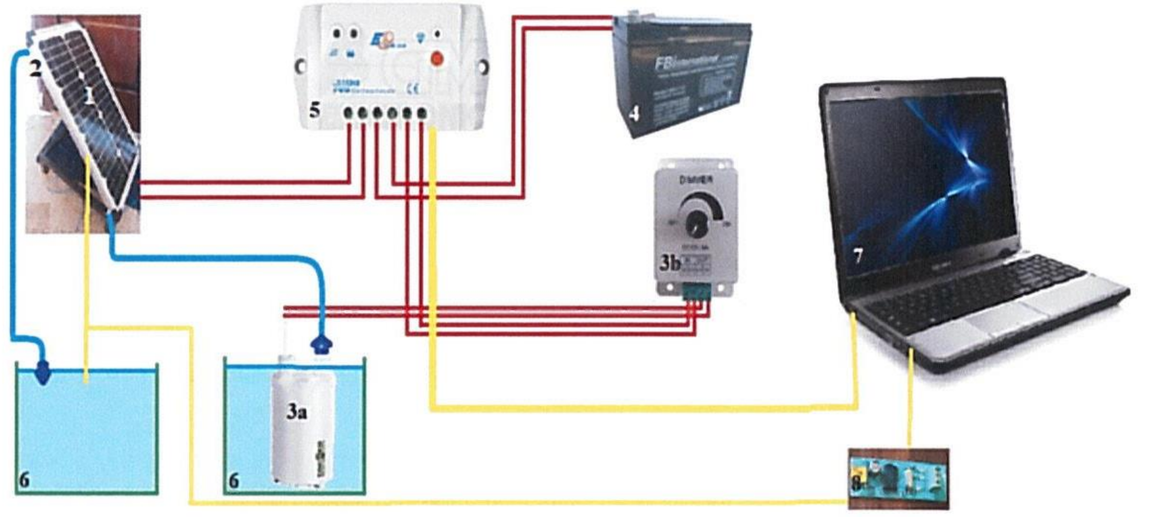


**Fig. 7** Diagram of the experimental setup (1- PFVT, 2 - radiator, 3a - submersible pump, 3b - voltage regulator, 4 - battery, 5 - battery charge regulator, 6 - water containers, 7 - calculation unit)

*Experimental results*

The first set of measurements was obtained for a PFV without cooling system, on 13.06.2015 between 13:16 - 13:36, the values of solar radiation between 874 - 905 W/m$^2$, the ambient temperature between 34.5 - 35.2$^0$C, and the temperature of the PFV in the range 46.8 - 58.7 $^0$C.

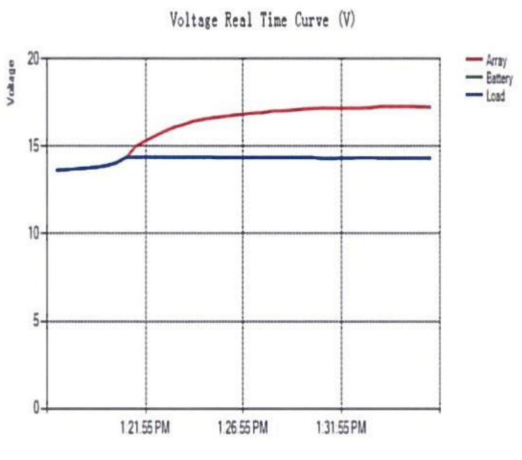


**Fig. 8.a** Time variation of PFV voltage.

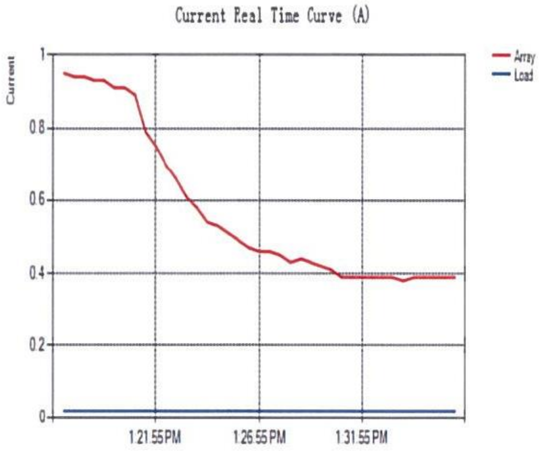


**Fig. 8.b** Time variation of PFV current.

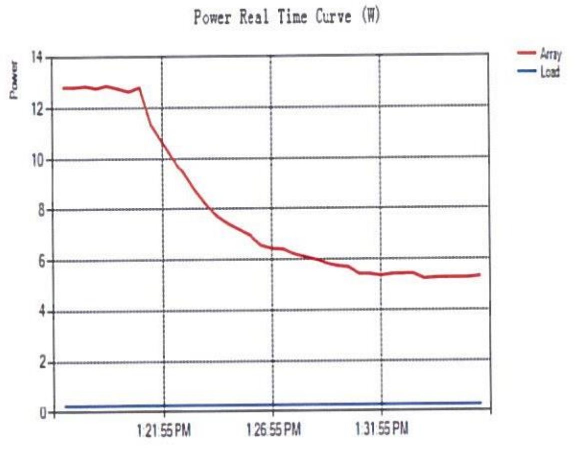


**Fig. 8.c** Time variation of PFV electric power.

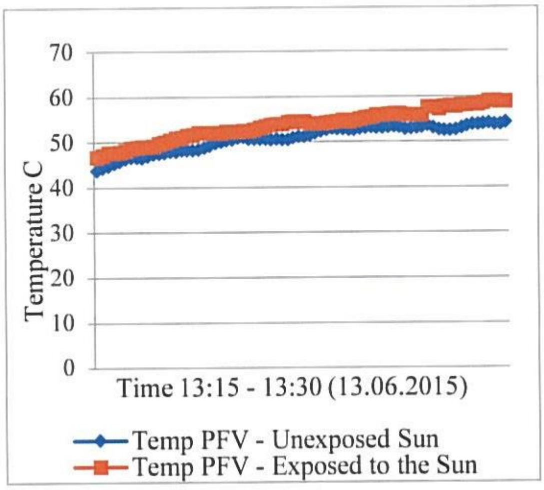


**Fig. 8.d** Time variation of PFV temperature.

The second set of measurements was obtained for a PFV equipped with cooling system, the recordings being made on 14.06.2015 between 14: 11-14: 38. In the considered time interval the values of the solar radiation were between 852 and 705 W/m$^2$, the ambient temperature varied between 36.9 and 37.2$^0$C, the temperature of the PFVT module on the top varied in the range 52.1 - 45.4$^0$C, and the temperature of the PFVT module on the lower part (cooling radiator) is in the range 50.2 - 33.7$^0$C. The PFV equipped with a cooling system was allowed to heat until the supplied current stabilized, after which water was pumped into the radiator. It can be seen that when starting the pump to cool the PFVT, the power provided by the panel increases and begins to decrease when the pump is switched off. If the pump starts up, the temperature on the bottom drops very close to the water temperature at the outlet, the temperature on the top exposed to the Sun drops slightly, due to the direct exposure to the Sun.

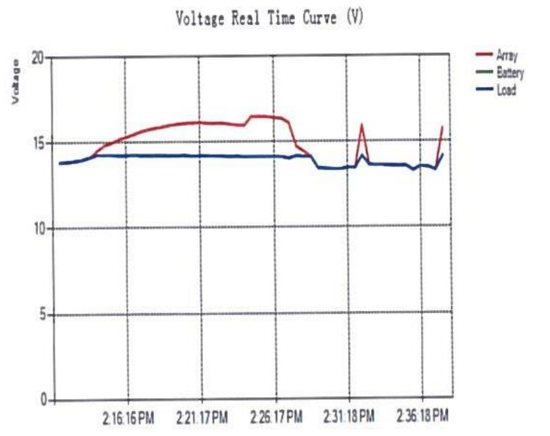


**Fig. 9.a** Time variation of PFVT voltage.

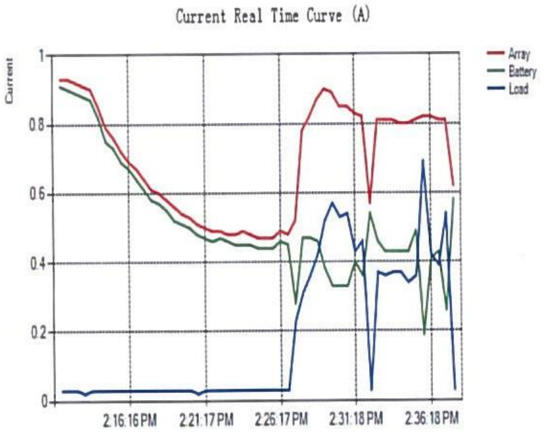


**Fig. 9.b** Time variation of PFVT current.

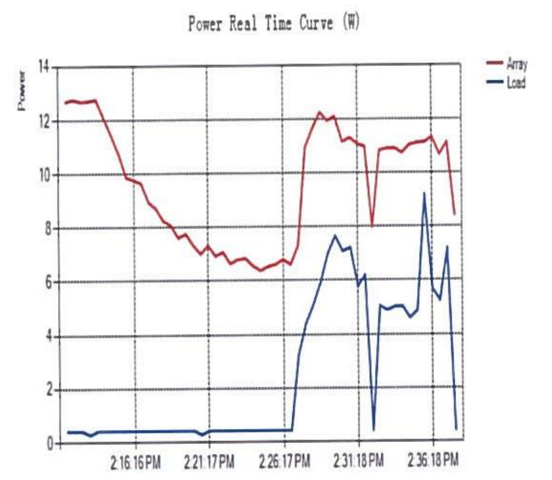


Fig. 9.c Time variation of PFVT electric power.

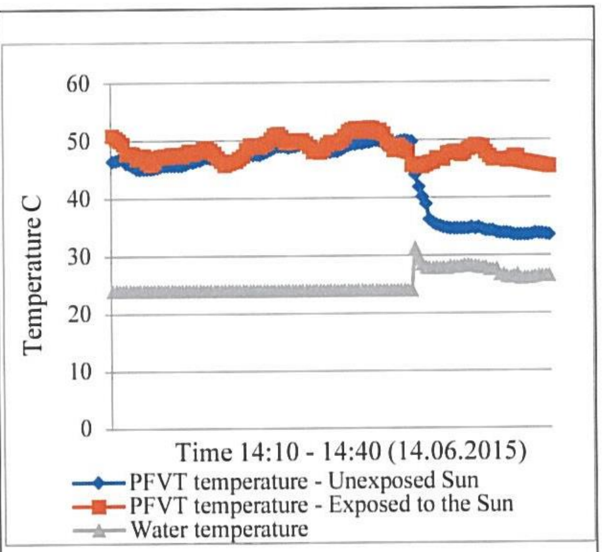


**Fig. 9.d** Time variation of PFVT temperature.

## Chapter 5. PFVT with water-cooled radiator and N-S oriented mirrors

PFVT is used for the conversion of solar energy into electricity and heat, with a net global output superior to classical PFV. The PFVT performance is improved by the addition of mirrors, properly sized and oriented, capable of contributing to the increase of solar irradiance on the PFVT surface [14].

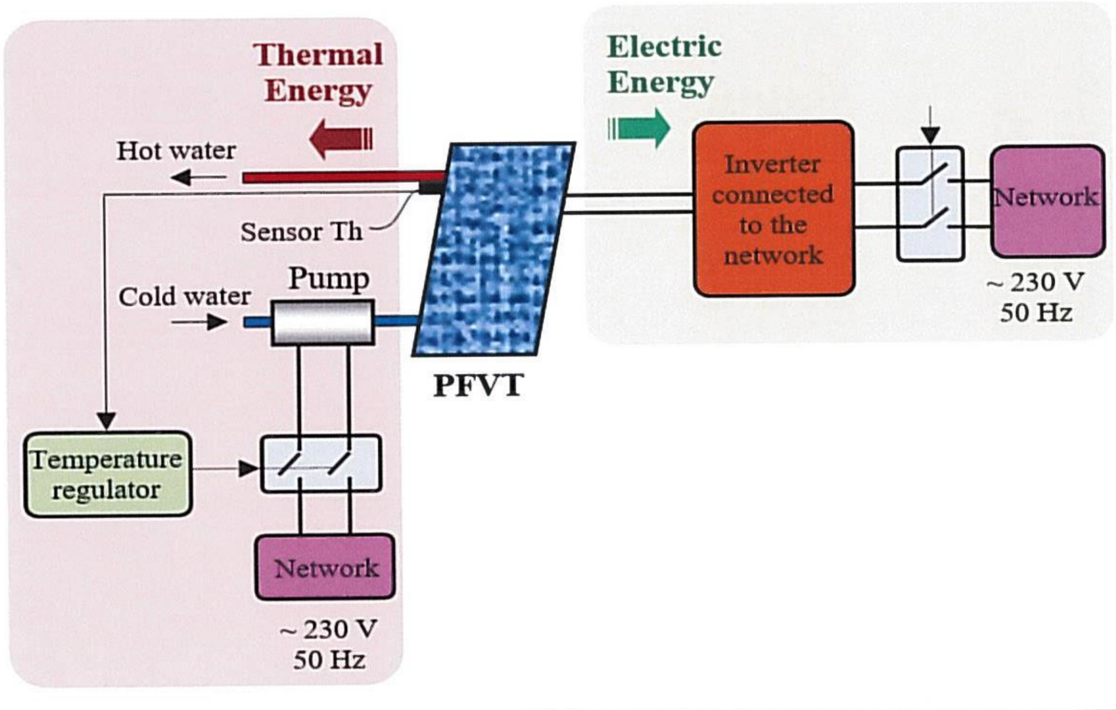


**Fig. 10** Principle diagram of the energy management system of PFVT [14].

*How PFVT works:*

The PFVT receives energy from the Sun directly and through the reflection of the mirrors, this energy being transformed into electrical and thermal energy Fig.10. The electricity generated by the PFVT will be injected by the inverter to the grid, the inverter converting the DC voltage into AC. The thermal energy will be recuperated by a distilled water cooled pipe system in contact with the back of the PFVT. A pump controlled by a temperature regulator will ensure the circulation of the cooling agent through the pipes. The pump on and off regime depends on the minimum and maximum thresholds values at which a contactor closes or open the supply circuit.

*PFVT electricity management.* In order to connect the PFVT to the network it is necessary to have a synchronization inverter with the network that converts the DC power produced by the panel into AC power with the parameters (voltage, frequency) compatible with those of the network [14].

*PFVT thermal energy management.* The thermal energy produced by the PFVT is managed by means of a specialized controller that monitors the temperature of the working fluid at the exit of the thermal circuit of the PFVT and which, depending on its value, gives control of starting or stopping a pump that injects thermal agent, in cold state, into the thermal circuit of the PFV. If the temperature of the thermal agent exceeds a required upper threshold, the pump is fed and injects the thermal agent in cold state into the pipes, the hot water being evacuated from the pipes. When the outlet water temperature drops below a lower threshold, the pump supply is disconnected. The operating times of the pump, respectively the average flow of the thermal agent, depend practically on the temperature of the working fluid [14].

**Fig. 11** Experimental model of PFVT equipped with solar concentration elements

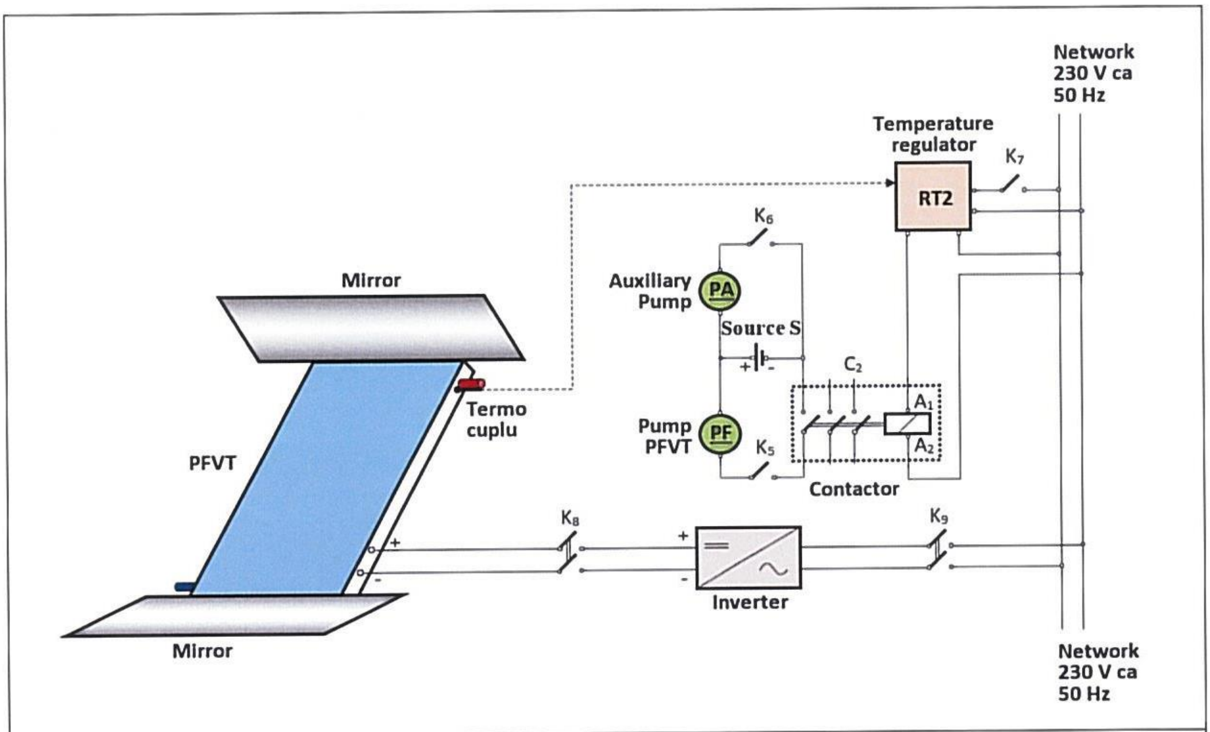


**Fig. 12** Electrical diagram of the PFVT system [14]

*Components of the PVT system*

This system consists of:

- PFVT of peak power 300 W
- PFVT connection inverter
- Temperature regulator
- Control, protection and switching equipment
- 12 V voltage source for submersible pump power supply
- Submersible pump
- Thermal energy meter

*Experimental results*

In Fig. 13 and 14 are shown the current - voltage and power - voltage characteristics of the PFVT equipped with mirrors (2 mirrors, each of 1.32 m2 = 0.8 mx 1.65 m), compared to the graphs obtained for PFVT without mirrors. It is observed that under similar weather conditions, the electric power provided by the panel equipped with mirrors is higher than that generated by a normal PFV. For these measurements, the cooling system of the solar PFVT was not supplied. The additional power supply of the mirrors at the optimum operating point is about 20% [14].

The measurements were made under the PNIII Program - BRIDEGE GRANT 68BG / 2016, Project Title "Power system based on the conversion of solar and wind energy". It should be noted that the measurements were made in March, for a certain position of the PFVT and of the mirrors in relation to the position of the Sun, respectively for certain weather conditions (atmospheric temperature Ta ≈ 17 ºC, solar irradiance G ≈ 920 W / m2). If the measurements would be repeated under other weather conditions or for other relative panel positions - Sun, the results may be different.

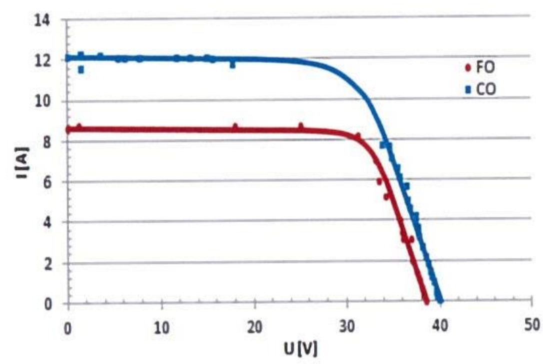


**Fig. 13** Current - voltage characteristic of PFVT with mirrors (CO) and without mirrors (FO) [14].

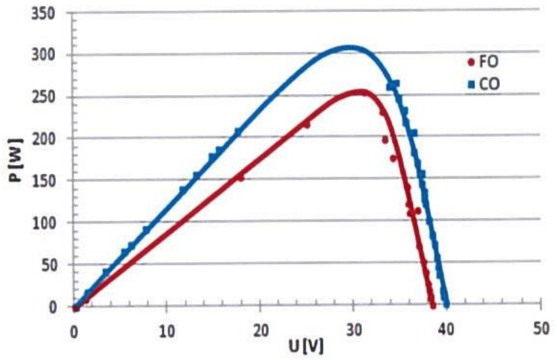


**Fig. 14** Power-voltage characteristic of PFVT with mirrors (CO) and without mirrors (FO) [14].

## Chapter 6. Experimental model of a water-cooled PFVT with E-W mirrors assisted by Arduino system

The experimental model is composed of a PFV equipped with E-W oriented concentrators (mirrors), with a cooling system and a data acquisition and control system based on the Arduino platform. Such a configuration significantly improves the PFV efficiency due to the sunlight reflection from the mirrors [8].

*How the system works*

The solar energy received directly by the PFV or through the mirrors will be converted into electrical energy as well as thermal energy and the electricity will be stored into a battery via a charge controller. As the charging regulator will change voltage and current parameters, their measurements will be made using the Arduino sensors (voltage divider and current sensor). Through the reflection of the mirrors the solar radiation received by the panel will increase significantly as well as the panel temperature. The thermal energy will be recuperated by a cooling agent (in this case, water) that will circulate through a honeycomb radiator mounted on the back of the PFV. The submersible pump will ensure the circulation of the cooling agent and it is controlled by the Arduino software based on the data received from the DS18B20 temperature sensor from the radiator exit, the on and off regimes being initiated when the minimum and maximum threshold temperature values are reached [8].

The other sensors will be used to monitor the temperatures at the radiator entrance, on the top and bottom of the PFVT and the photo-resistor will send a signal to the Arduino platform to connect the consumer at night.

The components of the experimental model are the following:

1. Arduino components:

- Arduino software;
- Development board;
- DS18B20 temperature sensor;
- PT100 temperature sensor;
- MAX31865 amplifier module;
- MicroSD Card Shield;
- Photo-resistor;
- 5V auxiliary battery for powering the Arduino module;
- 24V / 5V DC voltage divider;
- Current Sensor Module;
- YF-S201 flowmeter (1 - 30 l / min);
- Relays for pump supply respectively 12V consumer;

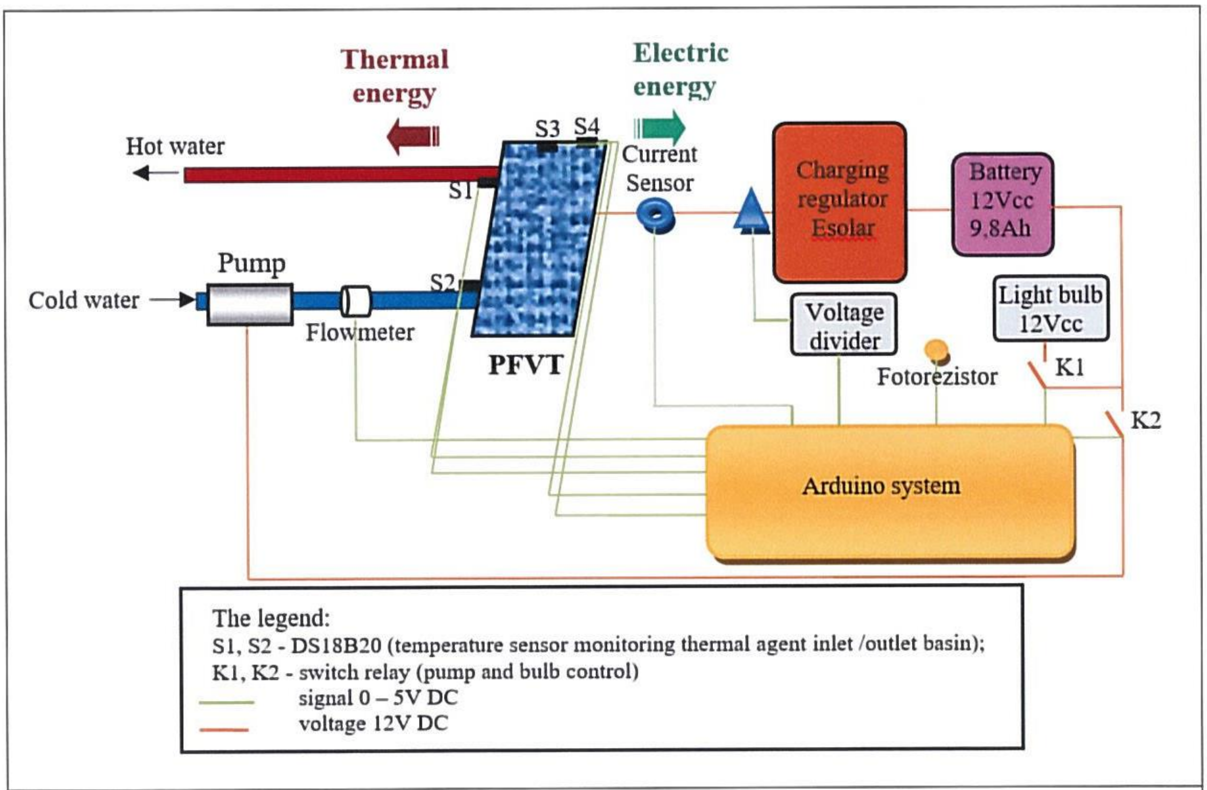


**Fig. 15** Principle diagram of the energy management system

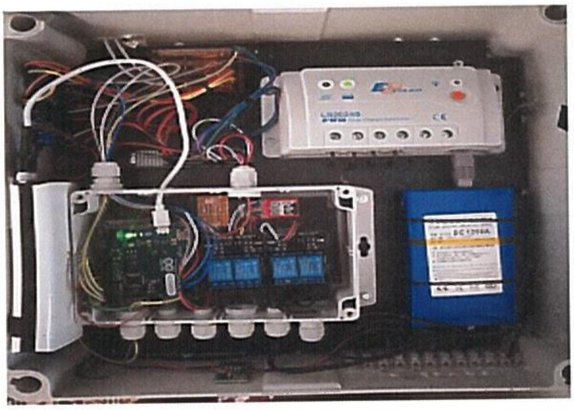


**Fig. 16.a** Control and data acquisition system [8].

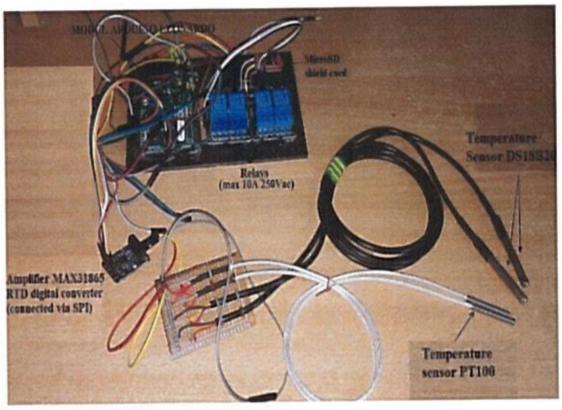


**Fig. 16.b** Connection of equipment components [8].

2. Photo-Voltaic-Thermal Panel (PFVT)

- PFV 20W- type YSP-20M (table 1) equipped with 2 mirrors (530mm * 300mm / pcs);
- Stainless steel tank for water glued on the back of the PFV separated by a heat-conducting paste. Dimensions of tank Db = 500 * 270 * 17 mm with a thickness of 1mm;
- Submersible pump (12 Vdc);
- Lithium-ion battery 12V 9, 8Ah;
- Battery Charger Controller EPsolar LS2024B;
- 2 water vessels;

**Fig. 17** PFVT with mirrors [8]

*Experimental results*

The following results presented in Fig. 18-19 are obtained by experimental measurements made using the Arduino system. Parameters that influence the output of PFV:

- the ambient temperature at the time of measurements 28-31$^0$C;
- 705-922W / m$^2$ solar radiation;

The PFV was equipped with a water tank as cooling radiator, with a pump that is turned on when the upper temperature exceeds a maximum threshold (40$^0$C) and turned off when a minimum threshold is reached (27$^0$C). It can be seen that when pump is turned on both the temperatures on the PFV surface and the water temperature at the radiator outlet decrease while the produced electric power increases.

According to Fig. 18 and 19, at 14:05, the PFVT is exposed to the Sun and at 14:10 the data collection begins. The temperature on the upper surface of the PFVT increases rapidly and at 14:55, it reaches 83$^0$C, and the solar radiation decreases due to the clouds, also influencing the PFVT temperature.

At 3:05 pm, the water temperature in the cooling tank reaches 40$^0$C, at which point the pump starts to push the hot water out and when the water temperature at the radiator outlet reaches 27$^0$C, the pump stops.

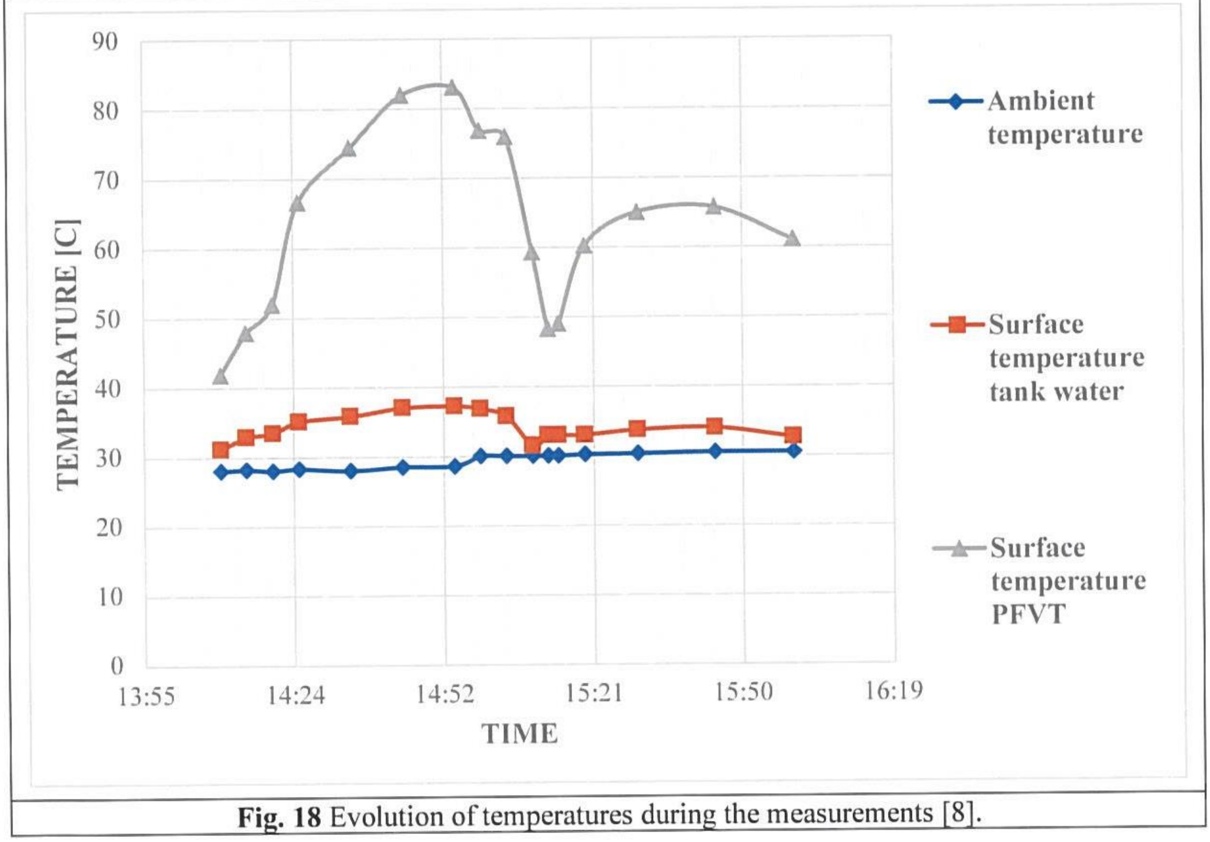


**Fig. 18** Evolution of temperatures during the measurements [8].

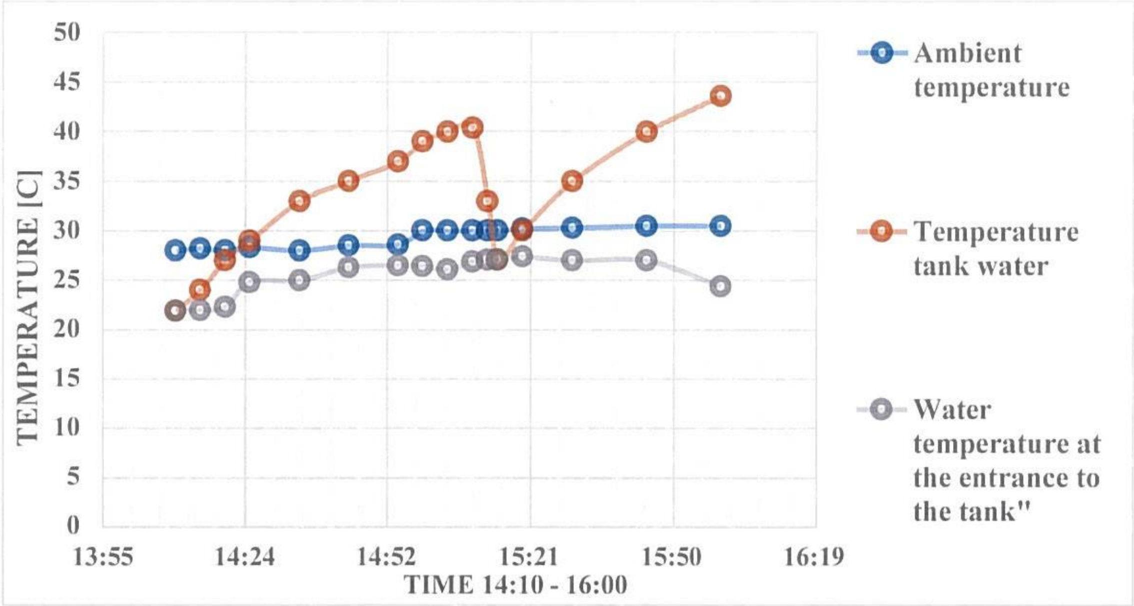


**Fig. 19** Evolution of water temperatures at the inlet and outlet of the basin / radiator [8].

In Fig. 20 we can see that due to the radiation amplified by the mirrors the current produced by the PFVT is 1.4 A higher than the rated value of a classical PFV (0.95A) under the same conditions.

The measurements were made in August, for a certain position of the PFVT and of the mirrors with respect to the Sun position, respectively for certain weather conditions (atmospheric temperature Ta ≈ 29 °C, solar irradiance G ≈ 770 W / m$^2$). If the measurements are repeated under other weather conditions or for other PFVT positions, the results may be different.

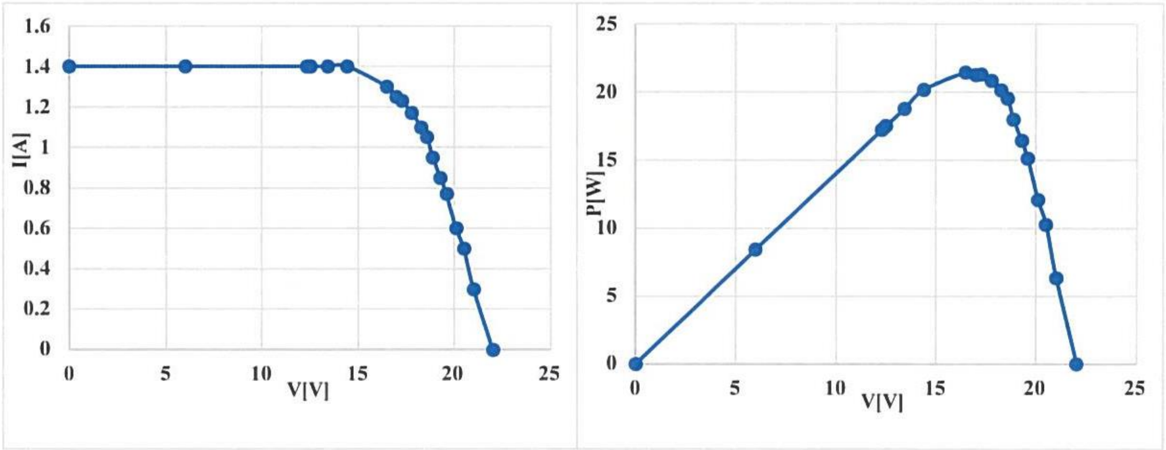


**Fig. 20** Characteristics P = f (V) and I = f (V) for the studied PFVT [8].

## Chapter 7. Comparisons between the experimental models

### 7.1 PFV of rated power of 20Wp

The first experiment was carried out using a 20Wp PFV in three phases:

- In the first phase the study refers to a simple PFV without any other form of efficiency improvement;
- In the second phase a radiator was mounted on the back of the PFV having the shape of a basin with baffles through which the water used as a cooling agent passes from the bottom upwards cooling the back of the PFV;
- In the third phase two mirrors were mounted on the sides of the PFV (EW oriented) having the same size as the PFV and a cooling system being equipped with a controller and data recording system based on Anduino platform;

Fig. 21 shows the characteristics regarding the evolution of the electric power produced by the PFV in the 3 phases analyzed as follows:

- *PFVT panel equipped with mirrors and cooling system.* From min. 14:10 - 14:15 the adjustment of the mirrors takes place, the panel reaching an output power of 20,1 W (for G = 852W/m$^2$, T = 30 °C). A decrease of the electrical power due to the PFV heating follows. At 3:05 pm, the submersible pump starts and cools the PFV until the outlet water temperature reaches 27 °C, another heating cycle follows (15:10 - 15:20) and then a cooling cycle. It can be observed that due to the mirrors the electric power produced at min. (15:05) is about 35% higher than in the other cases. If in the first part of the exposure to sunlight the slope of the electric power decrease is the same as in the other cases, after the first PFV cycle it heats up much faster and needs cooling.
- *PFVT equipped with cooling system.* In this case the heating of the assembly (14:10 - 14:25) is a little slower, the temperature of the assembly begins to increase and the electric power decreases until 15:05 when the pump is started manually and after 8 min. is stopped. Compared to the first case with mirrors, the heating is slower and the electric power is lower.
- *PFV without cooling system.* The power characteristic in this case is on a downward slope and at 15:20 it stabilizes.

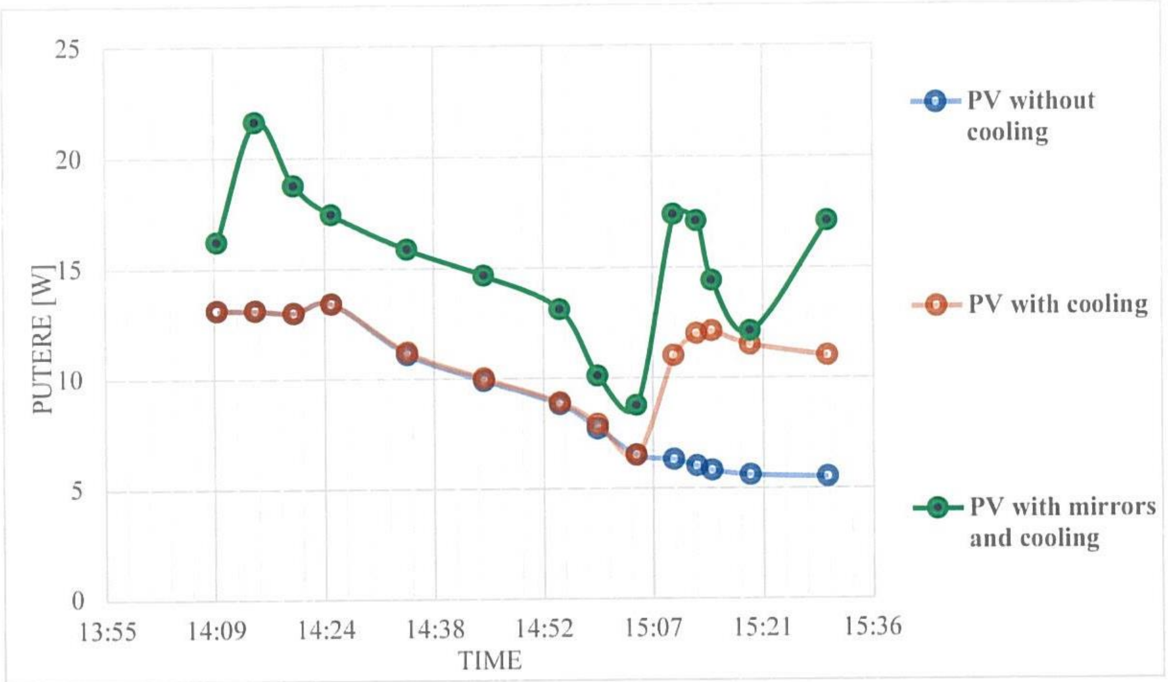


**Fig. 21** The evolution of the power characteristic for the three panel types analyzed

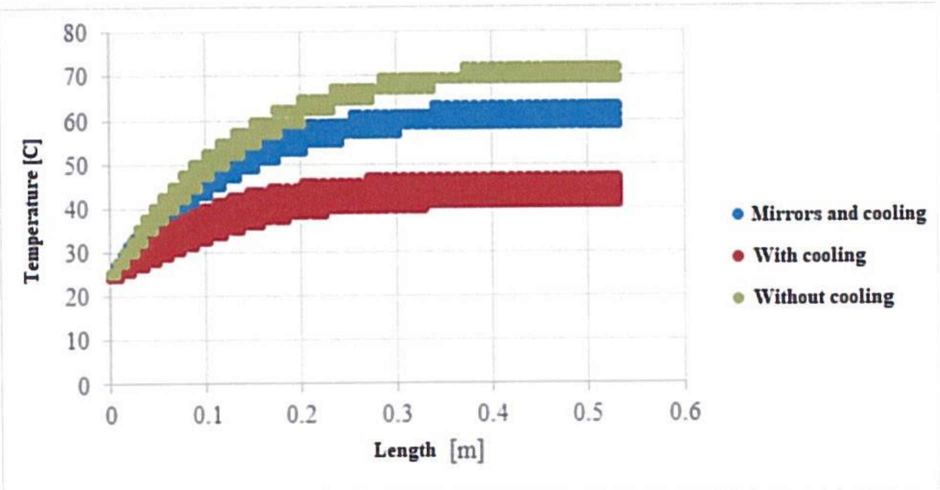
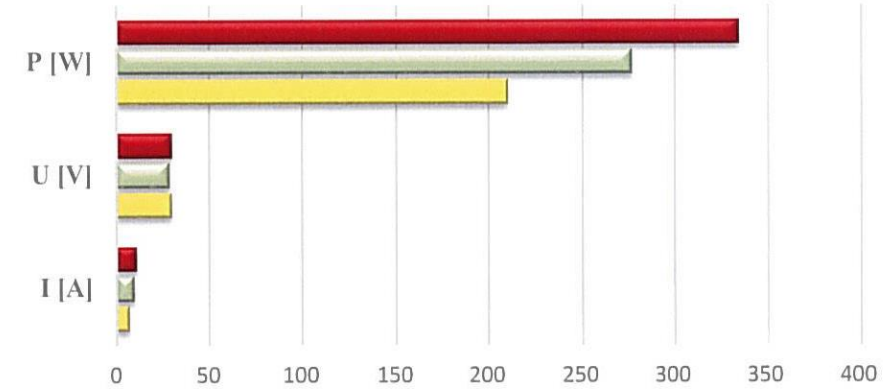


**Fig. 22** Temperature evolution along the solar panels.

### 7.2 PFVT of rated electric power 300Wp

The second experiment consists of a PFV panel equipped with thermal stabilization and heat recovery system respectively with solar plane concentrators. The experiment was conducted under the PNIII Program - BRIDEGE GRANT 68BG / 2016, Project Title – "Power system based on the conversion of solar and wind energy".

In Fig. 23 we can see the effect of the mirrors but also of the cooling system on the PFVT operation. So when mounting the mirrors, the electric output power increases by 31% and when the pump is turned on (cooling the panel) the electric power increases with 60%. The measurements were made in February at a temperature of $17^0$C and a radiation of $G \approx 920$ W/m$^2$, the influence of the heat being very small.



| | I [A] | U [V] | P [W] |
|---|---|---|---|
| 🟥 PFV - mirrors and cooling | 11.07 | 30.159 | 333.86013 |
| ▨ PFV - with mirrors | 9.65 | 28.67 | 276.6655 |
| 🟨 PFV | 7.09 | 29.594 | 209.82146 |

**Fig. 23** Electric quantity values at the maximum power point

Although the measurements were made in a cold period, the heat input is constant. As the ambient temperature rises, the electrical energy decreases, as a result of the PV cells heating. The share of the thermal energy in the total balance can be much more important than the electric energy during the summer. In the winter, the two types of energies produced by the panel could be approximately equal in certain periods.

### 7.3 The efficiency comparison between the studied types of solar panels

The efficiency of PFVT equipped with mirrors and cooling system was determined using the calculation relation below:

$$\eta_{PFVTO} = 100 \cdot (P_{el} + P_{th})/(P_S + P_p) \qquad (1)$$

where: $P_{el}$ is the active power produced by PFVT, $P_{th}$ is the thermal power of PFVT, $P_p$ is the power absorbed by the pumping system, $P_S$ is the total power received from the Sun (including the mirrors surface)

*Efficiency of PFVTO-NS with electric rated power 300W*

The resultant efficiency value of the PFVT equipped with NS oriented mirrors and cooling system will be:

$$\eta_{PFVTO}= 44{,}1\ \% \qquad (2)$$

In case of a classic PFV, without mirrors or cooling system the efficiency will be:

$$\eta_{PFV} = 12.22\ \% \qquad (3)$$

The value of the PFV efficiency only with mirrors was calculated in 2 ways:

a) The power received from the Sun on the mirrors was taken into consideration

$$\eta_{PFVM}= 9.19\% \qquad (4)$$

b) Without taking into account the power received from the Sun on the mirrors

$$\eta_{PFV}= 16.1\% \qquad (5)$$

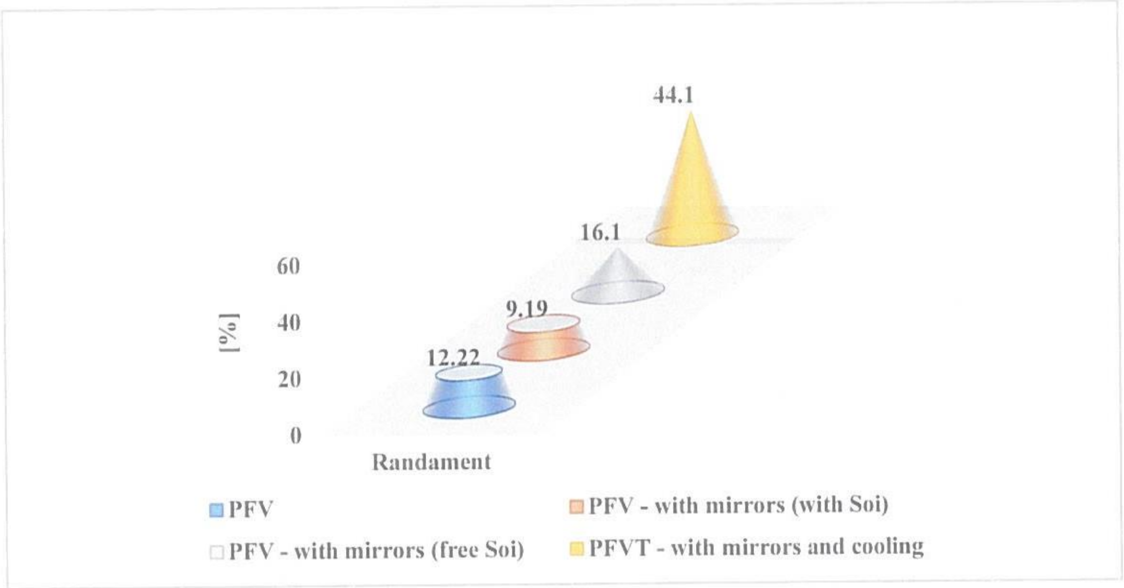


**Fig. 24** Calculated efficiency for each type of solar panel

*Efficiency of PFVTO-EW with rated electric power of 20W*

The experimental measurements made for PFVT equipped with EW oriented mirrors revealed an efficiency:

$$\eta_{PFVTO}= 47.3\ \% \qquad (6)$$

In the same environment a classic PFV has an efficiency:

$$\eta_{PFV}= 8.36\ \%. \qquad (7)$$

In the case of PFVT with cooling system the efficiency will be:

$$\eta_{PFVT} = 33.2\ \%. \qquad (8)$$

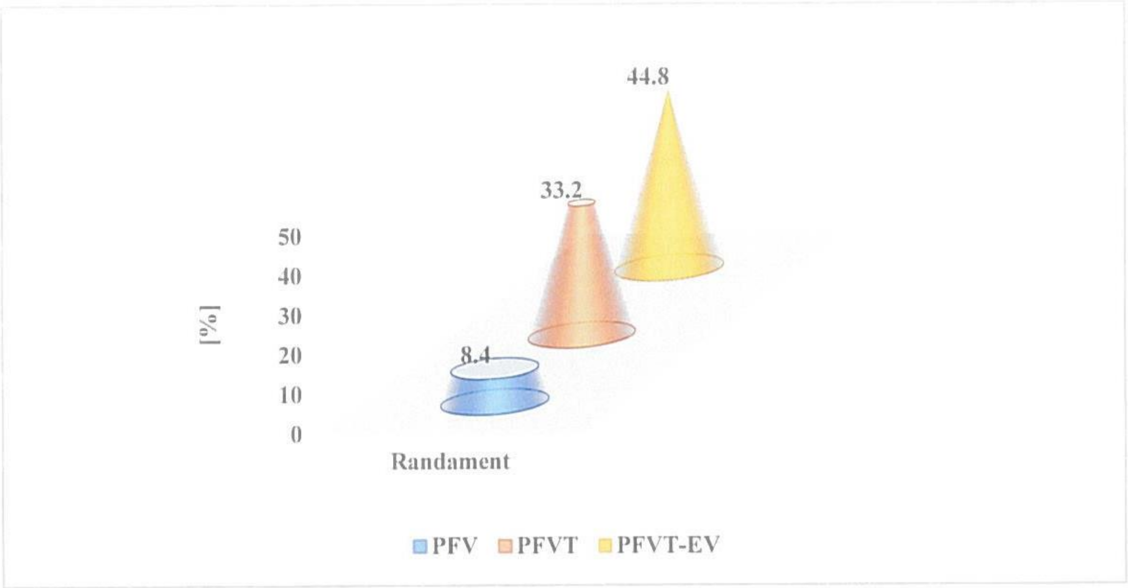


**Fig. 25** Calculated efficiency for various configurations of 20Wp solar panel.

## Conclusions

Based on the experimental measurements and studies, the following conclusions are drawn:

- An increase in the ambient temperature will automatically increase the operating temperature of the PFV which will affect their efficiency;
- The energy produced by a conventional PFV is lower than the energy produced by a water cooled PFVT, the additional energy obtained being greater than the energy required for cooling the panels;
- Water-cooled PFVTs have good potential in providing electricity and hot water for preheating applications;
- The material properties of the heat exchanger influence the PFVT efficiency;
- Inlet water temperature as well as ambient temperature plays an important role in PFVT cooling;
- As a cooling agent, water absorbs more heat than air;
- The thermal energy produced by the water cooled PFVT can be used for domestic hot water and in the case of air-cooled PFVT it can be used for room heating;
- The additional power produced by the mirrors at the optimal operating point for PFVTO - NS is about 20%, and for PFVTO - EW it is about 40%;

## Original contributions

The contributions of the author are the following:

- development of a mathematical model in Comsol that can be used to test several types of photovoltaic panels with cooling system to observe their behavior when changing various parameters (e.g. ambient temperature, solar radiation), as well as to optimize the cooling system by modifying the flow channel, the fluid and its flow;
- implementation of aluminum and stainless steel radiators used for the cooling system of PFV YSP-20M;
- implementation of the mirror support system for the YSP-20M PFVT;
- contribution to the implementation of the Arduino program for system monitoring and automation;
- creation and implementation of the electrical scheme for Arduino implementation;
- carrying out measurements in several stages of the project to improve the conversion efficiency of PFVT and of PFVT with mirrors;
- participation as a research assistant in the PNIII Program - BRIDEGE GRANT 68BG / 2016, Project Title “Power system based on the conversion of solar and wind energies”, at the implementation of the systems and at the experimental measurements;
- conducting various radiation and ambient temperature measurements using the sensors installed in the INFRASOLAR project in ICPE.
- dissemination of the research results obtained during the doctoral program by publishing 7 scientific papers / articles: 5 in IEEE proceedings, 1 in a BDI journal, 1 article being in the review stage for publication in the Scientific Bulletin UPB.
- the published papers were cited 10 times according to the Google Scholar database.

## References

[1] *Valeriu Bostan, **Gabriel Colț**, Tiberiu Tudorache, Sanda Victorinne Paturca, Ionel Bostan* - Analysis of a Photo-Voltaic-Thermal Panel Using Comsol and Simulink/Simscape Tools, The 10th International Symposium on Advanced Topics in Electrical Engineering, Bucharest, România, 2017;

[2] ***Gabriel Colț*** - Performance Evaluation of a PFV Panel by Rear Surface Water Active Cooling, International Conference on Applied and Theoretical Electricity (ICATE), Craiova, România, 2016;

[3] *Valeriu Bostan, Tiberiu Tudorache, **Gabriel Colț*** - Improvement of Solar Radiation Absorption of a PFV Panel Using a Plane Low Concentration System, The 10th International Symposium on Advanced Topics in Electrical Engineering, Bucharest, România, 2017;

[4] *Aurelian Crăciunescu, Claudia Popescu, Mihai Popescu, Marin-Leonard Florea, Elena Drugan and **Gabriel Colț*** - The Analyze of the Dynamic Performances of Two Maximum Power Point Tracking Algorithms for Photovoltaic System, AIP Conference Proceedings 1648:1,*Rhodes*, Greece, 2015;

[5] *A. Crăciunescu, A. M. Croitoru,* ***G. Colț****, C. L. Popescu and M. O. Popescu* - Thermal Experimental Investigation on Air Cooled PFV Panel, International Conference on Renewable Energies and Power Quality (ICREPQ'16), Madrid, Spania, 2016;

[6] *Tiberiu Tudorache, Leonard Melcescu, Valeriu Bostan,* ***Gabriel Colț****, Mihail Popescu, Mihai Predescu* - Electromagnetic Analysis of a Hybrid Permanent Magnet Generator, Revue Roumaine Sciences TechniquesSerie Électrotechnique et Énergetique. Vol. 63, 1, pp. 33–37, Bucharest, România, 2018;

[7] *Tiberiu Tudorache,* ***Gabriel Colț*** - Identifying the Parameters of a Micro-mcc with Permanent Magnets, Symposium on Electric Motors SME'12, Bucharest, România, 2012;

[8] ***Gabriel Colt****, Tiberiu Tudorache,Daniel Zdrentu, Daniela Dragan, Andrei Dragan* - Performance analysis of a PFVT module equipped with solar concentrators and arduino controller, University Politehnica of Bucharest Scientific Bulletin, Bucharest, România, 2020;

[9] ***Gabriel Colt****, Tiberiu Tudorache.* - Modeling of a photovoltaic system for electricity supply to a home - License Project, Faculty of Electrical Engineering, UPB, Bucharest, România, 2010;

[10] *Marcelo Gradella Villalva, J. R. Gazoli, E. Ruppert F.* - Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays, IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198-1208, 2009;

[11] https://www.mathworks.com/help/physmod/elec/ref/solarcell.html

[12] https://www.optimusdigital.ro/ro;

[13] https://www.arduino.cc/en/Main/Software;

[14] PNIII Nr.68BG/2016 - Electrothermal system based on the conversion of solar and wind energy; Bucharest, RO

[15] *Professor Ernesto Gutierrez Miravete*, - Active forced convection photovoltaic/thermal panel efficiency optimization analysis, Rensselaer Polytechnic Institute Hartford, CT April, 2012, pp 17-30;

[16] *Alboteanu Ionel Laurentiu,*- Increase efficiency of stand alone photovoltaic systems by reducing temperature of cells, University of Craiova, Faculty of Electrical Engineering, Craiova, ROMANIA, Annals of the „Constantin Brâncuşi" University of Târgu Jiu, Engineering Series, Issue 3/2011

[17] L. *Dorobanțu, M. O. Popescu, C. L. Popescu, and A. Crăciunescu*, - Experimental Assessment of PFV Panels Front Water Cooling Strategy,International Conference on Renewable Energies and Power Quality (ICREPQ'13) Bilbao (Spain), 20th to 22th March, 2013 Renewable Energy and Power Quality Journal (RE&PQJ) ISSN 2172-038 X, No.11, March 2013;

[18] *Sorin Florică Abagiu*, - Optimization of Power Systems with Photovoltaic Power Plants - PhD Thesis – University Transilvania of Brasov, 2016;

[19] *A.D. Jones and C.P. Underwood*, - A Thermal Model For Photovoltaic Systems, Solar Energy Vol. 70, No. 4, pp. 349–359, Printed in Great Britain, 2001;

[20] National Report 2018 - ANRE;

[21] *T.T. Chow*, - A review on photovoltaic/thermal hybrid solar technology, Applied Energy, 2010, 87: 365–379;

[22] *Douwe W. de Vries*, - Design of a photovoltaic/thermal combi-panel, Eindhoven Technical University, 1998;

[23] *Bergene T, Lovvik OM.*, - Model calculations on a flat-plate solar heat collector with integrated solar cells, Solar Energy, 1995;

[24] *Ing. Ana-Maria CROITORU*, - The analysis of thermal energy exploitation developed by photovoltaic systems, PhD Thesis, Univ. Politehnica of Bucharest, Romania, (2014);

[25] *Ibrahim A, Othman MY, Ruslan MH, Alghoul MA, Yahya M, Zaharim A, et al.*, - Performance of photovoltaic thermal collector (PFVT) with different absorbers design, WSEAS Transactions on Environment and Development, 2009;

[26] *Chow TT, Ji J, He W.*, Photovoltaic thermal collector system for domestic application, Proceedings of Solar World Congress, 2005, ISEC 2005-76128;

[27] *Alfegi MEA, Sopian K, Othman MYH, - Yatim BB.*, Experimental investigation ofsingle pass, double duct photovoltaic thermal (PFV/T) air collector with CPC and fins, American Journal of Applied Sciences, 2008, 5:866–71;

[28] *Alfegi EMA, Sopian K, Othman MYH, Yatim BB.*, The effect of flow rates on the performance of finned single pass, double duct photovoltaic thermal solar air heaters, European Journal of Scientific Research, 2009 25:339–4;

[29] *M. Ebrahim Ali Alfegi, Kamaruzzaman Sopian, Mohd Yusof Hj Othman and Baharudin Bin Yatim,* - Experimental Investigation of Single Pass, Double Duct Photovoltaic Thermal (PFV/T) Air Collector with CPC and Fins, American Journal of Applied Sciences, 2008, 5 (7): 866-871;

[30] *Othman MY, Yatim B, Sopian K, Bakar MNA*, - Double-pass photovoltaic-thermal solar air collector with compound parabolic concentrator and fins, Journal of Energy Engineering, 2006, 132:116–20;

[31] *Jin GL, Ibrahim A, Chean YK, Daghigh R, Ruslan H, Mat S, et al.*,- Evaluation of single-pass photovoltaic-thermal air collector with rectangle tunnel absorber, American Journal of Applied Sciences, 2010, 7:277–82;

[32] *Tsung-Hsi Wu ; Wei-Chen Liu ; Chin-Sien Moo ; Hung-Liang Cheng ; Yong-Nong Chang*, - "An electric circuit model of photovoltaic panel with power electronic converter", 17th IEEE Workshop on Control and Modeling for Power Electronics (COMPEL), 2016;

[33] *Mohammed S. Ibbini, Shadi Mansi, Mohammad Masadeh, Eid Hajri*, - "Simscape Solar Cells Model Analysis and Design", Conference: Computer Applications in Environmental Sciences and Renewable Energy, Malaysia, 2014;

[34] www.europarl.europa.eu/news/ro/press-room/20181106IPR18315/energie-noi-obiective-ambitioase-pentru-regenerabile-si-eficienta-energetica

[35] https://www.analog.com/media/en/technical-documentation/application-notes/AN709_0.pdf