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Energy Efficient Photovoltaic Systems using Thermoelectric Cooling System

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Abstract—Dual thermoelectric-photovoltaic (TE-PV) systems are a type of solar energy technology that combines two different technologies to generate electricity by concentrating solar radiation. These systems use a solar concentrator to focus sunlight onto a photovoltaic cell and a thermoelectric generator. The aim of this paper is to develop a dual thermoelectric-photovoltaic system with a water-cooled heat sink to generate electricity from concentrated solar radiation through Fresnel lenses.In addition, the detailed design for the components that will be integrated into an experimental prototype of the dual system on a laboratory scale is carried out and its functionality is determined. Finally, its functionality is evaluated and achieved an estimated maximum power of 1.5 Watts.

Keywords-Thermoelectric, Photovoltaic, Electricity, Solar Radiation

I. Introduction

Access to energy sources has been a vital factor for human development throughout its history. Day after day, population growth demands not only greater availability but also diversification of the energy matrix of possible generation sources. The growing need for energy has led the UN to declare power generation from non-conventional renewable sources as a sustainable development goal [1-6]. The foregoing is based on the continued depletion of non-renewable energy sources and the environmental impacts they have caused on natural ecosystems. Except for the production of geothermal energy, renewable energy generation systems are sourced from solar radiation. Currently, the development and installation of new generation systems based on photovoltaic panels is booming; Likewise, thermoelectric generation systems that concentrate solar radiation, with parabolic mirrors, on fluids that, when evaporated, drive turbines to produce electric current. In addition, the use of Peltier modules, based on thermoelectric semiconductors, to produce electrical energy from a temperature gradient is known. However, there are few reports on the combined use of Peltier modules with solar concentrators to produce electricity. Among these few experiences, a degree work carried out at the EIA University in 2015 has been found, in which an experimental prototype was built and tested that generated electrical energy by concentrating solar radiation with Fresnel lenses on Peltier cells cooled by radiation towards the surrounding air. Dual thermoelectric-photovoltaic (TE-PV) systems are a type of solar energy technology that combines two different technologies to generate electricity by concentrating solar radiation. These systems use a solar concentrator to focus sunlight onto a photovoltaic cell and a thermoelectric generator [7-12].The photovoltaic cell converts some of the sunlight directly into electricity using semiconducting materials. The thermoelectric generator, on the other hand, generates electricity from temperature differences between two materials. The generator has two dissimilar materials, typically made of different semiconductors or metals, with a temperature difference between them. The heat from the concentrated sunlight is absorbed by one material, causing electrons to flow from one material to the other, generating a voltage and producing electrical power.The combination of these two technologies in dual TE-PV systems has several advantages. Firstly, the photovoltaic cell and the thermoelectric generator can work in tandem to generate electricity more efficiently than either technology alone. Secondly, the use of a solar concentrator allows for the concentration of solar radiation onto the photovoltaic cell and thermoelectric generator, increasing the amount of electricity produced. Finally, dual TE-PV systems are able to generate electricity in both high-temperature and low-light conditions.Photovoltaic technology works by converting the energy from sunlight directly into electricity using semiconducting materials, while thermoelectric technology generates electricity from temperature differences between two materials [13-19]. By combining these two technologies, dual TE-PV systems can generate electricity more efficiently than either technology alone.In a dual TE-PV system, a solar concentrator is used to focus sunlight onto a photovoltaic cell and a thermoelectric generator. The photovoltaic cell converts some of the sunlight directly into electricity, while the thermoelectric generator uses the temperature difference between the hot concentrated sunlight and the cooler surroundings to generate electricity.The advantages of dual TE-PV systems include high efficiency, compactness, and the ability to generate electricity in both high-temperature and low-light conditions. However, these systems are still in the experimental stage and their cost and durability need to be improved before they can be widely adopted as a viable solar energy solution.However, these systems are still in the experimental stage, and there are several challenges to be addressed before they can become commercially viable. One challenge is the cost of the materials used in the thermoelectric generator. The materials used for the generator must be highly efficient and able to withstand high temperatures, which can be expensive. Another challenge is durability, as the system needs to be able to withstand the harsh conditions of prolonged exposure to concentrated sunlight [20].

Despite these challenges, the development of dual TE-PV systems shows great promise for the future of solar energy technology. As research continues, it is hoped that these systems will become more efficient, durable, and cost-effective, making them a viable option for generating electricity from solar radiation.In this work, it is recommended to couple photovoltaic cells on the Peltier cells to produce a dual photovoltaic and thermoelectric generation from the concentration of solar radiation; in addition to implementing a water-cooled heat sink to increase the amount of energy produced during the concentration period [21-23].

II. Literature Review

The system is comprised of a Fresnel lens array that acts as a solar concentrator, Peltier cells for power generation, an air-cooled heat sink that is coupled to the F face of the Peltier cell, and a solar tracking system. all mounted on an aluminum and acrylic base. As a result, it was possible to generate 8.16W per day. Therefore, as a conclusion, it was obtained that in quantitative terms of electric power generation, a photovoltaic cell is much better than a Peltier cell, but the recommendation is made for possible future work such as carrying out a redesign of the system taking advantage of a larger area in a passive, a collection of thermal energy that is wasted in industrial processes or an implementation of Peltier cells in a hybrid system where photovoltaic panels and vacuum tube solar panels are integrated [24].

The study theoretically analyzes the performance of combined hybrid systems of Bismuth-Tellurium (Bi2Te3) and Lead-Tellurium (PbTe) thermoelectric generation with photovoltaic (PV) solar panels crystalline silicon (c-Si), amorphous silicon (a- Si), Cadmium-Tellurium (CdTe), and Copper-Indium-Gallium-Selenium (CIGS), with results showing that the characteristic drop in efficiency of c-Si, CdTe, and CIGS PV panels affects the efficiency of the system, since the rate of change with which the efficiency of the thermoelectric generator (TEG) increases when the temperature increases, is unable to compensate the drop in efficiency of the PV panels. The only exception turns out to be the a-Si panel, whose efficiency drop is adequately compensated by the TEG for the coupled system, so it is concluded that the difference between the optimal operating temperatures of both devices prevents the viability of a system that couples a BiTe and PbTe TEG to the PV c-Si, CIGS, and CdTe panels since it does not increase its generation. They propose as future work to explore new materials that have optimal operating conditions in the temperature range in which the photovoltaic system is also optimal [25].

In this article, he analyzes the viability of the production of thermoelectric-photovoltaic energy (PV-TE) analyzing the efficiency of the different configurations that can be made with these two technologies, presenting a circuit to add the two voltages of the photovoltaic and thermoelectric cell without present conflict with each other, in addition, the types of cells that can be obtained in the market with their performance are reviewed, and finally the most optimal cooling method was studied in which it allows to have a wider temperature gradient between the two faces of the thermoelectric cell. As results, it was obtained that nanofluids as an alternative cooling medium presents a better performance compared to water, in addition it was obtained that the nanostructure could significantly improve the efficiency of the PVTE system. Finally, this article concludes that the hybrid solar system is positioned to potentially play a large role in contributing to global efforts for energy conservation and pollution reduction [26].

In this article, a photovoltaic-thermoelectric system is developed with an integrated hot mirror that allows a shorter wavelength to be transmitted to the photovoltaic module, and a longer one to the thermoelectric module. In the development of this system, artificial suns were used, in which light bulbs were used as an irradiation source located in the upper part of the system and the different lights (xenon, halogen and incandescent) were analyzed, demonstrating that the incandescent bulb provides the highest radiation. heat radiation of 54.76 W. nm and the lowest heat radiation is 25.65 W. nm by halogen before the hot mirror. After passing through the hot mirror, xenon light emits the highest visible light spectrum of about 479 nm, while halogen in the 800 nm range releases near-infrared, which is most needed by TEG [27].

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III. Methodology

Initially, a list of mechanical, electronic and heat transfer requirements of the thermoelectric-photovoltaic dual system was built based on the needs and opportunities identified in the background information previously consulted for the realization of the preliminary project.

Consistent with the list of requirements, we proceeded to carry out the black and transparent box schemes in order to understand the operation of the dual system and how the subsystems correlate with each other.

Once the operation of the system was understood, some solution proposals were raised based on the commercially available inputs and products, taking into account their characteristics and limitations to satisfy the needs of each requirement and to finish the design concept, the morphological matrix was made for each requirement. of the system. The alternatives or design options were qualified by means of weighted value scales, the alternatives generated with the solution concepts for the development of the prototype of the dual thermoelectric-photovoltaic system, managing to meet the established needs.

For the assembly of the laboratory, a study is made of the types of light bulbs that are on the market, analyzing which spectrums of sunlight they cover, in order to make use of it.

Carry out the detailed design for the components that will be integrated into an experimental prototype of the dual system on a laboratory scale:

Once the best qualified alternative was selected, the detailed design of the Peltier cell-photovoltaic cell interface was carried out, specifying the process required for a proper coupling between both modules. Subsequent to the design of the interface, the sketch of each mechanical subsystem (base of the system and the Fresnel lens) was made by means of the CAD Inventor three-dimensional modeling graphic software, in which each individual part was created and later an assembly was built. of these, in order to be able to make the plans with their respective measurements, including geometric characteristics and mechanical operation.

To finish the complete design of the dual thermoelectric-photovoltaic system, the electronic circuit that allows the capture of the cell voltages and unite them for a single output was designed. This design was executed through the Proteus software which allowed simulations and connection diagrams of the circuits.

Once the complete development of the detailed design was obtained, the suppliers of the elements and components required to build the experimental prototype were identified.

Once this stage was completed for the dual system and the additional prototypes, the study of the laboratory assembly that allows simulating solar radiation was carried out, to obtain measurements without depending on the state of the weather. For this, a test was carried out, with a photovoltaic cell and a solar concentrator (Fresnel lens) in real conditions at 12 noon where voltage and current data were taken with the help of a multimeter.

Once the data on how the cell behaves in a favorable climate condition was obtained, we proceeded to determine the distance at which the selected light bulb provides radiation similar to that produced by the sun. Taking the distance, we proceed to make the CAD to prepare the plans and their subsequent manufacture.

Build an experimental prototype with your lab setup to determine its functionality.

Having detailed plans for the prototypes and assembly of the solar radiation simulator to be built, we proceed to find suppliers of the using tools provided by metal mechanics at the Palmas headquarters. After the pieces are finished and ready for their assembly to their corresponding subsystem, they begin to assemble piece materials needed. Once the materials are obtained, the parts are manufactured by piece and make small validations to evaluate their integrity and if they have faults.

Evaluate the functionality of the dual system by physically simulating radiation conditions using the laboratory experimental setup to achieve an estimated maximum power of 1.5 Watts.

Having concluded the construction of the prototype of the dual system, the additional prototypes and the assembly of the solar radiation simulator, we proceeded and to locate the assembly in the bioprocess laboratory (this location due to availability of space and occupation in the laboratories) and demarcate the area where it is verified that it is always located in the same area, in the same way demarcate the area where it will be to position the prototype to ensure that all prototypes have the same conditions.

To measure the voltage, a program was developed in LabVIEW, in which it allows saving the graphs for later analysis, and for the current measurement, a 1Ω load is placed and the multimeter is used because the acquisition card It has an operating range of 4-20mA, the current sensors that transduce the current to voltage operate with 3-36V sources and the cells produce less than 3V, to capture the current data with the multimeter, a cell phone was used to record the multimeter screen so that you cannot lose any data when entering the Excel table from which Time vs. Voltage graphs are obtained.

IV. Development of the Dual Thermoelectric-Photovoltaic System

A. *Construction of the list of requirements*

Applying concepts of the Ulrich methodology for the elaboration of the dual thermoelectric-photovoltaic system, the needs identified from the academic background analyzed for the development of this project were taken into account, also

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considering the new needs that arose when linking the two modules with a refrigeration system and a solar concentrator, the technical requirements listed below were met.

- Stable power generation.
- Geometric congruence in the coupling of the modules.
- Simplicity in the installation and maintenance process.
- Adequate heat transfer between the cells and the refrigeration system.
- Greater capture of solar radiation throughout the day.
- Versatile structure.

B. *Concept Design*

Figures 1 and 2 show the black and transparent boxes of the dual system built from the previously informed technical requirements in order to understand its operation, establishing the respective inputs and outputs.

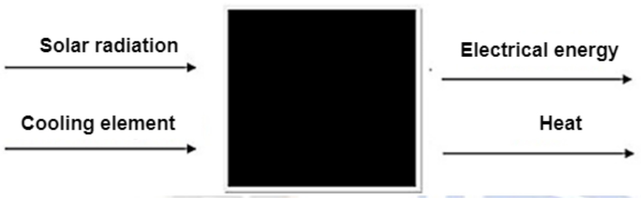

Figure 1. Black Box

The functionality of the dual system is to capture solar radiation and transform it into electrical energy, because this radiation brings with it light and heat, producing a heating of the system, which is why a cooling element is required to regulate the temperature; and thus not affect the efficiency of the components that make this energy transformation possible.

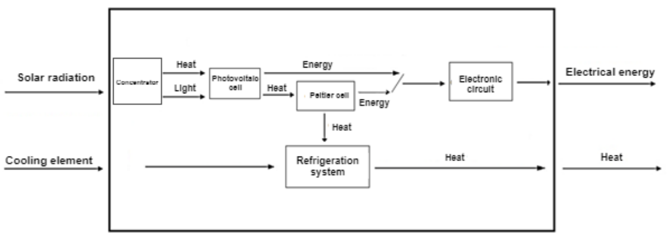

Figure 2. Transparent Box

The transparent box allows inferring the interactions between the elements that constitute each subsystem, because it was possible to observe that solar radiation is concentrated at a specific point by action of a concentrator and this is focused where the photovoltaic cell is located, allowing it to receive more light and heat amplifying the generation of electrical energy, but as a consequence of the high reception of solar radiation, the photovoltaic cell tends to heat up, so the Peltier cell acts as a heat sink and in turn as an energy generator, taking advantage of the heat transferred from the photovoltaic cell, and through a thermal coupling paste, to its hot face.

The thermal gradient that is established between the hot and cold faces of the Peltier cell induces the production of electrical energy that, as time goes by, the cold face heats up and thus loses efficiency. This is where the refrigeration system plays an important role, allowing the temperature of the cold side to be lowered in order to have a higher thermal gradient that leads to greater energy generation.

The energies coming from both cells are added by an electronic circuit for later use or storage in electric batteries.

C. *Solution Proposals*

With the list of requirements created and the details provided by the black and transparent box schemes (Figure 1 and 2), the following critical points were found with their respective solution alternatives to increase the efficiency of the dual system.

1) *Concentration of solar radiation*

In the previously mentioned background, it was possible to observe that concentrating solar radiation at one point increases the amount of light and heat received by the object located there, in this case the photovoltaic cell, so the option of incorporating a radiation concentrator Solar is the most indicated to increase the efficiency and production of electrical energy in the system. There are three alternatives for this system, the first is to concentrate the radiation by means of a parabolic concentrator which would point to a focus located in the center of the parabola, the second option is the cylindrical concentrator that, like the parabolic one, focuses the radiation at a point central cylinder, and finally there is the option of concentrating the sun's rays by means of Fresnel lenses, which receive perpendicular light and focus it on a point below it. The rest of the solar concentrators were not taken into account because the background reflected that these types of concentrators are used when an excessive amount of solar radiation is required, therefore special materials are required to be able to withstand the temperature generated by these hubs.

2) *Coupling of the photovoltaic cell with the Peltier cell*

To allow a good match between the power generating modules, it is required that both have a similar dimension in order to optimize the contact area through which heat is transferred. Because all Peltier cells have an almost standard dimension, photovoltaic cells need to have approximate dimensions of 4cmx4cm, so there are two options, a cell with the approximate dimension, but with low power, or a cell with a significant power but whose dimensions would present an inconvenience when coupling the cells.

3) *Heat transfer*

In order to guarantee the regular flow of heat from the rear face (not exposed to the sun) of the photovoltaic cell towards

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the hot face of the Peltier cell towards the heat sink, it is necessary to incorporate, between contact surfaces, a continuous medium that performs said function. As alternative solutions, there is the thermal pad and thermal paste, which are widely used in the field of microprocessors because they allow a high thermal conductivity between the chip and heatsink .

4) Cooling element

To cool the cold face of the Peltier cell and increase the temperature gradient between its faces, there are three alternatives, the first is to use the air, which cools as it passes through the cooling system heatsink, the second is to use the water that It is at room temperature and when it comes into contact with the heat sink, the temperature of the cold side of the Peltier will also drop. Finally, it is considered to use oil or refrigerants, which, like water, when in contact with the heat sink, will lower the temperature. temperature.

Table 1. Proposals for solutions to the concentration of solar radiation

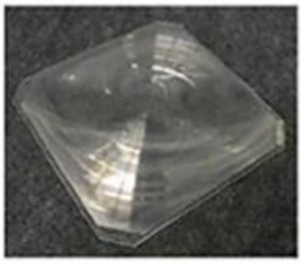
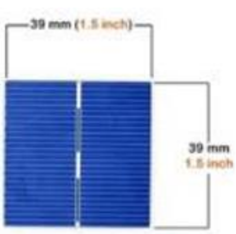
Solution	Definition	Advantages	Disadvantages
	Parabolic Concentrator: Concentrator that has an arrangement of mirrors that reflect sunlight and are aligned towards a target capable of capturing energy	Due to its geometry it allows to take advantage of the radiation from different directions. -Allows temperatures to exceed 400°C.	The mirrors that are used do not fully reflect the sun's rays. -The cold side of the Peltier cell is exposed to sunlight. -Complex maintenance and installation.
	Cylindrical concentrator: Concentrator that by means of mirrors reflects the sun's rays onto the focal line of the parabola.	Allows to reach temperatures above 420°C -Allows to be located in any direction.	Requires use of a solar tracker. -Difficult to incorporate the cooling system that is not by air. -The mirrors that are used do not fully reflect the sun's rays.
	Fresnel lens: Converging lens with a short focal length that has a plane geometry, which makes that the rays that arrive perpendicularly focus them towards a point in the center	It is low in weight and volume. matrix required -Allows the cooling system to be by any element. -Allows temperatures to exceed 400°C	An array made up of several lenses is required. - Being located perpendicular loses solar rays at certain times of the day.

Table 2. Proposed solutions to the coupling of the cells

Solution	Definition	Advantages	Disadvantages
	39mmx39mm polycrystalline photovoltaic cell: Cell capable of transforming photons of light into electrical energy, with an average power of 0.27 Watts, 0.54 Imax, 0.5 V average voltage and an efficiency of 17.8%	It allows a uniform heat transfer to the Peltier cell due to its dimension. -The cell connection line is on the sides so it does not interfere with the coupling with the Peltier.	Low electricity generation.

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	Amorphous silicon solar cell: Solar module with a dimension of 6cmx6cm, which generates a maximum voltage of SV and an amperage of 100mA, so its average power generated is around the solar. 0.5Watts	It generates considerable power. -Greater area for the absorption of solar radiation.	Being larger than the Peltier cell, it will not dissipate heat evenly. -It has glass coverage -The connection line is located in the center of the rear part, so the coupling with the Peltier is more complicated.
	Solar cell 5.5V 90mA: Solar cell with dimensions of 6cm high and 6cm wide that generates a voltage of 5.5V and an amperage of 90mA, its maximum power is 0.495 Watts	It is low in weight and volume. -Larger area for radiation absorption -Higher voltage generation.	Being larger than the Peltier cell, it will not dissipate heat evenly. -Lower current generation.

Table 3. Proposals for solutions to heat transfer

Solution	Definition	Advantages	Disadvantages
	MTG5 thermal paste: It has a high thermal conductivity to improve heat transfer in GPU processors, CPUs with a working range up to 280°C.	-It has no electrical conductivity. -It is not corrosive. -It has a thermal conductivity of 14.3 W/m.k	Having good heat transfer, it can transmit heat to the environment and not directly to the Peltier cell.
	Thermal silicone pad: Pad that has a thermal conductivity of 3.2 W/m.k with a thickness of 1mm	It guarantees a separation between cells of 1mm. -Easy installation	A cut must be made in the pad because its dimension is greater than the cells. -Does not guarantee complete contact on cell surfaces.

Table 4. Proposals for solutions to the cooling element.

Solution	Definition	Advantages	Disadvantages
	Air: Element by which it cools when it circulates through the area of the heatsink.	Designing a space to store the item is not required. --The air is free so no, investment and maintenance are required..	It is weather dependent. --Its ability to lower the temperature is not high, so a fan is required to increase its flow.

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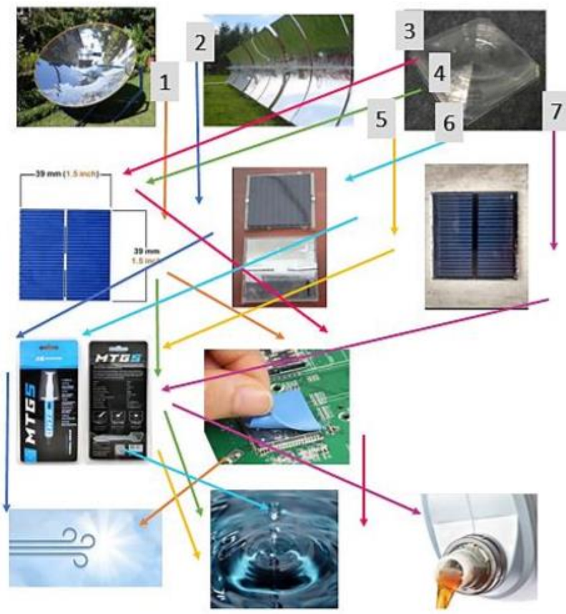
	Water: Element that is in a liquid state that lowers the temperature of the area through which it circulates.	It is free due to the fact that it can be captured from the rain. -It has a high degree of heat dissipation.	It is heated by the ambient temperature. It evaporates if its temperature is high. -Requires a container that is linked to the dual system.
	Oil: Synthetic lubricant ideal for refrigeration use.	It has a high heat absorption capacity. -In a use of medium / low temperatures, a change is not required followed by this.	It is polluting. A special treaty is required when replacing it with a new one. It has a high cost.

D. Generation of product concepts

For the generation of multiple designs of the dual thermoelectric-photovoltaic system using the different solution proposals (Tables 1 to 4), a morphological matrix was built, in which a solution is chosen for each critical point identified, thus obtaining the possible combinations that later mete will be evaluated to select the alternative that best satisfies the needs and technical requirements that, in principle, were raised for the system under study.

As can be seen, Table 5 presents the best solution concepts. Due to the fact that by combining the different alternatives of each critical point the matrix becomes difficult to understand, these seven concepts are represented by numbers and their route is differentiated by colors.

Table 5. Morphological matrix.

Critical point	Solution 1	Solution 2	Solution 3
Concentration of solar radiation			
Coupling of the photovoltaic cell with the Peltier cell			
Heat transfer			
Cooling element			

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[1] Solution concept 1 (orange):

In this concept of solution it is established that the dual system concentrates the solar radiation by means of a parabolic concentrator, this requires that the coupling of the two cells be in the focus of the same, allowing the photovoltaic cell to receive more light by So it generates more energy.

For the coupling, the 39mmx39mm polycrystalline photovoltaic cell is used because its size is equal to the size of most of the Peltier cells found on the market, this allows heat transfer between the cells to be uniform.

To join the cells together and the Peltier cell with the finned heatsink, the thermal silicone pad is used, allowing the union between these elements to be simple.

Air should be used as a cooling element due to its easy flow between the cells.

[2] Solution concept 2 (blue):

The cylindrical concentrator is suitable because it allows high radiation to be achieved in its focus, so the photovoltaic module receives more photons and generates more energy.

The amorphous silicon solar cell is used because it generates more power with respect to the other proposed cells. For heat transfer, the use of thermal paste is more appropriate because the cell surfaces are not totally smooth, so the paste, being fluid, will allow heat to be transmitted on all surfaces.

Because the cells are located in the focus of the concentrator, it is considered pertinent to use the air to cool the cold face of the peltier, since when the wind circulates between the fins of the heatsink it continuously extracts heat from the system.

[3] Solution Concept 3 (magenta):

In this concept, Fresnel lenses were chosen as solar concentrator due to their high capacity to divert solar rays to the specific point where the photovoltaic cell is located.

Like solution concept 1, the 39mmx39mm polycrystalline cell and the thermal silicone pad were selected to provide a solution to the coupling of the cells and the heat transfer that occur in the system, due to its advantages previously described in the first concept. .

For the cooling element that circulates in the finned heat sink, water was chosen, due to its high capacity to dissipate heat; In addition, the risks of environmental contamination that occur when refrigerating with oil are avoided. The use of water is made possible because the Fresnel concentrator allows the two cells to be horizontal and it is easy to attach it to the liquid container.

[4] Solution concept 4 (green):

This solution concept uses the same solution strategies as concept 3 except for heat transfer, as it uses the MTG5 thermal paste instead of the silicone pad to increase contact with the cell surface that is not totally smooth.

[5] Solution concept 5 (yellow):

This solution concept with respect to concept 4 generates more energy by virtue of the fact that the chosen photovoltaic cell generates more voltage and current with respect to the 39mmx39mm polycrystalline cell; However, having the contacts in the central part does not allow a correct coupling between cells, therefore there will not be a correct heat transfer.

[6] Solution Concept 6 (turquoise):

Fresnel lenses, like other solution concepts, are selected to concentrate solar radiation to the photovoltaic cell and at the same time allow the cooling system to be by water. What differentiates this proposed solution alternative from the previous six (6) is that it uses an amorphous silicon solar cell, which compared to the one selected in solution concept 5, generates 10mA more but sacrificing 0.5V in voltage.

[7] Solution Concept 7 (purple):

This concept of solution by using the Fresnel lenses as a concentrator allows the coupling of the cells to be located horizontally, so oil is used as a cooling element. This synthetic lubricant was selected due to its high heat absorption capacity, allowing the cold face of the Peltier cell is at low temperatures, added to them, the 5V and 90mA solar cell and the MTG5 thermal paste are used for their benefits explained above.

E. Selections of product concepts

With the seven proposed design concepts, they were evaluated under the selection criteria listed in Table 6, in which each alternative is rated from 0 to 5 with respect to each criterion, where 0 is that it does not satisfy the requirement and 5 that it does completely, in addition to this, a percentage assessment is made of the criteria that will be taken into account to carry out a weighting.

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Table 6. Evaluation of design concepts.

Selection criteria	Valuation (%)	Concepts													
		1		2		3		4		5		6		7	
		Calif.	Pond	Calif.	Pond	Calif.	Pond	Calif.	Pond	Calif.	Pond	Calif.	Pond	Calif.	Pond
Stable power generation	30	2	0.6	4	1.2	2	0.6	3	0.9	4	1.2	4	1.2	4	1.2
Geometric congruence in the coupling of the modules	8	5	0.4	3	0.24	5	0.4	5	0.4	3	0.24	3	0.24	3	0.24
Easy installation and maintenance process	10	2	0.2	2	0.2	4	0.4	5	0.5	5	0.5	4	0.4	3	0.3
Good heat transfer between the cells and the refrigeration system	25	4	1	5	1.25	4	1	5	1.25	5	1.25	5	1.25	5	1.25
Greater capture of solar radiation throughout the day	20	4	0.8	4	0.8	3	0.6	4	0.8	3	0.6	3	0.6	3	0.6
versatile structure	7	3	0.21	3	0.21	4	0.28	4	0.28	4	0.28	4	0.28	4	0.28
TOTAL	100	3.21		3.9		3.28		4.13		4.07		3.97		3.87	

According to the evaluation that was carried out on each design concept, it was obtained as a result that solution concept 4 is the most suitable for the thermoelectric-photovoltaic dual system, obtaining a result of 4.13, with 0.05 points above concept 5, which is the second.

This solution is adequate because when using Fresnel lenses it allows a greater capture of solar radiation that is focused on the polycrystalline photovoltaic cell that has a theoretical production of 0.5V and 0.51 Imax.

As the photovoltaic cell receives a good amount of radiation and produces energy it tends to heat up, and with a measurement of 39 x 39 mm it presents an excellent geometric congruence in its coupling with the Peltier cell which is 40 x 40 mm. Furthermore, thanks to the MTGS thermal paste there is an excellent heat transfer from the photovoltaic cell to the Peltier. Again, the thermal paste transfers the heat produced by the cold face of the Peltier cell and transmits it to the finned heat sink where, as the water circulates, the temperature of the water decreases, the temperature gradient increases, resulting in a increase in energy production.

F. Laboratory Assembly

The first step to start the assembly of the prototypes that will be used to simulate the functionality of the dual generator system; photovoltaic -Peltier, consisted of identifying its constituent elements according to their availability, technical characteristics and cost. As a source of light and heat that simulates solar radiation in laboratory conditions, it was decided to use light bulbs; Therefore, a study was carried out to identify those that would best meet the requirements based on their technical characteristics and availability.

It should be noted that because it is very expensive and difficult to find in the national market, the high-power ultraviolet bulb was discarded.

1. **LED bulb:**

This type of bulb covers a large part of the blue spectrum of sunlight, when doing experimental tests it was obtained that the photovoltaic cell reduces its energy production by approximately 45%, another disadvantage that was found of this bulb is that since it covers only the blue spectrum it is a cold light; and in consequence. the radiation it emits will not induce the expected heating of the photovoltaic cell. This fact prevents imitating the heating effect induced by solar radiation and limits the incorporation of the Peltier cell.

2. **Compact Fluorescent Bulb (CFL):**

This type of bulb, like the LED bulb, covers a large part of the blue light spectrum of sunlight, but with the advantage that it reaches a small part of the green and red light spectrum, therefore which can reach higher temperatures than the LED, however, it is not enough because at the time of testing it with a photovoltaic cell, it produced 65% of its energy production potential.

3. **Incandescent bulb:**

This bulb is the one that covers the spectrum of light that the sun emits the most, this bulb covers the spectrum of red light almost equal to that of the sun, but with the disadvantage that the spectrum of blue light is almost 38% from that emitted by the sun. The advantage of this bulb is that it contains a greater spectrum of green, yellow light than previous bulbs. When tested experimentally, it is reached that the photovoltaic

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cell produces 92% of its total production, it is also possible to observe a similar behavior when tested directly with sunlight on an optimal day at 12 noon.

With this result, it was concluded that this high-power incandescent bulb (Figure 3) is the ideal one to test the dual system since it is the one that best approximates the light and heat phenomena induced by direct solar radiation on a photovoltaic cell; which is why it was selected as the radiation source that was incorporated into the prototype of the dual power generation system.

Figure 3. Selected bulb

G. Detailed Design

This chapter contains the detailed definition of the selected solution concept, describing the design of each one of the subsystems of the dual thermoelectric-photovoltaic system taking into account the characteristics described during the design concept. Additionally, the detailed design of the structures in which the Photovoltaic and Peltier cells will be located respectively is made to carry out future measurements and compare them with the dual system. The construction of the laboratory assembly design is also carried out, in which the plans of the structure are made where the light bulb that simulates the conditions of solar radiation will be placed.

1. Cells interface

For the coupling between the photovoltaic cell and the Peltier cell, solder the positive and negative cables to the photovoltaic cell with tin (negative in the blue part of the cell, positive in the gray part) in such a way that it does not affect the coupling After that, the thermal paste is applied to the center of the hot face of the Peltier module and spread evenly to cover the area where the solar cell is located. The next thing is to place the photovoltaic cell on top of the hot face of the Peltier cell, applying pressure to ensure that the cells are in full contact.

Electronic subsystem

For the electronic circuit, the connection between the cells is made in series, because the cells have similar internal resistances, and when the connection is made in series, a voltage product of the sum of the voltages produced in each of the cells is obtained. , and the maximum current produced by the cell that produces the least between the two is obtained, in which theoretically the cells will produce similar currents, so it does not represent a large drop in current.

In addition to the connection between cells in series, two 1000uF capacitors are placed in parallel to accumulate the charge and thus deliver a stable voltage to eliminate sudden voltage drops that the cells can suffer.

Figure 4 presents the electronic circuit described above, and shows the equivalent circuits of each cell.

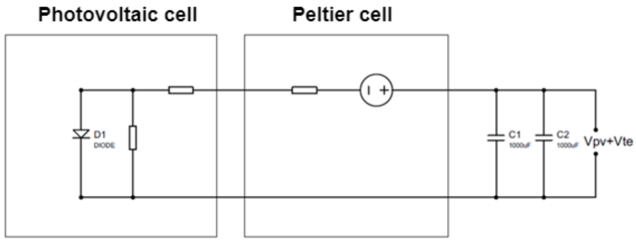

Figure 4. Electronic circuit

2. Refrigeration subsystem

To cool the dual system, an aluminum finned heat sink (indicated with the arrow) will be used, which is attached to the cold side of the Peltier cell by means of a layer of thermal paste. This heat sink will be submerged in water that is contained in a container made of acrylic (Figure 5).

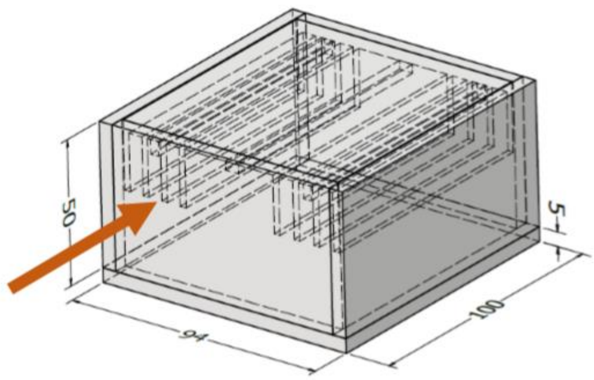

Figure 5. Cooling subsystem.

It should be noted that this container will be manufactured twice because, in addition to the dual system, it is required to make a measurement to the individual peltier cell, which also requires its refrigeration system.

3. Support structure

When building the structure of the frame, it was taken into account that the subsystems must work together, due to this, the base was made to support the Fresnel lens and the base to support the refrigeration subsystem and the electronic subsystem with the coupling of the cells. . The manufactured

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bases will be joined in a final assembly which will be by means of screws with nuts and washers to vary the distance between pieces that is needed.

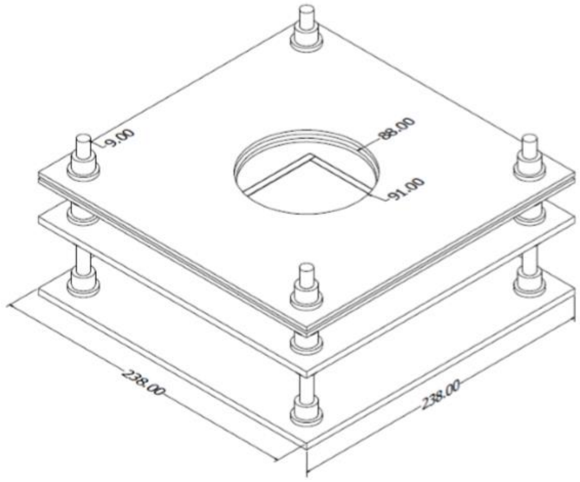

Figure 6. Dual system structure (view A)

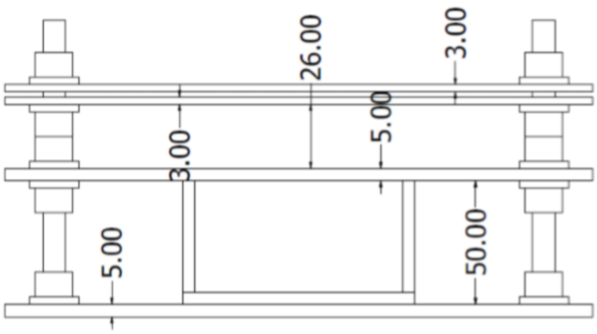

Figure 7. Dual system structure (view B)

Since measurements had to be made to each individual cell in the tests, the dual system structure described above was fabricated in duplicate because the Peltier cell requires the base for the cooling subsystem and the base for the Fresnel lens. In the particular case of the photovoltaic cell, it was not necessary to manufacture the base for the refrigeration system, so it did not have one of the designed pieces. Annex 2 presents the detailed plans of the structure for its subsequent manufacture.

4. Laboratory setup

Taking into account the characteristics of the bulb to be used and the conditions that the systems to be measured require, the design of the base is carried out where the bulb that will simulate solar radiation will be placed.

Table 7 shows the list of the main and auxiliary components that are required for the manufacture of the prototypes and the assembly of the laboratory that simulates solar radiation. These components can be found in large chain stores such as Homecenter and in hardware stores of the city.

Table 7. List of components

LIST OF COMPONENTS		
Description	Length	Qty.
Structure		
3mm thick MDF	$1m^2$	1
5mm thick MDF	$1m^2$	1
3/8 in. washers	N/A	72
3/8 in. stud	1m	2
3/8 in. nuts	N/A	80
Refrigeration subsystem		
Acrylic 5mm thick	$30cm^2$	1
Heat sink	84x90mm	2
Electronic subsystem		
1000uF Capacitors	N/A	2
Jumper male-male	N/A	4
Large protoboard	N/A	1
Small protoboard	N/A	1
Laboratory setup		
9mm thick MDF	$1m^2$	1
3/8" screw	10cm	1
High power incandescent bulb	N/A	1
bulb socket	N/A	1
Cable to AC connection	N/A	1

H. Manufacture of Prototypes and Experimental Systems

In this stage of construction of the prototype of the dual thermoelectric-photovoltaic system, of the prototype structures for the measurement of the Peltier and individual photovoltaic cells and the laboratory assembly, a series of steps were carried out based on the plans made and presented. in detail design. To carry out the construction of the aforementioned, the pieces were first cut by means of a laser cutter, importing the files in DXF format and establishing the cutting parameters for each material and thickness.

Following this, the necessary measures were taken for a subsequent cut of the studs for the future assembly. Once the acrylic pieces were obtained, the respective assembly was made with the help of Thinner to dissolve the material and it adhered to another piece. After this, the container was checked for leaks and blemishes (this process was done twice as two containers of water are required).

For the manufacture of the base of the refrigeration system, the assembly of the pieces cut in the laser was carried out together with the studs, nuts and bolts, to replicate the design that was carried out in the last stage, once this base was assembled, the container with its sink being in contact with water, it should be noted that this assembly was carried out

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twice because the system for the individual Peltier cell also requires this base.

For the base of the system that contains the individual photovoltaic cell, the piece cut in the laser was assembled with the studs with their respective nuts and washers (all the bases have the same height so that all the prototypes have the same conditions for subsequent validation. Once the manufacture of the bases was completed, the cells were coupled to them, taking into account that the Peltier cells go to the aluminum heatsinks and the photovoltaic cell goes directly to the base made of 5mm thick MDF. Following this coupling, the remaining pieces were entered, which will locate the Fresnel lens, remembering that the 3 prototypes must have the same height, and to locate these pieces at the same height, nuts and washers are used. These heights are calculated experimentally so that the rays that enter through the lens cover the entire cell.

Once the assemblies are finished, the respective electronic connections are made for the dual system since it requires it, for the other assemblies of the individual cells it is not needed because the positive and negative cables are directly taken to the MyRio or, failing that, to the multimeter for future measurements.

Having the prototypes built in their entirety, the assembly of the pieces that make up the laboratory assembly began, for this purpose, wood glue was used to join these pieces and have a fixed base without the danger of it falling.

I. Validation of the prototype

The process used in the validation of the prototype of the dual thermoelectric-photovoltaic system required that the experimental systems and assemblies be located in a place in the laboratory with low lighting to avoid affecting the data records acquired during the simulation tests carried out. Demarcations were made to ensure that the solar radiation simulator always points to the same point. After that, the demarcation is made in which the prototype to be validated is located.

Once the laboratory assembly has been completed, the program that allows capturing the voltage received from the MyRio acquisition card is programmed in LabVIEW and, in turn, graphs the data obtained from the prototypes, allowing them to be exported for subsequent analysis (Figure 8).

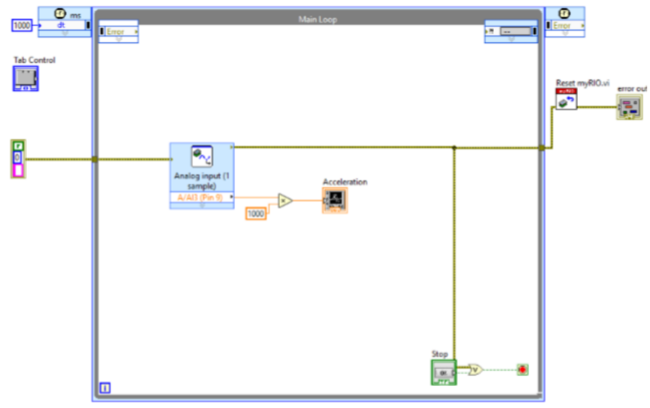

Figure 8. LabVIEW code

Figure 18 it can be seen that the voltage input of the system to be evaluated is carried out through pin A13 of the MyRio card, where the data is captured every 1000 milliseconds, which are displayed in real time on a graphical interface.

Once the program has been prepared, the dual thermoelectric-photovoltaic system is located and connected to an external breadboard to make the connections of the MyRio acquisition card for voltage capture.

By having the prototype located and connected, the connection to alternating energy is made to turn on the high-power incandescent In
bulb at the same time that the program is executed to turn on the data captures, it should be noted that since there is no resistive load in the measurement This capture voltage is the maximum voltage that the system to be evaluated can deliver.

Figure 9 shows the behavior of the voltage of the dual system in 17 minutes that the test was carried out.

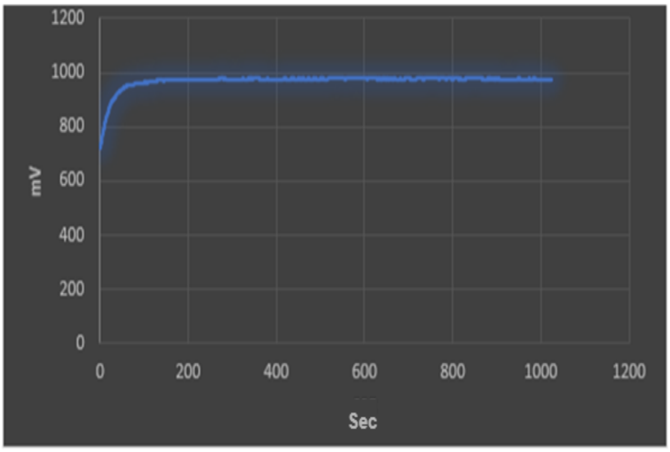

Figure 9. Dual system voltage curve

For the data collection of the current, the system was allowed to rest so that the measurement was not affected by the residual heat that can be stored by both cells and the refrigeration system. After the rest time, we proceeded to locate

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a resistive load of 1 ohm in order to obtain the maximum current that the system could provide; This data collection of the current is carried out through the use of the UT33C+ multimeter, in which a cell phone is located with a tripod to record the data that is taken during the 17 minutes that the data capture lasts, after which they are entered. the values displayed by the multimeter in an Excel table to obtain a graph with them (Figure 10).

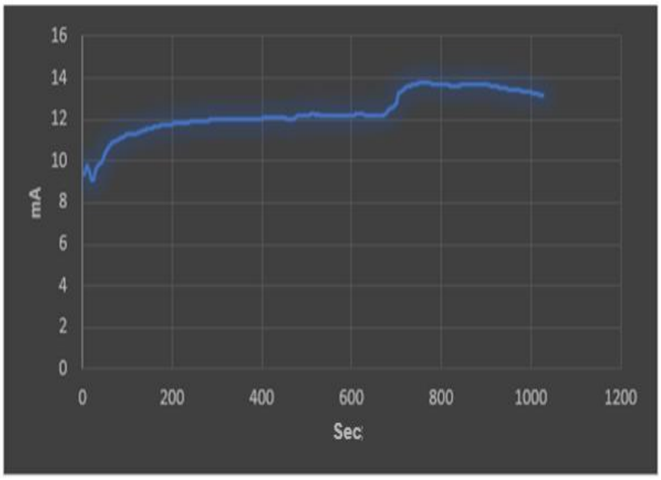

Figure 10. Dual system current curve

To find out if the dual system worked or not, the measurements of the photovoltaic cell and Peltier were carried out individually in their respective structures (Figure 21)(Figure 22), this is done for reference and to check in the future if the system double is effective.

Once the data collection of the dual system has been completed, we proceed to locate the structure that contains the individual Peltier cell, verifying that it has the same conditions as the dual system, to perform the data collection with the MyRio card of the maximum voltage. and graph them (Figure 11).

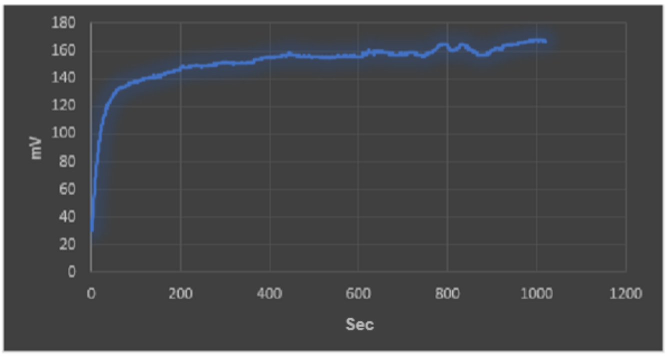

Figure 11. Peltier Voltage Curve

As with the dual system, the Peltier system is allowed to rest while the 1 ohm resistive load is connected to perform the maximum current measurement. Once the rest time is over, the current measurement is carried out and its respective graph is obtained (Figure 12).

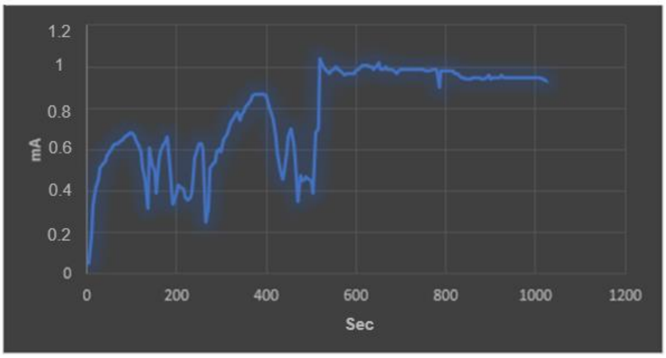

Figure 12. Peltier Current Curve

In the same way as it was done with the two previous prototypes, the voltage and current capture of the individual photovoltaic prototype is made and their respective graphs are generated (Figure 13) (Figure 14).

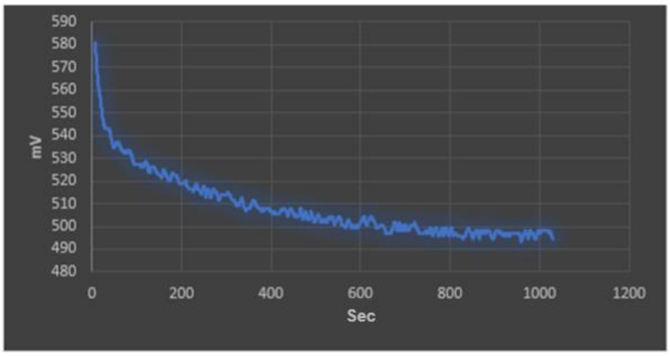

Figure 13. Photovoltaic Voltage Curve

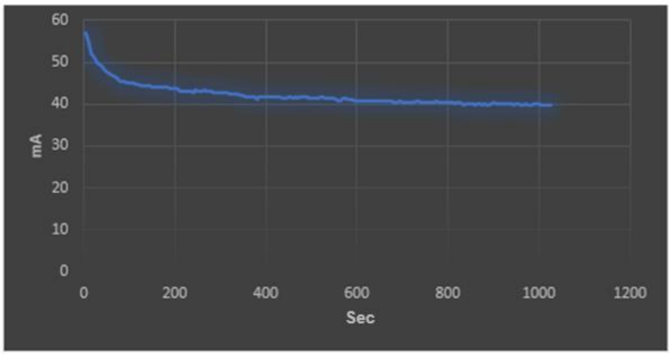

Figure 14. Photovoltaic current curve

V. Analysis of Results

With the curves obtained in the validation of the experimental prototypes, it is possible to verify that the Peltier cell acts as a good heat sink, because the photovoltaic cell does not lose efficiency as time passes, so the voltage output of the dual system is stable with high production. On the other hand, the current presents a low production with an average of 13 mA and presenting a small instability because the current varies between 12mA and 14mA with biased data that can reach up to 10mA.

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With the curves obtained from the individual photovoltaic cell, it is possible to observe more clearly that it loses almost a fifth of its voltage and current production, so the dual system works correctly in maintaining stable energy production, due to having a stable operating temperature does not lose efficiency. On the other hand, it can be seen that the current generated by the solar cell is much higher than that of the dual system and this is because, since the cells of the dual system are connected in series, it delivers the maximum current that the cell that delivers can offer. less between the two and since the Peltier cell is still in the process of heating up, it limits the system in its current delivery.

In the same way that the Peltier cell can be analyzed with the previously analyzed curve of the photovoltaic cell, in these curves we can see that the solar concentration through the Fresnel lens and the water cooling is not enough to create a sufficiently high temperature delta to generate considerable power, however, it can be seen that the Peltier cell in the dual system does deliver more power.

This is due to the fact that the photovoltaic cell heats up much more than the individual Peltier cell and it is due to the fact that, since it is a metal sheet that produces energy, it heats up almost 5 times more than what the Peltier cell heats up with direct sunlight, therefore that it may be thought that the Peltier module can be used more when it is put in tandem with another energy generation system such as the photovoltaic cell.

It should be noted that the current curve of the Peltier cell fluctuates a lot until minute 5, when it begins to stabilize. This phenomenon occurs because the Peltier cell has an internal resistance that changes with temperature, affecting current transfer. at low temperatures and as it was observed, the Peltier cell has a slow heating time when the heat source comes from concentrated solar rays.

Having said this, and having analyzed the curves, it can be seen that the dual system produces an average of 1V of voltage and 13mA of current, therefore, it has a power of approximately 0.013W. The Peltier cell with an average output of 160mV of voltage and 0.7mA of current results in an average power of 0.000112W and the photovoltaic cell with an output of 500mV of voltage and 40mA of current, on average delivers an average power of 0.02 W. Based on these results, it can be seen that the dual system and the Peltier cell have a tendency to increase their production as time goes by and the photovoltaic cell tends to decrease.

As this dual system makes use of solar radiation, it can be used 12 hours a day, so the power delivered daily is:0.013W*12h= 0.156Wh

VI. CONCLUSIONS

The use of Peltier cells as a heat sink for photovoltaic cells results in a stable power delivery and an increase in their life cycle because they do not heat up, however, the current drop represents a decrease in production of the photovoltaic cell, so it is necessary to make an analysis of the circuit in which the voltage can be added but the current generation is not affected.To correct the low energy production of the dual system, it is recommended for future studies the use of a Boost circuit (Voltage Booster) which is connected between the cells. This is done in order to increase the voltage delivered by the photovoltaic cell reducing the current generated in it, so when it is connected in series with the Peltier cell, they have a similar current generation, and therefore avoid damage to the cells due to excess current in one of them. In the same way in series connections, the voltage differences between the cells do not matter because they add up without any problem. Resulting in greater power delivered in the dual system and protection against future cell damage.This system can be made in such a way that several dual systems can be coupled, in order to connect them in series to increase the voltage, or in parallel to increase the current. for what to represent would increase production in the same space used with the solar panels.

This system can be located in dams or rivers where water circulates, which can dissipate heat more quickly, leading the Peltier cell to produce more energy and not significantly reduce the current of the system.Peltier cells are still under development and their production is still expensive, but they have high potential for energy production, as happened with photovoltaic technology in its early years of development, but materials and production methods were found after some time. which made it much cheaper.It should be noted that in this degree work cells with little energy production were used because in the national market there are no individual photovoltaic cells without glass coating that generate considerable energy, so if the system is carried out with one cell more powerful can raise even twice the power.Large industries have great potential for the use of Peltier cells because most of them have boilers that can reach up to 300 degrees and with the advantage that they operate 24/7, compared to sunlight, which has a duration of 12 hours and is affected by weather conditions, so the use of these cells in these spaces is very promising. It is recommended to carry out a study for its implementation.

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