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Development of Modular Cooling for Water-Cooled Photovoltaic Plant in Real Scale

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.79101>

Abstract

This chapter evaluates module architectures and units of photovoltaic cooling systems, aiming to determine, select and design a modular system that can be applied in a real-scale photovoltaic power plant (PVPP) in order to enhance the yields of electricity production (entitled cooled photovoltaic plant). An analysis of the local climatic, geographic and solar conditions as well as construction, operational and maintenance aspects was carried out. Worldwide, there are three main types of cooled photovoltaic systems: PVT liquid and air collectors, PV ventilated with heat recovery and non-PVT systems. Based on the local weather conditions (tropical warm and dry) with both temperature and solar irradiation index being high, it results the PVT-liquid system to be more suitable in a scenario with available cooling fluid. We conclude that the best design and arrangement of the cooling system are of the type coil and multiple channel because they permit better rates of heat exchange between the cooling fluid and the PV module.

Keywords: SFV, solar energy, photovoltaic/thermal, cooling photovoltaic system, PVPP

1. Introduction

Brazil is the fourth largest country in the world with 8.5 MMkm² [1]; therefore, it presents diverse climatic characteristics along its territory. Nevertheless, the annual mean global

irradiation remains uniform, presenting a relative high average in the country and varying in a range of 4200–6700 kWh/m²—these values are, for instance, greater than most of the values observed in Europe (900–1850 kWh/m²). The lowest global solar irradiation value observed in Brazil (4250 kWh/m²) occurs in the northern coast of the state of Santa Catarina due to the steady rates of rainfall distributed along the year, whereas the highest value pertains to the northern region of the state of Bahia (6500 kWh/m²), near the state of Piauí, because this region presents the lowest rate of cloud cover in Brazil [2].

As energy production (thermal or electrical) entails the increase of temperature of the equipment, directly affecting its efficiency, lifetime and pollutant emissions, cooling systems are employed in order to reduce the temperature of the system, such as radiators and water pumps employed in rotary machine of energy production (controlling overheating and NO_x emissions of internal combustion engines Diesel and Otto), heat exchangers of a great variety used in hydraulic and gas turbines, which guarantee the maintenance of pillow blocks and shovels, among others [3, 4]. The photovoltaic modules (PMs), which are basically stationary solid equipment, are damaged with the effects of high temperatures during their operation because they absorb 80% of the solar radiation, which in turn only 5–20% is converted into electricity (depending on the employed technology) [5]. The rest of the solar radiation is then converted into heat, causing the modules to reach temperatures 35°C higher than the ambient temperature [6]; in some regions, these modules might reach temperatures higher than 90°C, causing malfunction or even permanent damage [7]. Alternatively, the photovoltaic thermal (PVT) system, which extracts the heat produced at the PV module through a thermal absorber system, might replace the traditional PV systems, improving its performance.

The aim of this work is to determine a model of cooling technology for photovoltaic power plants (PVPPs) by means of analysing both established and on-development cooling systems for PV modules. Therefore, we intend to improve the energy performance of photovoltaic power stations.

In these terms, the methodology considers the following steps:

1. study of local and geographic factors of the region where the photovoltaic power plant (PVPP) is located;
2. study of the factors that impact the increase of temperature on the photovoltaic (PV) modules and therefore impacting electricity production;
3. extensive study of the technical and scientific basis of the state of the art of cooling technologies for PV modules aiming at the understanding of the factors, which influence its functioning and performance. This step shall gather information regarding the materials employed on the construction of the selected technologies, methods and processes of construction, operation, maintenance and quantitative measurement;
4. survey and analysis of the local water availability because the PVPP is located within an operating hydroelectric power plant (HPP) and
5. evaluation of the cooling technologies in order to support the selection of the most appropriate one, taking into consideration the local characteristics.

2. Climatic aspects of the region for verifying energy application

The Northwest region of the State of Sao Paulo presents the highest score of mean solar radiation of the state, with a mean annual value of 5.520 kWh/m² and daily maximum value of 5.970 and 6.672 kWh/m² day, respectively, in the summer and spring, which lie close to the maximum values observed in the country [8]. The installation site of the photovoltaic power plant (PVPP), where the cooling systems for the PV modules are installed [9], presents an average annual solar radiation of 5.5 kWh/m² day in the summer and minimum average value of 4.6 kWh/m² day in the autumn [8], as shown in **Figure 1**.

According to Köppen classification, the city of Ilha Solteira presents warm and dry climate [10], with an average annual atmospheric temperature of 24.8°C and the maximum and minimum average annual temperatures of 33.0 and 13.1°C, respectively. Ilha Solteira has an annual rainfall index of 1309.4 mm, varying from 288.3 mm during the dry season (from April to September with an average monthly index of 48.1 mm) to 1.021 mm during the wet season (from October to March with an average monthly index of 170.2 mm, comprising 77% of the total rainfall in a year). The minimum rainfall index is observed in August (22.8 mm), whereas the maximum one is observed in January (225.9 mm). Regarding atmospheric temperatures, the dry season presents average value and maximum average value of 22.8 and 30.0°C, respectively, whereas the wet season registers 26.9 and 32.5°C. The highest registered temperature was 42.0°C, which was registered on four different days, and the highest average daily temperature was of 34.9°C, with minimum of 29.3°C and maximum of 38.9°C on that day [11].

Figure 2 shows rainfall indices (mm) and daylight (h/day) for the period 2004–2013. The graphic reveals that the minimum values registered for sunshine duration coincide with

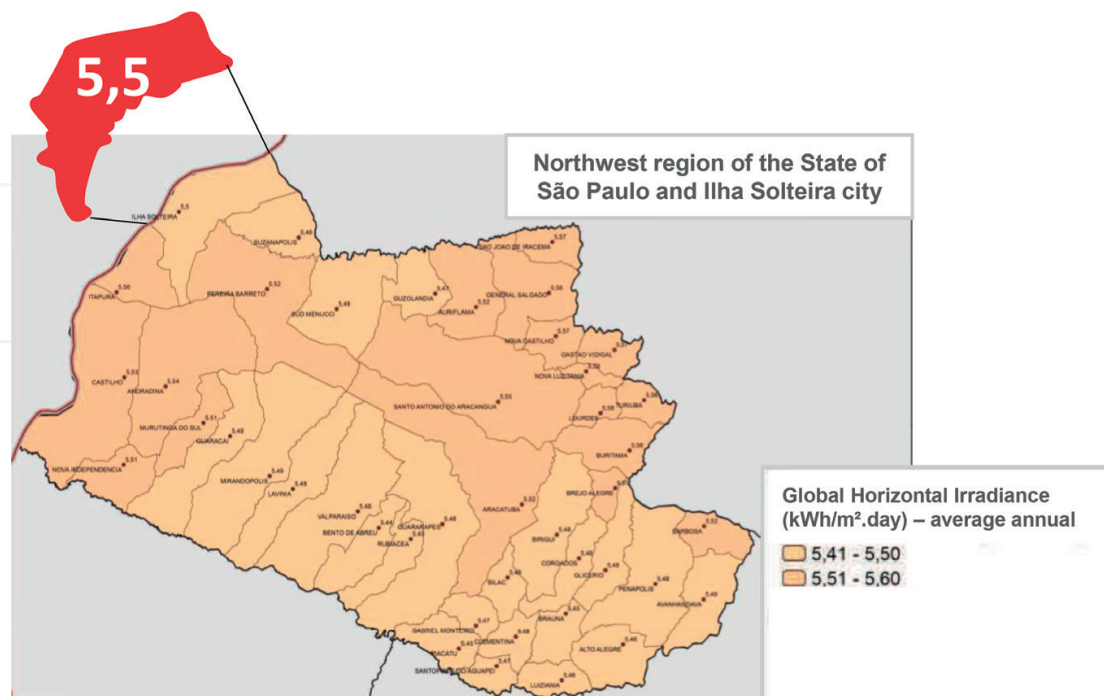


Figure 1. Global horizontal irradiance (kWh/m²) in the region on Ilha Solteira city [8].

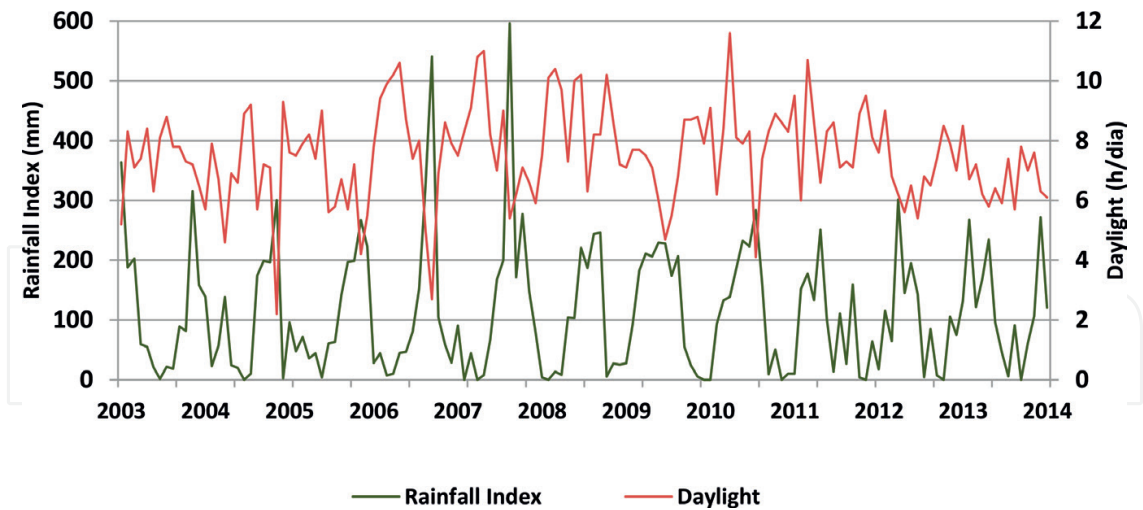


Figure 2. Rainfall index and monthly daylight for the period 2004–2013.

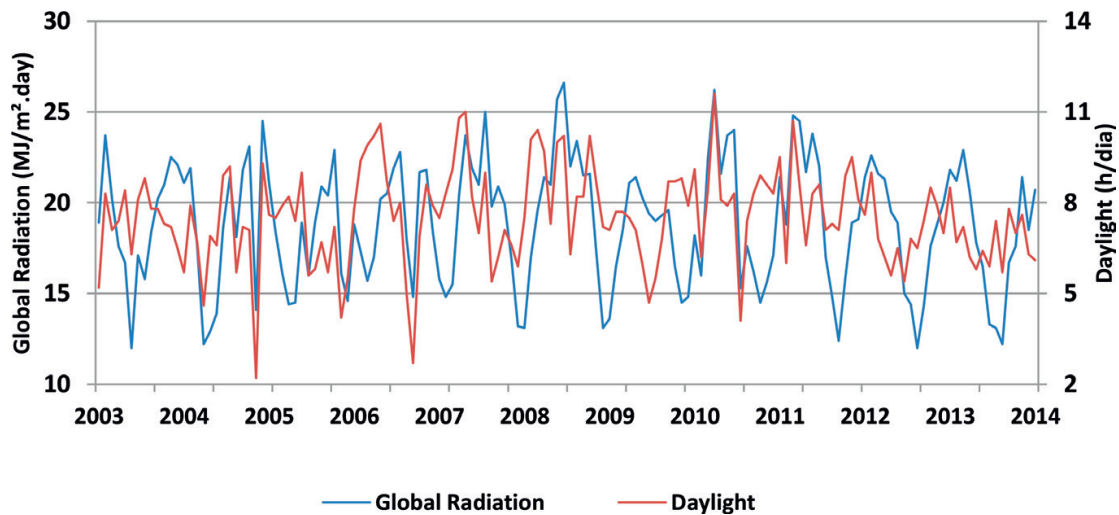


Figure 3. Mean global radiation and monthly daylight for the period 2004–2013.

the maximum values of rainfall, thus they are inversely proportional and oscillate along the year. The highest rainfall rates occur in the beginning of the year, whereas the highest sunshine duration occurs in the middle of the year. It is also possible to note that the highest rainfall index registered (596.1 mm) was followed by a monthly sunshine duration of 5.4 h/day, whereas the highest sunshine duration (11.6 h/day) registered in November 2010 was followed by a rainfall index of 138.9 mm. Overall, the mean monthly sunshine duration and rainfall indices for the analysed period are 7.7 h/day and 127.6 mm, respectively.

The global radiation ($\text{MJ/m}^2 \text{ day}$) is directly proportional to the sunshine duration, as described in **Figure 3**, and the peaks of maximum global radiation coincide with the peaks of sunshine. The highest mean global radiation ($26.6 \text{ MJ/m}^2 \text{ day}$ registered on December 2008) corresponds to the maximum mean atmospheric temperature of the same year (26.7°C), presenting a mean monthly sunshine duration of 10.2 h/day. At the period of highest sunshine (11.6 h/day on November 2010), the mean global radiation was $26.2 \text{ MJ/m}^2 \text{ dia}$, corresponding

to the second highest value for the period. The mean average global radiation for the whole period is $19.1 \text{ MJ/m}^2 \text{ day}$. Furthermore, the graphic shows that the oscillations registered for the maximum global radiation are smoother than the ones observed for the minimum ones, thus the minimum values vary more than the maximum ones. Another important characteristic to be noted is that the mean global radiation values along the period lie closer to the maximum values than to the minimum ones, demonstrating that conditions of high radiation are more present in the region. The average minimum and maximum global radiation for the period is, respectively, 9.4 and $24.9 \text{ MJ/m}^2 \text{ day}$, reaching a peak of $35.4 \text{ MJ/m}^2 \text{ day}$ observed on 4 December 2008, with a corresponding sunshine duration of 15.8 h/day .

3. Analysis of the effect of temperature on PV modules

The temperature is a very important parameter on PV modules due to its influence on the behaviour of a PV system. The PV cells heat up due to their exposure to the solar rays, modifying the efficiency of the system and the output energy, because high temperatures decrease the produced voltage, and inversely, higher voltages are produced in lower temperatures [12]. Any kind of PV system shall include a correction factor due to the effect of temperature [13]. This effect is a product of a natural characteristic of the silicon [12] because part of the absorbed solar rays is not converted into electric energy but dissipated in the form of heat. This is the reason for the PV cells and modules to present higher temperatures than the ambient while operating [14]. The highest temperatures on a PV system are observed at its inferior surface due to the higher thermal conductivity of the silicon that forms the PV cell, compared to the polymer material used at the superior surface [15]. This phenomenon is shown in **Figure 4**, presenting the difference of temperature among the superior and the inferior surfaces of 8.1°C [3, 4].

The voltage drop caused by the increase in the temperature is a result of the shrinkage of the semiconductor due to the band gap, which directly influences the open-circuit voltage (V_{oc}), which in turn decreases following the voltage drop of the p-n junction. This effect can be explained by the thermal voltage, q/kT . Thus, the PV cells contain a negative temperature coefficient for the V_{oc} . Moreover, lower output power given a constant photocurrent results from the charge carriers, which are released with lower potential [16]. As the temperature increases, followed by an opening of the band and thus shrinking the semiconductors, more incident energy is absorbed, leading to a raise in the charge carriers from the valence band to the conduction band [12]. As a result, a larger photocurrent is observed, producing a larger short-circuit current for a given insulation, and PV cells have a positive temperature coefficient I_{sc} [16].

According to Makrides et al. [17], the place in the PV cells, where the highest increase in temperature is observed, is at the main bus bar; a conductor line that enables the interconnection, capture and conduction of electrons from the secondary bars, which, as the primary ones, is a parallel conductor line responsible for the capture of electrons produced at the valence band of the PV cells. According to Prieb [18], as the silicon module temperature increases, the voltage decreases at a rate of $-2.2 \text{ mV}/^\circ\text{C}$ and the short-circuit current increases at a rate of

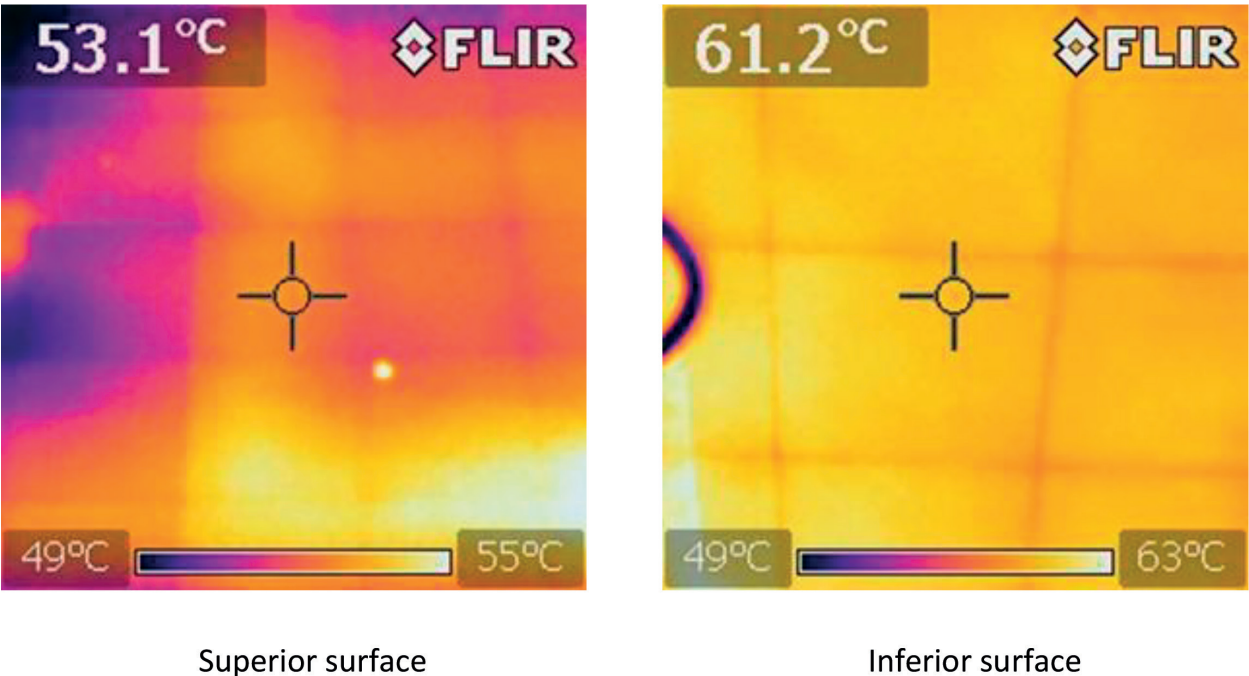


Figure 4. Infrared image of the superior (left one) and inferior (right one) surfaces of a PV module [3].

0.06%/°C, such increase rebounds on the power, but it is insufficient to compensate the loss of power due to the voltage drop. In summary, variation of temperature results in a corresponding variation of operational levels of maximum power extraction.

The energy conversion efficiency (η) of a PV cell is the percentage between power converted and power collected, when a PV cell is connected to an electrical circuit. This term can be calculated using the point of maximum power (P_{\max}) divided by the input light irradiance (E in W/m^2) over a PV cell surface under standard test conditions (A_0). In this way, it is possible to understand the decrease of η influenced by temperature increase, because such a decrease in the output power is directly proportional to the output voltage, which in turn is reversely proportional to temperature. Thus, just as the voltage, the efficiency of a PV module decreases with the increase of temperature.

4. Framework of cooling systems for photovoltaic modules

In photovoltaic thermal (PVT) systems, solar energy is converted into both heat, just as in conventional solar thermal collectors, and electricity. In other words, PVT systems consolidate the electricity production of PV systems and the heat production of solar thermal collectors (see **Figure 5**). The real conversion occurs at the absorber, but part of this energy dissipates to the environment through radiation and convection. Systems where the absorber is in direct contact with other means are called uncovered PVT. In this case, the heat loss to the environment is considerable, and both temperature and thermal efficiency are relatively low. The uncovered PVT systems are recommended in cases when lower heating temperatures for

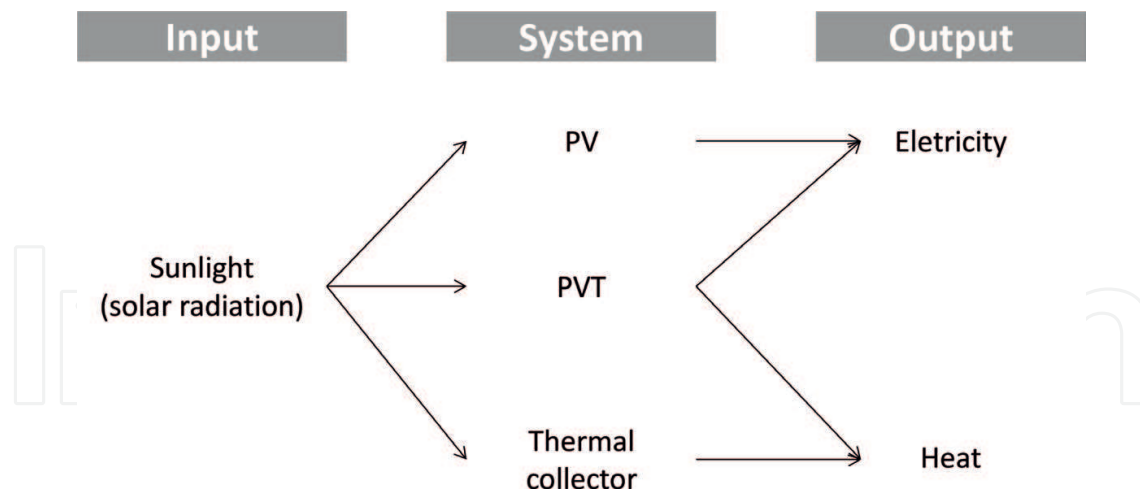


Figure 5. Comparison between the types of technology and the corresponding energy produced [19].

water are demanded or in order to improve the electric conversion yields of PV modules. The other kind of system is called covered PVT, and it is characterized by a cover, usually transparent, placed around the absorber. This cover transmits around 90% of solar incident radiation, depending on the material used. On most of the cases, the 10% reduction is less important than the effect of thermal insulation the cover achieves, improving the overall thermal efficiency of the system [6].

The parameters of a PVT project vary substantially according to the type of application, which can aim at the use of hot water for pre-heating ventilation air or at cooling the PV systems. Heating and electricity demands can be satisfied by the appropriate PVT system, and its technical viability is documented according to Hasan and Sumathy [19].

There are many types and forms of PVT systems, which vary according to the photovoltaic module, the type of working fluid, the amount of radiation and geographic location of the facility, and other system specifications (such as flat plate or concentrator). The actual classification of PVT systems varies in the literature—the working fluid (commonly air and water) is the most common attribute used for classification purposes.

Compared to the air-type PVT, the water-type PVT systems are more efficient in terms of heat removal from PV [20], due to the higher thermal conductivity of the water, resulting in a higher heat transfer from the PV modules to the working fluid. Thus, a balance between thermal and electric yields has to be taken into account while selecting the appropriate PVT system.

4.1. Water-based PVT collector

Water-based PVT collectors consist of a heat absorber, either a cooling coil or a series of parallel tubes coupled at the inferior surface of the PV laminate or glued with an epoxy adhesive material through which a fluid flows, cooling down the module. Moreover, the absorber might contain a thermal insulator in order to reduce thermal losses between the water and

the ambient—in contrast, in case heat removal from the PV module is intended, the thermal insulator is not added to the absorber. This type of cooling is accomplished by forced convection in which the fluid removes the heat from the module, increasing the system's electrical efficiency of 4–5% [3].

There are several types of configuration for these collectors, but in all cases, a pump has to be installed for water circulation purpose. The four major models found in the literature are: sheet-and-tube PVT collectors, channel PVT collectors, free flow PVT collectors and two-absorber PVT collectors. According to Zondag et al. [21], in order to improve the efficiency of the collector, it is preferable to design the water flow to occur below the PV module. However, in terms of the simplicity of the structure and the overall performance, a sheet-and-tube PVT collector is recommended. Additionally, in order to maximize heat transfer, the mean distance between the heat generation and the collectors should be minimum. Another suggestion regarding the area in which the liquid flows on the PV cell, this shall be as large as possible in order to cover the whole surface [22]. For this application, van Helden et al. [6] suggested a configuration with multiple channels that allow PV cells arranged in series to be cooled equally.

The simplest way to produce a PVT collector is to take a standard PV and integrate it into a thermal collector. However, this configuration exposes the PV module to the ambient, particularly to humidity, and therefore hampering practical applications. Furthermore, problems related to the electrical insulation may occur, such as the increase of thermal resistance between the PV laminate and the absorber due to the emergence of air layers—result from the low thermal conductivity triggered by irregularities at the inferior p-Si modules [21].

In order to increase electrical resistance between the PV cells and the absorber, a more advanced technique shall be applied, avoiding temperature increase and electrical loss. This technique is based on PVT modules that contain laminate photovoltaic cells followed by electrical insulation and finally an absorber. However, problems such as the deformation of the PVT laminate due to the thermal expansion between the glass surface and the metal laminate of the collector occur. In order to avoid this problem, a tedlar laminate can substitute the glass at the inferior surface. It is important to note that this substitution requires a sufficient rigid absorber that enables the cells to be supported [21]. Usually, PVT modules produced in strips with a superior plastic layer have been used. In this case, the support is guaranteed by a cooper tube absorber installed at the centre of the strips. A variation of this design uses the borders of a galvanized sheet as the support of the PVT modules. The border of the galvanized sheets is bent, providing the basin for the cooper tubes, which are then welded together. Sheet-and-tube absorbers present technical restrictions at the construction phase because the tubes are located underneath the absorber, leading to difficulties at the lamination process. Overcoming this problem is extremely complex because the high temperatures of the welder hamper the encapsulation process and diminish the reliability of the heat transfer. The utilization of an aluminium sheet, which is introduced by a cladding process, may overcome such limitation [23].

It is worthwhile to mention that, independent of the selected technique, the encapsulant material has to be resistant to temperatures as high as 130°C, and particular attention to the optical properties of the PV cells has to be paid [24]. An alternative way to avoid the complications

caused by high temperatures consists of applying silicon. However, this option presents the disadvantage of diminishing the efficiency of thermal exchanges in case an air layer is accidentally produced.

4.2. PVT-air collector and ventilated PV with heat recovery

PVT-air collectors are similar to a standard hot air collector with a PV laminate applied at the superior cover of the air channel. PVT-air collectors are cheaper than the liquid ones due to its flexibility and easy conversion properties. They can be constructed with or without glass, and, in general, they are recommended in the cases when the user has a demand for hot air specially to be directly applied for heating purposes. This application is restricted to places where there is a demand for hot air usually applied for pre-heating in building systems, where the temperature demand ranges from 15 to 25°C [19].

As the heat transfer in a PVT-air system is more critical than in the liquid ones, it is important to adopt an adequate heat transfer model. Due to heat transfer effects at the entrance, the Nusselt number (Nu) in PVT-air systems varies 10% along the entrance length for a given sufficient large channel, and therefore, the hydraulic diameter shall be twice the size of the height of the channel. The impact of the air flow induced by buoyancy and heat transfer through a vertical channel induces an increased velocity of the heat flux non-uniformly inside the duct. This effect is directly connected to the form of the exit side of the duct. Briefly, in order to enhance the heat transfer in a PVT-air system, it is necessary to control its induced flow and buoyancy. Another option extensively applied in experimental research consists of increasing both the turbulence in the flow channel and the heat transfer surface area [19].

In terms of constructive aspects of the fixation of the cooling system of the PV modules and the corresponding used materials, PVT-air systems are similar to PVT-liquid ones. The usage of air as the heat transport medium as opposed to other working fluids, for example, water, presents some advantages such as the non-freezing property of the collector fluid (important factor when applied in low temperature regions), no risk in case of leakage, and the input is freely and permanently available. This solution is indicated for regions where the access to water is restrict or economically unviable. Nevertheless, some disadvantages shall be taken into consideration, such as low heat capacity and low heat conductivity, which result in low heat transfer. Thus, this configuration is not recommended when the cooling of the PV modules is aimed (there is considerable heat loss), and, in case of a passive systems, without an air injection system, the PVT-air system may result in low yields due to the low density and thermal conductivity properties of the air.

The difference between a ventilated PV with heat recovery and PVT collectors reside in the fact that, generally, a PVT system is projected for a specific application (e.g., building), lacking a standardized production system. The similarities between both the systems cause practitioners to often select the wrong option for the project. This scenario may change in the short term once various institutes and manufacturers, specially in Europe, are channelling efforts towards standardization.

Conventional PV modules for facades and roofs, where frequently air incidence is present at the inferior surface of the modules due to its inclination, enable the air to cool the PV by means

of natural convection. This heat can be recovered, and, in this case, the PV is considered to act as a PVT collector. Due to its easier construction and operation, PVT with heat recovery systems is extensively studied as an alternative solution to “Building Integrated Photovoltaic” (BIPV). This system can operate either during the winter, providing heat, or during the summer as active cooling systems [25]. An extensive research carried out by Bazilian et al. [26] proved that this type of system is more suitable for low temperature applications. Moreover, he observed that building integrated systems could represent a cohesive project and become a good solution for providing energy in buildings, pointing the necessity to further increase the research in the area in order to make these systems commercially available. Another research [27] also showed that BIVP collectors are more suitable for low temperature ambient. This system, if applied at facades, can not only provide the electricity gains but also protect the building against solar radiation, reducing the thermal cooling load and providing the heat for internal uses in the building. In the absence of direct demand of heat, this can be utilized to induce a pressure difference, supporting the ventilation system. Additionally, the PV modules may substitute facade cladding materials [19].

4.3. Cooling system of PV module (non-PVT)

The cooling system of PV modules non-PVT consists of water injection on the module’s superior surface. As the water flows on the surface, it removes the heat stored at the module through conductive and convective heat transfer. This system is simple and is composed of a PV module, a pump and a water storage tank. The water injection is done over the module’s superior surface through various orifices installed along a tube, guarantying homogeneous heat exchanges along the whole surface.

Results obtained by [28] showed that the convective heat exchange between the cooling water and the module’s superior surface lead to increases of 15% in electricity production during peak solar radiation. Moreover, the results indicated that a 5% increase in the energy output can be obtained during dry and warm seasons. In another experiment, Odeh et al. [29] designed a system in which tubes were incorporated in order to allow the water to flow on the module’s surface based on gravity, improving the yields related to the water pumping system. The test was carried out in different cities of Australia (Sydney, Perth and Darwin) in order to consider different climatic conditions. The results showed that the increase in output power of the systems varied in a range of 4–10% when the cooling system was operating. Around 50% of the increase is attributed to the direct cooling effect resulted from the contact between the water and the surface, whereas the other 50% comes from the increase of solar radiation due to the refraction of the light beam on the water layer.

5. Important aspects of the water supply for PV systems

The PVPP to be tested in this work is located within the facilities of a hydroelectric power plant (HPP), enabling the ease of access to the cooling water. The use of the water is possible in two different ways: either it is done at the end of the hydroelectrical energy production process, after the water runs through the turbines, or it is directly applied at the reservoir,

before the energy production phase, with the condition that the water has to be reintroduced in the system, either in the reservoir or at any step of the hydroelectrical energy production. After analysing numerous configurations, the following two available options are analysed and discussed.

5.1. Output water from the cooling of the pillow blocks

Cooling water from the pillow blocks is permanent available along the year only at the operation period in which the cooling machines operate. Before the water enters the heat exchanger of the pillow blocks, it passes through a chemical process (chlorination) aimed to control mussel fouling. In order to seize the water at this step of the process, several interventions at the structure of the dam would have to be carried out, such as drilling on the walls and ceilings of the machine rooms, redeployment of electrical conduits and lubricants located at the dam's internal channels, power down and drilling of the main discharge line from the heat exchanger of four turbines and construction of a 700-m pipeline up to the dam's rockfill plus an enlargement of 77 m from the rockfill to the PVPP. During the summer, the water temperature measured at this site presents a maximum value of 39°C and an annual average of 32°C and, at the coldest period, a maximum of 29°C and an average of 26°C [3].

- Advantage: chlorinated water, avoiding the necessity of treatment water plant for the cooling of the PVPP; output water, avoiding the necessity of reintroducing the water into any other step of the HPP; no pumping process required.
- Disadvantage: several physical interventions at the dam's structure; power down of two generators, if these are operating during the implementation of the cooling system; redeployment of electrical conduits and lubricants used at the operation of the generators; construction and enlargement of pipes; high water temperature; water supply dependent on the operation of the generators.

5.2. Rockfill water from the HPP

The rockfill raw water from the HPP is collected at the bottom of the dam; therefore, its temperature is more constant along the year, with an average value of 24°C, a minimum of 19°C in the winter and a maximum of 29°C in the summer. The rockfill line runs over less than 500 m between the exit of the HPP's internal facilities and the administrative parking zone. The distance between the ending point of the rockfill line and the PVPP facility is of 77 meters. Among others, this water has been used for cleaning, gardening, hydrant backup and external supply. These conditions enable the permanent and continuous supply of water along the whole year [3].

1. Advantages: no necessity for interventions at the dam's structure; no necessity for shutting down any HPP's operation; ending process water, avoiding the necessity to return it; no pumping system required; relatively small extension of the pipeline; permanent water flow along the year.
2. Disadvantage: implementation of a chlorination system.

6. Conclusion

The PVPP's facility site presents a dry and warm weather, with an average temperature of 24.8°C and a rainfall index of 1.309 mm. The rain season occurs between October and March with 77% of the annual rainfall lying within this period, whereas the dry season occurs between April and September. The mean global solar radiation and the mean sunshine duration are, respectively, 19.1 MJ/m² day and 7.7 h/day. Furthermore, the highest historic temperature (42°C) was recorded within the rainy season. These characteristics demonstrate high sunshine duration and global radiation along the year.

Based on the analysis of this report, the liquid PVT without thermal insulation is the most recommended solution. The fact that the PV modules present inferior temperature 8.1°C higher than the superior one (field measurements), the absence of waste water (closed system) and the high demand for cooling the PV modules for energy production corroborates the adopted solution. Another advantage of liquid PVT systems is that it enables the use of standard PV modules, which present high thermal exchange rates, being highly recommended for warm regions. It is important to mention that three configurations are possible among the liquid PVT system, two of those regard sheet-and-tube (coil) and the other is of the type multiple channel.

Moreover, based on qualitative analysis of the local conditions observed on the site, the most suitable source of cooling fluid is the water from the rockfill line of the HPP, because of the proximity between the existing line and the PVPP area, permanent and continuous water supply along the year, no pumping required and, most importantly, the absence of structural interventions at the dam.

Acknowledgements

To CESP for funding the P&D ANEEL PE-0061-0037/2012, enabling the accomplishment of this chapter and especially for the engineer Diego Biaseto Bernhard of the company Flue8 that due to its engagement and experience solved all technical and constructive aspects of the cooling units.

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