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Assessment viability of a Concentrating Photovoltaic/Thermal-energy cogeneration system (CPV/T) with storage for a textile industry application

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ABSTRACT

In this paper, a simulation model of a Concentrating Photovoltaic Thermal-energy cogeneration system (CPV/T) is investigated in order to evaluate its thermal and electrical performances for hot water loads referring to a textile industry application. Simultaneous production of electrical and high-grade thermal energy is provided with a CPV/T system at high temperature. The electrical and thermal performances of the system operating in Monastir city, Tunisia, are numerically investigated. Using our developed simulation, the heat and electrical power of the system have been analyzed for four typical days of the year. Furthermore, the effect of water flow rate, the outlet fluid temperature and the loss coefficient of the collector have been involved to identify their impact on the output power.

The simulation process led to evaluate the energy feasibility of the CPV/T system and a comprehensive economic analysis study of the system under investigation was performed proving its viability in comparison with the conventional one.

Keywords:
Solar energy cogeneration, CPV/T, industry application

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1. Introduction

Tunisia is located in the most insolated regions of the globe for which the annual average global solar radiation exceeds the value of 2000 kWh/m² (El Ouderni et al, 2013); making it one of the promising candidates for meeting its energy needs based on solar energy in the near future. In fact, the share of renewable energies in the production of Tunisian electrical power would achieve 30% in 2030. Developments made over the last decade are very promising as the cost-price of renewable electrical power is continuously decreasing.

Energy from the sun can be directly converted into electrical and thermal energy by the use of (CPV/T) technology. It is a key barrier to achieve economic viability and widespread adoption of PV losses related to high operating temperature. In fact, conventional PV systems were suffering during many decades from low electrical conversion efficiencies. This is due to the important optic and thermal losses. Hence, the use of such concentrating PV system will enhance greatly the effective solar density of PV cells. This issue cannot be fulfilled without using a cooling cell system which insures a moderate PV cells voltage.

Various performances of PVT collector types had been studied. Concentrator type can be used for elevating the coolant temperature from medium to high level. In this condition, the numbers of commercially available collectors and systems are still very limited, because of the major obstacles like costs and product reliability. The numerical analyses become more comprehensive with the use of powerful analytical tools (T. T. Chow, 2010). X. Xu et al (2013) studied the heat transfer characteristics and fluid mass flow in a hybrid concentrating photovoltaic/thermal system (HCPV/T) with a tree-shaped channel. Results show that the straight channel heat sinks are more commonly used in the cooling because it guarantees a uniform temperature distribution between PV cells. Whitfield et al (2000) investigated several designs of small concentrator systems, which can be significantly cheaper than conventional ones. The prototypes have proved to be robust, reliable, and capable of operating for long periods. Cappelletti et Al (2015) studied an experimental and numerical approach to determine the capability of a concentrating PV/T system to heat water. Results presented a 64% thermal efficiency and concluded that the presence of one-way double channels could be preferred for higher temperature because it increases the difference of temperature in the receiver and could avoid damage to the operability of photovoltaic cells. Zondag H.A et al (2002) have developed numerical models for the simulation of thermal efficiency of a combined PV-thermal collector. It is found that all models are easily adapted to other configurations and provide more detailed information, as required for a further optimization of the collector. Reatty et al (2015) proposed an analytical method to allow the determination of the energy produced from a linear solar collector. Their method does not depend on the shape of the collectors and, therefore, it is suitable for diverse systems.

In the last years, a new important aspect of solar cell was discovered. A semi-conductor junction stack that absorbs solar energy on a wider light spectrum than conventional PV cells is used in concentrating solar system. CPV/T systems are based on cells with a high conversion efficiency, in particular those based on III–V materials which can tolerate higher temperatures. The stack of photoelectric material (Ga, As, In, B, P) constitutes a high performance PV cell. Nowadays, the use of triple junction cells is more adopted. They have an efficiency characteristic which can be increased logarithmically with the concentration level and they are less influenced by the cell temperature increase (Buonomano,2013;Del Col,2012;Basco,2012;Zondag,2008;skoplaki,2009) . Such cells are commercially available today; and the efficiencies of advanced cells under development have recently reached very high values. Researchers are performing a special effort seeking to realize a CPV/T collector providing elevated-temperature heat at high electrical efficiency. A possible alternative for increasing fluid CPV/T outlet temperature without decreasing PV electrical efficiency may consist in the use of an active coolant which absorbs the heat released from the cells. The amount of absorbed energy by the coolant fluid is very interesting on one hand to cool PV cell temperature and by the way to maintain a nominal operating voltage at its terminal buses junctions. In the other hand, this heat energy can be used in Rankine cycles for electricity production, cooling systems and so forth.

Unlike solar PV system, CPV/T technology is not well developed around the world. However, several research studies were established to investigate CPV/T system in laboratory scale and industrial cases. These works studied almost the thermal and electrical efficiencies of such technology. Calise et al (2012) studied a parabolic trough photovoltaic/thermal collector with a triangular linear receiver equipped with triple junction cells InGaP/ In GaAs/Ge (Indium-Gallium Phosphide/ Indium-Gallium Arsenide/ Germanium) which significantly increase the electrical efficiency of the system. Systems’ performances were improved by the use of this type of PV cells because their efficiency is expressively better than the silicon cells, especially when the operating temperature is high. The research institute of the National University of Australia has carried out a detailed study on a thermal photovoltaic concentration system (Xu et al, 2012). Several studies investigated the design of the collector as well as the PV cell characteristics. They worked on two CPV/T systems with a comparison between two types of

PV cells. They concluded that GaAs cells have the best electrical efficiency thanks to their low resistance in series; however, crystalline cells are characterized by the better thermal efficiency. Besides, when the direct solar radiation exceeds a certain value, the production performances are decreased because of the high series resistance leading to high power losses. However, for the GaAs cells the performance was always excellent. A parabolic trough photovoltaic thermal prototype was experimentally investigated by Coventry (2005).The concentration ratio of the system under investigation was 37, the thermal and electrical efficiencies were rated respectively 58% and 11%. Due to the complexity of the technology, GIBART and Buffet (2008) have chosen to study a cylindrical reflective surface. For a fixed cooling flow rate and two different water inlet temperatures, the results showed that the electrical and thermal efficiencies are higher than those of a conventional system. Moreover, economically, it is expected that the system will have a return time of 10.5 to 12.8 years. S.Quaia, 2012; Ming, 2011;Rosell, 2005 at the Center for Sustainable Energy Systems (CSES) at the Australian National University (ANU) developed a combined solar collector (CHAPS). The first commercial scale demonstration for this technology was completed by the end of 2004 and it provided electricity and hot water for the heating of a residential college at the ANU. The solar cells manufactured by ANU were mono-crystalline silicon cells. They were designed to have a low resistance in series around 0.043 Ωcm^2 and it was characterized by a yield around 20% at 25°C (under a concentration ratio of 30). The measured results showed a combined efficiency of 69%. Linear CPV/T performances were studied by N. SHARAN et al (1987); three types of absorber shapes: tubular, vertical plate and horizontal plate. Comparative performances have been presented and discussed. Results showed that the efficiency of the solar concentrator system with a tubular absorber can be distinctly noticed compared to the other configurations, as it provided the maximum electrical power, the optimum electrical efficiency and the lowest cell temperature.

Distinctive applications of CPV/T systems have also been studied by several researchers. Xu et al (2011) analyzed a novel low-concentrating solar photovoltaic/thermal system integrating a heat pump system with both electrical and thermal output power. Experimental results showed that the output electrical efficiency is 17.5% and the system heated the water from 30°C to 70°C. The generated hot water could be used for domestic hot water supply, space heating or a solar cooling system. Alili et al (2012) investigated a novel application for a hybrid photovoltaic/thermal collector. The hybrid collector is used to drive a hybrid air conditioner. The overall system performance was compared to the performance of a conventional vapor compression cycle (VCC), which is widely used in the UAE, powered by photovoltaic panels and a solar absorption cycle driven by evacuated tube collectors. The results showed that this system is very effective in meeting the humidity and temperature requirements of buildings in hot and humid climates. The overall coefficient performance of the proposed system is found to be higher throughout the year than that of the other solar air conditioners. Chemisana et al (2011) studied the coupling of a linear Fresnel concentrator with a channel photovoltaic/thermal collector. Experimental results are encouraging because the total efficiency is over 60% when the concentration ratio is above six suns.

The perspective of using high-temperature in CPV/T systems is very interesting since it extends the number of possible applications. But, such temperature cannot be reached by conventional PV cells since their voltage drops to low values around high temperature (Mittelman et al (2007). While higher operating temperatures increase the potential use of the cogenerated heat, it decreases the electricity production (calise, 2012; Xu et al, 2012; Conventry, 2005). In fact, for high-temperature the most suitable PV cells for CPV/T systems is the triple-junction whose nominal efficiency of 40% at 25°C drops around 20% at 240°C. Therefore, the adoption of such materials may lead to operating high temperature at reasonable conversion efficiency (slightly lower than 20%) (Calise and Vanoli, 2012). With this regard, Mittelman et al (2007) studied a CPV/T, which can operate at temperatures above 100°C .The thermal energy produced is useful for processes such as refrigeration, desalination and steam production. Buonomano et al (2013) investigated a collector based on a combination of a parabolic dish and high efficiency solar photovoltaic cells. The main aim of the study was the design and the analysis of a concentrating PVT system, which is able to operate at reasonable electric and thermal efficiency at 180°C. Kribus et al (2007) determined that the concentration operations have beneficial effects on high-temperature operations and in these conditions; triple-junction cells can approach a nominal efficiency of 40%. They found that the output of concentrator systems composed of high-efficiency triple-junction solar cells was higher than a conventional one with crystalline-silicon PV cells because of the high efficiency and superior temperature coefficient (Mittelman et al, 2007). Nishioka et al (2006) studied a CPV/T system with triangular receiver recovered with triple junction cells. Results showed that the performance of the system still excellent even when the fluid temperature is very high (>100 °C).

In particular, few numbers of researchers (Calise and Vanoli, 2012; Mittelman et al, 2007;Jiang et al,2010) performed some experimental and theoretical surveys dealing with CPV/T systems. A novel miniature CPV/T based on a dish concentrator and a thermal model of the system was developed in order to predict its performance. The operation at high temperature of CPV/T systems was also analyzed for both solar cooling (Mittelman et al, 2007) and water desalination applications .Otanicar et al (2015) proposed an innovative CPV/T system that incorporates spectral beam splitter and vacuum tube sensors. Results showed that the thermal load of the cell can be reduced and the outlet temperature can be up to 250 or 300°C. Recently, Kribus et al (2006) investigated the performance of CPV/T poly-generation systems at elevated temperatures using simplified models. The results showed that using the waste heat of CPV/T systems for cooling could lead to higher overall efficiency than trying to generate additional electricity. Among, the most important foreseeable applications were single effect and double effect absorption cooling, water desalination, steam production and other industrial process. The results of these studies and demonstrations showed that CPV/T systems hold very high potential for market penetration in the energy sector due to their unique features. Indeed, CPV/T at high temperature was studied by Buonomano et al (2013); the collector was based on a combination of a parabolic dish and high efficiency solar photovoltaic cells. The CPV/T system was designed to be integrated in a solar heating and cooling system and it drives a two-effect absorption chiller. Also an example consists in the use of the high-temperature heat provided by the PVT to drive a heat engine (Vorobiev et al, 2006) an Organic Rankine Cycle (ORC) (Kasmadakis, 2011) or a Solar Heating and Cooling system (SHC) (Calise and Vanoli, 2012).

Most of the studies in the literature are focused on the heat transfer improvement of a CPV/T system with medium outlet temperature and there are a limited number of papers in which the outlet temperature is high. However, in the present study, a CPV/T system operating at high outlet temperature is proposed and its output performances will be evaluated before being used in a textile industry application “Tissue Dyeing”. Differently from traditional photovoltaic systems, the CPV/T system, allows recovering thermal energy at high temperature with high electrical efficiency; hence, a coupling between a CPV/T system and storage devices allows fulfilling the heat demand. Detailed analysis will be performed using TRNSYS simulation tool (Klein et al,2006) to identify the significant parameters affecting the overall performance. Indeed, an optimal design of this system for this application will be proposed. The proposed model is applied to improve the co-generation system capacity and to retain competitive prices. Also, the model will be used to size the optimal CPV/T system components, to evaluate the output temperature and power and to compare it with the conventional system in order to prove its capacity for energy supply and its economic viability.

2. Design and dynamic model of CPV/T system

In this study, we aim to investigate the effects of several parameters influencing the performance of a CPV/T system dedicated to satisfy the thermal energy loads related to a textile industry application (BENETTON industry). This prototype is a CPV/T system which is presented in Fig. 1. It consists of a parabolic trough concentrator, a receiver, a triple-junction PV cells (InGaP/InGaAs/Ge) and a sun tracking system. The bottom surface of the evacuated tube in the parabolic concentrating solar collector is covered by PV cells and it is located at the focus of a parabola made of some highly reflective material. As such, parabolic concentrating collectors do not receive a significant amount of diffuse radiation. Their useful output energy is dictated by beam radiation as all the incident beam radiation on the aperture area is reflected onto the absorber contained in the evacuated tube. The solar cell arrays are superimposed on the lighting tube of the receiver, and generate electricity when the sunlight is concentrated on them. Depending on the temperature of the cooling fluid, the electrical efficiency penalization can be reduced by cooling the photovoltaic cells; and heat can be recovered. In fact, it must be considered that concentrating solar radiation devices determine an increase of radiative flux on PV, increasing its operating temperature and therefore decreasing its electrical efficiency. Hence, it is compulsory that the PV cells would be cooled by the coolant and especially where the flow would be fully developed. Here, the solar receiver plays a key role in the performance of energy generation since it houses the solar cells producing electrical power and it is used to absorb the heat of PV cells for further uses.

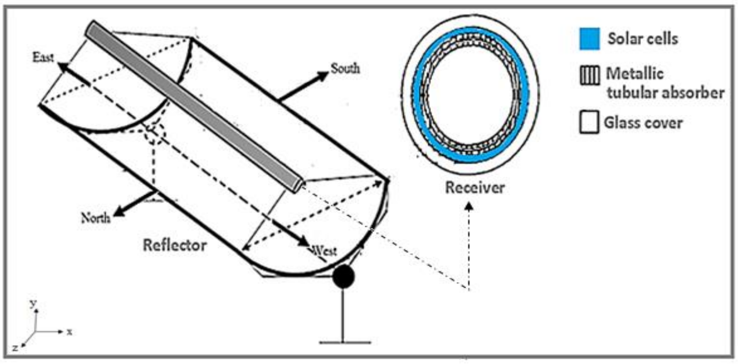

Fig. 1. Schematic representation of the concentrating photovoltaic thermal system (CPV/T).

The CPV/T system tracks the sun to collect the maximum of the direct beam radiation. The solar energy collected will be converted to electric power and thermal energy via the PV cells and the heated receiver tube. Concentrating photovoltaic thermal systems can operate at higher temperatures than conventional system such as flat plate collectors. The cooling system can be adjusted to provide a wide range of temperatures by regulating the flow rate of the cooling fluid. Therefore, thermal energy may be provided to a variety of thermal processes.

The thermal performance of the concentrating photovoltaic/thermal system depends essentially on a modified loss coefficient (o), it is based upon the standard collector loss coefficient (o_s) provided by collector manufacturers, the mass flow rate of fluid flowing through the collector (g_t), its specific heat (C_{fd}) and the concentration ratio of the collector (Gc) :

$$\mathrm{o} = \begin{cases} o_s, \ \frac{o_s}{g_t C_{fd} Gc} \geq 1 \\ g_t C_{fd}\left(1 - e^{\frac{o_s}{g_t C_{fd} Gc}}\right), \frac{o_s}{g_t C_{fd} Gc} < 1 \end{cases} \tag{1}$$

The concentration ratio (Gc) can be defined as the ratio of the aperture area A_{ap} to the receiver area A_{rec}:

$$\mathrm{Gc} = \frac{A_{ap}}{A_{rec}} \tag{2}$$

The CPV/T system produces both electrical and thermal energy, and each type of the produced power is described by a separate expression. The overall performance of the CPV/T is often evaluated using the well-known thermal and electrical efficiencies, which are conventionally related to the incident beam radiation and to the collector aperture area.

The electrical efficiency of the triple-junction cells,η_{pv}, depends on the concentration ratio,G_c, and to the PV cell temperature, T_{pv}, and it can be computed by the following equation (Buonomano et al, 2013;Minget al, 2011;Calise and Vanoli, 2012;Kribus et al, 2006):

$$\eta_{pv} = 0.298 + 0.0142 \ln G_c + [-0.000715 + 0.0000697 \ln G_c]\ (T_{pv} - 298) \tag{3}$$

At any time-step, the fluid outlet temperature,T_{out}, can be calculated using the following expression (Klein et al 2006):

$$T_{out} = T_{\mathrm{amb}} + o_{\tau\alpha} \times IAM \times G \times \frac{G_c}{o_s} \tag{4}$$

where T_{amb}, $o_{\tau\alpha}$, IAM are respectively the ambient temperature, the thermal collector loss coefficient and the Incidence Angle Modifier.

G, G_c o_s are respectively the beam irradiation, the concentrating ratio and the standard collector loss coefficient.

The PV module temperature $T_{pv,mod}$ can be then calculated with respect to the following equation (Klein et al 2006):

$$T_{pv,mod} = T_{\mathrm{amb}} + \frac{1 - \frac{\eta_c}{\tau\alpha}}{\frac{G\tau\alpha}{o_s}} \tag{5}$$

where $\eta_c, \tau\alpha$ are respectively the electrical efficiency at reference temperature and the module transmittance-absorption

For a given incident radiation energy on the collector aperture, each type of the produced power is described by a separate expression. The thermal output power depends essentially on the output fluid temperature and its characteristics such as the specific heat and the mass flow rate. The electrical output power depends mainly on the incoming solar radiation, the PV module efficiency and the outlet temperature. It is reduced by the electricity lost in the module connections (η_{mod}), the inverter and the optical losses (η_{inv}, η_{op}).The two forms of the output power can be expressed by the following equations (Buonomo et al,2013; Kribus et al,2006):

$$P_{elec} = G_c G A_{pv} \eta_{op} \eta_{mod} \eta_{inv} \eta_{pv} \quad (6)$$

$$P_{th} = \dot{m}_{fd} C_{fd} (T_{out} - T_{\text{in}}) \quad (7)$$

where C_{fd} is the specific heat at the average fluid temperature, $\dot{m}_{fd}$ is the mass flow, and T_{out} and $T_{in}$are the outlet and inlet temperatures respectively of the fluid.

The electrical and the thermal efficiency, (η_{th}, η_{elec}), of the system can be expressed respectively as the ratio between the electrical output power and the thermal output power to incident solar radiation on the aperture area of the CPV/T system as follows (Buonomano et al, 2013;Minget al, 2011;Calise and Vanoli, 2012;Kribus et al, 2006, Davide et al,2014):

$$\eta_{elec} = \frac{P_{elec}}{A_{ap} G} \quad (8)$$

$$\eta_{th} = \frac{P_{th}}{A_{ap} G} \quad (9)$$

CPVTs' high efficiency and multi-output nature can be applied for many industrial applications using high temperature. In this context, a CPV/T prototype will be designed and optimized to simulate its contribution for the cogeneration system production in order to meet the calorific and electrical requirements of a textile factory located in Monastir city. In fact, the energy produced has to meet the needs of the dyeing task of this company. Thus, we intend to establish the optimal size of the CPV/T installation based on a simulation of its performances using TRNSYS software. Solar tracking systems, weather data appropriate to the location, a better arrangement of the PV cells and a suitable sizing to the needs are crucial. Consequently, the simulation results will be used to evaluate energy and economic performance of the proposed CPV/T system.

2.1.CPV/T simulation model

A sensitivity analysis of some parameters will be made by TRNSYS simulations. The installation of the CPV/T system is modeled with this well-known software. If all the components of the system have been identified with a mathematical explanation of each component, parameter values of the geometry and the weather conditions used in the simulation are entered as input parameters and the output results are registered in the output format.

The use of this development model allows the acquisition of some parameters. Its validity is tested by comparing simulation results to experimental ones and good agreements were being noted. TRANSYS is a powerful simulation software, comprehensive and extensible, and it is dedicated to the dynamic simulation of energy systems. We have also noticed that TRNSYS is effective and support the choice as a reliable simulation tool which can be used to predict the performances of CPV/T system and to show the utility of all works which will be carried out in this study.

In order to investigate the dynamic thermal and electrical behavior of CPV/T system, a parametric study will be performed under different operating conditions. The influence of several factors such as date, mass flow rate, outlet temperatures of the working fluid and temperature of PV cells, collector loss coefficient on the instantaneous electrical and thermal performance will be analyzed. All simulations were introduced in the TRNSYS model, we note that all tests are presented in local time (GMT+1), we use a time step equal to an hour, and the geographical conditions of Monastir (Tunisia) region (35°46.6794′ N latitude, 10°49.5702′ E longitude and 20m above sea level).

Various assumptions have been taken into account to facilitate the theoretical analysis; the thermal exchanges in the absorber are studied according to the following assumptions:

- The dimension of the receiver and the surface of the collector are constant,
- The ambient temperature around the solar collector and the inlet temperature of the water are uniform,
- The solar flux at the absorber is uniformly distributed,
- Thermo-physical properties of the collector components are constant.

The parameters characterizing the simulated CPV/T system are illustrated in Table 1.

Table 1: CPVT design parameters used in the simulations.

	Parameter	**Value**
Collector	Length Width	4m 1m
	Rim angle	90°
	Concentration ratio	10
Receiver	Diameter	0.1m
triple Junction PV cell	Thermal conductivity Emissivity Inverter efficiency Module efficiency	50w/m.k 0.98 0.9 0.9
coolant fluid (water)	Flow rate Inlet temperature	10Kg/h 25°C

2. Results and discussions

To study the CPV/T behavior under Monastir climatic conditions, the numerical simulation has been carried out on four typical days of the year; the equinoxes of spring (21th March) and autumn (22th September) and days of the solstice summer (21th June) and winter (21th December) are considered in the simulation.

The hourly outlet temperature of the coolant during the above-mentioned days is shown in Fig.2. (a). Also the hourly electrical and thermal power of the CPV/T is illustrated respectively in Fig.2. (b) and Fig.2. (c).

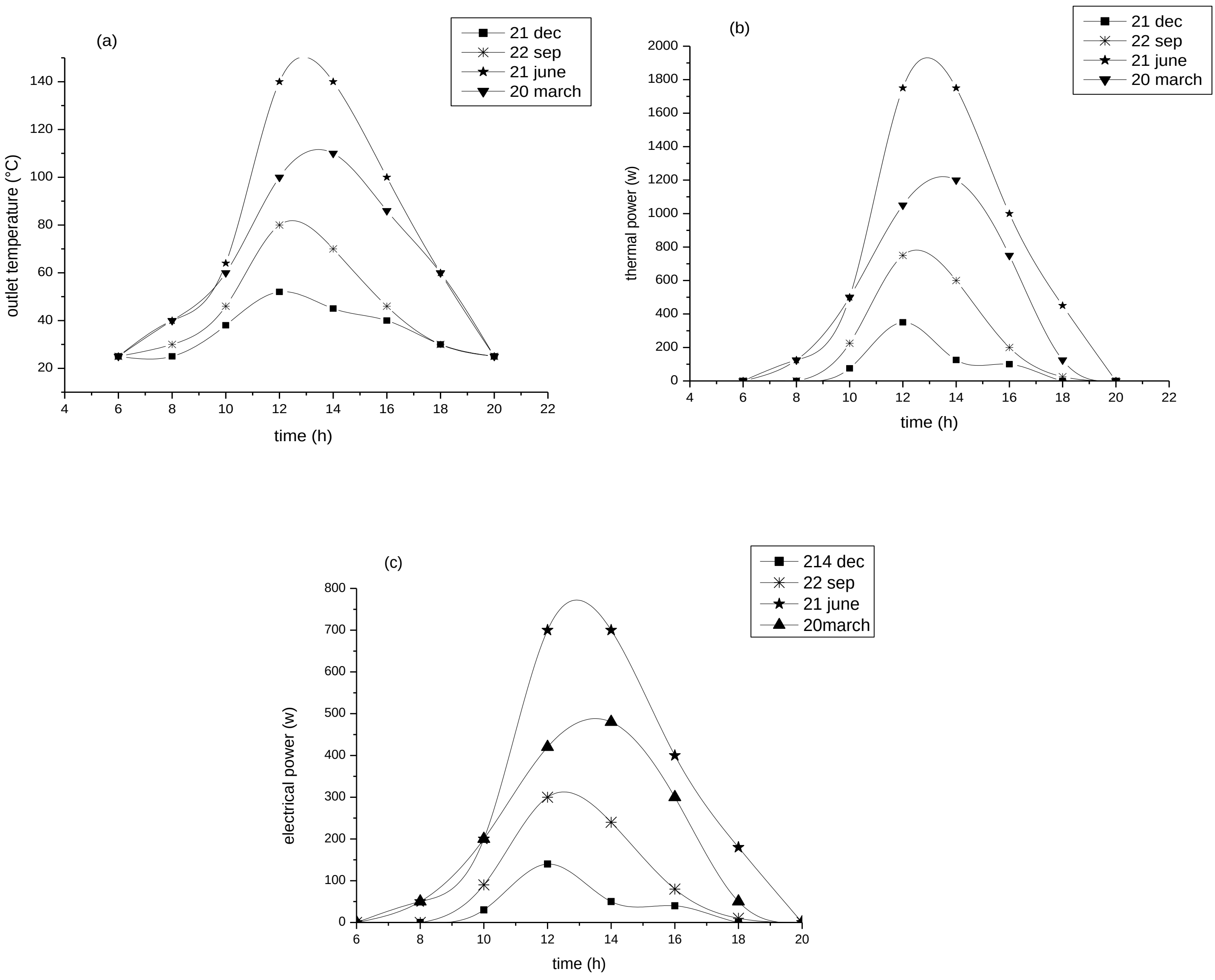

Fig.2.

Fig.2. Instantaneous variation of the outlet temperature (a), thermal power (b) and produced electricity (c) of the CPV/T module during the solstices (summer/winter) and the equinoxes (spring/autumn).

It is clear that the trends of variation of these parameters are linearly dependent to the solar radiation profile. As shown in Fig.2. (a)), the CPV/T outlet coolant temperature begins to increase from sunrise to midday from which it will decrease until the sunset. The maximum production of electricity and heat output power are registered at noon and they differ from one date to another (Fig.2. (b), (c)). The increase of the solar radiation leads to an increase in solar heat gain, so thermal and electrical efficiency increases. The value of the useful power absorbed by the receiver tube during the summer is greater than the gain power in the winter. The beneficial periods of the installation in winter are also shorter compared with those during the spring because the sunshine duration is shorter in winter than during other seasons of the year. We note also that the maximum thermal and electrical powers occurring in the summer solstice day while the minimum values are observed in the winter solstice day. This can be explained by the change in elevation of the sun and its apparent path in the sky and by the higher solar radiation occurred in summer day relatively compared to the lower solar radiation in winter day.

Fig. 3 illustrates the outlet temperature distribution and the cogenerated powers in terms of various flow rate values. In fact, when the flow rate is increased, a decrease in the outlet temperature is observed (Fig.3 (a)). This is can be explained by the fact that the convection heat transfer coefficient is very sensitive to the coolant flow rate variation; the increase of the mass flow rate increases the convection heat transfer coefficient and therefore the heat transfer rate. Indeed, at high flow rate, the flow residence time in the receiver becomes too short and less heat can be removed resulting in higher receiver channel temperature. So, the water temperature cannot be raised as much as estimated, leading to a decrease in the thermal output power (Fig.3 (b)) and an increase in the electrical one (Fig.3 (c)). Therefore, in order to optimize the CPV/T performance, it is thought that an optimal mass flow rate exists allowing the optimum thermal output power without dropping the electrical efficiency.

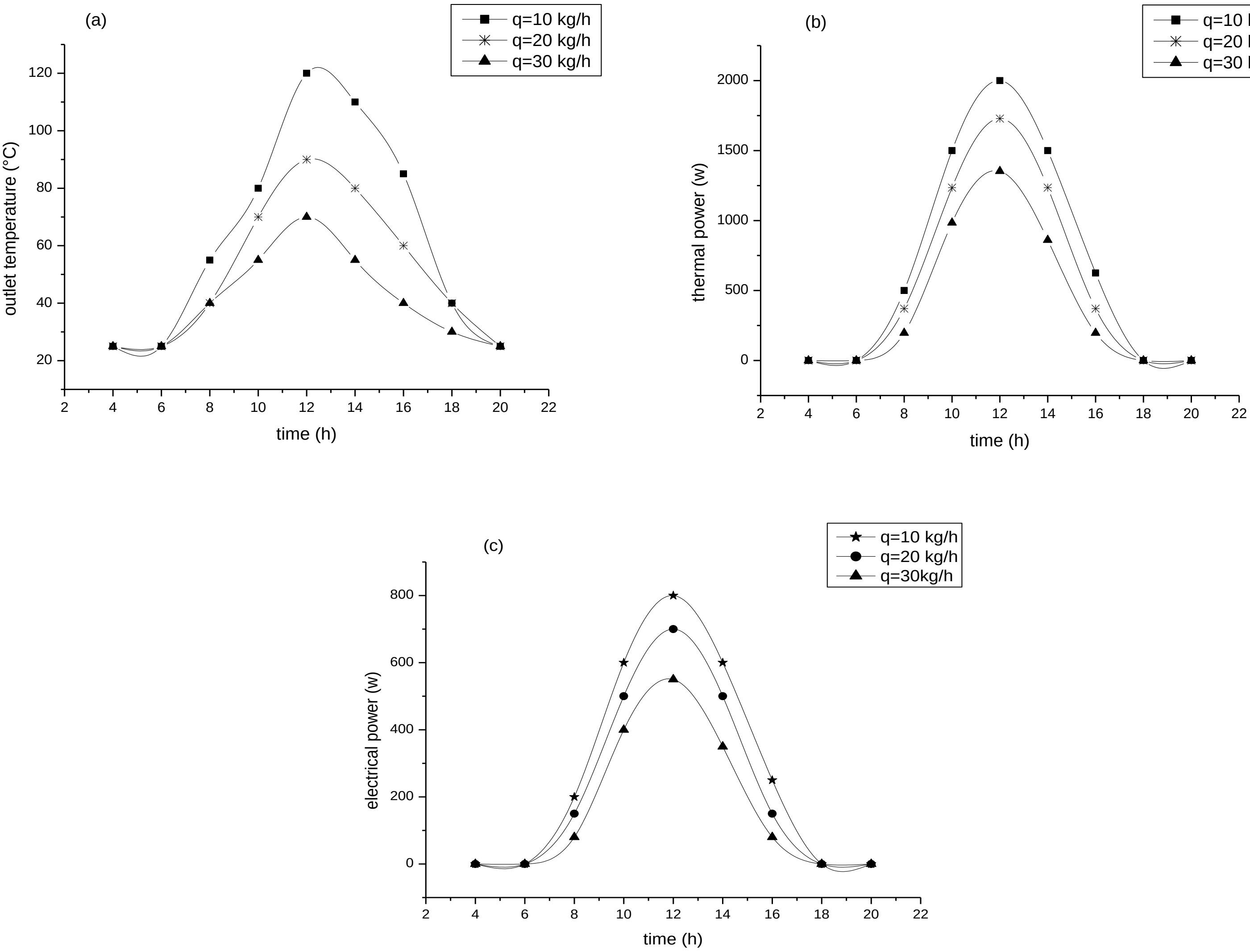

Fig. 3. Instantaneous variation of outlet temperature (a), thermal power (b) and produced electricity (c) of the CPV/T module in terms of mass flow rate values.

As shown in Fig. 4(a), during the day, the increase of the solar radiation leads to an increase in the outlet temperature. In fact, the higher the radiation is, the higher both radiative and convective losses are, because of the increase of the receiver temperature. Fig. 4(b) shows the variation of the thermal and electrical efficiencies in terms of the outlet water temperature. The thermal efficiency increases as the outlet water temperature increases due to higher thermal losses to the environment since the none converted energy to electricity is mostly regained as heat. This fact leads to decrease the PV cell temperature and therefore, its electrical efficiency rises.

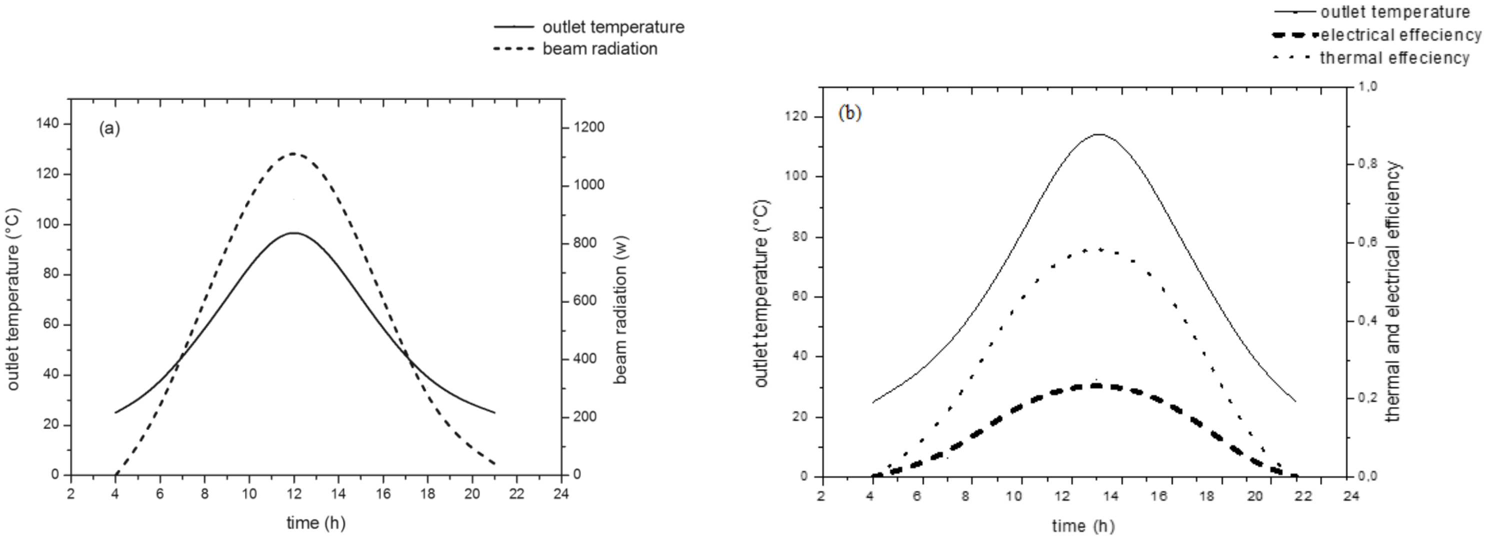

Fig.4. Instantaneous variation of the outlet temperature, beam radiation (a), electrical and thermal efficiencies (b) of the CPV/T module (b).

Fig.5 shows the variation of CPV/T performances in terms of different values of the collector loss coefficient (o). Decreasing the heat loss coefficient leads to an increase in thermal and electrical outlet energy. From Fig.5, one can observe that with low values of loss coefficient, the recorded outlet fluid temperatures are higher than those corresponding to high loss coefficients. In fact, the outlet fluid temperatures reach its maximum values equal to 130°C and 100°C corresponding respectively to loss coefficient values of 2 and 10. Besides, this caused a decrease of the maximum heat capacity and electrical power respectively from 580W to 450W and from 1300W to 1100W (fig. 5(b) and (c)). We can then notice that the produced power is inversely proportional to the heat loss coefficient. We can also deduce that it is fundamental to reduce loss damage to achieve optimum performance.

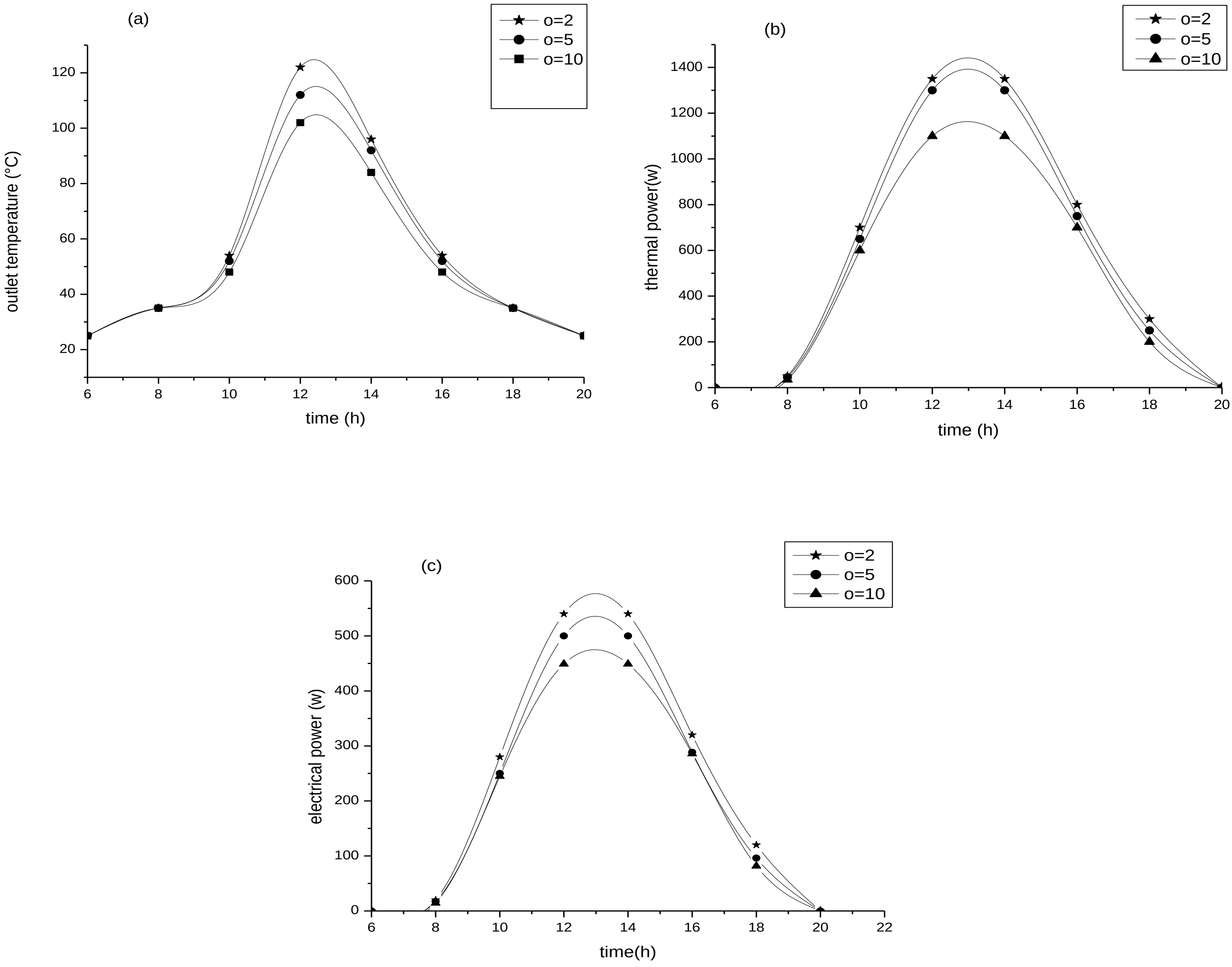

Fig. 5. Instantaneous outlet temperature (a), thermal power (b) and produced electricity (c) of a CPV/T module in terms of collector loss coefficients.

3. Technical sizing of the proposed CPV/T system for the industry application

A sensitivity analysis of some parameters has been made in order to evaluate electrical and thermal energy produced by a CPV/T system. Concentrator photovoltaic solar thermal energy offers enormous potential, but has not yet benefited the industrial sector, this energy can provide a natural and economical form of energy that a large part that the industry will need. Moreover, it has the potential of reaching competitive costs compared to conventional power. Hence, the CPV/T cogeneration plant may offer a significant advantages in economic viability particularly for medium and large thermal-energy loads. The energy demands (heating and electricity) of the industry are determined relating to many considered conditions. For the current industrial load, the dyeing task of BENETON industry has been considered.

The company of BENETTON, located at Monastir city, was created in 2003. After the dismantling of the multi-fiber agreement, the company decided to carry out two new projects in Tunisia, where several methods are applied on tissue which requires a high demand of electricity and gas consumption. Dyeing task is a technique for coloring a textile material in which a dye is uniformly applied to the tissue support. The penetration of the dye into the fiber requires that the fiber should be accessible. Nevertheless, the fibers are not accessible to the dye beyond the glass transition temperature, which sometimes is above 200°C. The textile factory uses a gas boiler to accomplish this task. The daily and monthly demands of this application and all its technical needs are summarized in table 2.

Table2. Textile industry Loads for dyeing task.

Data (Dyeing task)	**Value**
Water flow rate (day)	15 m^3
Focal Power Max (burner)	4650 kW
Highest temperature	200 °C
Gas consumption (m3/month) / (m^3/day)	105190 / 3504
Electricity consumption (kWh/month)/ (kWh/day)	125 000 / 4167

In order to satisfy the hot water demands related to the dyeing task, it is necessary to determine the optimum configuration of the CPV/T system which guarantees the maximum possible water outlet temperature. The analysis was performed for a system with storage tank of solar heat. In fact, basing on scenarios when there is a necessity for an auxiliary heat support, the addition of thermal storage may improve the competitiveness of the combined system by reducing the hourly need for a backup heat source and therefore the consumption of conventional energy.

Table3. Technical configuration of the proposed CPV/T system.

	Parameter	**Value**
Collector	aperture area	10*4m^2
	Rim angle (θ)	90°
	Concentration ratio	20
	Optical efficiency	0.9
Receiver	Diameter	0.2m
triple Junction PV cell	Thermal conductivity	50 w/m.k
	Emissivité	0.98
	Inverter efficiency	0.9
	Module efficinecy	0.9
coolant fluid (water)	Flow rate	220 Kg/h
	Inlet temperature	25°C
Simulation time	Day	21 juin

The proposed CPV/T system, described in table 3, for the industry dyeing task is equipped with a dual tracking system composed of two axis, a vertical one which ensure to follow the solar azimuth displacement while the horizontal axis track the angular high of the sun. Fig.6 illustrates the hourly variations of the outlet water temperature, the hourly output thermal and electrical power on the summer solstice day. One can observe that the outlet hot water temperature reaches a maximum value of 220°C at midday and attain values about 200 °C around solar noon, which meet the required temperature of dyeing. Moreover, the diurnal cumulated electrical energy is about 56 kWh with an average power of 3 kW while the thermal energy capacity of the CPV/T prototype produces 198 kWh with an average power rating 11 kW. (Fig.6)

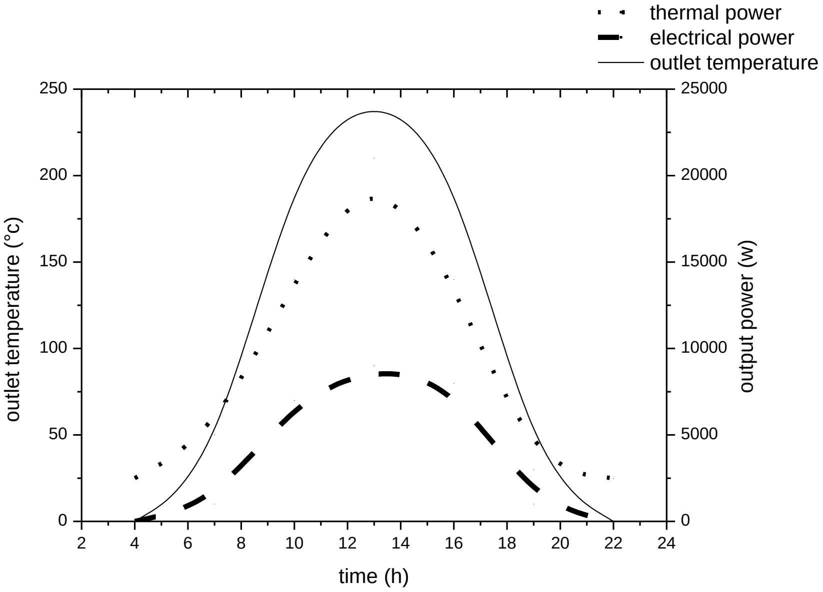

Fig. 6. Hourly variations of the outlet water temperature, the hourly output thermal and electrical power on the summer solstice day of the proposed CPV/T system

To insure a high-energy efficiency of the whole system, a storage tank has been combined. In addition, to limit heat losses on the distribution line it is recommended to set up a control system, so that the boiler has to supply only the heating of the fluid into the storage tank. Fig.7 shows the variation of the hourly heat losses of the storage tank to the environment. It is clear that these losses increase linearly during the night because of the strong temperature gradient whereas as soon as the sun rises, it oscillates around the value of 110 KJ/h.

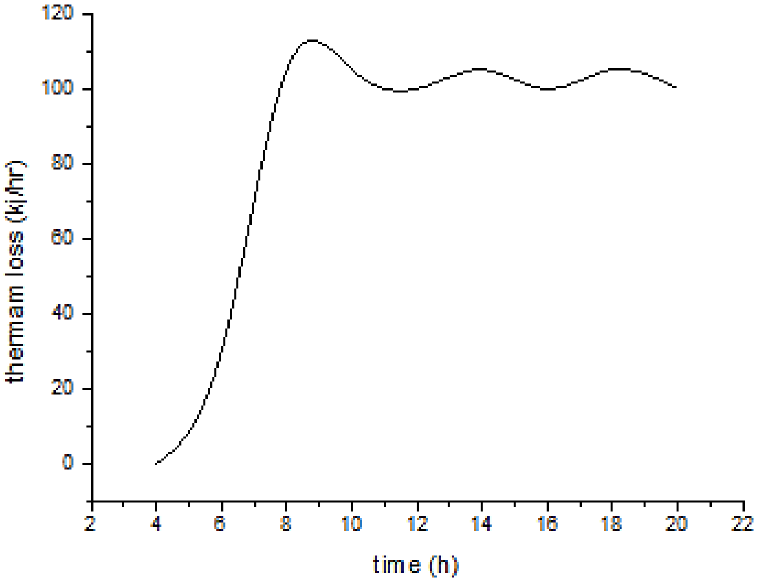

Fig.7. Instantaneous profile of the thermal energy losses from the storage tank to the environment.

These results are very encouraging since the proposed solution proved its capacity to satisfy the thermal load of the dyeing need of the plant with high thermal and electrical efficiency and it presents 20% of the industrial consumption. In fact, the maximum value of the thermal and electrical efficiencies were rated respectively 62% and 21% (Fig.8).

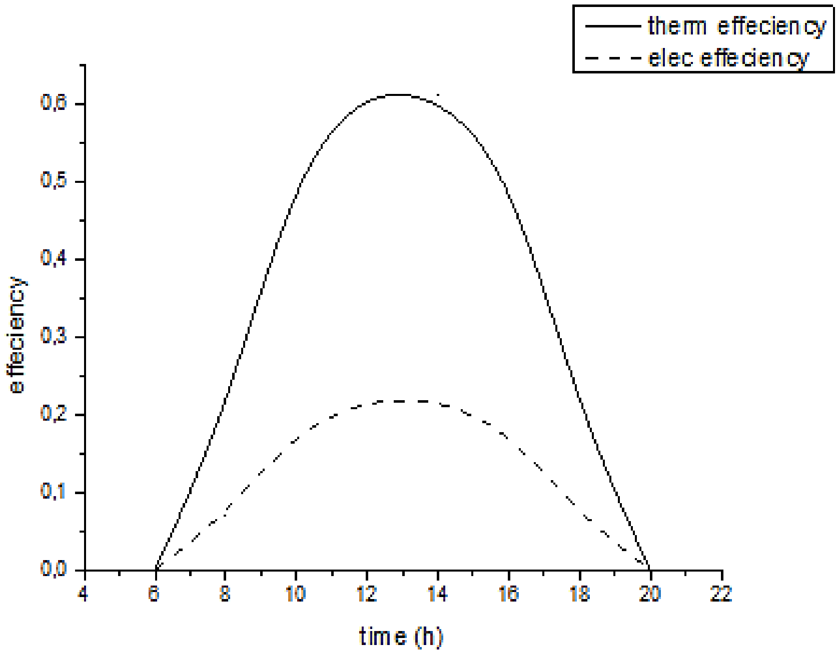

Fig. 8. Daily evolution of the electrical and thermal efficiency of the CPV/T.

We have developed an innovative process that deserves to be executed and developed, the energy efficiencies obtained are promising, and it is desirable that they are to be taken into account for a service not yet available in this company.

Hence, in order to satisfy the energy demands of BENETTON industry, it will be necessary to use three parallel CPV/T systems. Those systems dimensioned for the heat demand, uses three modules covering (40*3 m^2), and an outlet flow of hot water equal to 660 Kg/h and a storage tank of volume 0.66 m 3 (Fig.9).

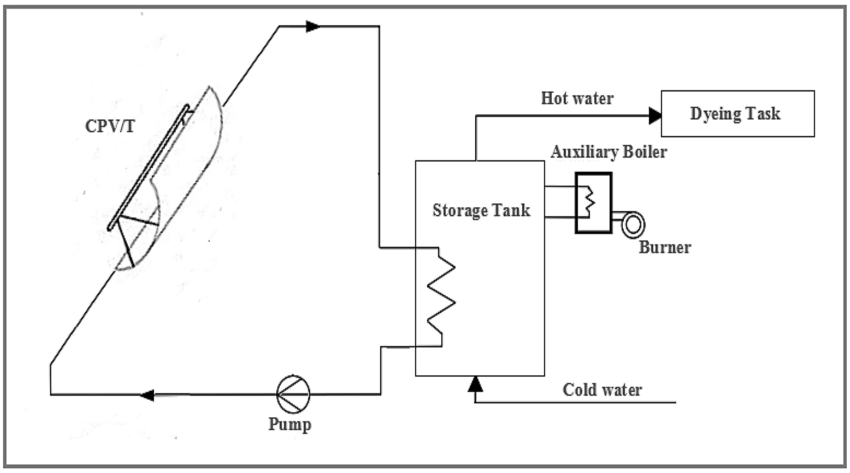

Fig.9. CPV/T system linked to the involved textile application.

4. Economic analysis of the proposed CPV/T system

The simulation model allowed us to evaluate the instantaneous thermal and electrical performance of the proposed CPV/T system plant by identifying its optimal characteristics for each component. The results show that a considerable amount of thermal and electrical energy can be produced by the proposed CPV/T. In fact, the monthly electrical and thermal production of the plant is respectively 4680 kWh and 17820 kWh.

The required natural gas and electricity for the dyeing task can be replaced by this solution, which has to prove its long-term economic viability. For this reason, an economic analysis has to be realized comparing the CPV/T system and the traditional system costs (gas boiler) operating under the same conditions.

The maintenance and operating costs of this installation$(C_{maintenance}, C_{operating})$ are associated with the modules cleaning, the control system, the imperfect component replacement, and the insurance in case of malfunctions due to weather conditions or user mismanagement. These costs depend on the system dimension and, together with the CPV/T system cost $C_{CPV/T}$ constitute the project cost $C_{project}$ (sheriff et al, 2006; Carlo and Fabio, 2013):

$$C_{project} = C_{CPV/T} + C_{maintenance} + C_{operating} \tag{10}$$

Also, the investment cost of the CPV/T system,, is estimated by considering the current costs of the various parts of the system (PV cells, inverter, pump, tank, tracking system, cables, etc.) The cost of the CPV/T system takes into account also the different necessary devices can be given by the following formula (sheriff et al, 2006; Carlo and Fabio, 2013):

$$\mathrm{C}_{\mathrm{CPV/T}} = C_{PVcells} + C_{optic} + C_{tracking\ system} + C_{additionnel\ components} + C_{cooling\ system} + C_{inverter} + C_{Tank} + C_{design} \tag{11}$$

Considering a system life span equal to 20 years, the yearly variation of the costs of the various sub-systems and the whole system are estimated and the yearly trend variations of the generated cash flows are described in Table 4.

Table 4: Economic analysis results.

CPV/T module cost		**CPV/T system cost**		**Economic analysis results**					
Component	**Cost(€)**	**component**	**Cost(€)**	**year**	**Cash-flow (€)**	**year**	**Cash-flow (€)**	**year**	**Cash-flow (€)**
PV cells	2800	Modules(3)	25176	0	-34233	7	-897	14	13206
Optic	2546	Cooling system	1215	1	-28008	**8**	**2297**	15	17845
Additional component	2076	Inverter	2025	2	-22349	9	5200	16	19335
Tracking system	970	Design and tank	5817	3	-17205	10	7840	17	0689
				4	-12528	11	10239	18	21920
				5	-8276	12	12420	19	23039
				6	-4411	13	14403	20	24056
Total	8392	total	34233						

From table results, we can calculate the profitability of the CPVT project to assess its potential by calculating the net present value (NPV) and the internal rate of return (IRR). The NPV can be computed using the following expression (sheriff et al, 2006; Carlo and Fabio, 2013):

$$\mathrm{NPV}=\sum_{t=0}^{T} c_f (1+k)^{-t} \tag{12}$$

Where c_f is the expected cash flow per period, k is the required rate of return, and T is the number of periods over which the project is expected to generate incomes (system life).

Thus, a discount pay-back (DBP) of about 8 years, a NPV of about 33 k€ and an IRR equal to 19%, compared to a discount rate of 10%, have been achieved representing satisfactory outcomes.

Indeed, in order to have a clearer view of the economic performance of the system taking into account the continuous increase of the gas and electricity costs during the next few years. A considerable average gain is earned basing on an annual economic study. In fact, the CPV/T reaches the required temperature for about 5 hours per day (around the midday), and during the period surrounding solar-noon an auxiliary boiler is necessary to be switched-on operating heating the water for the dyeing task. As it is shown in Fig.10 the hourly load for heating water of the dyeing task in the studied textile industry can be devised in two areas. The first one corresponds to hours around the midday when the CPV/T system work autonomously and guarantee the dyeing temperature 200°C, and the second one corresponds to a combined system (CPV/T +boiler) to reach the required temperature. Even though, during the boiler operating hours the amount of consumed gas and electricity will be reduced due the high outlet temperature insured by the CPV/T system. This will enhance the global system efficiency.

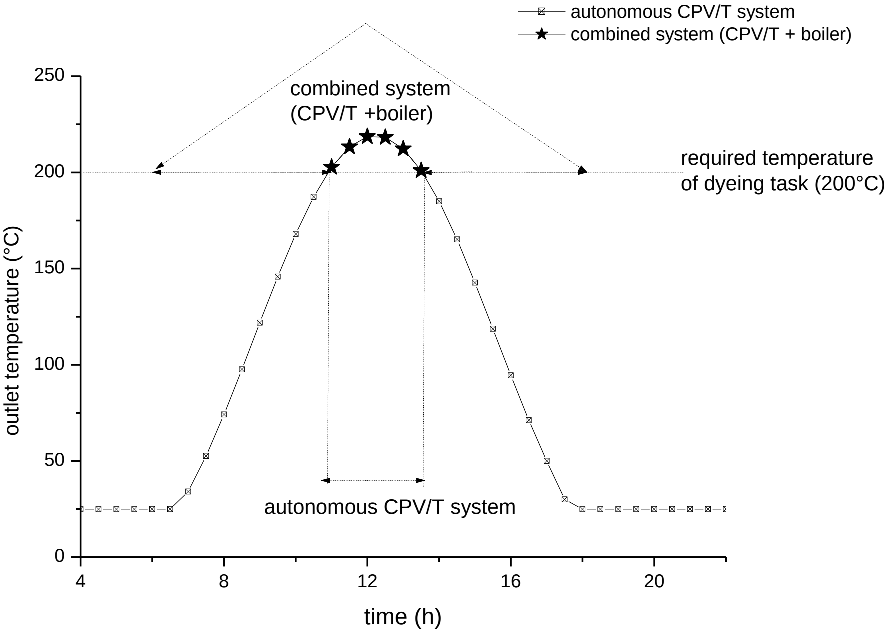

Fig.10.Hourly load for heating water of the dyeing task in the studied textile industry.

Otherwise, Fig. 11 shows a comparison between the analyzed operational costs of the cogeneration system and the conventional one (boiler). The analyzed operational costs include the prices of the consumed gas and electricity during the whole life span of the installation. One can observe that the analyzed operational costs of the conventional system are about two times those of the proposed system, using a CPV/T back-up system since the first operational years. Besides, due to the considered linear gas and electricity inflation prices the same conclusion can be deduced during the whole system life span. Even though, we did not consider the decreasing prices of the CPV/T technology (particularly the high-concentration PV cells), these outcomes prove the economic-viability of the cogeneration CPV/T system.

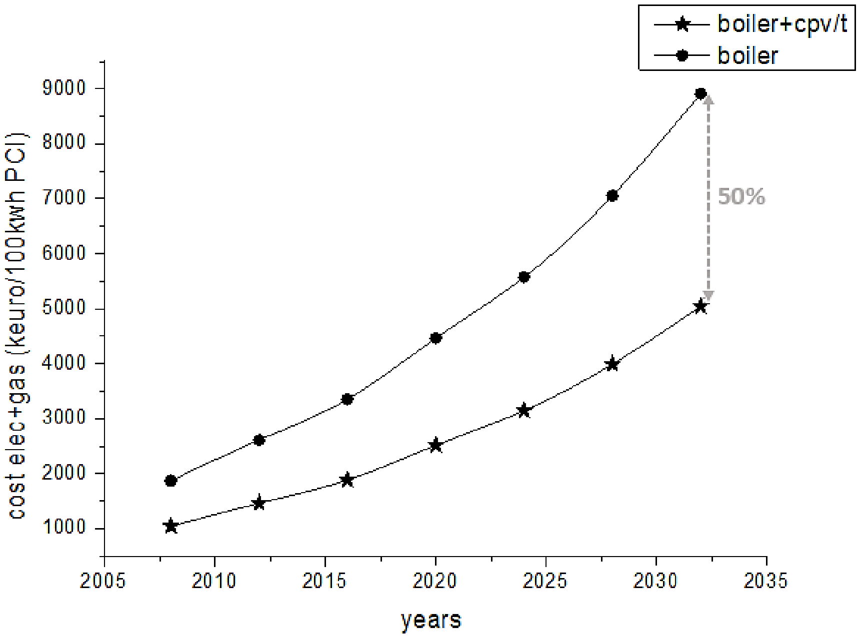

Fig.11. Comparative between the analyzed operational costs of the cogeneration system (CPV/T-boiler) and the conventional existing system (boiler).

5. Conclusions

In this paper, the potential of the concentrating photovoltaic technology has been evaluated under the conditions of Monastir city, Tunisia. This issue was based on the simulation of a (CPV/T) system under distinctive operating conditions, dedicated to a textile industry application.

The effect of several parameters has been investigated in order to optimize the performance of the proposed cogeneration plant. It has been concluded that the increase of the solar radiation leads to an increase of thermal and electrical efficiencies. Besides, low flow rates provide the best compatibility between electrical and thermal efficiencies because higher flow rates depress heat transfer between the fluid and the absorber receiver and therefore the useful energy absorbed will decrease and will influence the electrical power which reaches low values. Also, the increase of the useful absorbed heat power leads to a higher electrical efficiencies.

Moreover, it was found that the produced power of the CPV/T system is inversely proportional to the heat loss coefficient. Hence, it is fundamental to reduce loss damage to achieve optimum performances. The optimized CPV/T system with storage meeting the dyeing task loads is composed of three modules covering (40*3 m^2) and an outlet flow of hot water equal to 660 Kg/h. This proposed solution can supply autonomously an outlet hot water temperature reaching a maximum value of 220°C at midday and attain values about 200 °C surrounding this time lapse at least 5 hours per day. Hence, the diurnal cumulated electrical energy can reach the value of 56 kWh with an average power of 3 kW while the thermal energy capacity is about 198 kWh with an average power rating 11 kW. Assuming a CPV/T lifetime equal to 20 years, respect of an initial investment of approximately 34 k€, a NPV about 33 k€ and an internal rate of return equal to 19% have been found. This presents a promising outcome, and especially with the actual unremitting rise of electricity and gas prices and the decline in CPV/T technology cost.

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