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ORIGINAL ARTICLE

Feasibility analysis of a CPV system sized by means of a TJ cell black-box model and applied to a livestock farm welding

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ABSTRACT – In the Concentrating Photovoltaic (CPV) systems, the Triple-Junction (TJ) cell electrical power is separately evaluated as function of its temperature or of the solar concentration factor (C), but generally not simultaneously as a function of both variables. Because all these variables are difficult to link by means of a white-box model, a mathematical model of the black-box type based on experimental data, is defined in this paper in order to link directly the TJ cell electric power together with Direct Normal Irradiance (DNI) and TJ cell temperature at different values of C. The knowledge of a link among TJ cell electric power, DNI and TJ cell temperature is basic to evaluate the real performances of a CPV system when it has to be sized, adopting a modular configuration, to meet the energy demands of a user. Hence, the feasibility of a CPV system adopted for an agricultural livestock farm located in Salerno (Italy), is evaluated by means of the model. The main activity of the farm is the breeding of cattle and sheep for milk production; the farm is made up of a stable and a farmhouse. The optimal number of TJ cells is defined to maximize the profitability of the investment, expressed in terms of Net Present Value. A CPV plant made up of 3000 cells, with an electric peak power of 6.6 kW, allows to maximize the NPV value up to about 16 k€.

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INTRODUCTION

The increasing importance that the environmental pollution is assuming in the energy production field has led to the development of different renewable technologies. Solar energy is among the main renewable energy sources, due to its large availability and the possibility to satisfy the energy demands of heterogeneous users [1]. In particular, the Concentrating Photovoltaic (*CPV*) systems and the Concentrating Photovoltaic and Thermal (*CPV/T*) systems combine different technologies in order to satisfy both the electrical and thermal energy demands in several applications [2]. For this reason, these systems promise excellent results in the generation of clean energy at competitive costs [3]. In the last years, the scientific community has developed models that reproduce the electrical and thermal performances of these systems [4] according to the different configurations and operation conditions, comparing their performances with those of traditional energy systems. These systems are adopted in wider and heterogeneous areas, with applications also of cogenerative type concerning both residential users and industrial processes. For example, in Renno et al. [5] a *CPV/T* system is adopted to satisfy the electrical, thermal and cooling loads of a residential user, while in Youssef et al. [6] a model of a *CPV* system is used in a textile industry. The potential of the concentrating photovoltaic systems from a polygeneration point of view, is also underlined in Kribus et al. [7] where the authors highlight several opportunities that they offer if combined with thermal engines or absorption heat pumps. Positive results related to the simultaneous production of electric and thermal energy even at high temperature by means of a *CPV/T* system, have been analyzed in Renno et al. [8]. Several studies in the literature show that the concentrating photovoltaic modules can operate at high temperatures maintaining a reasonable electrical conversion efficiency [9]. Hence, varying the mass flow-rate of the cooling fluid, it is possible to obtain different output temperatures and then thermal energy can be supplied to several thermal processes [10].

Therefore, the energy performances of a *CPV* system depend above all on the temperature of the Triple-Junction (*TJ*) cell and on the solar radiation concentrated on it. However, in literature, generally the *TJ* cell electrical power is separately evaluated or as function of the *TJ* cell temperature or of the concentrated solar radiation, but not simultaneously as a function of both variables [11]. There are methods based on an energy balance on the *TJ* cell and methods based on electrical parameters. The first characterize the cell working referring to external variables such as Direct Normal Irradiance (*DNI*), concentration factor (*C*), environmental temperature, wind speed, etc. The model proposed in Renno et al. [12] calculates the *TJ* cell electrical power as function of *DNI* and *C*, considering an energy performance decrease depending on the operation temperature.

On the contrary, the methods based on the electrical parameters analyze the I-V characteristic curve of the *TJ* cell when the working conditions vary. These methods require sophisticated measurement equipment not always available. In Muhammad et al. [13] the cell electric power is determined as function of photogenerated current, saturation current

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of the diode, load voltage, shunt and series resistances and cell temperature. Moreover, other models [14] allow the calculation of the maximum power that can be supplied by the *TJ* cell, considering different atmospheric parameters that influence the module behavior such as *DNI*, Air Mass, air temperature and wind speed. Another approach to determine the maximum power involves the use of Artificial Neural Networks (*ANN*) models [15]. The *ANNs* allow to predict the maximum power of a *CPV* module starting from inputs such as *DNI*, solar spectrum, air temperature and wind speed.

Because of its high influence on the electrical producibility, several methodologies in literature evaluate the *TJ* cell temperature in high concentration photovoltaic systems [16]. An interesting review of the different methodologies is reported in Fernandez et al. [14]. The authors present a classification of methods based on direct measurements on the module and indirect methods based on atmospheric parameters. The comparative analysis shows that, althought the first are more accurate, methods based on atmospheric parameters are a useful tool when direct measurements on the module are not possible, allowing to estimate the cell temperature from meteorological data of the installation site. In Renno et al. [17] a Random Forest model that evaluates the temperature of the *TJ* cells adopted in a *CPV* system, is studied. The *TJ* cell temperature trend has been analyzed referring to two different *TJ* cells corresponding to several values of the concentration factor and varying the environmental conditions.

Hence, it is clear that for an accurate evaluation of the energy performances of a *CPV* system, its electrical power should be linked simultaneously with *DNI*, *TJ* cell temperature and concentration factor. Because all these variables are difficult to link by means of a white-box model, a mathematical model of the black-box type based on experimental data [18], is defined in this paper in order to link directly the electric power supplied by a *CPV* system together with *DNI* and *TJ* cell temperature at different values of *C*. In particular, a model that links cell electric power, *DNI* and *TJ* cell temperature is fundamental to accurately size a *CPV* system in order to meet the energy demands of a user; this represents the main aim of this paper. Moreover, the feasibility of a CPV system adopted for an agricultural livestock farm located in Salerno (Italy), is evaluated by means of the model. The main activity of the farm is the breeding of cattle and sheep for milk production; the farm is made up of a stable and a farmhouse. As it is known, there is not a standard configuration on the market of *CPV* systems, but it must be defined according the user characteristics. In the present study, a modular configuration of a point-focus *CPV* system, with the same characteristics of the *CPV* plant used in the experimental activity, is considered.

EXPERIMENTAL SETUP DESCRIPTION

The experimental *CPV* plant, realized in the Applied Thermodynamics Laboratory of the University of Salerno, is reported in Figure 1.

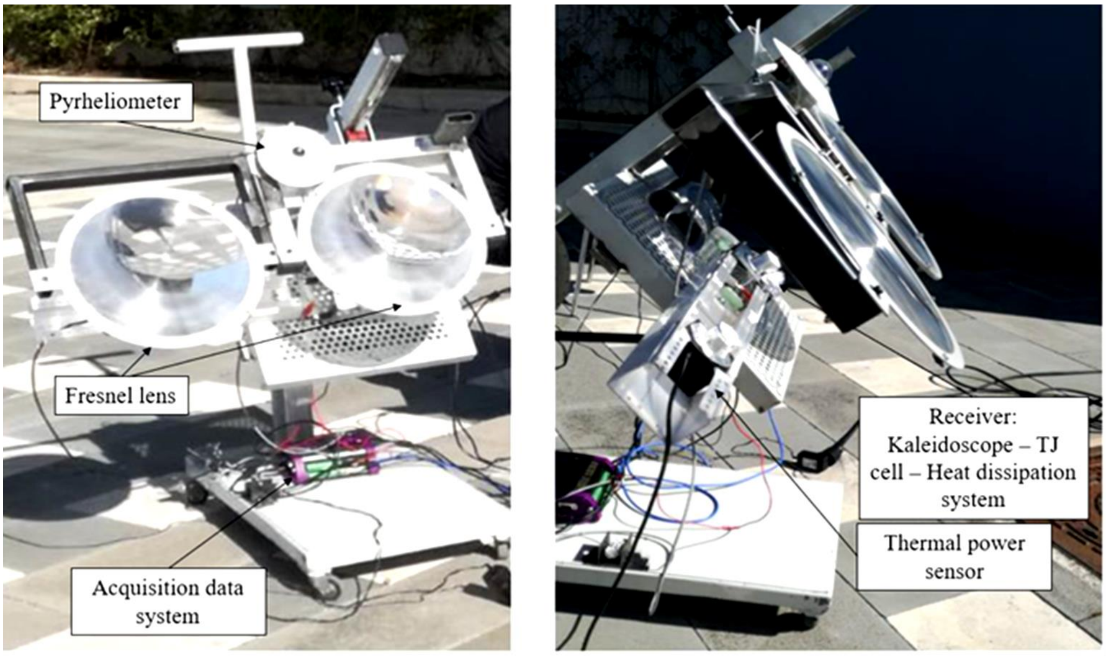


Figure 1. Photo of the experimental CPV system

It presents as point-focus primary optics a Fresnel lens, made of acrylic material, whose diameter and thickness are respectively equal to 30cm and 0.4cm. The receiver includes both a Triple-Junction (*TJ*) cell, placed in the lens focus, and a passive finned cooling system [19]. The *TJ* solar cell is constituted by InGaP/GaAs/Ge and presents an area equal to 5.5×5.5mm^2 as reported in Table 1 together with electric efficiency in the reference conditions (η_r), temperature coefficient (σ_t), open circuit voltage (V_{oc}), short circuit current (I_{sc})

Table 1. Parameters of the Triple-Junction cell

Parameter	***Value***
Material	InGaP/InGaAs/Ge
Dimensions	5.5mm x 5.5mm
η_r (at 25°C, 50W/cm^2 – 1000 suns)	39.0%
Temperature coefficient (σ_t)	-0.04%/K
V_{oc} (at 25°C, 50W/cm^2 – 1000 suns)	2.94V
I_{sc} (at 25°C, 50W/cm^2 – 1000 suns)	4.49A

A kaleidoscope is used as secondary optics to uniform the incident solar radiation for unit of active cell area in order to avoid chromatic aberration problems and to improve the optical efficiency. A tracking system is adopted in the experimental *CPV* system to converge the maximum *DNI* on the receiver. In particular, the experimental plant presents different degrees of freedom allowing both the solar tracking and the variation of *C* [20]. There are three degrees of freedom. The first two allow the solar tracking by means of a rotation both in the horizontal plane to follow the sun in the azimuth direction and in the vertical plane to follow the sun in the zenithal direction. Moreover, the *TJ* solar cells are placed at a variable distance from the primary optics and then the focal length is considered as a further degree of freedom in the experimental tests. In particular, the experimental plant allows to move the Fresnel lens, located perpendicularly to the sunrays, on a vertical axis to modify its height respect to the *TJ* cell; hence, the incident solar radiation on the *TJ* cell can be varied modifying *C*.In Figure 2 the plant scheme is reported with the measuring sensors.

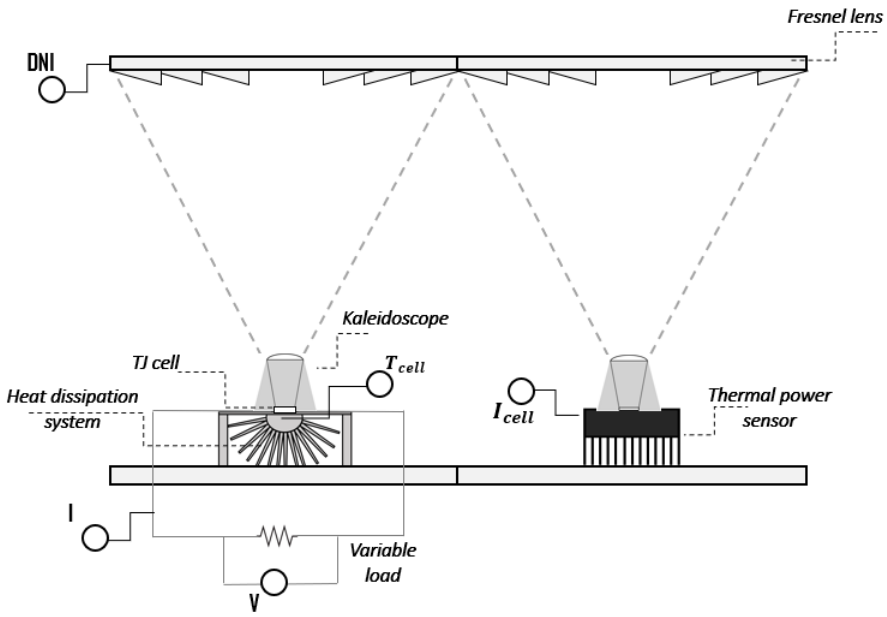


Figure 2. Scheme of the measurement sensors

PT100 thermo-resistances (accuracy of ±0.2°C) [21] are used to measure the cell and outdoor temperatures; a pyrheliometer (accuracy of 2%) measures the *DNI*. A variable load is linked to the TJ cell and an acquisition data system is adopted for the experimental measurements of voltage, current, *DNI* and temperature. Moreover, an experimental procedure for the direct measurement of *C*, has been adopted. This method allows the calculation of the optical concentration factor (C_{opt}) as ratio between the solar radiation concentrated on the solar cell (I_{cell}) and the DNI that represents the incident power flow on the optical system (Renno et al. [12]):

$$C_{opt} = \frac{I_{cell}}{DNI} \tag{1}$$

Hence, C_{opt} becomes independent from the *TJ* cell electrical performance, while it depends only on the system optical performances. I_{cell} has been measured by means of a thermal power sensor (accuracy of ±3%) accurately selected. The thermal sensor allows the measurements of solar radiation in a wide spectral range (0.19-20μm). It presents a series of bimetallic junctions (thermopile). The heat flow in the sensor creates a voltage proportional to the power absorbed when it flows in the thermopile. The voltage signal is then converted into a power measurement by means of a specific software provided by the manufacturer. In order to make comparable the measurements coming from thermal power sensor and pyrheliometer, an accurate calibration of the thermal power sensor has been defined. During the measurement of C_{opt}, it is necessary that the solar radiation concentrated on the *TJ* cell and on the power sensor, are the same. Finally, both *TJ* cell and power sensor have been mounted in parallel and with a same kaleidoscope to have the same power flux, as shown in the Figures 1 and 2.

THEORETICAL AND EXPERIMENTAL MODELLING

As before reported, several approaches for the characterization of the *TJ* cell electrical performances have been developed in literature. In this study, the authors propose a different modeling approach, based on experimental data measured during the point-focus *CPV* system operation previously described, linking the *TJ* cell electrical power simultaneously with *DNI*, *TJ* cell temperature and concentration factor. The main variables of the model that characterize the *CPV* system operation can be divided into: input variables (*DNI* and environmental temperature (T_{env})), internal variables (optical concentration factor (C_{opt}) and *TJ* cell electrical efficiency (η_{cell})) and output variables (*TJ* cell temperature (T_{cell}) and *TJ* cell electric power ($P_{el,cell}$) obtained by means of the product between the photo-generated current $I_{ph,cell}$ and voltage (V_{cell})). The experimental tests have been realized in different weather conditions with a sampling interval of 15 seconds, from January to July 2019. The ranges of the variables experimentally monitored are reported in Table 2.

Table 2. Monitored variables and their variation ranges

Monitored variable	***Variation range***
DNI	$300 \div 930 W/m^2$
C	$50 \div 310$
T_{env}	$12 \div 33°C$
T_{cell}	$15 \div 68°C$
I_{cell}	$15 \div 288 kW/m^2$

In particular, the variables *DNI* and C_{opt} have been substituted by a single parameter: $I_{cell}=DNI \cdot C_{opt}$. Because the aim of this paper is the system *CPV* performance evaluation, the model input data are I_{cell} and T_{cell} while the model output is the electric power supplied by the TJ cell ($P_{el,cell}$). Hence, adopting a black-box modeling approach, a multivariable regression of the measured data, with a significance level α=0.05, has been realized in Matlab [22]. The study of the dynamic behavior and transient response of a system is complex as the mathematical model is described by non linear partial differential equations. For this reason, in this paper a black-box approach is applied to the *CPV* system. With this type of modelling, a system can be represented by a set of transfer functions with several constants have been identified by experiments [18].

Two different relations have been determined; the first is valid for low values of concentration and the second for medium-high values. Hence, the multivariable regression of the measured data has allowed to obtain two different relations between $P_{el,cell}$, I_{cell} and T_{cell}:

$$P_{el,cell} = P_{el,cell}(I_{cell}, T_{cell}) = \begin{cases} 0.0080304 \; x \; I_{cell} + 0.82818 \; x \; {T_{cell}}^{-1} & (2) \\ 0.010790 \; x \; I_{cell} - 1.4167 \cdot 10^{-4} \; x \; {T_{cell}}^{2} & (3) \end{cases}$$

The validity ranges of two equations are:

$$15 \; kW/m^2 < I_{cell} < 70 kW/m^2 \text{ and } 15°C < T_{cell} < 50°C \quad (4)$$

$$70 \; kW/m^2 < I_{cell} < 288 kW/m^2 \text{ and } 22°C < T_{cell} < 68°C \quad (5)$$

Case 1 refers to low values of *C*, while Case 2 refers to middle-high values of *C*. The values of the model parameters in the Case 1 are $a_1 = 0.0080304 \pm 0.0001283$ and $a_2 = 0.82818 \pm 0.16443$. In the Case 2 they are $b_1 = 0.010790 \pm 0.000109$ and $b_2 = (-1.4167 \pm 0.0734) \cdot 10^{-4}$.

In order to verify the model reliability, the following indices have been calculated for each case.

Case 1

- Correlation factor $R^2 = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 / \sum_{i=1}^{n}(y_i - \bar{y})^2 = 0.9768$, where y_i are the experimental data, $\bar{y}$ their average value, $\hat{y}_i$ the data estimated by the model and n the total number of observations. Hence, the model represents very well the experimental data.

- Root Mean Squared Error $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} = 0.0247$ whose low value indicates an excellent model reliability [23].
- Relative Root Mean Squared Error $RRMSE = RMSE/\bar{y} = 7.97\%$ which, being lower than 10%, indicates that the model accuracy is good [23].

Case 2

- Correlation factor $R^2 = 0.9791$.
- Root Mean Squared Error $RMSE = 0.1496$ and then also in this case the estimation made has an optimum reliability.
- Relative Root Mean Squared Error $RRMSE = 10.15\%$, result to be considered satisfactory [23].

With reference to the Case 1, it can be observed in Figure 3 a comparison between a wrong regression (a) and a correct one (b).

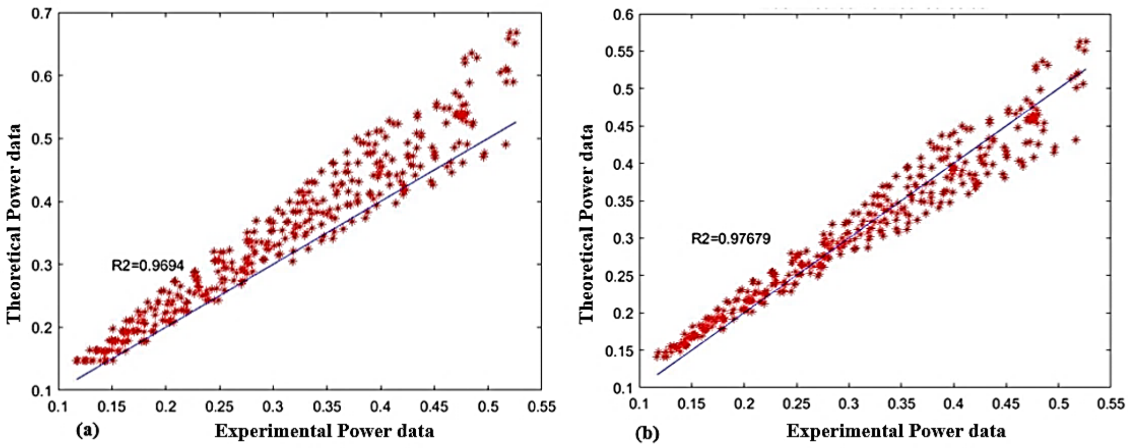


Figure 3. Wrong (a) and correct (b) regression in the Case 1

As shown in the Figure 3(a), assuming a parabolic decrease of the electrical power with the temperature, the model output is always over estimated. A similar situation is verified in Figure 4(a) for the Case 2 where the deviation between theoretical and experimental electrical power values is shown, assuming an inverse proportional relationship between power and temperature.

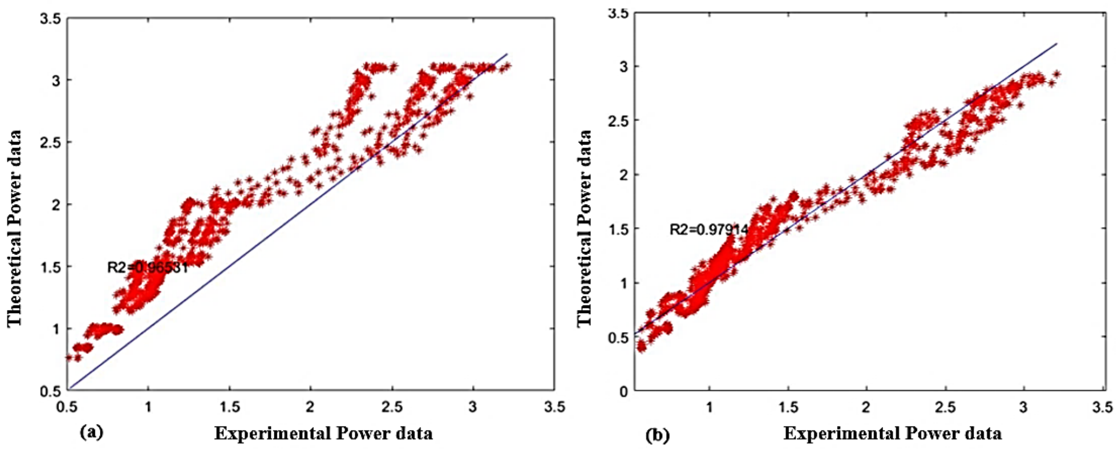


Figure 4. Wrong (a) and correct (b) regression in the Case 2

Hence, the model accuracy is clearly shown in the Figures 3(b) and 4(b), where it can be observed that the experimental data are distributed with very good approximation along the bisector. The model validation is important to test the accuracy and reliability of the results. In particular, the model validity has been verified comparing theoretical and experimentally measured data corresponding to another TJ cell with different area (10x10mm^2). The experimental results, carried out on 5th July 2019 between 5:00 p.m. and 6:00 p.m for a C value of 50, are shown in Figure 5. The maximum error (i.e. the maximum difference between theoretical and experimental value) is 0.01972, i.e. equal to 1.519%.

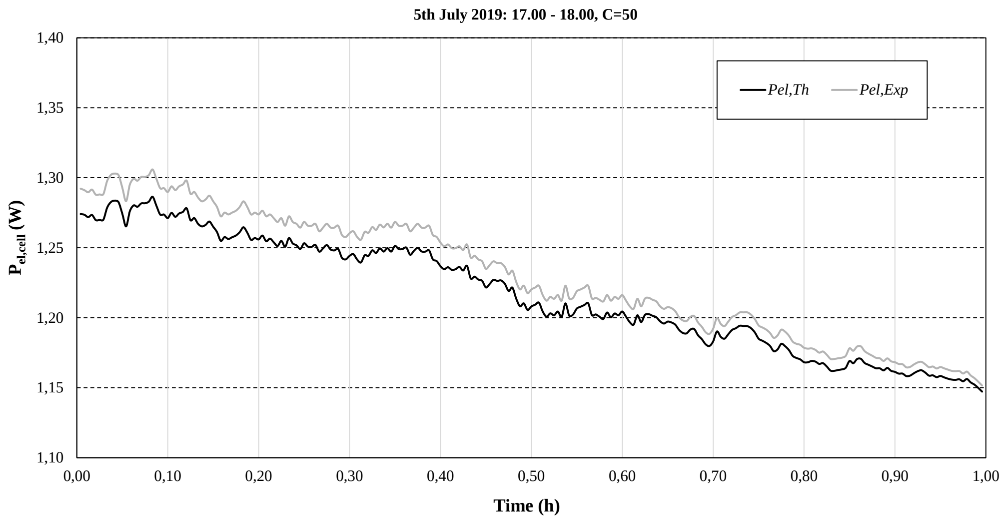


Figure 5. Model validation: theoretical electric power vs experimental electric power for a TJ cell of 10x10 mm^2

It can be observed that the measured and calculated electrical powers show very similar trends that differ by an average deviation factor of 3.34. Considering that the TJ cell used for the validation has the same characteristics of the TJ cell adopted during the experimental tests but presents a different area equal to 10x10mm^2, an electrical producibility increase of about 3.31 times is expected and then close to the average deviation factor above mentioned. Finally, it can be observed in Figure 5 that $P_{el,Th}$ represents the theoretical electrical power supplied by the TJ cell and adjusted by the correction factor CF=3.31 that takes into account the dimensions difference between the two TJ cells.

RESULTS AND DISCUSSION

Modelling of the Triple-Junctio cell performances

The model presented in this paper represents an important tool to evaluate the real energy performances of a point-fous CPV system operating in the conditions previously described. It has been developed starting from experimental measurements conducted during a long period of the year in order to evaluate a wide range of operation conditions.The results of the model are reported in Figure 6 in terms of the electrical power supplied by the TJ cell of area equal to 5.5×5.5mm^2. The electrical power increases linearly with I_{cell} and decreases when T_{cell} increases. The increase of I_{cell}, in fact, leads to an increase of electric current supplied by the cell and, consequently, of its electrical power (Renno et al. [12]). The increase of the TJ cell temperature, on the other hand, causes a reduction of its electrical efficiency, as shown in several studies in literature (Rodríguez et al. [9]). For low values of C, the decrease of the TJ cell electrical power is less marked due to the lower values reached by the TJ cell temperature. For medium-high values, the TJ cell electrical power decreases with a parabolic trend when the TJ cell temperature increases.

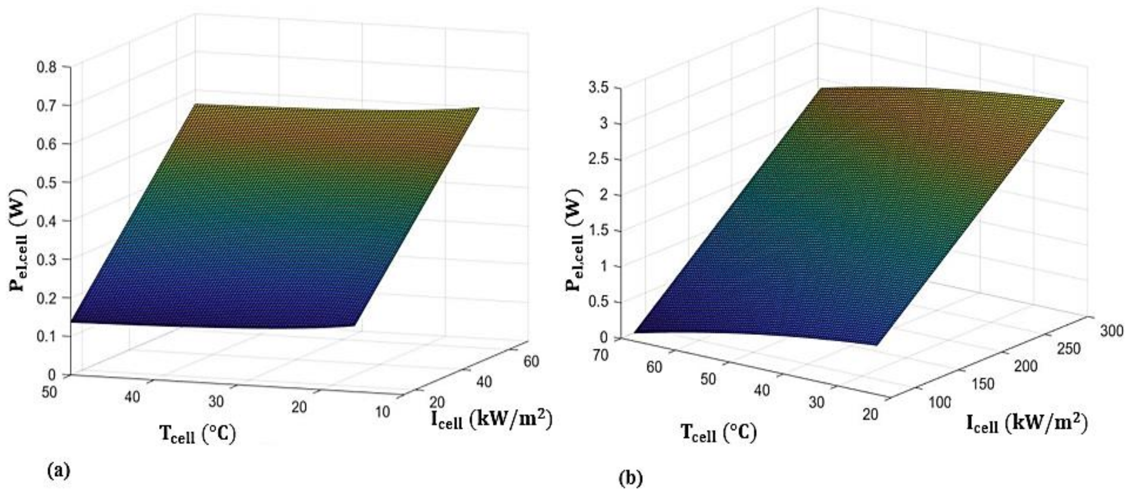


Figure 6. Electrical power supplied by the TJ cell as function of Icell and Tcell in the: (a) Case 1 and (b) Case 2

Hence, it is clear that the TJ cell operation temperature constitutes a fundamental parameter related to the energy performances evaluation of a CPV system. In particular, the TJ cell electric power depends on the TJ cell temperature values as well as the cell electric efficiency whose values are reported in Figure 7, related to the cases 1 and 2, as function of I_{cell} and T_{cell}. As shown in Figure 7, the TJ cell electric efficiency decreases when T_{cell} increases for each value of I_{cell}; for each value of I_{cell}, the efficiency trend is only shown in the T_{cell} range actually reachable from experimental point of view. As shown, in the same ranges of temperature, the efficiency assumes different values that depend on the concentrated solar radiation I_{cell} which affects the TJ cell electrical parameters (Renno et al. [24], Kribus et al. [7]).

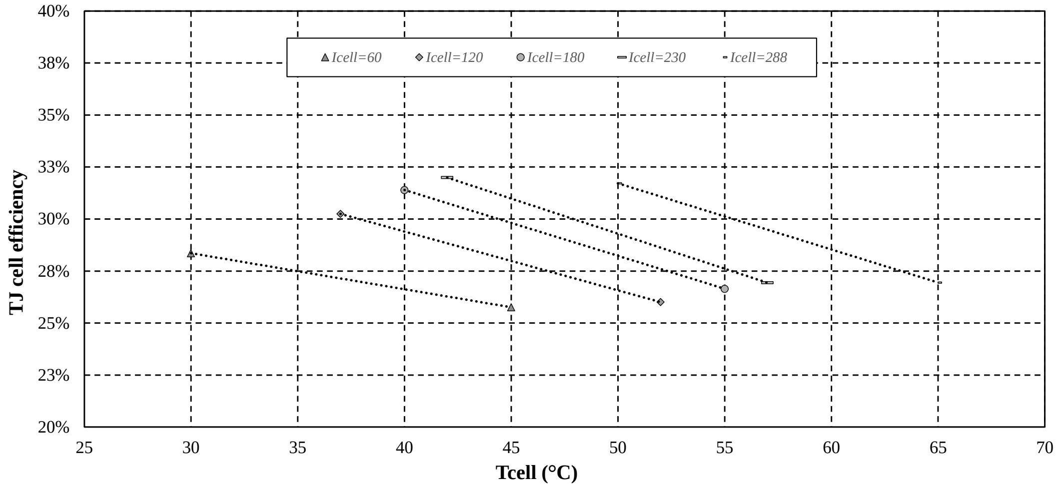


Figure 7. TJ cell electrical efficiency as function of I_{cell} and T_{cell}

As for the thermal aspects, it is interesting to evaluate the increase of T_{cell} compared to the environmental temperature when the concentration levels vary. The evaluation of this deviation is very useful since it allows to estimate the temperature reachable by the TJ cell under concentration when the environmental temperature changes. The increase of T_{cell} with respect to the environmental temperature raises logarithmically with the concentrated radiation (Renno et al. [10]), reaching values of about 30°C higher than the environmental temperature corresponding to a concentrated irradiation value equal to about 290 kW/m^2 (Figure 8). Hence, once known the data of DNI and T_{env} of a given locality, it is possible to estimate the values of T_{cell} by varying C.

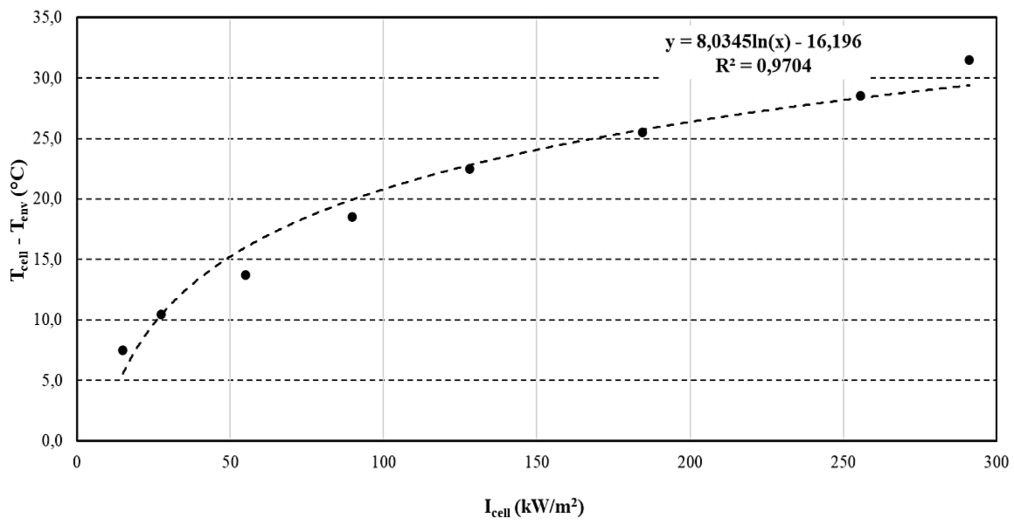
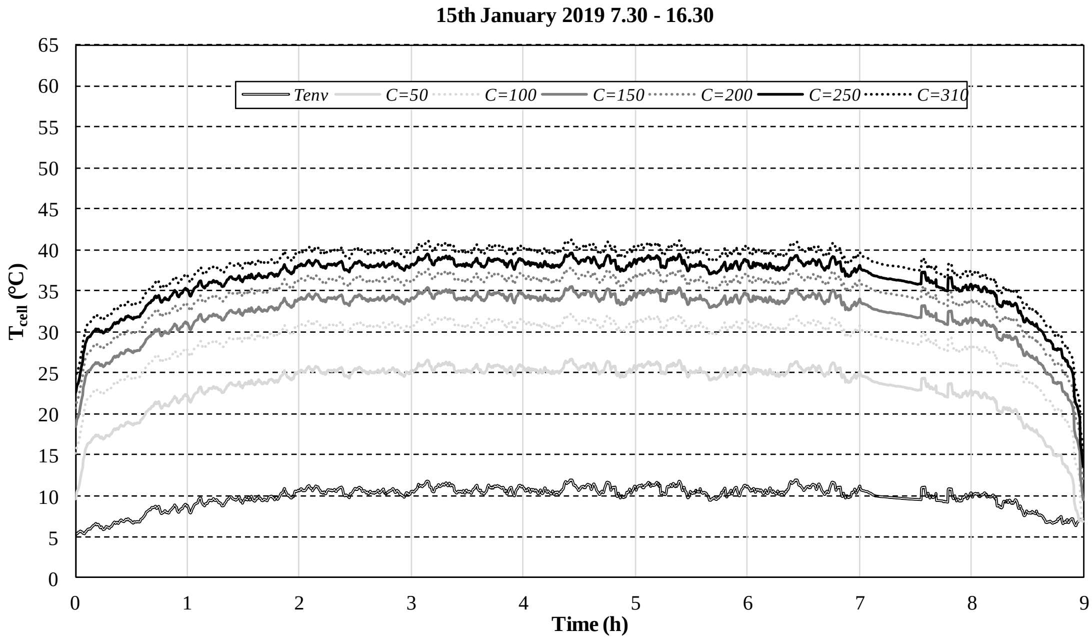


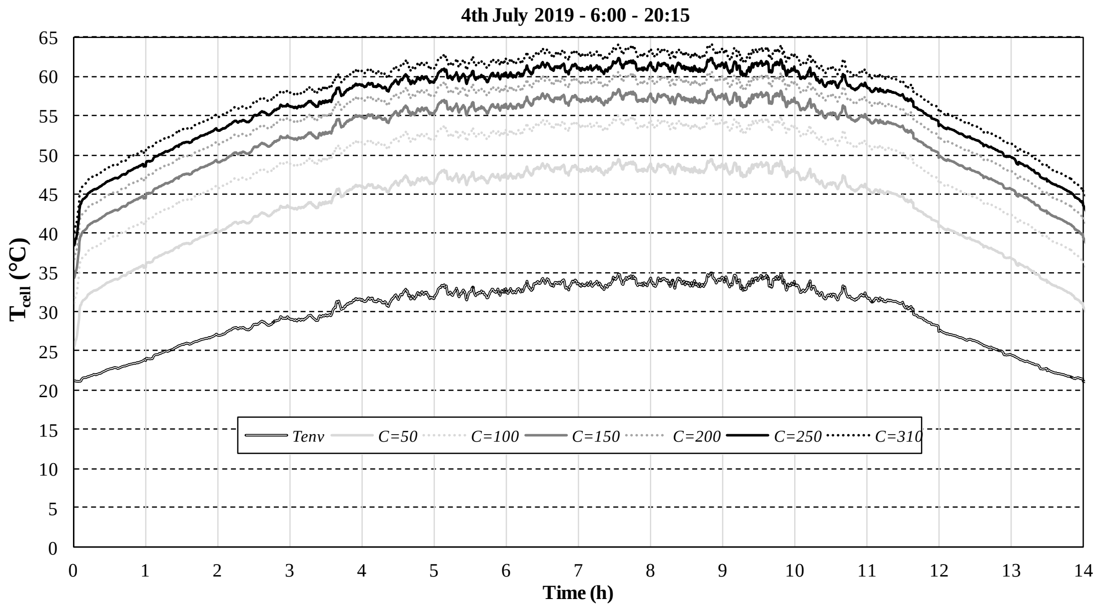
Figure 8. Increase of the TJ cell temperature due to the solar concentration

The TJ cell operation in terms of $P_{el,cell}$ and T_{cell} is also analyzed during the year when C changes, considering summer and winter days, and sunny and cloudy days. Hence, it is possible to estimate the minimum and maximum energy performances of the TJ cell. The analysis focuses on some typical days, for which the trends of DNI and environmental temperature are available or experimentally measured; these data refer to the locality of Fisciano (Italy). It is interesting to compare a typical winter sunny day (15th January 2019) and a typical summer sunny day (4th July 2019). The trends of $T_{cell,}$ and $P_{el,cell}$ corresponding to different C values analyzed, are reported in the the Figures 9 and 10.

In Figure 9 the values of T_{cell} by varying C both for a winter sunny day (a) and for a summer sunny day (b), are reported. The increase of C leads to high values of T_{cell} , thus increasing the potential energy recovery (Kribus et al. [7]). It can be observed that for high C values also in a winter sunny day it is possible to reach values of T_{cell} of about 40°C. On the contrary, in a hot summer day the temperature obtained with high concentration levels reaches about 65°C. Obviously, adopting larger cells, it is possible to obtain higher values of termperature, as shown in [12].



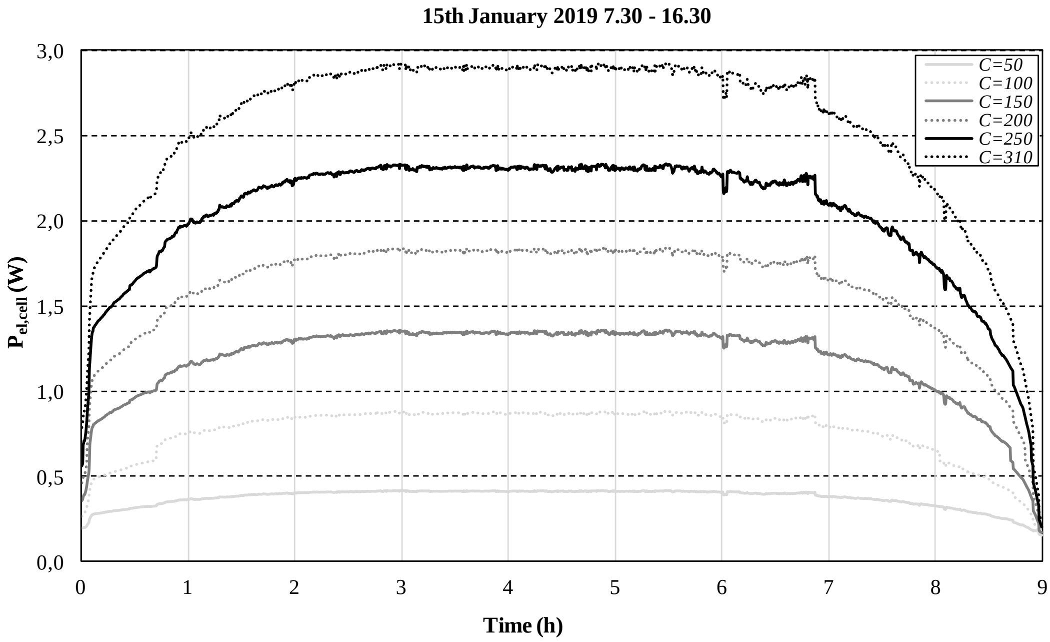
(a)



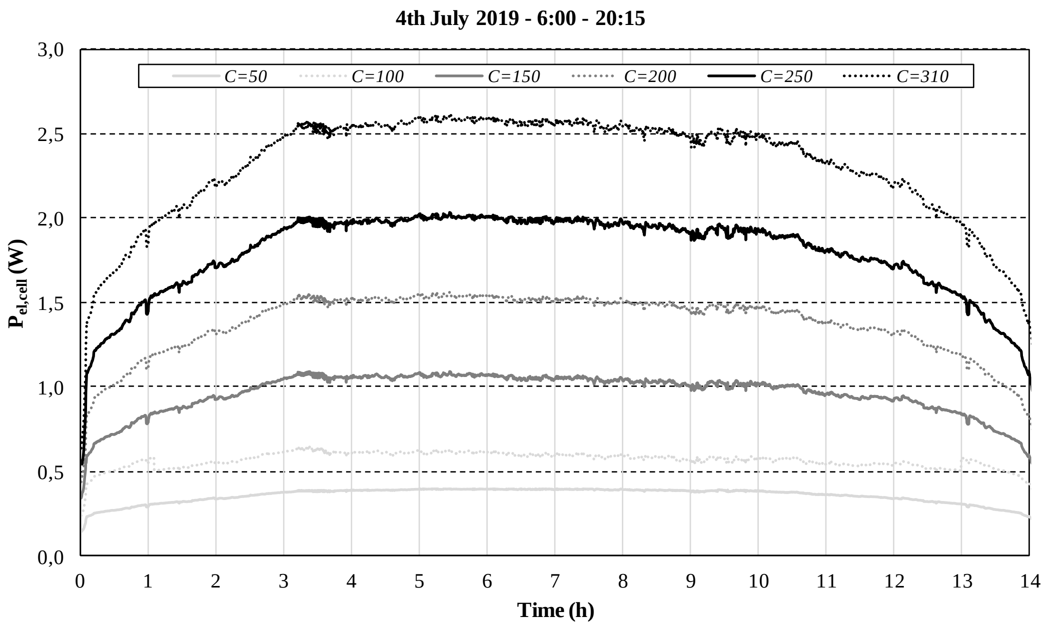
(b)

Figure 9. T_{cell} for different values of the concentration factor on: (a) 15th January 2019 and (b) 4th July 2019

In Figure 10, the high increase of the electrical power supplied by the cell when C increases, is shown. It can be observed that the higher temperatures reached in a summer day cause a decrease of the TJ cell electrical efficiency, thus leading to lower values of its electric power with respect to the winter day when the other conditions are similar.



(a)



(b)

Figure 10. $P_{el,cell}$ for different values of the concentration factor on: (a) 15th January 2019 (a) and (b) 4th July 2019

Despite this, the greater number of hours of sunlight ensures a greater electrical producibility, as reported in Figure 11 where the electric energy produced by the TJ cell for each analyzed value of C_{opt} and for both days, is shown. The electric energy produced in the summer day analyzed is higher than energy of the winter case, with a percentage increase of about 42% in correspondence with a C of 310. Hence, it can be noted that localities characterized by a high sunlight ensure a greater electrical producibility, despite the lower instantaneous values of electric power due to the higher TJ cell temperatures reached [24].

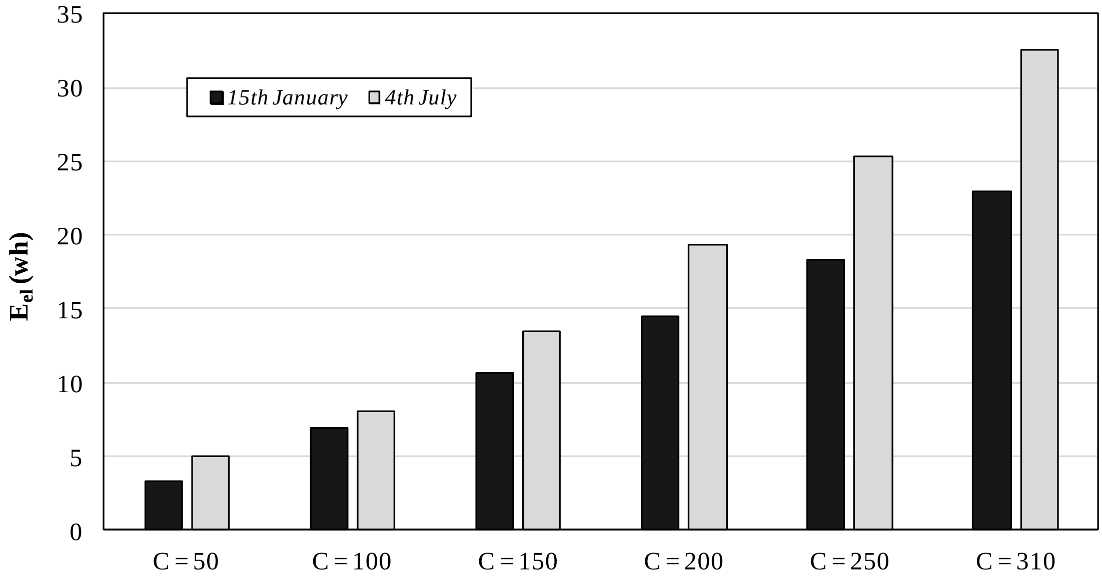
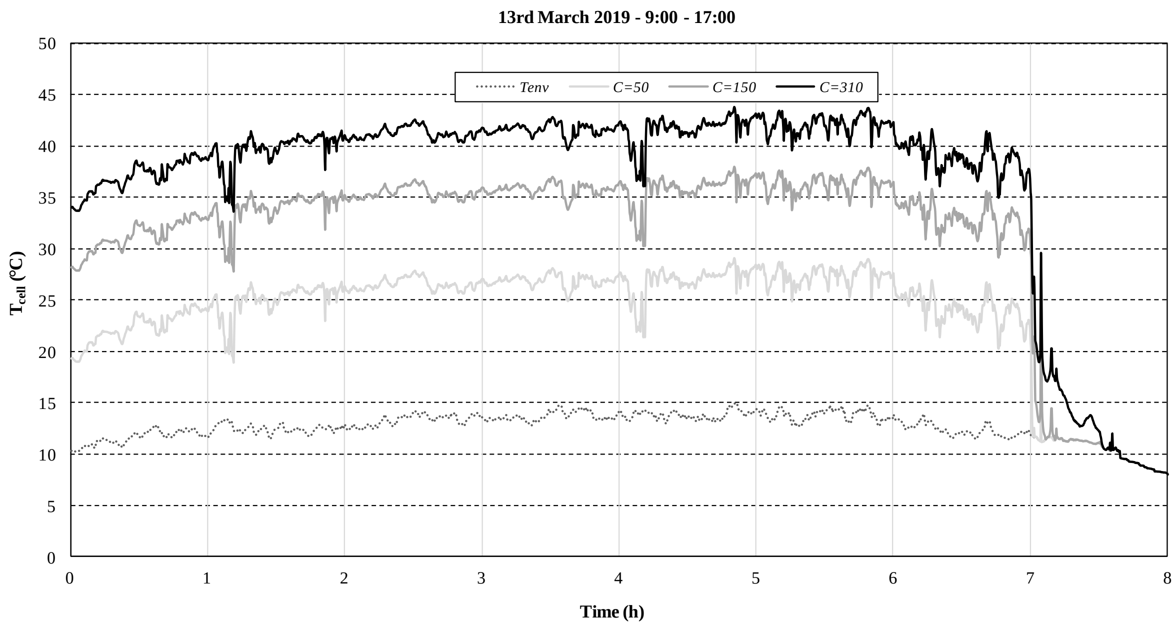
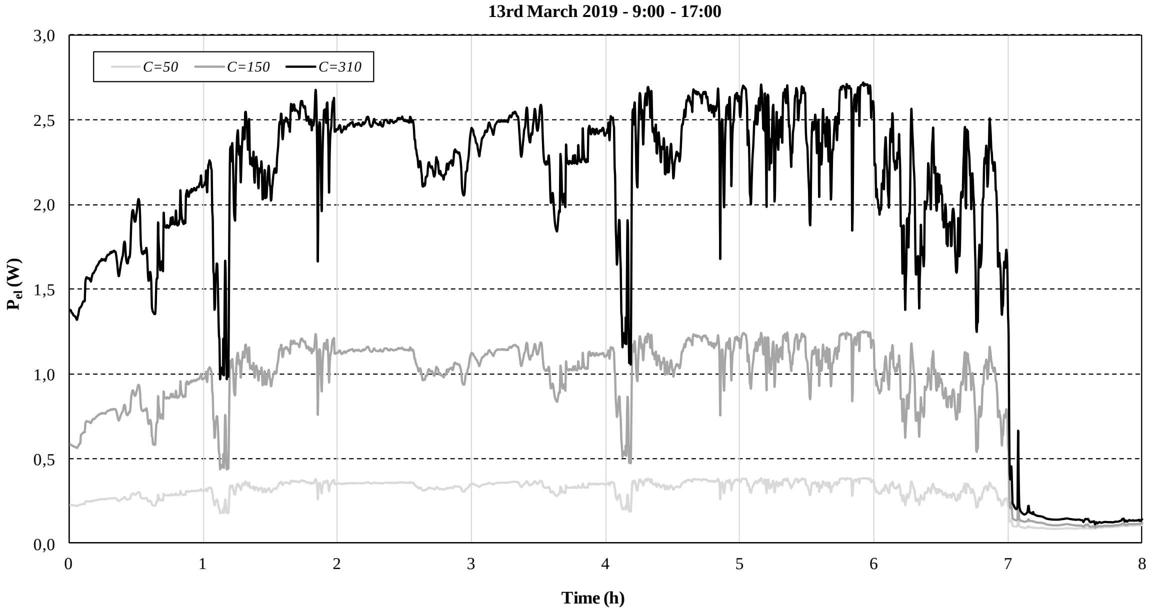


Figure 11. Electric energy supplied by the TJ cell for the different values of the concentration factor on 15th January 2019 and on 4th July 2019

The two days analyzed constitute the extreme situations where the TJ cell operates, but it is also necessary to analyze intermediate situations. Hence, it is interesting to observe the CPV system output in the case of a partially cloudy day. In particular, the measurements have been taken on 13rd March 2019, between 9:00 a.m. and 5.00 p.m.. The trends of $P_{el,cell}$ and T_{cell} corresponding to different C values are reported in the Figures 12a and 12b related to the temporal interval 9:00a.m. - 4:00 p.m., because in the interval 4:00 p.m. - 5:00 p.m the DNI is very low. There is a wide variability of $P_{el,cell}$ and T_{cell} due to the highly variable trend of the DNI. Hence, especially in partially cloudy days, it is necessary to use energy storage systems in order to guarantee a continuous operation of the adopted CPV systems.



(a)



(b)

Figure 12. T_{cell} (a) and $P_{el,cell}$ (b) for different values of the concentration factor on 13rd March 2019

Modular configuration and feasibility analysis of CPV system used in a livestock farm

The black-box model described in this paper has allowed to evaluate the performances of a single TJ solar cell under the operation conditions reported above. The electric power supplied by a single TJ cell is rather limited, reaching a maximum of about 2.95W. Adopting several cells in order to constitute one or more modules, it is possible to match the electric power supplied by a CPV system to the energy demand of a given user. Hence, it is also interesting to evaluate the potential of a CPV system constituted by a high number of cells. Because there is not a standard configuration on the market of these systems, a modular configuration of a point-focus CPV system similar to that reported in [12] can be considered in order to vary both the number of TJ cells and the number of modules matching the electrical load of a specific user. The electric power supplied by a single module is given by (Renno et al. [10]):

$$P_{el,mod} = P_{el,cell}\ x\ f\ x\ n_{c,mod}\ x\ (1 - p_{par})\ x\ \eta_{mod} \tag{6}$$

where $P_{el,cell}$ can be calculated with the Equations 2 and 3, f is a loss factor related to a non-ideal tracking system, $n_{c,mod}$ is the number of cells per module, p_{par} is a loss factor taking into account the parasitic current losses generated in the module and η_{mod} is the module efficiency which takes into account the coupling in series of the TJ cells along a line. Hence, the electric power supplied by a modular CPV system can be calculated as (Renno et al. [10]):

$$P_{el,CPV} = P_{el,mod}\ x\ n_{mod}\ x\ \eta_{inv} \tag{7}$$

where n_{mod} is the number of modules that constitutes the plant and η_{inv} is the inverter efficiency. The trend of $P_{el,CPV}$, when the number of cells varies, is shown in Figure 13. It can be noted that a CPV system made by 1500 cells can reach an electric peak power of about 3 kW, thus satisfying the typical electrical energy demand of a residential user.

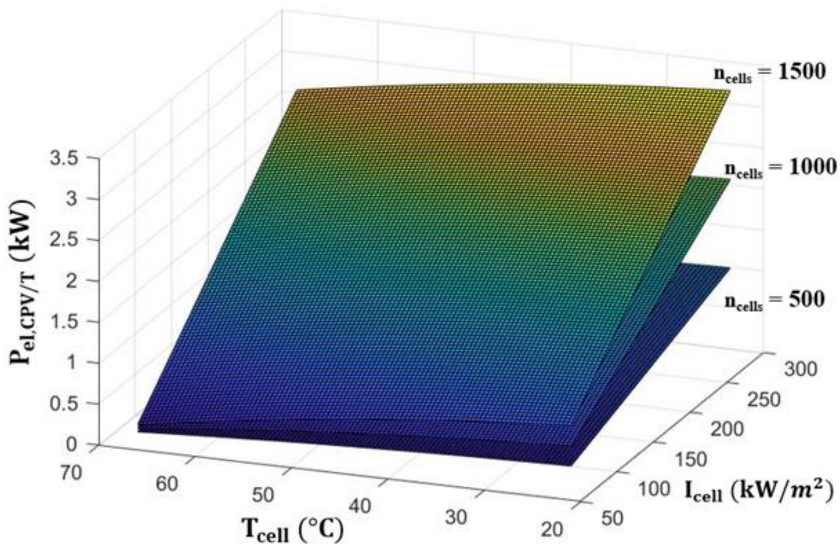


Figure 13. Electric power supplied by a CPV system varying its number of cells

Other studies, such as [5] and [25], have already analyzed the cost-effectiveness of the CPV systems, showing that their cost can be comparable with the cost of a traditional PV system. The model presented in this paper for a single TJ cell can be used to estimate the peak electric power of a CPV system when its number of cells varies. Moreover, the black-box model presented in this paper allows from one hand the evaluation of the increase of the TJ cell temperature that affects the electrical production, from another hand this increase of the TJ cell temperature can be adopted to obtain thermal energy. Hence, adopting an active cooling mechanism, the CPV system could be modified in a CPV/T system in order to produce also thermal energy [26].

The model developed in the present study is fundamental to evaluate the feasibility of a CPV system for an agricultural livestock farm located in Salerno (Italy). The main activity of the farm is the breeding of cattle and sheep for milk production. The building complex is made up of a stable and a farmhouse respectively. As for the stable, the electrical loads (Figure 14) are due to the milking machines, refrigerators for the milk preservation and to lighting and machinery for cleaning the barn. The electrical loads of the farmhouse activity present a more discontinuous trend (Figure 14).

Hence, once known the annual hourly distribution of DNI and T_{env} [27] and considering the increase of T_{cell} shown in Figure 8, the system CPV electrical producibility by varying its number of cells, has been evaluated by means of the Equation 7. In particular, the optimal number of cells has been defined in order to maximize the profitability of the investment, expressed in terms of NPV (Net Present Value). The trend of the NPV of the investment at the 20th year, average useful life of a CPV system, is shown in Figure 15 as function of the number of cells.

In this analysis, the initial investment, given by the cost of the CPV system, has been calculated considering a cost per unit of power equal to 2.94€/W and a discount rate of 0.015 [28]. The cash flow for the i-th year has been calculated as sum of the cost savings for the purchase of the electricity necessary to the user and the gains obtained by the sale of the electrical energy surplus. It has been considered a unit purchase cost of electricity equal to 0.25 €/kWh and a lower sale price to the energy network, equal to 0.06€/kWh.

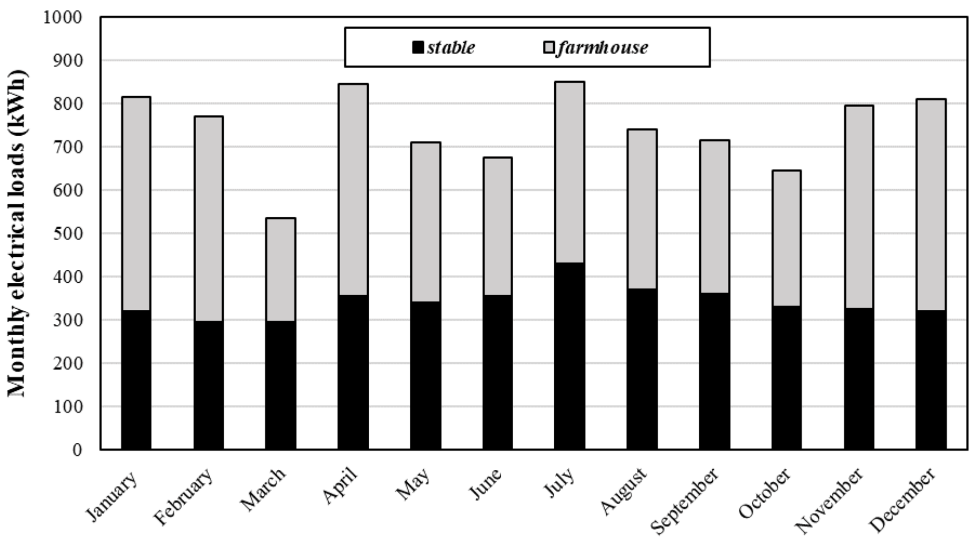


Figure 14. Electric loads of the agricultural livestock farm due to stable and farmhouse

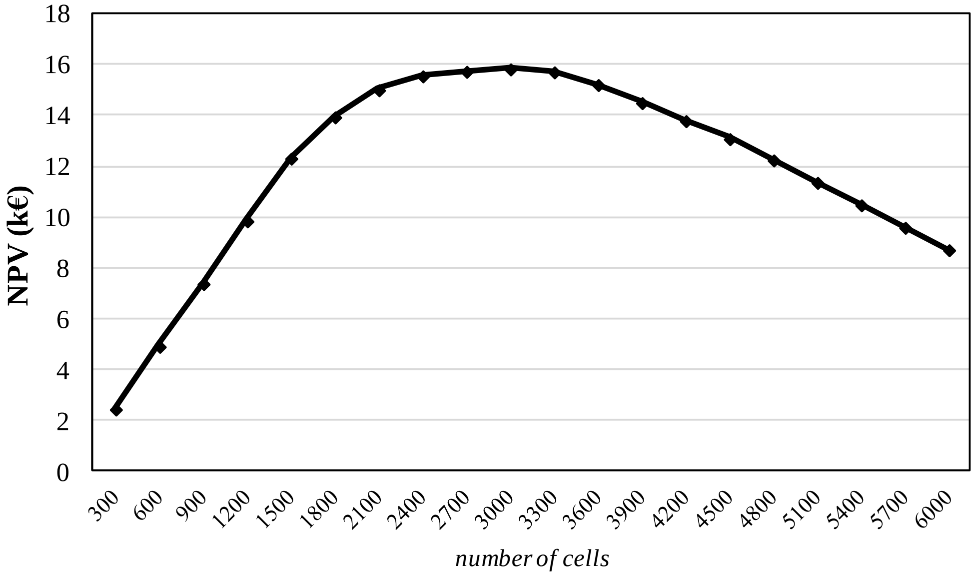


Figure 15. NPV trend at the 20th year as function of the TJ cells number

As shown in Figure 15, a CPV plant made up of 3000 cells, with a peak power of 6.6 kW and an area of about 270m^2, allow to maximize the NPV value, which reaches a value of 15.9 k€. By increasing further the number of cells, the NPV decreases because of an increasing share of CPV electrical producibility sold to the energy network at a lower price.

CONCLUSIONS

An experimental model that links electric power supplied by a CPV system with DNI and TJ cell temperature at different values of C has been adopted in this paper to size a point-focus CPV system adopted to meet the energy demands of an agricultural livestock farm located in Salerno (Italy). The multivariable regression of the experimentally measured data has allowed to obtain two different relations between $P_{el,cell}$, I_{cell} and T_{cell} both for low and for middle-high values of C. It has been also evaluated the T_{cell} that increases, compared to T_{env}, logarithmically with the concentrated radiation, reaching values of about 30°C higher than T_{env} corresponding to the concentrated solar irradiation equal to about 290kW/m^2. This allows to estimate T_{cell}, reached in a given locality, when the C values vary and once known DNI and T_{env}. The TJ cell energy performances for different weather conditions and periods of the year of the locality of Fisciano (Italy), have been then analyzed. It has been noted that for high C values, values of T_{cell} of about 40°C and 65°C are respectively obtainable in a winter sunny day and in a summer sunny day. The maximum value of $P_{el,cell}$ observed has been equal to 2.92 W for the winter day and 2.61W for the summer day, with a decrease of about 10.6%. The energy analysis has shown that the greater daily number of hours of sunlight ensures an electrical producibility in summer up to 42% higher with respect to winter in a sunny day.

Hence, the model presented in this paper for a single TJ cell has been used to accurately estimate the CPV system electric power when the TJ cells number varies. This has allowed to perform a feasibility study of a CPV system adopted to satisfy the electrical loads of an agricultural livestock farm located in Salerno (Italy). The NPV at the 20th year of the investment as a function of the number of cells has been evaluated. Results have shown that a CPV plant made up of 3000 cells, with an electric peak power of 6.6kW and an area of 270m^2, allows to maximize the NPV value up to 15.9k€.

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