Definition, theoretical – experimental modeling and energy management of concentrating photovoltaic and thermal systems

Abstract

The evolution in the renewable energies field led to search for solutions that allow the combined achievement of heterogeneous energy vectors. This theme introduces multiple levels of analysis, from the definition of new systems and the environmental impact analysis to the overall economic performances, in the traditional cost – benefit paradigm.

In this context, the Green Renewable Technologies redefines the concept of innovative solution, as they represent a choice based on eco – sustainability princes. This aspect provides a driving force, both for the basic and industrial research. The key point of the analysis can be summarized in two basic concepts: the definition of new systems not yet standardized and the combined energy production in order to meet different demands.

In this analysis, the systems based on the solar concentration present wide margin of study. Such devices don't have established standards from the specific system configuration point of view and as regards the basic components. In addition, although primarily designed for the electrical or thermal energy production, in a separate way, they have a high potential of combined energy capability.

In the presented work a complete analysis of the concentration systems is provided. Considering both the electrical and the thermal energy production, we can talk of concentrating photovoltaic and thermal systems.

Generally, the basic principle of these systems is to focus the solar radiation, by means of optical devices, on specific solar cells, the multi – junction ones, in order to increase the obtained energy and decrease the solar cell area. The sunlight concentration lead to an increase in the solar cell temperature, hence a right cooling is needed. By employing a cooling fluid it is possible to avoid electrical losses and simultaneously obtain thermal energy.

The main aim of this work is the definition and theoretical – experimental modeling of such kind of systems in order to evaluate their energetic and economic performances. In particular, the work is not referred to a specific plant but, by means of different simulations, a parametric analysis has been conducted in order to understand the different variables influence on the system configuration. Hence, it was possible to adapt the system operating with different configurations and to assess the electrical and thermal potential depending on a specific application.

A concentrating photovoltaic and thermal systems is principally composed of three parts, the optics that allows the sunlight concentration, the receiver, where the solar cells are placed and the tracking system. The solar cells chosen are triple junction solar cells, in particular the characteristics of Indium – Gallium phosphide, Gallium arsenide and Germanium (InGaP/GaAs/Ge) cells have been experimentally analyzed.

The work evaluates the main parameters of a concentrating plant, such as the concentration factor which describes how many times the incident radiation has been amplified, the acceptance angle which affects on tracking and the configuration. This describes how the cells and the optics are arranged to each other. The concentration systems are described in each component, highlighting what is present in the literature.

The analysis defines both the part to modeling and the employed tools in order to achieve an overall assessment of these systems.

In this way, starting from the input, a procedure for the solar potential evaluation has been defined by means of the artificial neural networks. In particular, as these systems work only with the direct component of the solar radiation, two networks have been analyzed both for the global and direct radiation, employing a recombination process. The first network considers seven input parameters while the second one, for the direct radiation evaluation, exploits four input variables, including the cloudiness. These models have been trained, validated and tested exploiting data from national databases and experimental measures for different years. The neural networks designed have also been statistically compared with the main literature results in this field, reporting excellent performances.

In order to evaluate the energetic performances of a concentration system, different models have been introduced. In particular, models for the electrical analysis, starting from the cells characteristics and the chosen configuration, have been defined. Moreover, the thermal analysis has been conducted, studying the cell temperature. Hence, the definition of a Random Forest model for the cell temperature predicting has been a key point of the analysis. The evaluation of the cell temperature under concentration, in fact, represents a problem which effects both the electrical and the thermal analysis. Hence, the realized Random Forest model, allows to solve different problems. As for the neural networks models, also for the Random Forest model the use of experimental data has been fundamental. Once known the cell temperature, different thermal model have been realized in order to evaluate the cooling fluid temperature. In particular, depending on the concentration level and the number of the cells, two different cooling circuit have been realized. The first one based on a point – focus configuration, while the second one based on a line – focus configuration. By means of graphic softwares, such as Catia and Solidworks, and implementing a numeric analysis in Ansys, the fluid temperatures in the different cooling circuits have been evaluated. The line focus configuration has shown the best performances both for the reached temperatures and the response time. The last modeling phase analyzed the system connection with a residential user. In particular, the use of a tank which would represent a thermal energy storage has also been evaluated. Moreover, different inefficiency analysis has been conducted in order to evaluate the energetic end economic performances of the concentration systems in different conditions.

The experimental analysis represented a key point for all the realized model. It had a dual role, on one hand, it allowed to understand the influence of different variables, not theoretically evaluable. On another hand, it allowed to obtain a database of experimental measures, which have been fundamental for the different realized models, such as the neural networks and Random Forest.

The experimental analysis starts with the development o a concentrating system at the University of Salerno. This plant presents a point – focus configuration with a Fresnel lens, as primary optics, a kaleidoscope as secondary optics, and a triple junction solar cell.

This plant allowed to define an experimental procedure for the concentration factor evaluation. By changing the Fresnel lens height, it was possible to modify the concentration factor and to evaluate different cell parameter such as the open circuit voltage, the short circuit current, the efficiency, the fill factor and the series and shunt resistances. The maximum concentration factor reached has been of 310 suns, with a lens height of 24 cm.

The experimental phase provided for the definition of a measurement equipment that, on the one hand, allowed the monitoring of the system performances, while on another hand it permitted to collect measures useful for the theoretical models. In particular, different thermo – resistances, a pyranometer, an acquisition system and a Source Meter Unit have been employed in order to monitor the electrical signals and for the cell characterization.

The last phase of the experimental study allowed to design a new line focus system with a concentration factor of about 100 suns.

The main results of the theoretical – experimental modeling, after the input analysis and the study of the system variables, show the electrical and thermal performance of the concentration systems defined. In particular, considering a residential user and exploiting a choice model, a point – focus system with 180 triple junction cells has been chosen. With this configuration, considering the electric national grid and a thermal energy storage, the system allows to meet the user energy demands. Another application example, for a residential user, led to define a line focus system with 500 triple junction solar cells.

The experimental results, over the estimation of the concentration factor, have shown a maximum temperature for the solar cell of about 70°C. Hence, it allowed the parametric analysis of the cell temperature by means of the

Random Forest model, which shows as, increasing the concentration factor, the system can be employed both for the winter heating and the summer cooling.

Generally, for a domestic user in the South of Italy, the concentrating photovoltaic and thermal system allows an annual electric energy production of about 3000 kWh and an annual thermal energy production between 10000 and 13000 kWh. Taking into account of average energy demands and considering the system possibility of work with the electrical national grid and a tank, the concentrating systems represent a good solution for a residential user.

Moreover, as shown by the analysis of the different configuration, the systems can meet the energy demand with a simple payback period between 8 and 11 years, considering some inefficiencies.

Hence, the presented work shows the great potential of the concentration system in the combined energy production field. The theoretical and experimental analysis have been conducted focusing on the study of the different parameters influence. The main results are connected to the input prevision, the system operating analysis for both the electrical and the thermal part and the designing of different prototypes.

The concentrating photovoltaic and thermal systems represent an interesting alternative solution which shows a high flexibility in the system configuration and which constitute a topic for further development, in particular for the definition of a standard plant.