Energy Performance of a Cogenerative Photovoltaic System for the Production of Electrical Energy and the Air-Conditioning of an Open-Space Building

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Abstract

The energy performance of a co-generative system, represented by hybrid solar capture field with PV-T parabolic concentration having a degree of freedom, was determined. Thermal energy is provided to the building by means of the radiant ceiling distribution system, which is not an integrated part of the structure. The refrigerant flow rate is stored in a hot tank which is used directly in winter to supply the radiant ceiling, or by means of a water-water heat pump. In summer, stored thermal energy is instead used by a simple effect absorption chiller. The produced electrical energy is entirely self-consumed. The dynamic simulation of the building-plant system was carried out with the TRNSYS simulation code which allowed for the determining of the main performance indices by varying some parameters, referring to climatic data for a location in southern Italy.

1. Introduction

In Italy, in recent years, thanks to an advantageous incentive system, a notable increase in the installation of photovoltaic plants has been recorded, whose total power has gone from 273 MW in 2008 to 398 MW in 2009, which corresponds to an increase of 46% [1]. A limit to the spread of such equipment is represented by low electrical efficiency of the modules, which render the investment not very appealing. The conversion efficiency of electrical energy from photovoltaic modules, today, still reaches limited values, oscillating between 14% for panels made from monocrystalline silicon [2]. Such limits can be partially overcome by turning to two different solutions: solar concentrators and cells refrigeration. In the first case, parabolic concentration systems are used, generally with a degree of freedom, which are capable of increasing solar flow. In such a case, electrical energy production undergoes an increase due to the greater solar power incident on the cells. In the second case, module refrigeration allows for lowering of the functioning temperature and, consequently, of improving the electrical efficiency [3]: the decrease in electrical power is about 0.4% for each increase by °C of the module temperature compared to the reference temperature. The advantages are even more evident combining concentration and refrigeration techniques [4]. For systems with high concentration ratio, refrigeration becomes necessary in order to contain cells temperature, which would otherwise lead to certain damage. From an economic viewpoint, it is necessary to consider the thermal energy which is made available following refrigeration, which can be used to partially cover the thermal energy requirements of a building, both for heating and cooling, with benefits for the running costs of the air-conditioning plant. In this work, the energy performance of a hybrid PV-T system, with parabolic concentration with a degree of freedom, used to cover the energy requirements of an open space building situated in Cosenza (Italy, 39.30 N;16.25 W) was determined. The electrical efficiency of the cells is improved by means of a refrigerant water flow rate, the storing of which in a storage tank renders thermal energy available to be used for the heating and summer cooling of the building. For the supply of thermal loads required for heating and cooling, non integrated chilled ceiling systems are used, which require inlet temperatures which are much more advantageous compared to those of traditional systems. The plant provides for the direct use of the hot storage tank to supply the radiant ceilings in winter. In the case in which the thermal level of the accumulator is insufficient, the load is supplied by a water-water heat pump using the hot tank as a thermal source. In order to avoid risks of freezing in the tank, the heat pump uses outdoor air as an alternative thermal source. This plant solution allows for the obtainment of moderate thermal levels in the tank, with advantages in the production of electrical energy. During summer, the same heat storage system supplies a simple effect absorption chiller, which produces chilled water flow rate which are conveyed to a cold storage tank. In order to guarantee the complete coverage of the refrigerant load required by the building [5], an air-water heat pump is used which operates in parallel to the absorption chiller. Both during winter and summer the use of a cross flow heat exchanger is provided for, which uses an outdoor air flow rate, in order to further reduce the inlet temperature of the PV-T modules. The simulation of the building-plant system was obtained with the TRNSYS 16 simulation code [6], and the seasonal energy performance was determined referring to the plant configurations obtained by varying some of its parameters. The comparison of the various solutions considered in terms of primary energy and performance indices permitted the identification of the best plant configuration.

2. Description of the considered building

The considered hybrid solar plant is used for the supply of thermal and electrical requirements of an open space building used as a call center. The building is parallelepiped in shape and, according to plans, is 20x25m in dimension, with a height equal to 3m. The longest sides have East/West facing and are formed by uniform insulated walls with a thermal heat loss coefficient of 0.46 W/m²K. Each opaque vertical surface hosts a glazed system with clear double glazing, with thermal heat loss coefficient equal to 2.83 W/m²K and a total solar gain coefficient of 0.755. The glazed surface area on each side is equal to 50% of the corresponding opaque surface area. In order to reduce the incidence of thermal loads during summer, the glazed surfaces with Southern, Eastern and Western exposure are equipped with a system of external mobile shading devices which attenuate incident solar energy to 50%. Activation of the shading devices occurs between 10.00 and 14.00 for those with Southern exposure, from 08.00 to 11.00 for those with Eastern exposure, and from 15.00 to 18.00 for Western exposure. The covering roof is flat, with a thermal heat loss coefficient of 0.59 W/m²K, and on the inside it hosts a radiant chilled ceiling. Such a distribution system is realised with parallel network of polymer pipes with an internal diameter of 1.27 cm and pitch of 10 cm. It is separated from the surface of the ceiling by an air gap and the inlet flow rate is 455.8 kg/h with a speed of 1 m/s so as to guarantee turbulent flow conditions. The building is operative all week from 08.00 to 18.00 and hosts 60 people, each of whom provides a total power of 150 W in the indoor environment. Furthermore, personal computers are present which have a sensible contribution within the indoor environment of 140 W, as well as an artificial light system, which is in use from 08:00 to 18:00, which supplies the environment with a sensible load equal to 5 W/m². The electrical load required by the building is 55.4 kWh/day, while the maximum required power for heating and cooling are respectively 42.3 kW and 33.5 kW. The heating period begins the 15th of November and finishes the 31st of March, as provided for by the Italian decree DPR 412/93 [7], while the air-conditioning period begins the 27th of April and finishes the 9th of October, determined according to the UNI TS 11300-1 procedure [8].

3. Considered plant and control strategies

In Figure 1, the plant sketch plan is reported which provides for the supply of electrical and thermal energy to the building formed by a parabolic concentration collection field, by a hot and cold storage volume, by an absorption chiller and a heat pump operating with two thermal sources. The electrical requirements of the building were used in order to size the surface area of the concentration PV-T panels. The global opening surface area required is equal to 50 m², which ensures a peak power of 5.8 kW; the electrical energy produced is then self-consumed. The photovoltaic cells used tolerate operating surface temperatures up to 185 °C. The concentration ratio is equal to 20, the gross area of each cell is 4 cm² and each string on the absorber is formed by 10 cells in series. The pump (1) operates on the fluid of the solar collectors each time that the outlet temperature is 2°C higher compared to that measured in the hot tank. If the temperature of the hot tank exceeds 50°C, the switch valve (b) intervenes, bypasses the tank, until the internal temperature of the tank does not fall below 45°C. In such a way, an ideal storage system temperature is obtained for the winter supplying of the radiant ceilings. Activation of switch valve (b) also leads to the activation of the switch valve (a), which allows for the sending of the refrigerant flow rate to the heat exchanger in order to further reduce the inlet temperature of the PV-T modules.

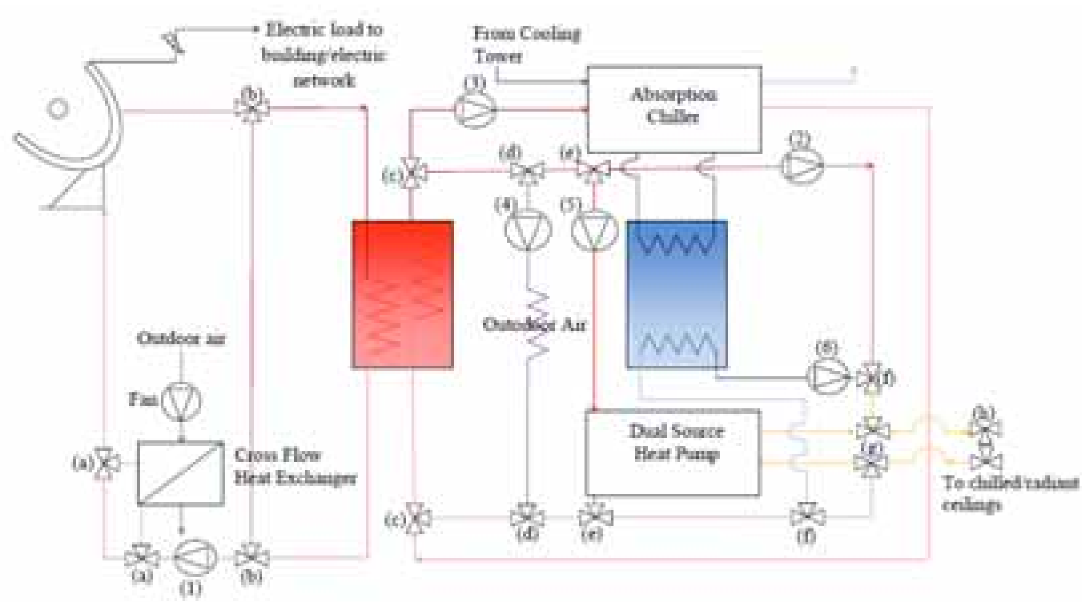

Fig. 1. Scheme of the considered plant.

The control signal for valves (b) and (a) also activates the fan, which uses an outdoor air flow rate as cold fluid. In the secondary circuit, pump (2) directly supplies the radiant ceilings if the heat storage temperature is greater than 30°C, by means of the three-way valves (c), (f), and (g). In the case that this condition is not satisfied, and if the temperature of the hot tank is greater by 6°C, pump (5) is activated which, by means of valve (e), supplies the heat pump which used the hot tank as a hot source. For temperatures lower than 6°C valve (d) and heat pump fan (4), which in this case uses outdoor air as a thermal source, intervene. The heat pump supplies the radiant ceiling by means of valves (g) and by bypassing valve (f). The nominal thermal power of the heat pump for water-water configuration is 28 kW and for air –water configuration is 22 kW to provide temperatures in the range of 35÷40 °C. For summer running, switch valve (b) of the primary circuit is never activated, and the PV-T refrigerant flow rate is always conveyed to the hot tank. The absorption chiller considered, sized in relation to the cooling loads required by the building, has a nominal power of 35 kW and requires a minimum generator temperature of 75°C. The heat in the condenser is dissipated by evaporative towers. The heat exchanger is activated when the hot tank temperature exceeds 80°C, and is deactivated by means of the switch valve (a) when the temperature in the hot tank becomes lower than 75 °C. In summer, it is inconvenient to continuously activate the heat exchanger because the possibility to obtain low thermal levels in the hot tank that would not ensure the functioning of the absorption chiller. In the secondary circuit, if the hot tank temperature is greater than 75 °C, the heat pump circuit is bypassed by valve (c), and thermal energy is provided to the absorption chiller by means of pump (3). In relation to condenser and generator temperatures, the absorption chiller provides a variable temperature chilled flow rate which is conveyed to the cold tank. The chilled flow rate is extracted by means of pump (6) and sent to the radiant ceilings by means of valves (f) and (g). An auxiliary system, represented by the air-water heat pump, integrates cooling energy if that provided by the absorption chiller is insufficient. The heat pump is activated by valve (c) and provides the chilled flow rate by means of valves (g) which connect the device to the building. The mixing valves (h) in the circuit in Figure 1, allow for regulation of the inlet temperature of the radiant ceilings by re-circulating a fraction of the outlet flow rate. In winter, the ceiling is supplied when the indoor air temperature is lower than 19°C and is interrupted when a temperature of 21°C is met. By means of a preliminary simulation campaign, and by using procedures developed in previous works [9], the control function was determined which allows for the evaluation of the inlet temperature in relation to both indoor and outdoor air temperatures:

$$t_{Ceiling}^{Inlet} = \left(-0.47 \cdot t_{Air}^{Outside} + 29.40\right) + \left[\left(0.05 \cdot t_{Air}^{Outside} + 1.02\right) \cdot \left(20 - t_{Air}^{Indoor}\right)\right] \tag{1}$$

In summer, mixing valves (h) regulate the inlet temperature, in relation to the dew-point temperature of the indoor environment "t_{dp}" according to the relation:

$$t_{Ceiling}^{Inlet} = t_{dp} - (t_{Air}^{Indoor} - 25) \tag{2}$$

Such a control is necessary to avoid the formation of condensation on the chilled ceiling surfaces, and was obtained by referring to authors in previous works [10]. The refrigerant flow is activated by an environment thermostat when the temperature rises above 27 °C and is interrupted when a temperature of 25 °C is reached. In order to limit dew-point temperature values, it is necessary to maintain indoor relative humidity values lower than 60%. This is ensured by imposing an exchange of outdoor air within the environment of 1.58 volumes/hour, as provided for by the UNI 10339 standard for the type of building analysed [11].

4. Energy evaluations

Plant simulations were conducted distinguishing between winter and summer functioning. The average monthly and seasonal values of various energy contributions were evaluated, and some performance indices with reference to different hot and cold storage volume values were determined. Furthermore, the influence of the refrigerant flow rate on PV-T module performance was evaluated. In particular, it was possible to identify the fraction of primary energy saved F_p, the fraction of electrical energy F_{el} and fraction of thermal energy F_{th} provided by the PV-T plant, compared to that required by the building. Thermal energy during winter has been distinguished between thermal energy supplied directly from the hot storage tank to the radiant ceilings $F_{th,d,}$ and thermal energy supplied by the heat pump $F_{th,hp}$. The fraction of primary energy saved is defined as the relation between the primary energy saved by means of the PV-T plant and the primary energy required by the building in the case in which natural fossil fuels are used. The primary energy consumed considers the electrical energy required by the building $E_{el,req}$, diminished by the quantity of electrical energy $E_{el,PVT}$ produced by the PV-T modules, and the electrical energy necessary to supply the heat pump $E_{el,hp}$, converted into primary energy by means of the actual efficiency of the Italian electrical system (η_{el}=40.16%) [12]. The thermal energy required by the building for heating E_{th} is converted into primary energy hypothesising that the heating plant is supplied exclusively by the heat pump, with a theoretical seasonal COP_t equal to 4.0. The fraction of energy saved is expressible with the relation:

$$F_p = 1 - \frac{\left[\left(\frac{E_{el,req} - E_{el,PVT}}{\eta_{el}}\right) + \frac{E_{el,hp}}{\eta_{el}}\right]}{\left(\frac{E_{el,req}}{\eta_{el}} + \frac{E_{th}}{COP_t}\right)} \tag{3}$$

In Figure 2 the average seasonal temperature values, for winter, of the hot tank and the fractions of saved primary energy F_p, electrical F_{el} and thermal F_{th} varying the hot storage volume are reported. From the analysis of Figure 2, it is possible to deduce how the average hot tank storage volume temperature increases with the storage volume. This apparent anomaly is actually justified by the fact that for small storage volumes, temperatures remain moderate due to the intervention of the heat exchanger. Moreover, due to modest variations in temperature, the electrical fraction is slightly variable round 43%, while the fraction of saved primary energy increases slightly with the volume and varies around 45%. The thermal fraction increases with storage volume, while that supplied by the heat pump diminishes. In Figure 3, the average seasonal values for electrical efficiency η_{el}, thermal efficiency η_{th} and total efficiency η_{TOT} in relation to the hot storage volume, are reported. They are defined respectively as the relation between electrical E_{el}, thermal E_{th} and total energy made available by the PV-T collectors, and solar energy $E_{sol,inc}$ incident on the modules:

$$\eta_{el} = \frac{E_{el,PVT}}{E_{sol,inc}} \qquad \eta_{th} = \frac{E_{th,PVT}}{E_{sol,inc}} \qquad \eta_{TOT} = \frac{E_{el,PVT} + E_{th,PVT}}{E_{sol,inc}} \tag{4}$$

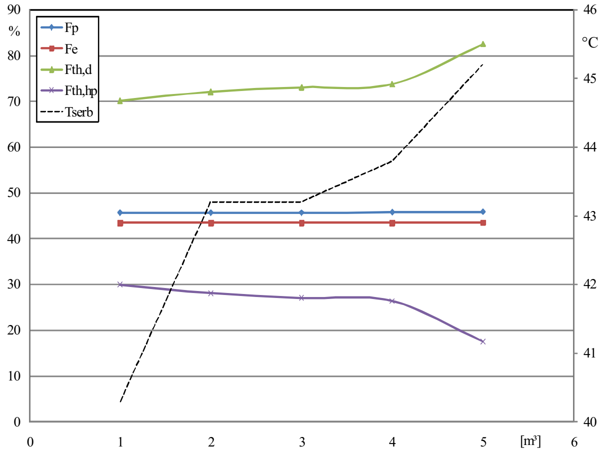

Fig. 2. Average seasonal winter values of the saved primary, electrical and thermal energy fractions and the average temperature of the tank, varying the hot storage volume.

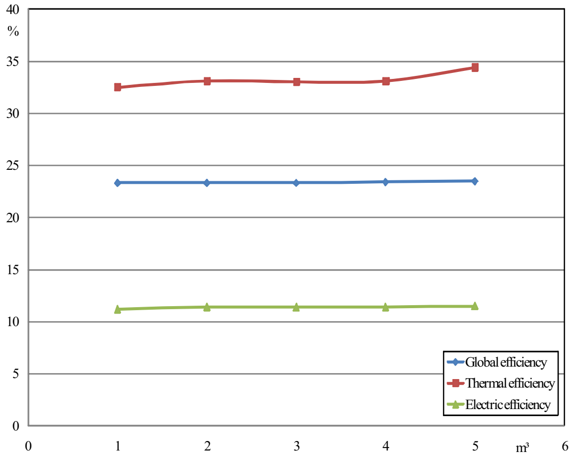

Fig. 3. Average seasonal values for electrical, thermal and total efficiency varying hot storage volume.

It is possible to observe, with the exception of thermal efficiency which undergoes a slight increase, that by varying the hot volume, both the electrical and total efficiency remain unvaried. For a storage volume of 5 m³ an electrical efficiency of 11.5%, a thermal efficiency of 34.4% and a total efficiency of 23.5% were obtained. In order to identify the most suitable hot storage volume, it is necessary to refer to the primary energy fraction, and not the efficiency, in that the latter uses a free source of primary energy. On the basis of such a presupposition, in winter, the influence of the hot storage volume on plant performance can be held to be negligible.

Figure 4 for a storage volume of 1 m³ reports the average seasonal trend of the saved primary energy fraction, the electrical fraction and the thermal fraction supplied directly by the tank and the heat pump, varying the refrigerant flow rate. In Figure 5, in similar way, is reported the seasonal values of the efficiencies and of the operating cells temperature. It is possible to observe that the fraction of saved primary energy reaches higher values for flow rates greater than 450 kg/h, since in these conditions the electrical efficiency becomes the highest.

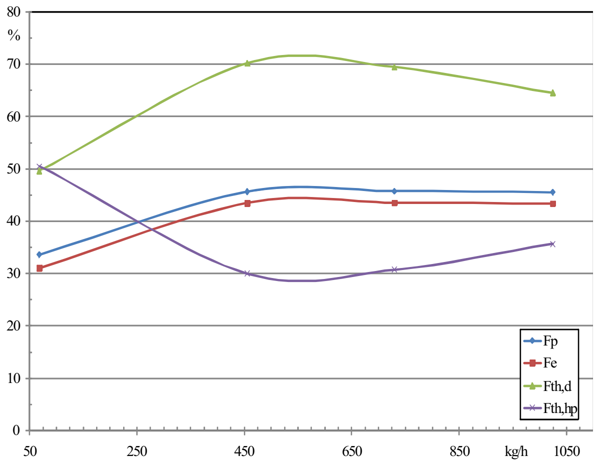

Fig. 4. Average seasonal winter values of fractions of saved primary energy, electrical energy and thermal energy supplied directly by the tank and the heat pump, varying the flow rate in the PV-T collectors. Storage volume equal to 1 m³.

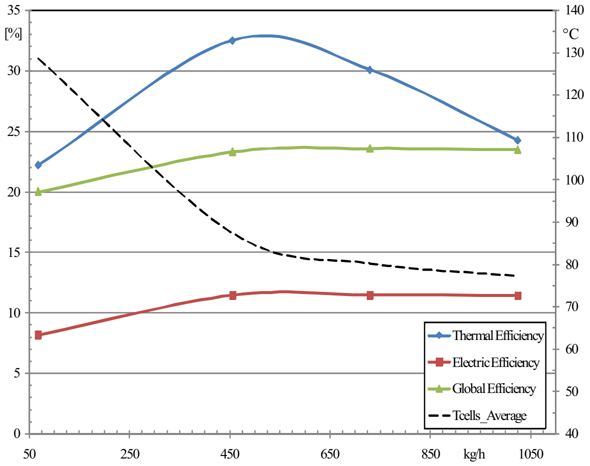

Fig. 5. Average seasonal winter values of electrical, thermal and total efficiency, and the functioning temperature of the cells varying the flow rate in the PV-T collectors. Storage volume equal to 1 m³.

For an airflow of 456 kg/h, the primary fraction is 45.6%, the electrical one 43.4%, the direct thermal one 70.1% and that supplied by the heat pump 29.9%. The flow rate was set to vary between 68.4 kg/h, which corresponds to a laminar flow, and 1025 kg/h which corresponds to a turbulent flow. Turbulent conditions are recorded for flow rates greater than 400 kg/h. It is possible to observe that the refrigeration obtained with laminar flow penalises the electrical efficiency, due to the higher cell functioning temperatures, and the total efficiency tends to stabilise for flow rate values greater than 450 kg/h. Thermal efficiency presents a maximum point (32.6%) for a flow rate of 456 kg/h; for greater flow rates it diminishes due to reduced heat exchanger use which leads to higher temperatures in the PV-T collector circuit.

In summer, Eq. (3) is still used, but with a more limited average seasonal theoretical COP for the heat pump and equal to 3.5. This correction takes into account the fact that in winter, the average seasonal theoretical COP is positively influenced by greater use of the water-water heat pump, which is characterised by higher performance coefficients. In summer the air-water heat pump is used exclusively, which operates with more limited performance coefficients compared to the water-water heat pump. In Figure 6 the trend for the saved primary energy fraction, in relation to the hot storage volume and for three different values of cold storage volumes is represented. It is possible to observe that the highest fraction values of saved primary energy are reached with a hot storage volume equal to 1 m³, since in such conditions activation of the heat exchanger leads to greater benefits for the production of electrical energy. The increase in cold storage volume leads to a contained diminishment of the saved primary energy fraction. The highest fraction of saved primary energy is obtained with a hot and cold storage volume of 1 m³ and is equal to 66.4%. Variations of the electrical fraction and the thermal fraction, varying the hot and cold storage volumes, are reported in Figure 7. In Figure 8, the corresponding values of thermal, electrical and total efficiency are reported.

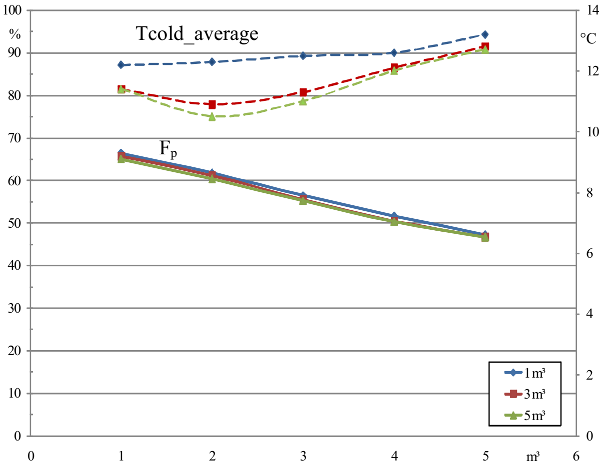

Fig. 6. Summer trend of the saved primary energy fraction and of the cold tank temperature, varying the hot and cold storage volumes.

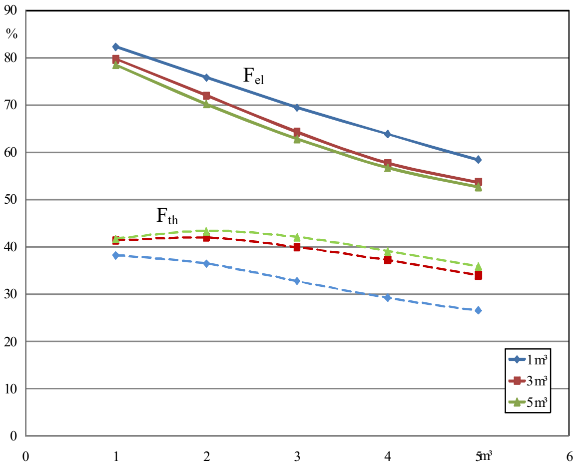

Fig. 7. Average summer seasonal values of electrical and thermal energy fractions, varying the hot and cold storage volumes.

With an increase in the hot storage volume, the electrical fraction records a greater variation compared to the thermal fraction. An increase of the cold storage volume leads to a reduction in the electrical fraction and to an increase in the thermal fraction. The thermal fraction presents its maximum point for 2 m³ hot storage volume, and for 5 m³ cold storage volume. With regards to the efficiencies, the increase in volume for hot storage leads to an increase of the thermal efficiency, while the electrical and total efficiency diminish. Total efficiency is influenced to a greater extent by the electrical efficiency. The effect of the cold storage volume is, instead, contained in the trends of the three efficiencies. The thermal and the total efficiency increase with the cold storage volume while, on the contrary, the electrical efficiency diminishes. The thermal efficiency reaches a maximum value of 41.7% with a hot and cold storage volume of 5 m³. Whereas, the global efficiency reaches a maximum value of 19.7% with 2 m³ of hot storage and 3 m³ of cold storage. Even in this case, the best plant configuration is identified by means of the primary fraction, which, in summer functioning, requires hot and cold storage tanks with a volume of 1 m³. In Figure 9, the trend for electrical efficiency, thermal efficiency, and total efficiency, varying the PV-T modules refrigerant flow rate, is reported, for a plant with a hot and cold storage volume equal to 1 m³.

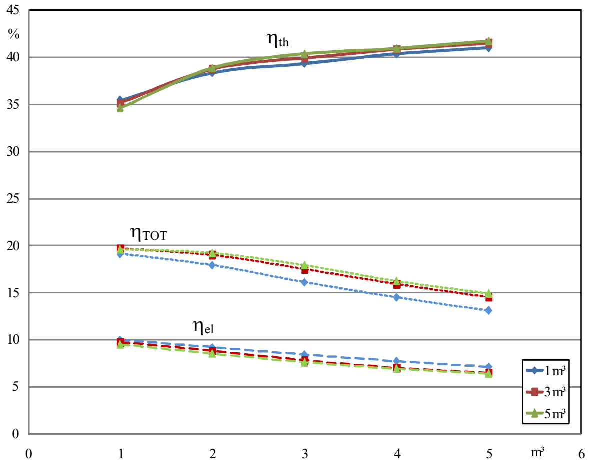

Fig. 8. Average summer seasonal values of electrical, thermal and total efficiencies, varying hot and cold storage volumes.

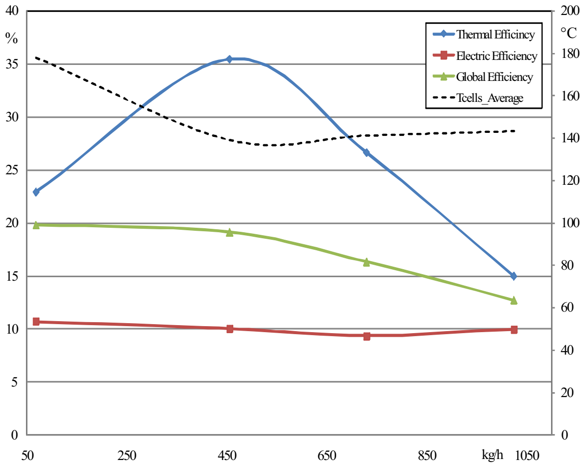

Fig.9 Summer trend for efficiencies and cell temperature varying the refrigerant flow rate. Hot and cold storage volume equal to 1 m³.

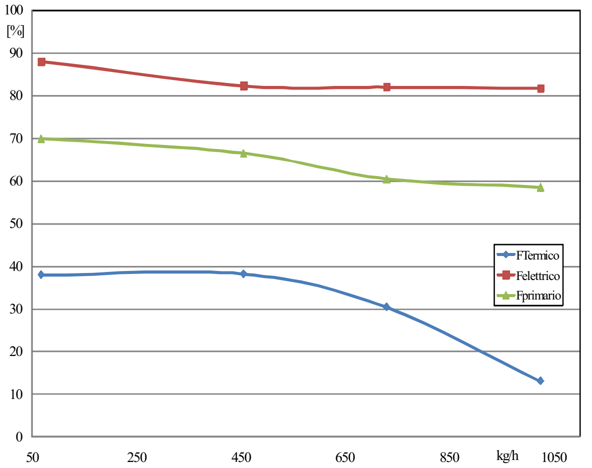

Fig. 10. Average summer seasonal values of primary, electrical, thermal energy fractions, varying the flow in the PV-T collectors. Hot and cold storage volumes equal to 1 m³.

In Figure 10, the trend for saved primary energy, electrical fraction, and thermal fraction varying the refrigerated flow rate, is reported. The best results, in terms of electrical and total efficiency, are obtained with laminar flows while, from a thermal viewpoint, the best result is obtained with turbulent flows. For a refrigerant flow rate of 68.4 kg/h the average monthly cell functioning temperature is about 178 °C, approximate to the allowed temperature limit of 185 °C. With regards to the saved primary energy fraction, excluding the functioning with laminar flows, the best result is obtained with a refrigerant flow rate of 456 kg/h which ensures a value equal to 66.4%, with an average cell functioning temperature of about 140 °C. In these conditions, the electrical load is covered for 82.3% while the thermal one is covered for 38.2%.

Finally, in table 1, the monthly values of the determined performance indices are reported, considering a hot and cold storage volumes of 1 m³ and a refrigerant flow rate of 456 kg/h. During winter, the thermal fraction, and total efficiency of the system were determined not considering the energetic requirement from the air-water heat pump. Considering the annual performance, the considered plant has a saved primary energy fraction of almost 60%, covering the annual electrical and thermal requirements of 66.2% and 45.6% respectively. The average annual electrical efficiency is 10.3%, the thermal one is 34.7% and the average global efficiency slightly lower than 20%.

5. Conclusions

The energy performance of a co-generative system used for an open-space building, using parabolic thermo-photovoltaic collectors with a degree of freedom were determined. The plant provides for winter and summer conditioning of the building, by means of an absorption chiller and a heat pump using outdoor air or hot water to cool PV-T panels stored in a storage tank as thermal sources. The chosen plant configuration and relative control strategies were determined in such a way as to favour the production of electrical energy compared to thermal energy. Inlet temperature regulation at the photovoltaic collectors was also obtained using a water-outdoor air heat exchanger. The energy analysis was developed by means of the definition of some performance indices of the building-plant system.

Table 1. Monthly values of primary energy saved, electrical and thermal energy fractions, thermal, electrical and total efficiencies for a plant with a hot and cold storage volume of 1 m³ and refrigerant flow in the PV-T collectors of 456 kg/h.

Month	F_p	F_{el}	F_{th}	η_{th}	η_{el}	η_{TOT}
Jan	33.9%	29.5%	83.3%	33.8%	11.2%	36.4%
Feb	50.3%	47.6%	97.8%	32.4%	11.5%	25.0%
Mar	71.1%	70.6%	100.0%	35.2%	11.6%	14.7%
Apr	81.0%	79.7%	86.4%	26.0%	10.8%	12.6%
May	87.2%	90.7%	66.0%	33.4%	10.5%	16.6%
Jun	73.7%	96.3%	40.9%	40.6%	9.5%	19.7%
Jul	65.0%	99.9%	33.0%	41.6%	9.4%	22.8%
Aug	59.9%	86.6%	34.1%	42.4%	9.5%	23.4%
Sep	54.1%	64.8%	35.1%	34.7%	9.3%	19.9%
Oct	50.9%	49.5%	57.5%	15.8%	11.1%	15.0%
Nov	38.9%	38.2%	100%	27.5%	11.4%	14.7%
Dec	34.9%	31.4%	95.1%	31.4%	11.3%	30.6%
TOT	***59.7%***	***66.2%***	***45.6%***	***34.7%***	***10.3%***	***19.9%***

The largest fraction of saved primary energy was obtained with a hot and cold storage volume of 1 m³, and by supplying the PV-T panel refrigeration circuit with a refrigerant flow rate of 456 kg/h. This configuration permitted fossil primary energy savings greater than 66% during summer, and of 45% during winter. For a locality characterised by a typical Mediterranean climate, an annual saved primary energy fraction of 59.7% was obtained, with electrical requirements covered by a fraction of 66.2% and with a thermal requirement met by 45.6%. The average annual electrical efficiency of the PV modules results as being equal to 10.3%, while the thermal one is slightly lower at 35%.

From an energy viewpoint this type of plant ensures, with the same collection surface areas, high thermal and electrical fractions, and the maintenance of considerable efficiency values of conversion of solar energy into thermal and electrical energy.

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