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Optimization of solar thermal fraction in PVT systems

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Abstract

Over the last years there has been a growing interest in hybrid Photovoltaic-Thermal (PVT) collectors for their applications in building integration. The hybrid systems integrate the features of the photovoltaic and the solar thermal (water or air) systems in one combined product/system.

The PV electricity production in a hybrid system could be significantly different from the one of a standard PV module because, mainly, cells temperatures change according to the amount of heat removed by the absorber of the PVT system and, moreover, to the insulation level of the PVT system. This last factor is related to many parameters, among which it is possible to identify water flow rate and temperature, which are directly related to PVT plant configuration and size as a function of users heat demand.

Starting from these considerations, the aim of this paper is to calculate the optimal value of solar fraction *f* for hybrid PVT systems, under energetic end economic point of views, and to find a correlation between the percentage of heat demand covered by the PVT system and photovoltaic cells temperature. In fact, changes in solar fraction imply different average cells operating temperatures and consequently, variation in total energy efficiency. For this purpose, simulations of liquid-based PVT systems for domestic application have been performed through TRNSYS energy simulation tools, carrying out subsequently a detailed energetic and economic analysis.

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Keywords: PVT collectors; solar thermal; f factor; TRNSYS

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1. Introduction

The European Solar Thermal Industry Federation has predicted that by 2020, the EU will reach a total solar thermal capacity of between approximately 90 and 300 GW, thus leading to saving of equivalent to at least 5,600 tonnes crude oil. According to the same federation, by 2050 the EU will probably achieve 1,200 GW of solar thermal capacity [1].

Simultaneously, the series of years of growth of the PV market, even during times of financial and economic crisis, has continued in 2011. The volume of new grid-connected PV capacities world-wide was equal to 27.7 GW in 2011, and almost 21 GW of this growth could be counted in Europe [2]. This trend leads to forecast that in Europe, by 2016, the total PV installed power will reach a total amount comprised between 95 an 155 GW [3], confirming that PV technology will cover a central role in EU future energy strategy.

In this context, a significant amount of research and development work on the photovoltaic/thermal (PVT) technology has been done since the 1970s and moreover during the last years there has been a growing interest in hybrid Photovoltaic-Thermal (PVT) collectors for their applications in building integration [4,5]. In facts, hybrid systems integrate the features of the photovoltaic and the solar thermal (water or air) systems in one combined product/system. The basic concept of the conventional hybrid systems is rather simple and is based on the removal of waste heat from photovoltaic cells for its successive utilization through the circulation of heat transfer fluid behind the PV panels.

A typical hybrid system contains a solar thermal collector in which a PV laminate is used as a thermal absorber. In this kind of system, besides generating electricity, it is possible to recover the thermal energy, which is otherwise lost, decreasing simultaneously the operational temperature of the photovoltaic cells and increasing, therefore, the PV conversion efficiency, in particular for C-Si cells. As a consequence, a relevant fraction of before-mentioned future solar thermal and photovoltaic installed power could be achieved through PVT technology. In particular, it was observed that the largest market for PVT is in domestic applications, where it is important to produce electricity and thermal energy with compact products, suitable for small roof surfaces [6]. Given the continuing efforts for reducing the energy demand in the residential sector, this market is expected to grow substantially over the decades to come, in particular for liquid-based PVT systems, which are more appropriate for DHW production since their production can be exploited throughout the year.

More in detail, the liquid-based PVT system uses PV technology to produce electricity and has a typical efficiency 5-15% higher than traditional PV modules. In facts C-Si products, for example, have typically higher temperature coefficient, while for thin film panels temperature has lower influence on conversion efficiency. Hybrid configuration reduces, in general, temperature losses on the collector.

The solar energy not converted in electricity is transformed into thermal energy and it can be partially used for different purposes, such as DHW production, heating etc., with an average efficiency equal to PVT/liquid systems in the range of 45–70% for unglazed to glazed panel designs [4].

F-Chart method is the most common and wide-spread simplified method to estimate the thermal energy performance of solar thermal system [7]. The optimal value of solar fraction f, which is precisely the percentage of DHW demand that is covered by the solar system, typically corresponds to 50-70% [8] of the total energy demand, while the remaining fraction of this energy need is covered by auxiliary equipments. These dimensioning criteria allow satisfying the whole DHW demand in summer and a smaller part in winter. Therefore, a thermal demand coverage higher than 60-70%, would provide more energy saving in winter but also a surplus production in summer time that, if not used, could affect the cost effectiveness of the system during its lifetime and could cause problems like overheating.

Considering the above mentioned thermal and electrical performances and typical system costs, the installation of a PVT system could easily become more affordable than that of the two solar technologies separately [9]. However, since that thermal and photovoltaic performances requirements could be conflicting, system sizing and design has to be carried out according to innovative procedures.

Therefore it's not possible to assume that the optimal solar fraction commonly considered for solar thermal plants could be effectual also for PVT systems.

According to these considerations, it is important to precisely estimate the potential of liquid-based PVT systems for DHW application, depending on climatic context and thermal loads.

2. Methodology

The overall efficiency of a liquid-based PVT system depends on many factors that determine the useful total primary energy production. As introduced before, once defined the specific system technology (e.g. PVT collector characteristic and plant configuration), climatic conditions and solar fraction are two key factors to assess system performance.

Starting from these considerations, a methodology is presented to calculate the best value of thermal f factor for hybrid PVT systems and then to find an optimization between the percentage of heat demand covered by the hybrid system and production of PV electricity production.

In detail, a glass-covered collector PVT plant (glass-air gap-cells-absorber-insulation) connected to a defined DHW load was chosen as a benchmark, and varying the collector surface different performances were simulated, corresponding to variable solar fractions f, ranging between 20% to 110%, depending on different climatic conditions.

2.1. Reference conditions

To evaluate the influence of the climate on performance and cost-effectiveness of different configurations of the analyzed PVT system, three Italian locations were considered, representing different climatic zones: Milan (Continental), Rome (Temperate) and Palermo (Mediterranean). The climatic conditions chosen can be considered representative for the entire region of southern Europe, which is one of the geographical areas that in the coming years will be characterized by greater spread of solar plants [10].

In Table 1 main climatic data are summarized.

Table 1. Representative cities chosen as a reference for different climatic contexts.

Site	*Climate*	*Latitude*	*Degree-Days*	*Max summer temp. [°C]*	*Winter design temp. [°C]*	*Average sum of global irradiation [kWh/m²year]*
Milan	Continental	45°	2404	31.9	-5	1270
Rome	Temperate	41°	1415	33.8	0	1470
Palermo	Mediterranean	38°	751	32.6	5	1660

Subsequently, regarding DWH load, a defined and fixed quota was supposed, varying consequently only the surface of PVT (number of collectors) and not the dimension of the other components of the system (storage, auxiliaries, etc.).

Thus, the DHW loads profiles were estimated; the amount of energy required to warm water is dependent on several factors such as, consumption rate, inlet and hot water utilization temperatures.

A hot water consumption of 500 l/day was assumed, as a 10 persons' DHW need. The average inlet water temperature was set equal to 15°C, assuming a utilization temperature of 40°C [11]. The average distribution during the day was set considering common literature values [12], as shown in Fig. 1.

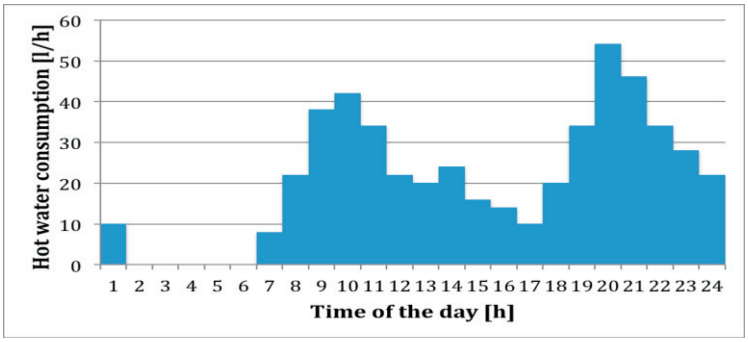

Fig. 1. Hot water consumption distribution

2.2. PVT plant scheme and control logics

A forced circulation system with flow loop between PVT solar collector and tank was assumed for this study, considering the technical configuration hereafter described.

In detail, the proposed PVT module is a so-called one glazed flat plate collector. A copper absorber is covered with photovoltaic cells with packing factor of 0.8 (80% of the absorber surface is covered by the cells). A PV cells' efficiency of 15% at STC and a temperature coefficient on power equal to 0.4%/°C have been assumed; these parameter are typical of C-Si modules that are currently most popular on the market.

The PVT collectors are array hydraulically connected in parallel. This configuration allows to maintain low pressure drop, with the result of significantly decreasing in energy consumption of circulation pump. Parallel connection also allows maintaining a lower temperature differential between the inlet and outlet manifolds. Optimal flow rate of collector array should be calculated depending on the number of connected modules and the characteristics of each module. According with some related works [13-14] the optimal flow rate can was to 50 kg/m^{2}h. It has to be noted that when the flow rate is around that value, there is not much benefit by increasing it further [15].

Furthermore, it must be considered that external ambient temperatures could fall below 0°C, for that reason the use of water–glycol was considered for the collector loop. This choice requires the use of intermediate heat exchangers located inside the storage tank, in order to keep the different heat transfer fluids separated. In detail, a circulation pump serves the collectors-tank loop. The storage tank works on the thermosiphon principle: the hot water from the collector heats up the water on the lower part of the tank, which flows upward in the tank to satisfy DHW load through a second heat exchanger. The volume of the tank was sized equal to 500 litres, which correspond to 50 l/person daily hot water consumption [16]. In order to reduce the heat losses of the tank, it was considered an insulating layer which provides thermal transmittance of 0.5 W/m^{2}K.

An auxiliary heater, connected to the heat exchanger in the highest part of the tank, is considered to supply the thermal energy which the collectors are not able to deliver. For the present study, two kinds of auxiliary heaters were considered: an electric one (equipped with electric resistance) and a natural gas boiler, as long as these two technologies correspond to the most widespread DHW generators in residential sector [17].

In Fig. 2 a general scheme of the PVT-DWH system is shown.

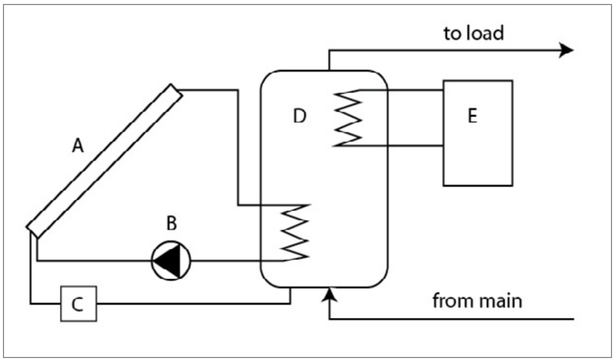

Fig. 2. PVT plant scheme (A: PV-T collector; B: Pump; C: Differential controller; D: Tank; E: Auxiliary heater)

An on/off differential controller that generates the on/off signals operates the pump. The controller turns on the pump only when the outlet temperature from the collector is higher than the temperature of the bottom side of the tank.

PVT collector thermal efficiency, which is the ratio of useful heat gain to the solar energy received by the collector, was calculated according to the well know Duffie-Beckman [18].

The other selected collector design parameters are given in Table 2.

Table 2. Main selected design parameters about the selected absorber

Design parameters	*Values*
Collector Area A_c	2 m^2
Flow rate	50 kg/m^2h
Collector efficiency Factor F’	0,94
$(\tau\alpha)_n$	0,81
Overall loss coefficient U_L	5,4 W/m^2K
Packing Factor	80 %
Electrical efficiency of the cell η_{cell}	15 %
Temperature coefficient	0,4 %/°C

As introduced before, in order to analyze the dependence of PVT system performance on the *f* solar fraction, five configuration have been considered, specifically assuming different PVT collector surfaces, respectively to 2, 4, 6, 8 and 10 m^2.

2.3. Simulation tools

Different computational tools have been developed to numerically evaluate the long-term performance of solar systems and to study the effect of design parameters. In recent years, one of the most used worldwide software to evaluate thermal and electrical performances of PVT modules is TRNSYS [19-26].

It has been shown by analyzing the results of several validation studies that TRNSYS provides results with a mean error between the simulation results and the measured results below 10% [27].

As a consequence, for the present study, a TRNSYS model for the hybrid PVT solar system under investigation was designed, according to above-described PVT plant scheme.

In particular, the main component of the TRNSYS deck file constructed for this purpose is Type 50, which represents the PVT collector. Additional used components are Type 3 (pump), Type 60 (stratified storage tank), Type 2 (differential controller), Type 14 (load) and some other subsidiary components. Meteorological data was taken from the Typical Meteorological Year (TMY) data bank of Meteonorm [28-31] for the references sites.

3. Simulation result and discussion

From the thermal point of view, once chosen plant configuration and the above described reference conditions, simulation were carried out with TRNSYS software. Different solar fractions were calculated for each collector's area based on the following equation:

$$f = (Q_{Thermal} - Q_{auxiliary})/Q_{load}$$

The results obtained are reported in Fig. 3.

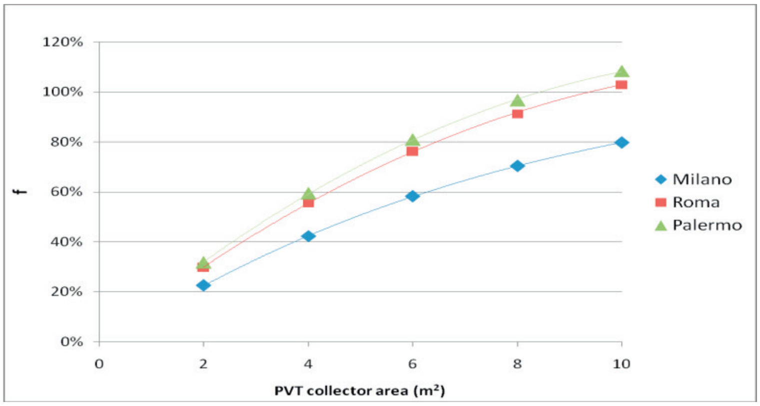

Fig. 3. Calculated solar fractions for different collector areas

As it can be obseved in the graph, results show that the solar fraction isn't a linear function of collector surface, since a greater number of installed collectors corresponds to lower thermal efficiency.

Subsequently, different values of produced thermal and electrical energy were calculated, evaluating also the energy which must be supplied by heating auxiliary system (in terms of thermal energy) in different conditions, as shown in Fig. 4-6. However, in order to analyse the overall production of thermal and electrical systems, comparing different solutions and plant's designs, it is necessary to reduce different energy fluxes to primary energy, considering an electricity to primary energy conversion factor for Italian context equal to 2.17 kWh_p/kWh_e (η_{sen}=46%) [32].

As told before, energy delivered by auxiliary system was reported in terms of thermal energy, which will be converted in primary energy depending on selected auxiliary heater system in the next step of the analysis.

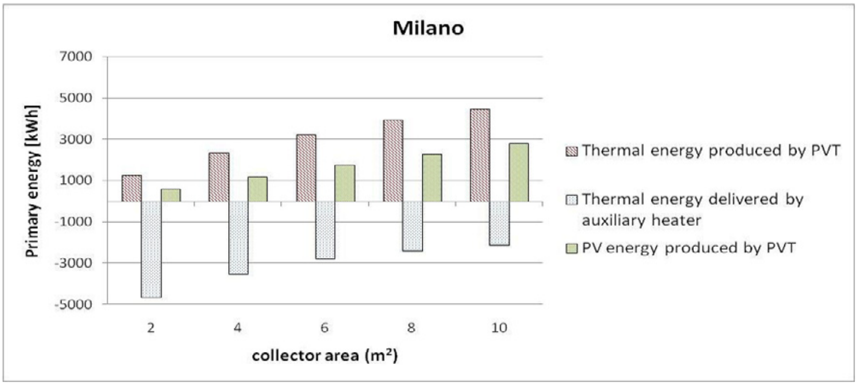

Fig. 4. Milano, energy produced by PVT system Vs energy delivered by auxiliary heater for different collectors' surfaces

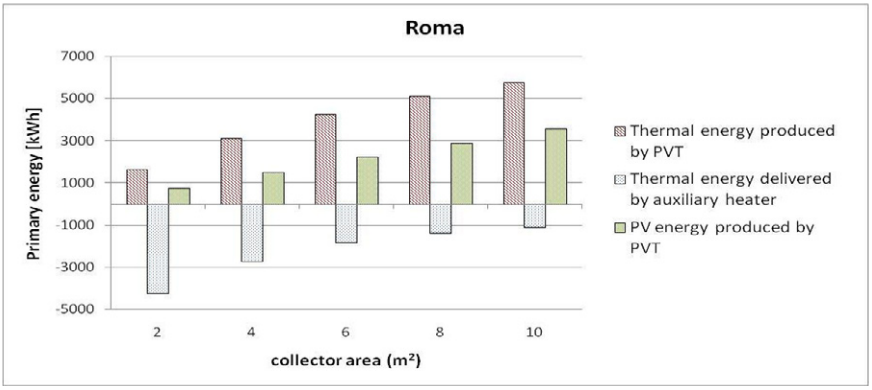

Fig. 5. Roma, energy produced by PVT system Vs energy delivered by auxiliary heater

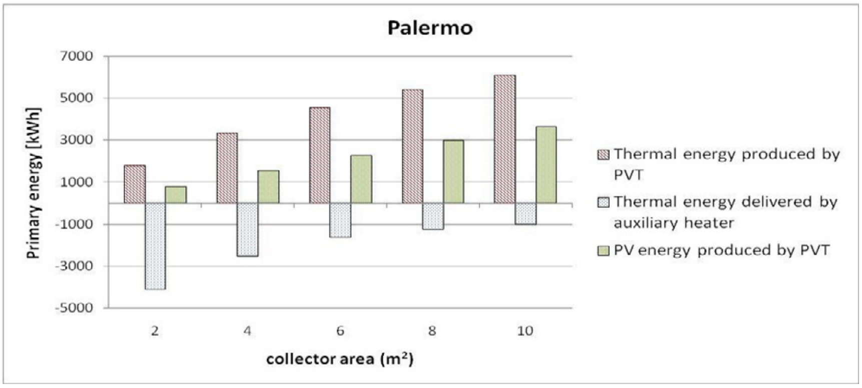

Fig. 6. Palermo, energy produced by PVT system Vs energy delivered by auxiliary heater

As expected, for lower values of solar thermal fraction, the heat required by the auxiliary system is considerable. Moreover a larger area of PVT collectors corresponds to an increasing of primary energy produced by the PVT system.

Anyway, the analysis has to be deepened considering the overall energy balance, including total primary energy production and consuption for each configuration.

3.1. Energy saving potential

Previously obtained data, related to auxiliary heating needs, must be converted to primary energy and compared with saving potential calculated with respect to specific DWH production technologies. As told before, in the present study two main technologies were considered, and average efficiencies are summarized in the following table [33].

Table 3. DHW auxiliary heaters efficiencies

DHW heater	*Overall generation efficiency*	*Primary energy conversion factor*
Electric heater	85%	2.17
Natural gas heater	90%	1

The total primary energy demand of the auxiliary system corresponds to the ratio between the heating requirements and the system efficiency, multiplied by the corresponding primary energy conversion factor.

The performance of the PVT system consists in the renewable energy production, net of auxiliary devices' consumption. Expressed in terms of primary energy, this balance is in general considered an energy saving for the users. Obtained results are shown in the following figures.

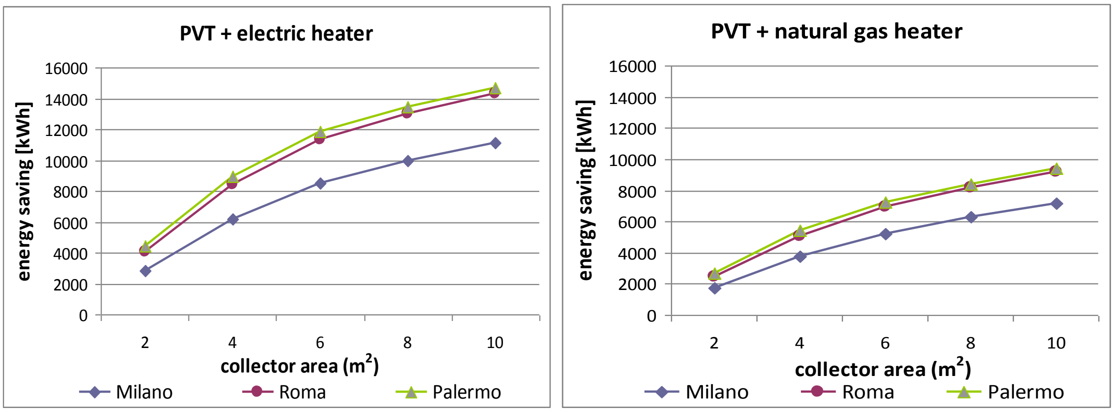

Fig. 7. Total energy saving in case of electric heater and natural gas heater

By observing the graphs, it can be seen that primary energy savings are much more consistent in case of electric heater in comparison with natural gas one. Anyway, in both cases, by increasing the PVT collector surface the total energy saving is not increasing linearly, which leads to conclude that global system efficiency is slightly decreasing by increasing PVT area.

This happens because the largest number of collectors increases the heat transfer fluid mean temperature in each loop, while progressively reducing both the PV and thermal efficiency.

However, to perform a complete assessment of the PVT energy performance, global system costs and savings potentials must be taken in consideration, as reported hereafter.

3.2. Economic evaluation

In order to evaluate which is the best solution under the technical-economic point of view, previous results were analyzed in terms of costs and benefits. In particular, a long-term economic analysis has been carried out using NPV (Net Present Value) index based on a discount rate equal to 4%. In this sense, for yearly cash flows, electricity and natural gas prices have been calculated considering an estimated value for electricity equal to 0.18 €/kWh and for natural gas 0.7 €/m^3, according to current market prices in Italy. From literature [33] an estimate has been considered regarding the increment in the future energy prices and this value is set between 2–5% per year. In present study, 3% has been assumed for electricity and 4% for natural gas. Moreover, as an additional benefit, a PV feed-in tariff has been considered on the electricity production of the PVT system, according to Italian existing incentives (among the most interesting on the PV market last years).

PVT installation cost (Tab.4) were determined analyzing average market costs of different products, and has been considered variable proportionally to the number of PVT collectors. On the other side, outcome related to other plant components (e.g. DHW storage, auxiliary heater, etc.) can be considered constant and independent from PVT solar collectors area; this amount was set equal to 2000€.

Table 4. PVT system costs

Variable costs including installation	*[€/m^2]*
PVT flate-plate collectors with C-Si PV cells	360
Mounting structure, inverter, wirings, electric board	200
Pump, main hydraulic components,	150

Subsequently, the economic payback time periods (PBT) were calculated for the different solutions, obtaining hereafter shown results. They represent the year in which the NPV is equal to zero fore each configuration.

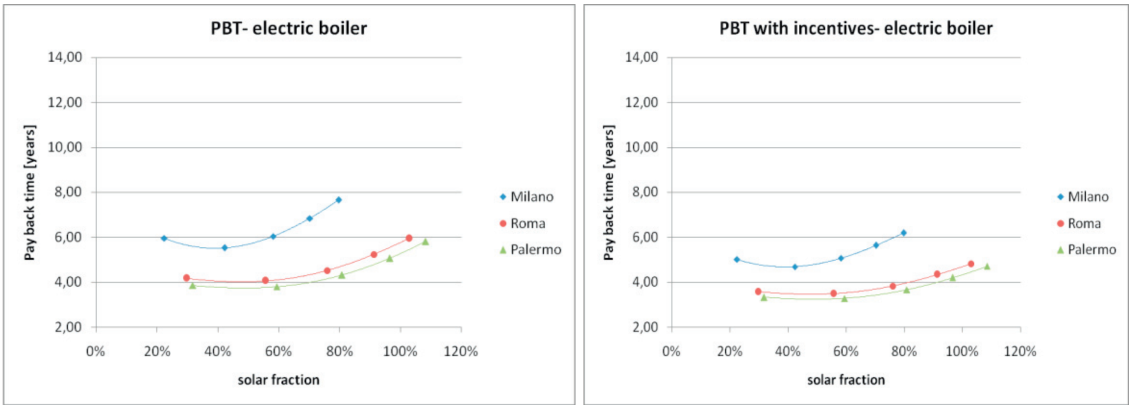

Fig. 8. Economic payback time periods (PBT) in case of electric heater

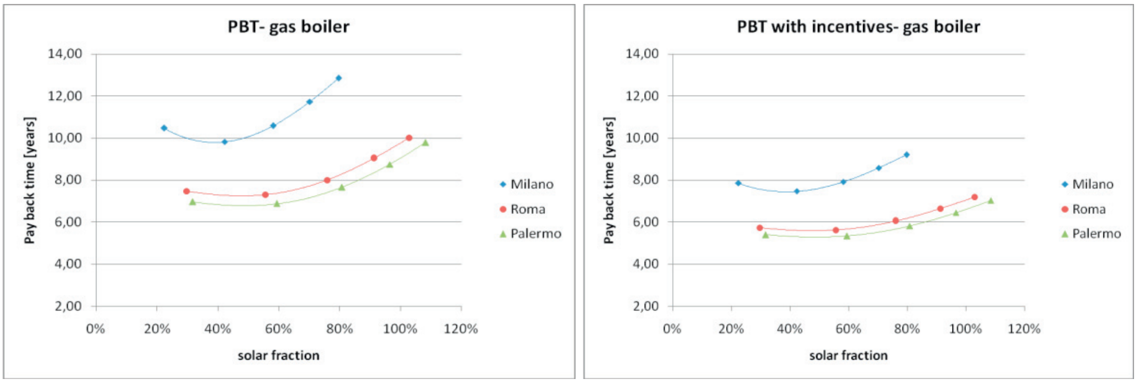

Fig. 9. Economic payback time periods (PBT) in case of natural gas boiler

As it can be observed in the previously reported graphs, the payback time has minimum values when *f* ranges about 40%-50% in colder climates (Milano) and to roughly 60% in warmer climatic conditions (Roma and Palermo).

4. Conclusions

The observation of the technical-economic evaluation presented in this paper, allows some interesting considerations. Obviously, the convenience of the systems increase by moving towards climates with greater availability of solar radiation, however, the optimization of global energy performance of the PVT system (both heat and electricity) imposes a constraint on the solar plant size, depending on the boundary conditions. While for conventional solar thermal systems an *f* factor is recommended equal to about 70%, this analysis shows that, however, for hybrid PVT systems the optimum value of the thermal solar fraction falls around 40-60% depending on the analyzed case. An effective exploitation of solar energy, especially in complex systems such as that treated in this study, cannot be carried out without in-depth analysis, beyond the mere assessment of efficiency.

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