Hybrid PhotoVoltaic–Thermal heat pump systems: energy and economic performance evaluations in different climates

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ABSTRACT

PhotoVoltaic/Thermal cogeneration (PV/T) aims to utilize the same area both for producing electricity and heat. An electric compression heat pump can be coupled to the PV/T panels to contribute to the space heating demand partially using the self-produced electricity. Some Italian climates and economic incentives scenarios are considered with Trnsys simulations to evaluate the energy and economic viability of PV/T-heat pump hybrid technology. Primary energy saving results to be between 35% and 65%, and discounted payback of the investment can be around 10 years in mild climates and southern resorts.

Keywords: heat pump; hybrid solar system; photovoltaic; PV/T; thermal collector

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1 INTRODUCTION

Not all the wavelengths of the incoming irradiation are usefully converted into electricity in PhotoVoltaic (PV) cells: commercially available single junction PV cells convert between 6% and 25% (under optimum operating conditions and depending on the semiconductor material) into electricity, while the rest is dissipated as heat [1]. This is due to the band-gap energy of the semiconductor material. For example, crystalline silicon PV cells can utilize the entire visible spectrum plus some part of the infrared spectrum, but the energy of all the other wavelengths (the far infrared and the higher energy radiation) is unusable in order to be converted in electricity and instead is dissipated at the cell as thermal energy. The main drawback is that the PV module can reach temperatures as high as 40°C above ambient; this causes an increased intrinsic carrier concentration which tends to increase the dark saturation current of the p–n junction. The main effect is the decreasing of the available maximum electrical power, typically 0.2–0.5% for every 1°C rise in the PV module temperature for crystalline silicon cells.

The well-known main idea to face the issues just described is to increase the electrical production of PV by decreasing the normal operating cell temperature by cooling the panel by a liquid (or air) [2]. So PV/Thermal technology (PV/T) aims to utilize the same area both for producing electricity and heat. This also implies to have higher global efficiency with an enhanced use of solar energy [3, 4]. The most common technology is the PV/T flat-plane solar collector where heat extraction from the PV panel is forced by the utilization of a pump for water circulation.

Many experimental and theoretical studies have been done in the recent past on the performance of PV/T water cooled plane collectors [5–7]. An experimental study was carried out by the authors as well [8, 9]. From the technical point of view, the performances strongly depend on the channels absorber design, the glazed or unglazed configuration and the flow rate and inlet temperature of thermal fluid. Considering the European Directives constraints on energy efficiency and renewable energy, solar energy is an interesting option in Italy due to the high values of annual solar radiation. Furthermore, different granting systems based on the promotion of electricity from photovoltaics and thermal energy from solar thermal plants have been churned out by the Italian government during last decade.

The proposed work aims to sound the energy and economic viability of using PV/T panels for cogeneration purposes for a typical four-bedroom house over different cities in Italy. An electric compression heat pump can be coupled to the PV/T panels to contribute to the space heating (SH) demand partially using the self-produced electricity. The analyses take into account an

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innovative design useful to mitigate the typical constraints of PV/T flat-plate collectors. These are due to the high operating temperature of the photovoltaic laminate in stagnation conditions (with high risk of damage for the PV, the lower electrical efficiency apart) when considering glazed collectors, and to the lower thermal efficiency when considering unglazed collectors. The analysis here reported takes into account also the present granting system for electricity and thermal energy produced by the PV/T system, evaluating the great energy and economic potential of such technology coupled to an electric compression heat pump for heating, domestic hot water (DWH) and electricity production purposes.

2 THE PV/T PLANT SYSTEM

The proposed system is supposed to supply both electrical energy from PV and thermal energy from the liquid cooled thermal collector for a typical two-stage Italian house. The building has a volume of 364 m^3, a height of 5.5 m, with a surface of 77 m^2 on the ground floor and 58 m^2 on the first floor.

The proposed PV/T system is depicted in Figure 1: it is intended to supply electrical energy and thermal energy for DHW and low temperature SH, i.e. radiant floor. The whole plant is thought as follows:

- Liquid cooled PV/T panel with laminate with a surface of 2.0 m^2. The panel is thought to be constituted by two glass layers incorporating 60 monocrystalline silicon cells spaced between them, each cell being 156 mm × 156 mm, 3.75 W_p (peak condition). Below the PV layer there is the thermal absorber plate. So, of the total solar radiation incident on the PV/T panel surface, 73% is intercepted by the PV surface ((0.156 × 0.156 × 60)/2 = 0.73), the remaining 27% by the thermal surface (Figure 2). This configuration has been simulated in Trnsys [10] by coupling a PV (type 94a) (with a PV surface of 1.46 m^2 and the total solar incident radiation) with a solar thermal collector (type 1) (with a surface of 2 m^2 and the 27% of the total solar incident radiation). The liquid is a mixture of water (70%) and glycol (30%) to prevent the liquid from freezing. The plant is constituted by eight PV/T panels in parallel (from the thermal point of view), giving 3.75 × 60 × 8 = 1800 W_p (electrical efficiency at reference conditions = 15.4 %);
- the DC electrical power produced is converted in AC power by an inverter (efficiency 90%) and so measured by a meter. Another bi-directional meter counts the inlet/outlet energy from/to the grid (net metering);
- the thermal part of the PV/T panels is connected to a tank internal heat exchanger (type 91) that exchanges heat with water coming from tank-to-tank storage (type 60); the fluid is pumped with one variable speed pump absorbing 60 W;
- a 500 l tank-to-tank storage (type 60) is used to collect hot water for SH (outer tank) and to pre-heat water for DWH uses (inner tank); and
- a natural gas fired boiler for DHW and SH integration (seasonal mean efficiency of 85% LHV) (type 6).

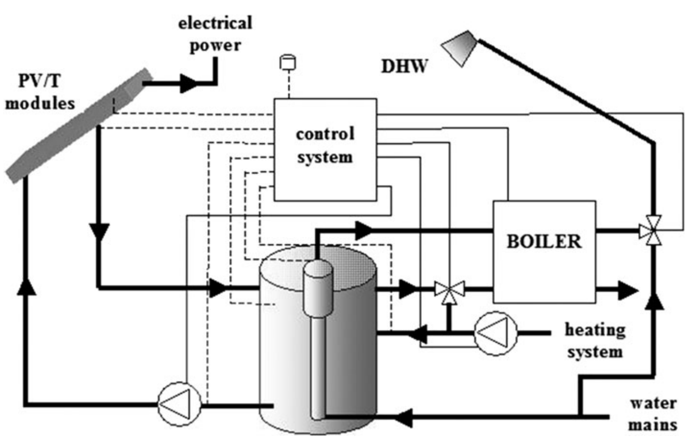

Figure 1. *Scheme of the proposed PV/T system for production of electrical energy and thermal energy for DHW and SH.*

Acontrol system handles the plant from a series of input (dashed line) and output (continuous line) signals (Figure 1). This has been modeled by a type developed by the authors. In particular:

- DHW: water enters the storage from the network at 12°C and is heated up to 45°C by the hot water stored from the PV/T first and then the boiler. The water is supposed to be delivered to the user at 45°C through a three-way valve; the water consumption is supposed to be 200 l per day.
- SH: water is drawn from the tank and heated up by the boiler to the water delivery temperature of the SH system (t_{water}). If the storage tank temperature is lower than the water temperature from the radiant floor plant, a three-way valve is supposed to bypass the storage. The set temperature follows a climatic curve with a maximum temperature of 38°C (when ambient temperature $t_{ambient}$ is equal to 0°C) and a minimum temperature of 25°C ($t_{ambient}$ = 17.33°C):

$$t_{water} = 38 - 0.75 \cdot t_{ambient} \quad (1)$$

The heating load comes from a dedicated Trnsys model of the house and considering the annual local weather conditions (Test Reference Year (TRY) [11]).

- Pump in the PV/T modules circuit turns on when outlet temperature from PV/T is 7°C higher than that at the bottom of the storage and irradiance is higher than 300 W/m^2.
- Pump in the PV/T modules circuit turns off when outlet temperature from PV/T is <3°C higher than that at the bottom of the storage and without considering irradiance.
- Pump is variable speed type (type 3d) allowing the cooling fluid to suitably increase its temperature during winter and low availability of solar energy.

The plant considers eight PV/T panels set to the South (0° of azimuth angle) with the optimal tilt angle from the energy point of view (substantially 30° for all the climates): this solution was

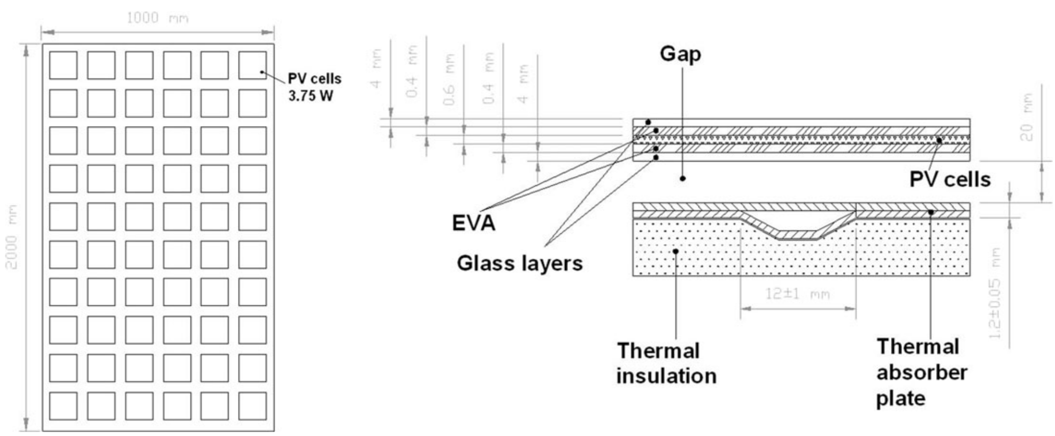

Figure 2. *Scheme of the proposed PV/T panel (drawings not to scale).*

thought to have an interesting value of the electrical power (1800 W_p) without exceeding in thermal production, considering the low thermal energy uses during summer months. The parallel connection of the panels allows a satisfactory thermal production: other configurations (e.g. four parallels of two panels in series each) are more penalized from the thermal point of view. Furthermore, the here considered PV/T panel configuration (with the thermal plate absorber not directly in contact with the PV layer and the latter substantially unglazed) allows to reduce the risk of damage of the PV layer due to stagnation temperature (~120–140°C).

3 ENERGY ANALYSIS

Three different resorts were selected over the Country at three very different latitudes: Venice (45°30′ N), Rome (41°48′ N) and Crotone (39°04′ N). For the sake of brevity, the detailed results are reported for Venice only, the main considerations for the other climates are reported as well.

Figure 3 depicts the electrical energy quantities related to PV/T plant: the electrical energy produced is the AC energy, inclusive of pumps consumption. Incident solar radiation is the part, of the total radiation, incident on the PV surface (73%). So electrical efficiency is the ratio between these two quantities. The lower values in summer months (when ambient air temperature and solar radiation are higher) are due to the sensitivity of electrical efficiency of crystalline silicon cells to their temperature.

Figure 4 shows the thermal energy quantities related to PV/T plant: the thermal energy produced is net of tank losses and referred only to periods when it is useful (that is it is used for DHW or SH aims). Incident solar radiation is the part, of the total radiation, incident on the thermal surface (27%). Again, thermal efficiency is the ratio between these two quantities. In this case, the lower values in summer months are due to the low uses of thermal energy in this period (only for DHW).

In Figure 5, it is depicted the heat energy used for DHW and SH per month over the year: the total heat is net of the losses at the storage tank which are seen to be around 10% of the total heat produced by the PV/T plant. The contribution to

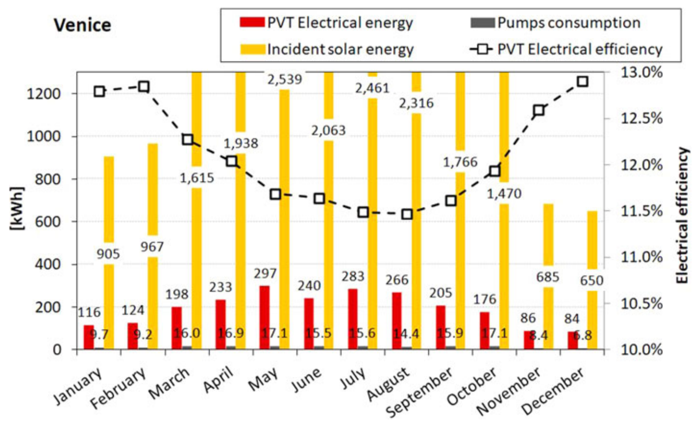

Figure 3. *Electrical energy produced by PV/T plant, consumed by the pumps, incident solar energy and electrical efficiency (Venice).*

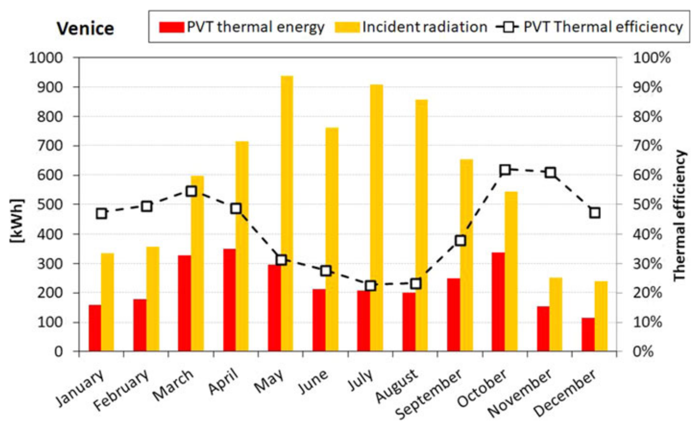

Figure 4. *Thermal energy produced by PV/T plant, incident solar energy and thermal efficiency (Venice).*

the SH is quite limited (solar ratio is below 10% in winter months), while during summer months thermal production allows to fully satisfy the load. In Southern resorts, such figures are even better, with a solar ratio in winter months varying from 13 to 25% in Rome and from 19 to 37% in Crotone.

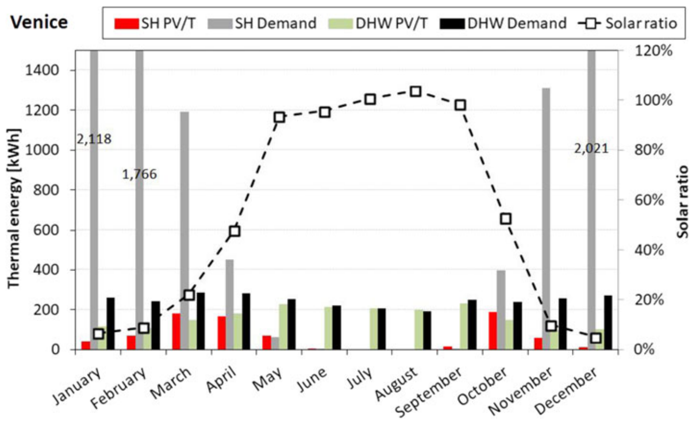

Figure 5. *Heat energy produced by the PV/T plant for DHW and SH purposes, DHW and SH demands (Venice).*

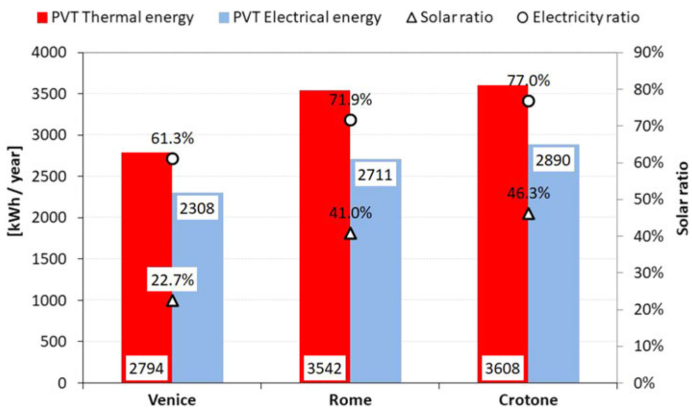

Figure 6. *Annual thermal and electrical loads covered and thermal/electrical annual energy produced by the PV/T plant among the three resorts in Italy.*

Figure 6 resumes the annual electrical and thermal energy production of the PV/T plant for the three climates: the first covers the great part (61.3% in Venice–77% in Crotone) of the annual electrical consumption of an average four-people Italian family, that has been fixed in 3500 kWh. The thermal energy production allows to obtain the solar energy ratio reported in the same figure: in the South of the Country, abundance of sun energy and reduced heat loads lead this figure to be near 50%. Finally, primary energy saving (PES) of the PV/T plant with respect to two different reference scenarios has been calculated:

- reference scenario A: gas fired boiler both for DHW and SH, seasonal mean efficiency = 85% (LHV); and
- reference scenario B: electrical air–water heat pump for SH (seasonal mean COP = 3 – 3.2 – 3.3 respectively for Venice, Rome and Crotone) + natural gas boiler for DHW (seasonal mean efficiency = 85% (LHV)).

In both reference scenarios, electrical uses of the house are supposed to be satisfied by electricity from the grid. In case of reference scenario B, when considering the use of the PV/T plant, the heat integration is obtained by an electric heat pump for SH, and by a natural gas fired boiler for DHW, both with the characteristics just described above. Such hypothesis is taken in order to consider the most diffuse situation. In this case, the PV/T electrical energy production is used to satisfy the needs of heat pump and, if in excess, the other electrical uses of the house (Table 1). Mean efficiency of the electricity from grid (for heat pump and the other electrical uses of the house) is considered to be 46%. This is the energy conversion factor from kWh to toe for the Italian energy efficiency certificates market and it is based on the average efficiency of the Italian electricity system (largely based on natural gas thermoelectric (Rankine and Brayton–Joule) plants) [12]. Table 2 and Figure 7 report (fossil) primary energy consumption (PE) and PES for both the electrical and thermal uses of the house, and the total, following the equations:

$$PES_{TH,A} = \frac{\frac{LOAD_{TH,TOT}}{0.85} - \left(\frac{AUX_{DHW}}{0.85} + \frac{AUX_{SH}}{0.85}\right)}{\frac{LOAD_{TH,TOT}}{0.85}}$$

$$PES_{EL,A} = \frac{\frac{LOAD_{EL,TOT}}{0.46} - \left(\frac{LOAD_{EL,TOT} - PVT_{EL}}{0.46}\right)}{\frac{LOAD_{EL,TOT}}{0.46}} \quad (2)$$

$$PES_{TOT,A} = \frac{\left(\frac{LOAD_{TH,TOT}}{0.85} + \frac{LOAD_{EL,TOT}}{0.46}\right) - \left(\frac{AUX_{DHW}}{0.85} + \frac{AUX_{SH}}{0.85} + \frac{LOAD_{EL,TOT} - PVT_{EL}}{0.46}\right)}{\left(\frac{LOAD_{TH,TOT}}{0.85} + \frac{LOAD_{EL,TOT}}{0.46}\right)} \quad (3)$$

$$PES_{TH,B} = \frac{\left(\frac{LOAD_{TH,SH}}{COP \cdot 0.46} + \frac{LOAD_{TH,DHW}}{0.85}\right) - \left(\frac{AUX_{DHW}}{0.85} + \Theta\right)}{\left(\frac{LOAD_{TH,SH}}{COP \cdot 0.46} + \frac{LOAD_{TH,DHW}}{0.85}\right)}$$

where

$$\Theta = \text{IF} \quad PVT_{EL} < \frac{AUX_{SH}}{COP} \quad \text{THEN} \quad \frac{\frac{AUX_{SH}}{COP} - PVT_{EL}}{0.46} \quad \text{ELSE } 0 \quad (4)$$

$$PES_{EL,B} = \frac{\frac{LOAD_{EL,TOT}}{0.46} - \Psi}{\frac{LOAD_{EL,TOT}}{0.46}}$$

where

$$\Psi = \text{IF} \quad PVT_{EL} < \frac{AUX_{SH}}{COP} \quad \text{THEN} \quad \frac{LOAD_{EL,TOT}}{0.46} \quad \text{ELSE} \quad \frac{\left(LOAD_{EL,TOT} - \left(PVT_{EL} - \frac{AUX_{SH}}{COP}\right)\right)}{0.46} \quad (5)$$

Table 1. *Different reference scenarios (A and B) for the primary energy saving analysis (SH = space heating; DHW = domestic hot water). Arrows represent energy flows from the sources (or carriers as electrical energy) to the energy conversion appliances to the final uses.*

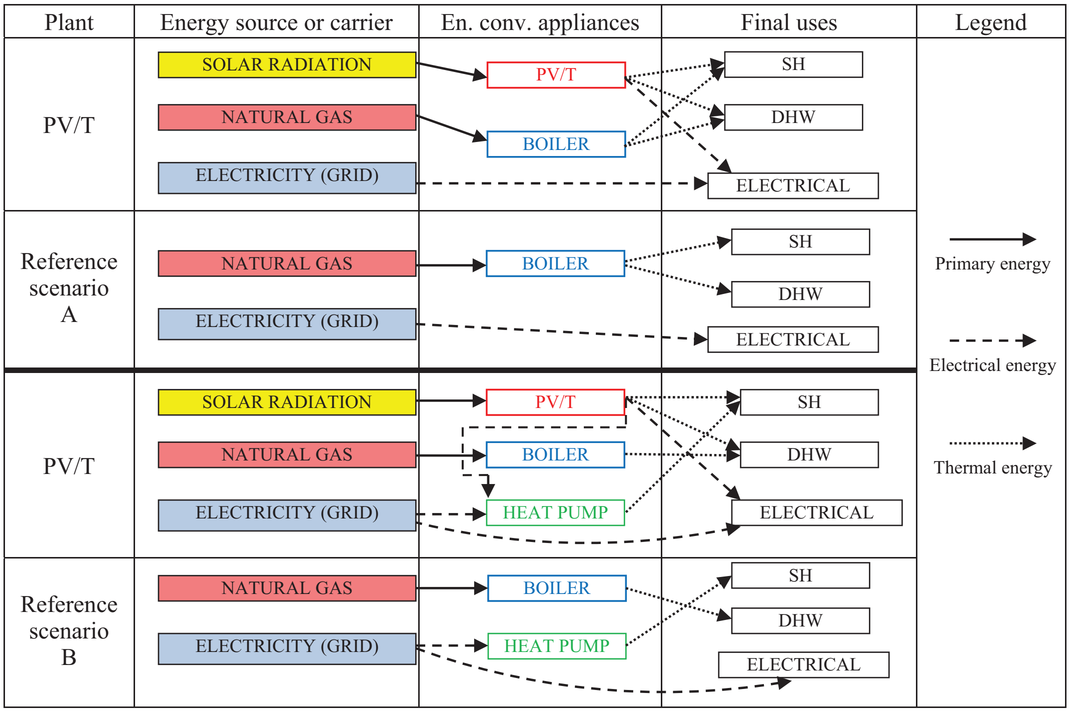

Table 2. *Fossil primary energy (PE) consumption for the different energy uses (space heating (SH), domestic hot water (DHW), electricity) of the house considering the two different reference scenarios (A and B) (in kWh).*

A	Venice	Rome	Crotone	B	Venice	Rome	Crotone
Reference scenario (only Boiler)				Reference scenario (HP+Boiler)			
				PE SH	6756	3845	3168
PE SH + DHW	14 464	10 155	9155	PE DHW	3496	3496	3496
PE electricity	7609	7609	7609	PE electricity	7609	7609	7609
PE Tot	22 073	17 764	16 763	PE Tot	17 861	14 950	14 273
Innovative scenario (PV/T + Boiler)				Innovative scenario (PV/T+HP+Boiler)			
PE DHW	1304	1038	987	PE DHW	1304	1038	987
PE SH	10 020	5116	4093	PE SH	1508	0	0
PE electricity	2944	2141	1750	PE electricity	7609	5095	4042
PE Tot	14 269	8295	6831	PE Tot	10 420	6133	5029

$$PES_{TOT,B} = \frac{\left(\frac{LOAD_{TH,SH}}{COP\cdot 0.46} + \frac{LOAD_{TH,DHW}}{0.85} + \frac{LOAD_{EL,TOT}}{0.46}\right) - \left(\frac{AUX_{DHW}}{0.85} + \Theta + \Psi\right)}{\left(\frac{LOAD_{TH,SH}}{COP\cdot 0.46} + \frac{LOAD_{TH,DHW}}{0.85} + \frac{LOAD_{EL,TOT}}{0.46}\right)} \quad (6)$$

with the following meanings:

LOAD = energy requested by users;
AUX = energy provided by integration (boiler or heat pump);
PVT = energy produced by the PV/T plant;
COP = coefficient of performance of electric compression heat pump;
EL = electrical; TH = thermal; TOT = total;
DHW = domestic hot water; and
SH = space heating.

From the thermal point of view, PES obtained by the PV/T plant with respect to scenario B (heat pump + boiler) are always by far higher than those with respect to scenario A (boiler). The behavior from the electrical point of view is reversed: in Venice there is no energy advantage (for the electrical uses) of the PV/T plant (+heat pump + boiler) with respect to heat pump + boiler + grid, because the electrical production of the PV/T plant is completely absorbed by the heat pump and so there is no electrical energy available for electrical uses of the house. Because of the configuration of the plants here considered, the total PES is not so different between the two scenarios, for all the resorts: with respect to scenario A, the PV/T plant allows to get advantage from the electrical point of view, while with respect to scenario B the advantage is mainly from the thermal point of view because of the presence of the heat pump.

4 ECONOMIC ANALYSIS

The economic analysis of the proposed system takes into account the capital costs both for buying the collectors and for all the components: from the tank-to-tank storage to valves, connections, pipes, installation, inverter and so on (Table 3).

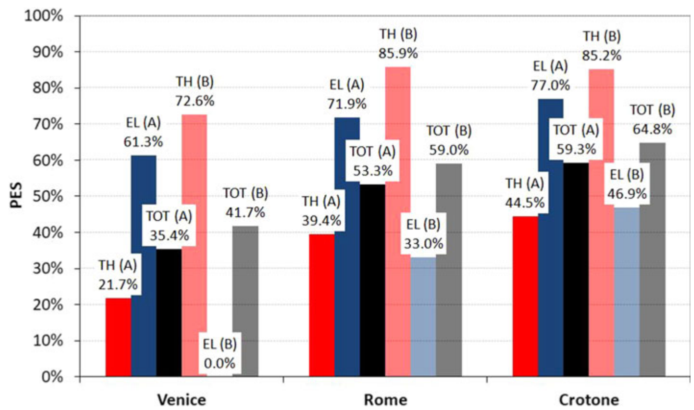

Figure 7. *Primary energy saving of the PV/T plant (on thermal (TH), electrical (EL) and total energy (TOT)) with respect to two different reference scenarios: A = natural gas fired boiler both for DHW and SH; B = electric heat pump for SH + boiler for DHW.*

The investment costs for the heat pump and the boiler are supposed to be sunk costs, that is such appliances are considered to be anyway available to the user. The incomes/savings are:

- Incentives from the Italian government are now over for photovoltaics: the feed-in tariff terminated in 2013. In the meantime cost of photovoltaics has extremely decreased during last years: we considered a cost of the PV/T panels equal to 700 € per module (that is about 3.10 €/W_p). The only grant concerns the electricity produced by photovoltaics injected into the grid when electricity demand is less than production. We have considered the two possibilities actually in force in Italy: the so called 'RItiro Dedicato' (RID) (Simplified Purchase and Resale Arrangements) and the 'Servizio di Scambio sul Posto' (SSP) (Net Metering Service). The former is an agreement entered between the producer and GSE (Gestore Servizi Energetici, the public society regulating the renewable energy in Italy), whereby GSE purchases and resells the electricity to be fed into the grid at the zonal price or, for small-sized plants with a nominal electrical capacity of up to 1 MW, at a minimum guaranteed price. We have considered the minimum guaranteed price equal to 3.9 c€/kWh [13] for 658, 955 and 1134 kWh, respectively for Venice (Table 3 and Figure 8), Rome and Crotone annual electricity injected to the grid.

Under the Net Metering Service, the electricity generated by a consumer/producer in an eligible on-site plant and injected into the grid can be used to offset the electricity withdrawn from the grid. GSE pays a contribution to the customer, based on injections and withdrawals of electricity, which covers part of the charges incurred by the customer for withdrawing electricity from the grid. Without entering in details of the calculation of the contribution, we have calculated it to be equal to

Table 3. *Economic analysis of the PV/T plant (operational annual costs for Venice).*

Total capital costs	[€]		11 648.10
Expected annual cash flows			
a) Electrical incomes/savings	[€/kWh]	[kWh]	Total [€]
1-RID	0.039	658	25.67
2-SSP			75.02
Electrical energy savings (D2)	0.20	2308	461.61
Electrical energy savings (D1)	0.15	2308	346.21
b) Thermal incomes/savings	[€/Nm^3]	[Nm^3]	Total [€]
Thermal energy savings	0.70	346.0	242.21
c) Tax deduction (50% in 10 years)	[€]		[€]
	11 648.10		582.41
d) Total incomes/savings		First 10 years	Other years
1-RID/D2	[€]	1311.89	729.49
1-RID/D1	[€]	1196.49	614.08
2-SSP/D2	[€]	1361.25	778.84
2-SSP/D1	[€]	1245.85	663.44
e) Operative costs	[%] [€/kWh]*	[€] [kWh]*	Total cost [€]
Maintenance costs	1 %	11 648.1	116.48
Pumps consumption*	0.20	162.4	32.49
f) Total operative costs			148.97

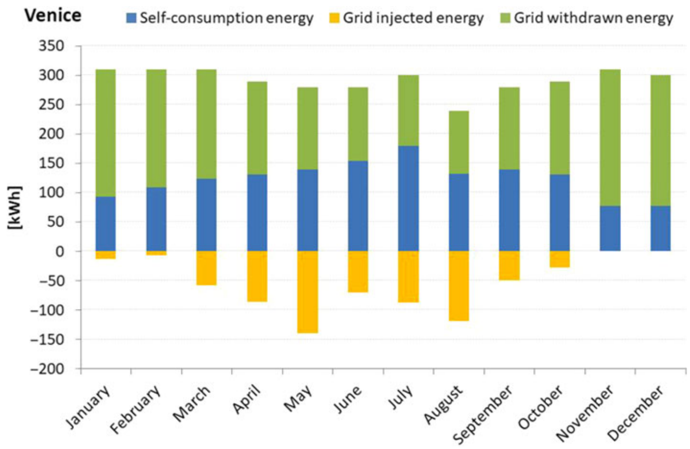

Figure 8. *Annual electrical energy balance for Venice.*

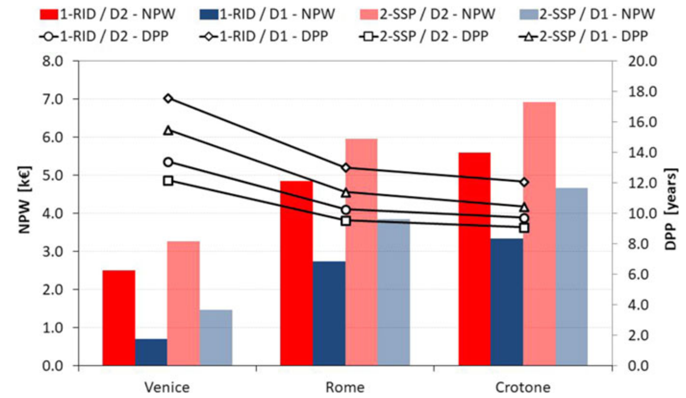

Figure 9. *Net Present Worth and Discounted Payback Period for the investment in PV/T plant for the three resorts, comparing different granting systems for electricity produced by photovoltaics injected into the grid (RID and SSP) and different tariffs for electricity purchased by the grid (D1 and D2).*

75.02, 108.91 and 129.22 € per year, respectively, for Venice, Rome and Crotone (Table 3).

- There is an economic saving due to electrical energy produced by the PV/T that has not to be purchased by the grid. It has been calculated by means of two different tariffs. The D2 is the traditional price applied to residential home (it is progressive, provide, namely, that the variable component has a value which increases with consumption, here we consider a constant price of 20 c€/kWh due to small values of annual electricity purchased). On the contrary, with the new special rate D1 [14] (for electricity dedicated to private customers who use electric heat pumps as the source of heating) the variable component has a constant price, regardless of the annual consumption, here considered to be equal to 15 c€/kWh.
- There is also an economic saving due to thermal energy produced by the PV/T that has not to be produced by using fossil fuel. It has been calculated by considering a cost of natural gas of 70 c€/Sm^3 (LHV = 9.5 kWh/Sm^3).
- Furthermore we have considered also the incentive in Italy for photovoltaics to have a tax deduction of 50% of the capital costs applicable in 10 years.
- We have considered maintenance of the plant (which is supposed to be 1% of the initial cost) and PV/T system pumps consumptions as annual operational costs.

No incentive on the installation of thermal collectors to produce hot water in residential buildings (Ministerial Decree of 28 December 2012, the so-called 'Renewable Energy for Heating & Cooling Support Scheme') has been here considered, as the plant does not satisfy the technical requirement of a minimum thermal production of 300 kWh/m^2 per year (with reference to Würzburg site) (the thermal production is 174, 221 and 225 kWh/m^2 per year respectively for Venice, Rome and Crotone). The interest rate and the period time of the analysis are respectively 2.5% and 20 years.

In Figure 9, a comparison is proposed among the three cities for both the Net Present Worth (NPW) of the investment and the Discounted Payback Period (DPP); moreover, the four solutions (RID or SSP for the PV/T electricity injected into the grid and D1 or D2 tariff for the electricity withdrawn from the grid) are examined. All the solutions appear economical advantageous, that is NPW is positive and DPP is lower than 20 years. The advantage increases in southern resorts and, in one city, Net Metering Service (SSP) is always more favorable than Simplified Purchase and Resale Arrangements (RID). It is interesting to discover that the solutions with D2 tariff are always more advantageous than the ones with D1 tariff, as NPW are higher and DPP are lower. This advantage is greater in colder climates like Venice as in milder ones less electrical energy is needed by the heat pump to integrate SH and DHW energy demands. Moreover, with such an integrated photovoltaic–thermal solution one can get to quite acceptable payback time (especially for center and south of Italy) making the PV/T solution interesting not only from the energy point of view but also from the economic one. It is worth to consider that the maintenance cost is an important variable to consider for the economic viability of the system: for example, the DPP of the best solution (SSP and D2 tariff) increases from 9.1 to 10 years in Crotone, but from 12.2 to 15.6 in Venice.

5 CONCLUSIONS

The use of PV/T technology in Italy has revealed a viability. The application of traditional PV/T panels (with the thermal absorber plate glued to the rear of the photovoltaic laminate) for producing electrical and thermal energy could find a main constraint on the use of thermal energy:

- needs for higher thermal efficiencies ask for glazed system with lower electrical efficiencies and higher operating temperature of the photovoltaic laminate; and
- the lack of user thermal requests can leave the PV/T system in stagnation conditions with high risk for the correct operation of the PV, the lower electrical efficiency apart.

So the PV/T panel considered in this article is made up of a PV layer (silicon cells incorporated between two glasses) that replaces the cover glass of the one-glass glazed flat thermal solar collector. In this way the two constraints just described can be mitigated. The energy analysis show a profitable possibility of savings in all the resorts analyzed: annual electrical energy production of the PV/T plant covers the great part (61.3% in Venice–77% in Crotone) of the annual electrical consumption of an average four-people Italian family. The thermal energy production allows to obtain a solar energy ratio near 50% in southern resorts, and PES with respect to mere traditional solutions results to be between 35 and 65%. The economic analysis here reported, taking into account different electricity tariff and granting systems coupled to the tax deduction of the 50% of the capital costs applicable in 10 years, shows a discounted payback of the investment around 10 years in mild climates and southern resorts.

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