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Research paper

INTEGRATION BETWEEN A GEOTHERMAL HEAT PUMP AND THERMO-PHOTOVOLTAIC SOLAR COLLECTORS

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ABSTRACT

This article describes the experimental facility which has been realized by RSE consisting in a geothermal heat pump coupled with thermo-photovoltaic solar collectors. The coupling of these two devices is particularly interesting because thermo-photovoltaic collectors can generate the electricity used by the heat pump and, at the same time, can support it in domestic hot water (DHW) production. Moreover, in this specific case, the low temperature heat produced by hybrid panels during winter, when the solar collectors have reduced performances due to lower insolation and outdoor air temperatures, is used to heat the water in the geothermal circuit.

Results of the monitoring campaigns, shown in this article, allow to assess the actual performances of the geothermal heat pump and of the thermo-photovoltaic solar collectors and the best logic for using the two sources.

Keywords: Solar assisted ground source heat pumps; Reversible heat pumps; Photovoltaic/thermal solar collectors; Energy efficiency

1. Introduction

The demand for thermal comfort in buildings is increasing sharply and with it the energy consumption for air conditioning. The problem is well known at UE level and overseen through measures meant to limit the increase in energy consumption. In fact the 2010/31/EU Directive intends to launch new energy challenges to the buildings. In particular from 2020, newly built buildings will be subjected to the mandatory requirement of nearly zero energy.

In the energy scenario that can be envisaged, a fundamental role will be played by all the devices that allow to reduce the energy input and that use renewable sources. For this reason many experimental and theoretical studies concerning the coupling of heat pump and solar collectors have been carried out in recent years. Results of the monitoring campaign performed on a experimental facility consisting in a geothermal heat pump coupled with PV-T solar collectors are presented in this article. PV-T solar collector consists in a photovoltaic panel behind which is placed an absorber plate, in order to capture the produced thermal energy that would otherwise be lost in the environment. In fact, only a small part of the solar radiation (normally 12%-20%) is converted into electrical energy in standard PV modules, the other part is wasted as heat. This PV-T collectors are particularly suitable for low temperature applications due to the optimization of the thermal and electric production.

The coupling of this device with the heat pump is particularly interesting because PV-T solar collectors can produce electricity used by the heat pump and can support it for the domestic hot water (DHW) production. Moreover, in this specific case, low temperature heat produced by PV-T collectors during winter is used to heat the water of the geothermal circuit. This system can help to avoid the gradual cooling of the ground, called thermal drift, that can take place in a geothermal plant, with consequences on heat pump performances. The results presented in this article show the efficiencies achievable by this two technologies and highlight the influence of the management system on the plant performance.

2. Experimental facility

The plant is installed in a laboratory consisting of a prefabricated house with a heated floor area of 60 m2 divided in four rooms simulating a living room, a kitchen, a bedroom and a bathroom. The house is located in Milan and is equipped with five fan coils used both for heating and for cooling. The drawings of DHW, in order to simulate the use by a typical family, are performed daily according to a household profile: a total of 150 liters are drawn per day at a temperature of 40 ° C.

The machine is a geothermal heat pump with a rated capacity of 7.8 kW; the compressor is a variable speed rotary which allows to modulate the capacity supplied, the refrigerant is the R410A. The heat pump is equipped with a 186 liter DHW tank. The geothermal field is constituted by a 100 meters deep single U heat exchanger.

PV-T modules, “sheet and tube” type, were also installed, with a covered area of 6.4 m^2 and a typical electric power of 1 kWp. These collectors are able to produce, at the same time, thermal and electrical energy, thanks to the heat exchanger placed in the rear of the PV module. The PV-T modules can provide the heat both to the DHW tank, integrated to the heat pump, and to the water leaving the evaporator of the heat pump, before entry in the geothermal boreholes. A 80 litres tank is used for the heat exchange between geothermal and solar circuits with a pipe coil in which water from the solar collectors flows, while the geothermal fluid circulates outside. In order to compare PV-T collectors performances with PV ones, an equivalent area of 6.4 m^2 was covered by PV panels of the same quality and electrical power of 1 kWp.

Plant scheme and monitoring system are shown in Figure 1.

During the winter, when the solar collectors have reduced performances due to lower insolation and outdoor air temperature, it is possible to exploit the low-temperature heat supplied by the solar collectors as auxiliary source for the heat pump.

The heat produced by solar collectors during the summer, instead, is used exclusively for DHW production. Consequently, the heat pump can be used mainly for cooling and, in case of insufficient solar radiation, for charging the DHW boiler.

In Figure 2 a part of the plant is shown. Green pipes are the connection between heat pump and geothermal heat exchange, red pipes are for domestic hot water.

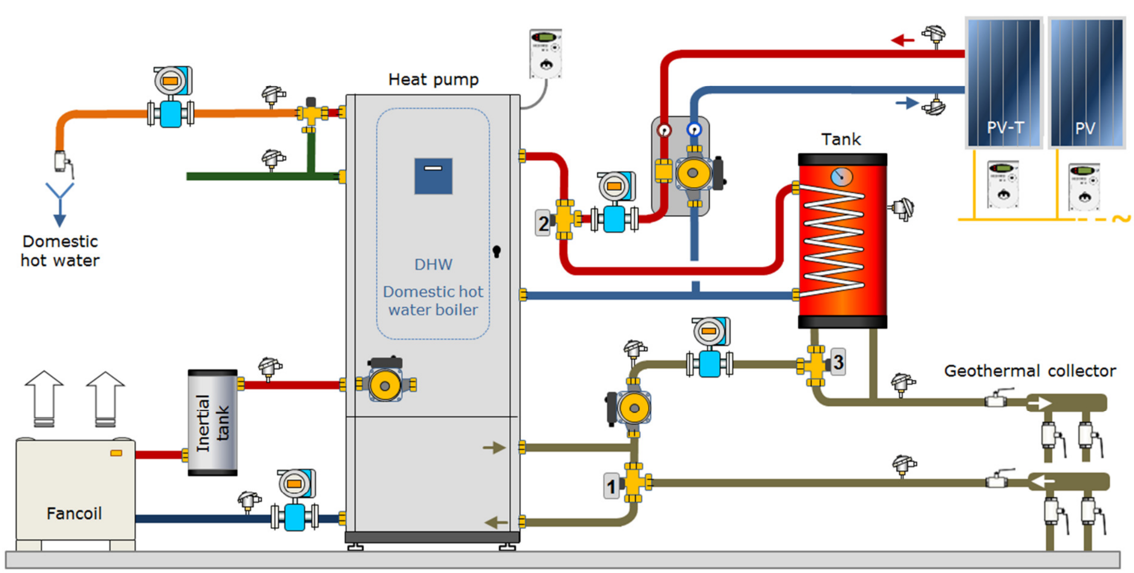

Fig. 1 - Plant scheme and monitoring system

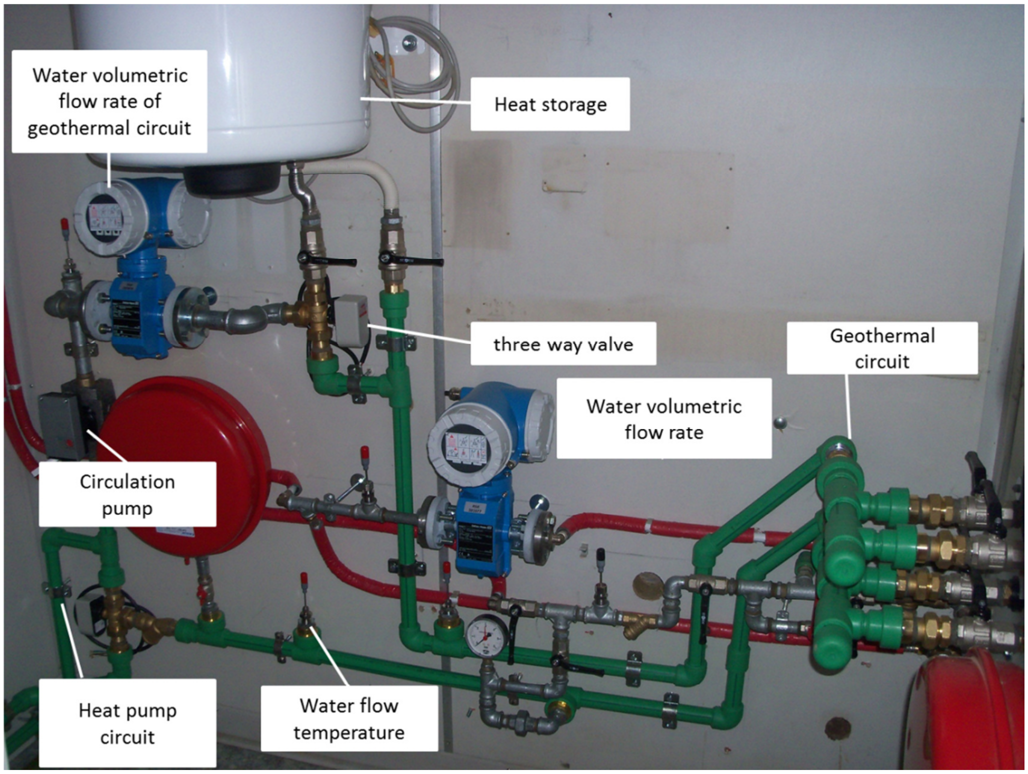

Fig. 2 - Plant hydraulic scheme

3. Heat pump efficiency

Results of one year of monitoring campaign are shown in Table 1. Heating season includes data from the 1st of January 2014 to the 31st of March 2014 and from the 22nd of October 2014 to the 31st of January 2015. Cooling season includes data from the 11th of June 2014 to the 13th of September 2014.

The operation set point is 22 °C, both in heating and cooling mode, automatically controlled via a wall-mounted thermostat. The outlet water temperature is set at 8.5 °C during cooling period. While, during heating period a weather compensation strategy is employed. It means that a controller measures the temperature outside the building and varies the temperature of the water supplied to the heating systems accordingly. The water temperature is set at 45 °C if outdoor air temperature is below -2 °C, whilst if the outdoor air temperature increases, the outlet water temperature is reduced by 0.625 °C per each degree.

It can be seen that the seasonal performances of the heat pump, both in heating and in cooling, are equal to 3.8 in heating and 5.1 in cooling. It has to be noticed that both seasonal COP and EER are calculated including geothermal circulation pump consumptions.

The daily average water temperature from and to the boreholes is shown in Fig. 3 compared to the daily average air temperature, during the entire year monitored. It can be noticed that average water temperature from boreholes is always higher than the external air temperature during the heating period and lower during the cooling period. It can also be noticed that there is a difference of 4 °C between the temperature of the water from the boreholes at the beginning and at the end of the winter season; the source tends to cool gradually in the colder months and to return to the initial temperature when the climate becomes warmer. Instead, only daily fluctuations occur during the summer; this is due to the low thermal request of the building in this period.

Tab. 1 - Results of monitoring campaign differentiated in heating and cooling season

Month	n° of days	Average external air temperature	Average water supply temperature	Average water return temperature	Average water temperature to boreholes	Average water temperature from boreholes	Water temperature in the domestic hot water tank	Thermal energy delivered / absorbed by the heat pump	Thermal energy extract from the domestic hot water tank	COP/EER Heat pump	COP/EER Heat pump + geothermal pump
	[n]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[kWh]	[kWh]	[-]	[-]
January 14	31	5.7	36.4	33.4	8.3	10.2	45.2	1528	182	4.07	3.84
February 14	28	7.4	36.0	33.2	9.9	11.4	45.2	1173	164	4.09	3.83
March 14	30	11.2	35.7	33.1	11.7	13.0	45.4	685	160	3.96	3.70
June 14	17	22.6	9.9	12.4	22.7	19.0	44.2	-481	56	5.45	5.36
July 14	31	22.7	10.0	12.3	22.6	18.7	44.1	-759	99	5.13	5.06
August 14	31	22.4	10.1	12.4	22.5	19.1	43.3	-751	97	5.33	5.24
September 14	13	21.0	10.0	12.3	22.3	18.4	44.3	-249	43	4.75	4.69
October 14	10	12.1	35.5	32.8	12.6	13.7	46.3	261	44	4.31	4.04
November 14	25	11.7	34.8	32.3	11.4	12.7	46.3	744	120	4.21	3.94
December 14	31	5.6	37.7	34.7	8.8	10.5	46.1	1817	163	3.96	3.75
January 15	31	4.8	38.8	35.6	8.0	9.7	44.4	1969	177	3.90	3.69

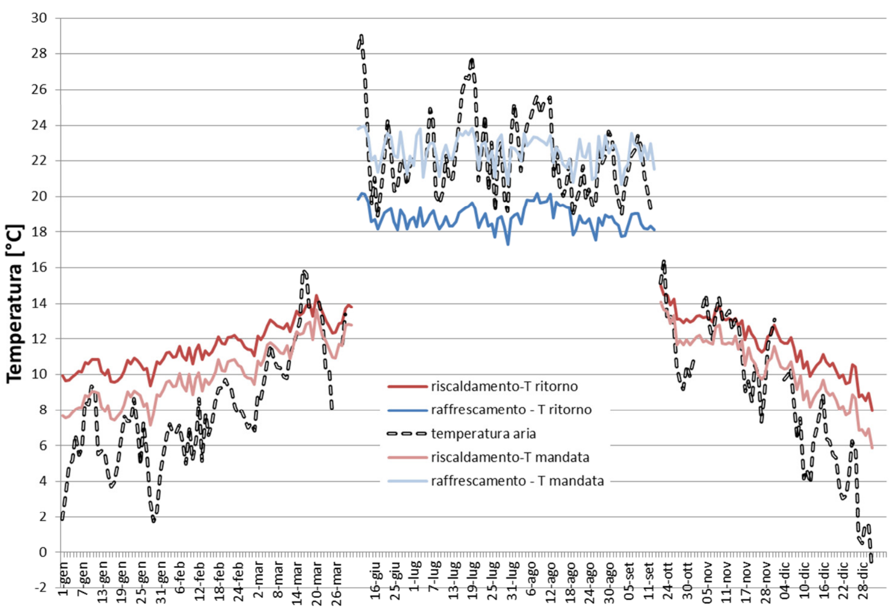

Fig. 3 - Daily average temperature of external air and of water from boreholes

In Figure 4 hourly average COP is related to hourly average water temperature from boreholes. The linear relation is due to the influence of source temperature on the heat pump performance and to the weather compensation strategy.
The same trend can be observed comparing the COP with average external air temperature (Figure 5). The external air temperature, in fact, influences the thermal load requested to the heat pump and to the geothermal borehole. In Figure 6 COP values are reported related to the thermal power delivered by the heat pump.

In Figure 7 hourly average EER is related to the average water temperature from borehole. The trend is not significant as in the heating mode, due to the building's low cooling request during the summer and the consequent partial load of the heat pump.

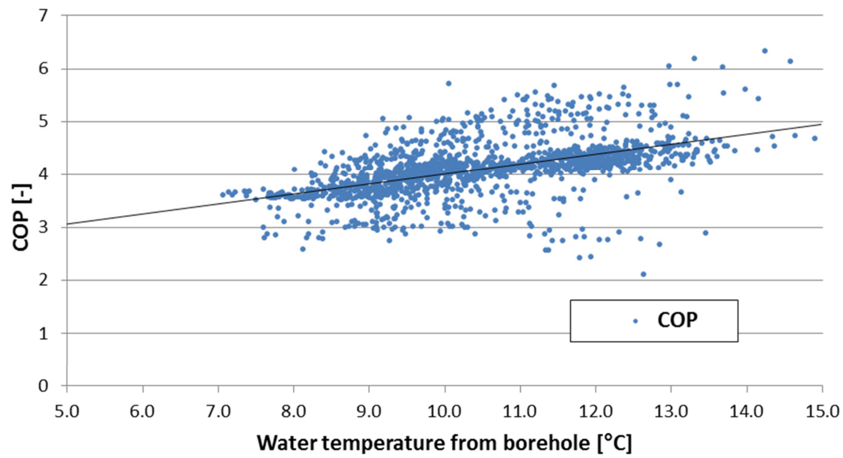

Fig. 4 - Hourly average COP related to hourly average water temperature from boreholes. Heating mode

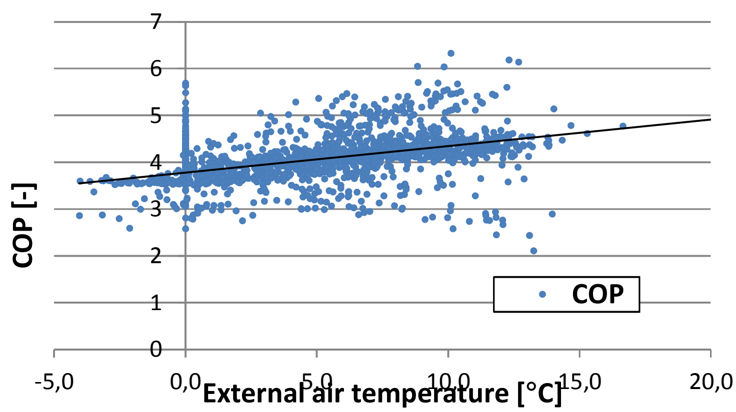

Fig. 5 - Hourly average COP related to hourly average external air temperature. Heating mode

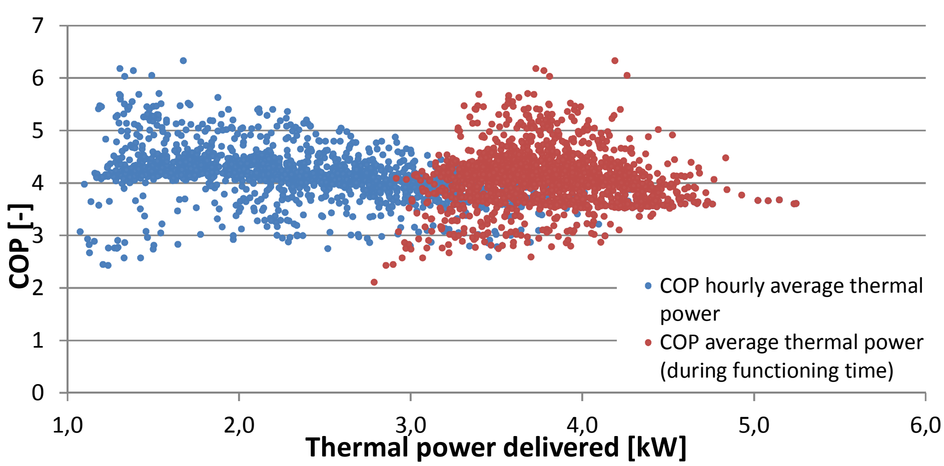

Fig. 6 - Average COP related to themal power delivered to the plant: hourly average value in blu and average value, calculated only when the heat pump is functioning, in red. Heating mode

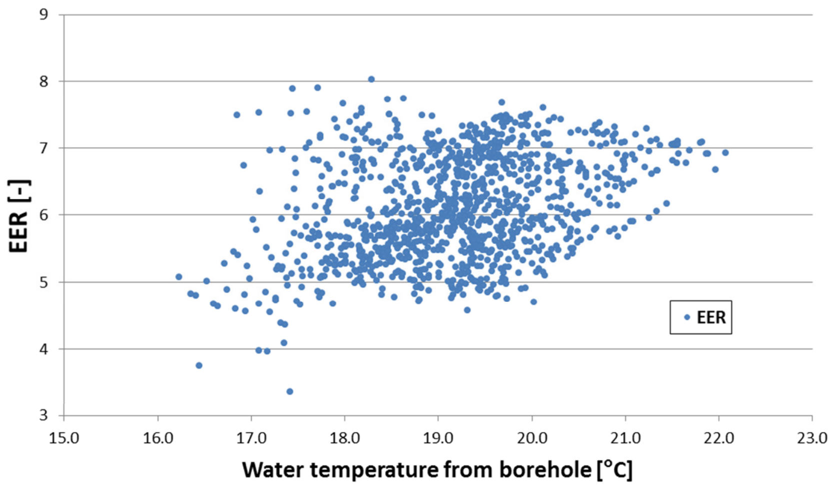

Figure 7: Hourly average EER related to hourly average water temperature from boreholes. Cooling mode

4. Solar collectors performances

In Table 2 the monthly performances of the solar collectors is summarized, both PV-T and PV ones. The table also includes the months of April and May 2014 that were not considered for the heat pump, because of very low or zero thermal load.

The different ratio between thermal energy produced at low and high temperature depends on the different logics that have been used during the monitoring period, which also influence the value of the corresponding thermal efficiency. During the summer, PV-T solar collectors are dedicated exclusively to the DHW production. While two different logics are used during the winter period. In the first part of the year two thermal levels are set: high temperature (minimum 42 °C) for DHW production and low temperature (22 °C on average) for boreholes regeneration. The PV-T collectors produce high temperature DHW only when measured solar radiation is higher than 800 W/m^2, otherwise thermal energy is used for regenerating the geothermal tank. In the last part of the year PV-T collectors are dedicated only to regenerate the boreholes. This method eliminates the possibility to produce DHW but increases thermal efficiency.

It is to be noticed that the electrical efficiencies are calculated considering also the inverter, which has his own specific efficiency (95% on average).

In Figure 8 an image taken with the thermo camera is shown: it is clear the different temperature between PV-T and PV panels. The different temperature zones that can be identified in the PV-T panels are due to the hydraulic connection of the thermal circuit. In fact the four panels are connected in series by two, with the cold water entering in the centre (Figure 9).

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It is to be noticed that the electrical efficiencies are calculated considering also the inverter, which has his own specific efficiency (95% on average).

During summer PV-T collectors produced 85% of the thermal DHW needs. Efficiencies of the PV-T solar collectors are calculated as:

$$\eta_{th} = \frac{Q_{collectors}}{Rad} \qquad \eta_{el} = \frac{E_{collectors}}{Rad} \qquad (3)$$

where η_{th} is thermal efficiency, ηel is electric efficiency, $Q_{collectors}$ is the thermal energy produced, $E_{collectors}$ is the electric energy produced and *Rad* is the total solar radiation incident on 45 ° plane calculated only when there is thermal production. The thermal efficiency for the summer period results to be 16.1%. Electric efficiency is equal to 13.2%.

Fig. 8 - Thermocamera image of the laboratory

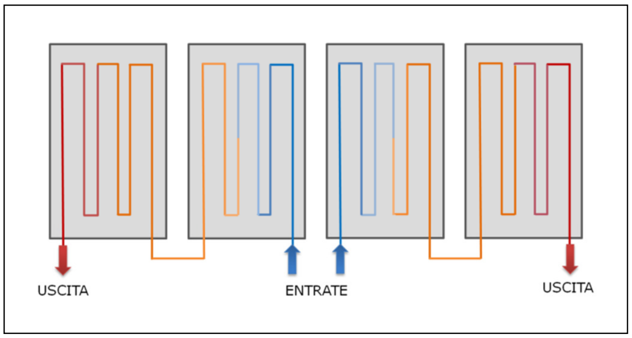

Fig. 9 – Hydraulic connection of the PV-T panels

Tab. I - Results of monitoring campaign: PV-T collectors and PV solar panels performances

Month	n° of days	High tem-pera-ture thermal energy (DHW) produced by PV-T collectors [kWh]	Low tempe-rature thermal energy produ-ced by P-V-T collec-tors [kWh]	Electric energy produ-ced by PV-T collec-tors [kWh]	Electric energy produ-ced by PV panels [kWh]	PV-T col-lectors thermal efficiency [-]	PV-T col-lectors electric efficiency [-]	PV panels electric efficiency [-]	Electric consum-ption of the heat pump for space heating or cooling [kWh]
January 14	31	2	39	41	40	16.8%	14.1%	13.8%	376
February 14	28	6	39	55	54	12.8%	13.9%	13.8%	287
March 14	28	31	104	135	134	15.8%	14.4%	14.3%	173
April 14	30	36	139	129	127	19.3%	13.7%	13.5%	-
May 14	26	45	182	151	149	22.7%	13.5%	13.4%	-
June 14	17	52	31	73	73	17.3%	13.4%	13.5%	88
July 14	11	96	15	123	125	16.2%	13.3%	13.5%	148
August 14	17	61	137	130	129	17.0%	13.1%	13.3%	141
September 14	13	42	3	54	54	13.4%	12.9%	13.0%	52
October 14	10	-	64	36	36	25.7%	13.3%	13.1%	61
November 14	25	-	48	33	32	25.8%	13.4%	13.1%	177
December 14	31	-	42	42	41	19.8%	13.2%	13.0%	459
January 15	31	-	92	77	77	19.8%	13.5%	13.4%	505
Total	296	371	935	1079	1071	18.6%	13.6%	13.5%	2467

Thermal efficiency for the winter period is 18.3%; analysing separately the two different logics used, thermal efficiency is 15.4% for the first period and 22.1% for the second. This difference allows to evaluate the influence of the heat produced temperature on the thermal efficiency. Electric efficiency in the winter season is 13.8%.

Both PV-T and PV panels, for a total covered surface of 12.8 m^2, have produced 73% of the electric consumption of the heat pump (both for air conditioning and DHW production): 34% during heating mode (from January to March and from October to January), whereas during cooling mode (from June to September) the electric production exceeded the consumption.

PV-T collectors allow, in theory, to obtain higher electric efficiency than PV ones because the cooling of panels, due to the thermal energy production, can increase electric production. In fact, catalogue data report that temperature coefficient for this collector typology is 0.43%/°C, i. e. every degree Celsius over the reference temperature (25 °C) the electrical production is 0.43% less than the nominal one. This improving takes place only when PV-T collector's temperature is lower than the PV one.

For this reason is interesting also to compare panels temperature in both cases: PV-T and PV ones. Temperature of PV panels is measured by a thermistor placed on the back of one panel; temperature of PV-T collectors is calculated from the water supplied temperature and with a delta of 5°C in order to consider the inefficiency of heat exchange.

Fig. 9 is an example in order to describe the logic used for the DHW production and its consequence on system efficiency. In the figure, in fact, the PV-T and PV functioning is described for two different days: temperatures of the two panels are reported and also the two power productions. It can be noticed that, during the day described in the figure on the left, PV-T collectors are cooler than PV panels so they produce more electric power. Otherwise, there are two different zones during the day represented in the figure on the right. In the first zone PV-T collectors are cooler and so they can produce more electric power than the standard ones. In the middle of the day, instead, when the logic switches the PV-T production from regenerating the geothermal tank to DHW production, there is a reversal of this trend , due to the high temperature DHW production. Consequently, the electrical production of PV-T collectors is lower than the PV one. When the solar radiation reduces PV-T collectors are switched again to low temperature heat production and collectors temperature reduces consequently.

This result means that, when producing high temperature DHW, PV-T panels have lower efficiency than PV ones. On contrary, when producing low temperature heat, their efficiency increase. The choice between these two conditions has to be done depending on the component that has to be optimized.

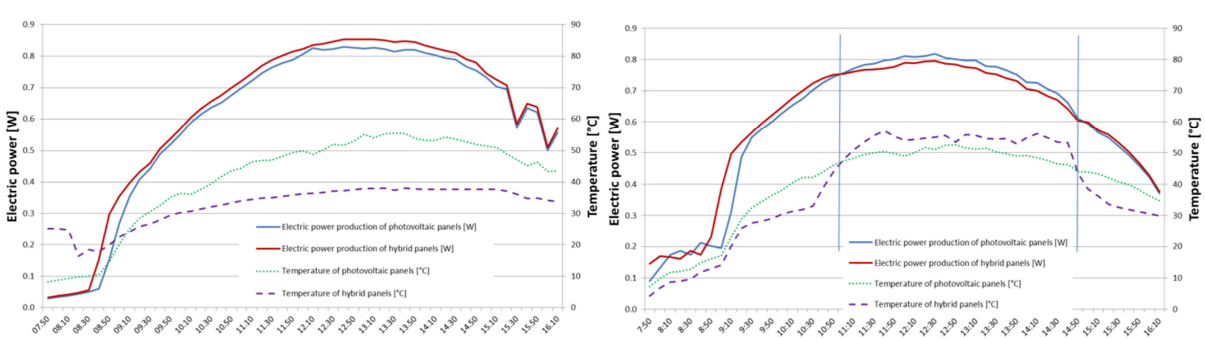

Fig. 9 – Electric power production of PV-T collectors (red line) and PV panels (blue line), temperatures of PV-T collectors (green dotted line) and of PV panels (purple dotted line).

5. Conclusion

Results of the monitoring campaign performed on an experimental facility consisting in a geothermal heat pump coupled with PV-T collectors are presented in this article.

Results are focused on heat pumps and solar PV-T collectors efficiencies, and on the interaction between the two devices. Collected data show that the heat pump seasonal performances are 3.8 in heating mode and 5.1 in cooling mode. Results also show that PV-T collectors allow to produce both electric and thermal energy without penalizing electric efficiency. So this can represent a valid solution to have a double production with the same roof surface occupied. A covered surface of 6.4 m^2 of these collectors can produce during summer the 85% of the DHW need of a family of three people (150 litres per day). It can also produce 37% of the electric need of an heat pump used for space cooling and heating of a small building of 60 m^2. The electric production can rise up to the 73% of the electric need of the same heat pump if the entire surface covered by solar collectors is considered (PV-T and PV).

The results also highlight that logic used to manage the plant strongly influences component efficiency and the best solution has to be evaluated considering every component functioning. In particular, producing low temperature water increases PV-T efficiencies (both thermal and electric) but experimental and simulation results show that using this heat to regenerate the ground has not a visible effect on heat pump performance.

ACKNOWLEDGEMENT

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