Performance of a Solar Assisted Heat Pump for Building Heating: Control Problems and Improvements

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Abstract. Palacus project is a solar assisted heat pump pilot plant in Genoa, Italy. The heat pump combined with solar hybrid photovoltaic thermal panels provides both electrical energy from the solar irradiation and hot water sent into the heat pump circuit. The photovoltaic field covers the energy need of the heat pump and it is even capable of producing extra electrical energy, stored in the national grid through a net-metering, looking for an energetically independent installation. The benefits coming from the net-metering, considered during the design stage, reduced dramatically due to a change in Italian laws concerning feed-in-premium. A brief report on the global facility performance during the past two years is proposed, proving the difficulties of the plant to reach its maximum design potential due to its complexity and problems related to the end users’ “acceptance”. Possible strategies to restore or increase the economic balance of the facility are discussed according to the new feed-in-premium criteria. Supervision and detection of any failure of the plant are performed by means of a large data acquisition system. New related regulation criteria, presented in this work, are compulsory to optimise the plant.

1. Introduction
Palacus project (“Carmine Romanzi” Sport Palace, Genoa) is a Solar Assisted Heat Pump with hybrid Panels (SAHP-PVT) pilot plant [1] representing an example of sustainable technologies coupled with traditional heating systems. The plant has a Technological Readiness Level (TRL 7) very close to the maximum. The devices are ready for competitive standardised production. The project refers also to two wider research frameworks: Demand Side Management (DMS), which aims to level any daily pick in energy consumption into a more homogeneous distribution, and the Energy Smart Grids project which includes the implementation of smart sensors collecting real time data. Domestic Hot Water (DHW) and heating systems (Space Heating, SH) are produced throughout the “technological convergence”, the conjoint interaction between the heat pump and the classical burner to satisfy the common DHW+SH target [2]. The complexity of the plant affects its performance from two different aspects: the end users’ acceptance [3] and the issue of optimisation. A high-performing plant is commonly associated to extended working periods and effective optimisation criteria achievable with an efficient remote data collection system.

2. Description of the plant
The heating system is made up of a newly installed Heat Pump (HP) combined with a Photovoltaic Thermal (PVT) hybrid system which allows the solar energy conversion into both electrical and thermal,
following the users’ actual needs. This means that a single panel can manage the so-called photovoltaic
cogeneration embracing both the functions of a thermal and a photovoltaic solar panel.
The pilot plant works in parallel with two traditional DHW and SH gas burners which are used in case
of harsh climate very near to the design conditions of the site or in each case the boundary environmental
conditions cause a sudden stop of the SAHP-PVT plant. A deeper insight on the plant, including the
problems during the design stage of the interface between the existing heat exchangers (DHW and SH
classical burners) and the newly introduced ones (SAHP-PVT) are presented in [1]. From a thermal
point of view, the SAHP-PVT is designed to cover up to the 70% of the total thermal energy demand
expressed in terms of DHW and SH. It is an integration of the two existing gas burners, which previously
satisfied the entire facility needs. As far as the electrical consumptions are concerned, the energy derived
from the PVT panels ensures the electricity need of every HP component (e.g. compressors, pumps,
electrical valves, monitoring consoles). The annual based electrical energy balance of the plant even
offers a surplus from the PVT installation, which could be used to partially supply the energetical need
of the building itself. The reference working period is different according to the plant application:
- the solar field can produce electricity and eventually hot water for DHW on a yearly basis.
- the HP side can work for a maximum of about 2000 hour per year during the heating season (12
  hours per each day of a 166 days long heating season typical of installations in Genoa).

A recorded operating period of about 1000 hours with a reference working time of about 2000 hours
brought to the introduction of a remote-control system to bypass the continuous end users’ and
traditional manual operators’ manual intervention [1]. The correct functioning of SAHP-PVT depends
on the level of automation among the different plant subsystems: solar system, heat pump and burner.
Each time a failure happens, technical staff is called to solve the problem to guarantee users’ comfort.

Since they often have no experience on these technologically advanced systems, the easier working
solution consists in shutting down the HP and PVT switching to the traditional fossil fuel burner.
Therefore, a data acquisition and management system are necessary; the extended dataset collected over
a grid of 50 measurements points required a web application, online since November 2016. As it will be
shown in the following sections, its implementation offered another step forward to a completely self-
managed plant, revealing also a design flaw regarding the HP working temperatures. The block diagram

![Figure 1. Block diagram of the PALACUS solar assisted heat pump with hybrid PVT panels and Data
Acquisition and control System (DAS)](image)
in figure 1 provides a synthetic description of the main subsystems composing the plant, including the monitoring system (DAS-Data Acquisition and control System). Emphasis will be payed to the elements strictly related to the control problems and improvements proposed in the present paper.

2.1. Heat pump subsystem and Water Storage Tanks (WSTs)
In nominal conditions, the heat pump has a refrigeration capacity of about 50 kW$_E$ against a nominal 12 kW$_E$ absorbed power at the compressor. The operativity range of the specific HP installed is between 8 °C and 18 °C on the evaporator side thanks to the contribution of the solar field. The condenser works between 25 °C and 50 °C. Thanks to the integration with the solar panels on the cold side, the thermal boundary conditions during the working period give rise to a variable COP, with a maximum of 6-8, as shown in figure 2.

The graph illustrates for a wider range of temperatures on the evaporator and condenser sides the performance of the HP (mean COP = 4). For higher evaporator temperatures the compressor would reach critical suction pressure and temperature levels, so that a safety valve will gradually shut down the plant. On the other hand, a decrease in the evaporator temperatures determines a progressively lower COP up to reach the HP Temperature Operation Limit (TOL). The range of the outlet temperatures on the evaporator side are appropriate to the external conditions of the site (the design external temperature for Genoa is equal to 0 °C) while the mean efficiency (COP = 4) of the plant is granted in most operating conditions (T$_{out, cond}$ ϵ [45 °C, 50 °C] and T$_{out, eva}$ ϵ [0 °C, 10 °C]). The thermal panels integration with the evaporator determines a higher SCOP (Seasonal COP), since a higher temperature on the cold side contributes to lower the electrical power consumed by the compressor. The SAHP specific operating range is shown by means of the azure dashed lines and it is concerned with the higher achievable values.

![SAHP specific operativity range](image)

**Figure 2.** Three-dimensional graph showing the COP of the HP as a function of the outlet temperatures on the evaporator and condenser side. The values have been tested and measured by the manufacturer.

Both sides of the HP are equipped with Water Storage Tanks (WSTs) of 500 liters each, granting proper thermal inertia. WSTs ensure a stable heat transfer rate and temperature regulation and hydraulic separation between the solar field and the heat pump evaporator and condenser exchangers.

2.2. The solar field
The solar field is made up of 80 hybrid PVT modules, with a net capturing surface of 140 m$^2$, corresponding to a total peak power of approximately 20kW$_E$ (electrical) and 60kW$_T$ (thermal). The plant is divided into 20 rows, 4 modules for each row, with southwest orientation. The PVT hybrid field is coupled to two solar inverter groups, connected to a bi-directional counter for national grid connection.

A dedicated exchange electric power contract was available in Italy at the time of first installation, to
use the grid connection as a virtual electric storage over a reference time of one-year PV operation. With reference to the main HP electrical consumption in the heating season working conditions, a simple cost-benefit analysis can be carried out assuming:
- mean electrical panel efficiency 0.15
- net solar capture area 140 m$^2$
- number of working hours equal to the duration of the standard heating season in Genoa, which amounts to 166 days (from November, 1$^{st}$ to April, 15$^{th}$, twelve hours per day).

The irradiation in table 1, obtained with the online software [4], is expressed as mean daily global solar radiation per each month $I_{\text{mean,daily}}$. The monthly photovoltaic energy $E_{\text{el,PV}}$, is computed as:

$$E_{\text{el,PV}} = I_{\text{mean,daily}} \cdot A \cdot N \cdot \eta_{\text{PV}}$$  \hspace{1cm} (1)

Where:
- $I_{\text{mean,daily}}$ is the mean daily global solar radiation per each month [MJ/m$^2$]
- $A$ is the net solar captation area [m$^2$]
- $N$ is the number of days in which heating systems are operative [-]
- $\eta_{\text{PV}}$ electrical efficiency of the panels [-]

**Table 1.** Irradiance, monthly average temperature [5] and photovoltaic energy collected by the hybrid field over a standard year simulation ($A = 140$ m$^2$)

| Month   | Days | $I_{\text{mean,daily}}$ (MJ m$^{-2}$) | $T_{\text{mean,ext}}$ (°C) | $E_{\text{el,PV}}$ (kWh) |
|---------|------|--------------------------------------|-----------------------------|---------------------------|
| January | 31   | 5.86                                 | 8                           | 908.3                     |
| February| 28   | 8.33                                 | 9                           | 1166.2                    |
| March   | 31   | 13.57                                | 11                          | 2103.35                   |
| April   | 30   | 16.82                                | 14                          | 2523                      |
| May     | 31   | 19.98                                | 17                          | 3096.9                    |
| June    | 30   | 22.73                                | 21                          | 3409.5                    |
| July    | 31   | 22.45                                | 24                          | 3479.75                   |
| August  | 31   | 19                                   | 24                          | 2945                      |
| September| 30 | 14.6                                 | 21                          | 2190                      |
| October | 31   | 9.48                                 | 17                          | 1469.4                    |
| November| 30   | 6.21                                 | 12                          | 931.5                     |
| December| 31   | 4.41                                 | 9                           | 683.55                    |
| **Total year** | **365** | **29057.5** | **24906.45** |

Therefore, the energy produced over a year can be estimated at about 25000 kWh$_{el}$, in accordance with [6], over a global yearly mean irradiance of 4980 MJ/m$^2$.

The consumed electrical power of the HP is about 12 kW$_{el}$ only in nominal peak conditions, reached only in heavy duty conditions. Equation (2) expresses the electrical energy consumed monthly by the HP:

$$E_{\text{el,HP}} = \frac{E_{\text{th,HP}}}{\text{COP}_{\text{month}}}$$  \hspace{1cm} (2)

With:

$$E_{\text{th,HP}} = m'_{\text{HP}} \cdot c_p \cdot (T_B - T_g)$$  \hspace{1cm} (3)

$$\text{COP}_{\text{month}} = \xi \frac{T_{\text{mean,ext}}}{T_{\text{user}} - T_{\text{mean,ext}}}$$  \hspace{1cm} (4)
Where:

- \( \eta_{th} \) thermal panels efficiency [-], equal to 0.80.
- \( T_{mean,ext} \) mean external temperature, expressed on a monthly base in table 1, [°C]
- \( T_{user} \) final useful user temperature, about 55 °C, [°C]
- \( \xi \) exergetic efficiency; according to the Second Law of efficiency, it assumes as first approximation maximum values of the order of magnitude of 0.5 [-]
- Eq.(4) has been obtained from the definition of exergetic efficiency formulating the effective COP as function of the exergetic efficiency and the ideal COP. Moreover the ideal COP has been expressed by means of the temperatures \( T_{user} \) and \( T_{mean,ext} \) instead of the ones at the condenser/evaporator. Actually, evaporator exchanges with a temperature which is usually higher or equal to the environmental one according to the solar radiation captured by the solar field. As far as the winter working period is concerned (HP operativity period), the solar radiation availability is very low. So, an average monthly estimation of the COP can be carried out referring to the mean external temperature.

The total energy consumed is about 13500 kWh \( E \). Thanks to the control system of the SAHP, the panel surface temperatures are always very close to the external one, so the only solar panels thermal losses are due to reflection (about 20%). Detailed month by month HP consumptions are shown in table 2. The balance is positive since the electrical energy produced over a year is greater than the consumed one over the same reference period saving about 55% of the total electricity produced. These estimations on the records of the past two years are in accordance with [6] where a prediction 14000 kWh \( E \) of electrical consumption and 25000 kWh \( E \) of electrical production was reported.

During the past biennium, the Italian Laws concerning the feed-in-premium strongly changed penalizing the net-metering. The previous feed-in-premium consisted in a balance between the total annual produced energy against the used one (annual energy balance). Now the electrical energy balance is carried out on a monthly basis and accounts for the related produced power. The electricity production, \( E_{el,PV} \), during summer can double or even triple the winter production (table 2), highlighting the importance of this contribution to the yearly balance. Table 2 shows the electrical energy consumed by the heat pump \( E_{el,HP} \) during the heating season according to the thermal energy produced by the HP. The last three columns contain, respectively, the electrical energy transformed from solar irradiation \( E_{el,PV} \) and the gain/deficit computed for each month, in accordance with previous and existing laws. Negative differences show a lack of electricity compensated by the national grid, with consequent operating costs. A positive balance means a not-paid surplus in energy production injected into the grid and not payed.

Under these new conditions, the solar field covers up to 60% of the average electrical need of the plant. The surplus of electricity during mild seasons is injected into the grid, but without any positive economic benefit for the prosumer, representing therefore a net economic loss for the plant financial balance. The balance can be restored involving the energy demand of the structure (e.g. illumination or summer air conditioning). The new Italian electrical feed-in-premium aims to create independent and self-producing electricity plants able to cover gradually the global electrical needs of the building and not only seasonal ones of a single heating plant.

2.3. Bypass

Thanks to a three-way valve, the hot water stored in the tank on the cold side of the heat pump can bypass the pump itself and reach the collector, leading either to the DHW storage or directly to heating system. This bypass is activated whenever the temperature inside the cold storage reaches a limit temperature, set by means of the monitoring system. The value is usually above 50 °C; clearly this condition is seldom reached during winter and the bypass is mainly used during summer, when the HP is off, and the solar field can be directly connected to the DHW storage.
Table 2. Summary of the electricity consumed by the HP, the photovoltaic energy collected by the hybrid field over a standard year simulation and the difference between energy consumption and collection (negative values stand for net energy consumption from the grid)

| Month | COP<sub>m</sub> | E<sub>d,HP</sub> (kWh) | E<sub>c,HP</sub> (kWh) | E<sub>EL,PV</sub> (kWh) | ΔE (kWh) (Yearly balance) | ΔE (kWh) (Monthly balance) |
|-------|-----------------|----------------------|----------------------|----------------------|-------------------------|-------------------------|
| January | 3 | 5651.6 | -1883.9 | +908.3 | -975.6 | -975.6 |
| February | 3.1 | 7256.4 | -2340.8 | +1166.2 | -1174.6 | -1174.6 |
| March | 3.2 | 13087.5 | -4089.8 | +2103.4 | -1986.5 | -1986.5 |
| April | 3.5 | 7849.3 | -2242.7 | +2523 | +280.3 | 0 |
| May | - | 0 | 0 | +3096.9 | +3096.9 | 0 |
| June | - | 0 | 0 | +3409.5 | +3409.5 | 0 |
| July | - | 0 | 0 | +3479.8 | +3479.8 | 0 |
| August | - | 0 | 0 | +2945 | +2945.0 | 0 |
| September | - | 0 | 0 | +2190 | +2190.0 | 0 |
| October | - | 0 | 0 | +1469.4 | +1469.4 | 0 |
| November | 3.3 | 5796 | -1756.4 | +931.5 | -824.9 | -824.9 |
| December | 3.1 | 4253.2 | -1372 | +683.5 | -688.5 | -688.5 |
| **Total** | | **43894** | **-13685.6** | **+24906.45** | **+11220.4** | **-5650** |

2.4. Monitoring and remote-control systems

The plant design includes about 50 measurement points (temperatures, flow rates, insulation, HP performance) and 15 control points (circulation pumps, mixing valves, burners, by-pass) to cope with the strongly discontinue trends due to the dynamic working conditions of the plant. The main guidelines of monitoring, control, audit and optimization translate into the following functional targets:

- Automatic adjustment procedures and control to avoid human intervention as much as possible;
- Optimisation of the regulation criteria to decrease consumption of primary energy;
- Programmed maintenance instead of demand failure interventions and remote failure control
- Measurement of the instantaneous consumption and data elaboration on monthly and yearly basis
- Energy efficiency evaluation as a function of the operating conditions.

3. Case study: sudden stop of the heat pump

The monitoring system recorded many periods of sudden stop of the HP. Their occurrence was often in conjunction with stable meteorological conditions characterised by high irradiance and external temperatures between 10-15 °C. Figure 3 shows the recorded trend of temperature, orange line and irradiance, blue line over one single day (May, 2<sup>nd</sup>), chosen as a representative example of the problem. The sudden stop occurred at about 10.00 a.m. (grey vertical line in figure 3). After an interview with the technical staff, the facility resulted to be open and no manual switch from HP to fossil burners or HP failures were detected. According to the monitoring system, the integration burners for DHW and SH where operative during the period of stop of the HP (between the grey and yellow line). So, excluding issues associated to end users’ acceptance or maintenance aspects, the problem is concerned with the operativity range in terms of temperatures and pressures of the heat pump.

After a detailed analysis of the database collected that day, a temperature between 20 °C and 25 °C was recorded in the cold storage. The same condition was met in the other cases of “suspect” stop of the HP.
Each time the temperature of the inlet water on the exchanger in the cold storage reaches this range of temperature, a safety valve stops the HP to limit the compressor suction pressure, to prevent early cracks.

**Figure 3.** Trend of irradiance $G(\tau)$ and external temperature $T_{\text{ext}}(\tau)$ on May, 2nd. The grey and yellow vertical lines represent the hours respectively of the HP stop (about 10.00 a.m.) and the hour up to the plant might have worked (7.00 p.m.)

Consequently, a short circuit after the bypass but before pump $P_2$ has been created. Figure 4 proposes a detail of the block diagram in figure 1 before and after the variation of the original configuration shown in figure 1. The solution is to guarantee the inlet set point temperatures at the HP evaporator to the working limit of 18 °C as deduced from the COP operating map of figure 2. With the use of a three-way valve, the cold water exiting the evaporator is mixed with the hot one from the cold WST before entering the evaporator.

**Figure 4.** Detail of the HP from the block diagram of figure 1, before and after configuration changes

With reference to figure 3 some interesting considerations can be drawn:

- the HP has completely lost the solar thermal energy (the area swept by the irradiance between the vertical grey and yellow lines). Furthermore, the system automatically switches to fossil fuel burners to integrate the DHW and SH needs.
- Each time the HP stops suddenly, a safety control requires the manual restart of the machine. According to the maintenance contract, the technicians’ intervention would occur not before 48 hours after the call, with the associated energy loss of an inoperative period about 24-36 hours long. The technical staff has to understand the reasons of the HP stop before restarting the system. In some cases, the technicians bypassed the HP and heated the facility only with the fossil burners since the causes of the HP block were not clear to them. The greater losses in terms of operativity time are due not to the stop itself, but to the end-users’ and technicians’ “acceptance” which can lead to the shut off of the HP for different days without any technical reason.
Table 3 contains a brief estimation about the dataset collected where the total amount of nominal working time (considering only the sport facility opening days) and the HP actual working hours are shown month by month. An average of 3 hours per month for maintenance have been deducted.

| Year 2017 | January | February | March | April | November | December | Total | Reduction |
|-----------|---------|----------|-------|-------|----------|----------|-----|-----------|
| nominal working hours | 180 | 204 | 324 | 132 | 288 | 192 | 1320 | 13.2% |
| actual working hours | 171 | 175 | 275 | 99 | 240 | 190 | 1150 | |

| Year 2018 | January | February | March | April | November | December | Total | Reduction |
|-----------|---------|----------|-------|-------|----------|----------|-----|-----------|
| nominal working hours | 180 | 204 | 324 | 132 | 288 | 192 | 1320 | 14.3% |
| actual working hours | 172 | 160 | 254 | 87 | 267 | 191 | 1131 | |

This issue caused an average decrease of the working hours per year of about 6%. A first estimate shows that only the HP block would cause a 5% reduction with respect to the total nominal working hours. The influence of “acceptance” determines a reduction of about 15%. The economic impact of these failure periods on the energy savings achieved should be assessed in detail.

4. Conclusions
The SAHP-PVT with hybrid field pilot plant installed at PALACUS Sport Centre in Genoa has been described, focusing on the heat pump and the solar field. The change in the feed-in-premium regulations moved the profitable energy balance into a negative one, affecting the economic viability of this installation. For instance, the summer contribution of the solar field, no more computed in the new feed-in-premium criteria, compensated the lack of electricity during the heating season in which consumptions are large and the solar electrical production is very low. With the old feed-in-premium criteria, the yearly need of the facility was covered with about 50% of the total solar field electricity production. Today the solar field can cover only up to 60% of the electrical needs of the plant. The data acquisition system plays a key role to manage the complexity of the system and the widespread grid of sensors over the plant.

A case study concerning a failure of the HP checked by the monitoring system highlighted the need of a change in the system configuration. A three-way valve has been included between the cold storage and the evaporator heat exchanger to control the inlet hot water of the exchanger to a reasonable setpoint of 18 °C. This upper limit restrains the COP of the HP, as shown in figure 2, because of the operativity range of the commercial installed HP. A “hand-tailored” heat pump, made of specific compressors with higher suction limit pressures, should be designed evidencing the commercial SAHP-PVT limited applications field. The monitoring system allowed to study the failure relevance over two years with respect to the total possible working period. About 60% of the reduction computed is due to the end-users’ “acceptance” issue, while only 40% is strictly related to the stop of the plant due to reaching critical temperatures.

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