Experimental analysis of a self consumption strategy for residential building: the integration of PV system and Geothermal Heat Pump

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Abstract

The paper analyzes the perspective of a solution for the mutual interaction of a Photovoltaic (PV) generator and a Ground Source Heat Pump (GSHP) in the context of a residential building. The idea is to analyze the operating performance of a system that permits the maximum self-consumption of the energy generated by a small-size PV system installed on the same building: this kind of systems could be useful for further penetration of renewable energy in a complex energy context. The problem is analyzed basing on the data of an experimental analysis of a real case, in the town of Pisa, Italy. A typical house equipped with a GSHP and a PV plant of similar size (about 3.7 kW of peak power) is monitored during a year of operation in order to test the feasibility of the technical solution for a more general application. The data concerns both the operation of the two systems and the interaction with the electric grid. The possible utilization of this solution in the perspective of promotion of self-consumption policies and of Nearly Zero Energy Buildings (NZEB) is discussed and analyzed showing that the level of interaction with the electrical grid is quite high.

Keywords: Renewable Energy Systems, Distributed Generation, Photovoltaic Plants, Ground Source Heat Pumps, Experimental analysis.

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Nomenclature

A	Surface of the building envelope (m^2)
A_{PV}	Area of the PhotoVoltaic plant
COP_c	Coefficient of Performance in cooling mode
COP_h	Coefficient of Performance in heating mode
En_{el}	Electrical energy (kWh)
$En_{th,c}$	Thermal energy for cooling (kWh)
$En_{th,h}$	Thermal energy for heating (kWh)
GSHP	Ground Source Heat Pump
H_{SN}	Annual solar irradiance (kWh/m^2)
HP	Heat Pump
I_{SC}	Short circuit current (A)
I_{mpp}	Current of maximum power (A)
K_{shade}	Shading factor
nZEB	nearly Zero Energy Building
PES	Primary Energy Saving
PV	PhotoVoltaic
$Q_{in,solar}$	Solar gain (kWh)
RES	Renewable Energy System
STC	Standard Test Conditions
t	time (h)
T_{in}	internal temperature (°C)
$\bar{T}_{ext}$	average external temperature (°C)
$\bar{U}$	average value of the heat transfer coefficient for the building (W/m^2 K)
V_{mpp}	Voltage of maximum power (V)
V_{op}	Voltage of open circuit (V)
η	PV plant efficiency
η_{PV}	efficiency of the PV module
η_{BOS}	efficiency of Balance of System of PV plant

1. Introduction

In several countries of European Union, in energy production sector, the last ten years have been characterized by a relevant development of intermittent Renewable Energy Systems (RES), mainly photovoltaic (PV), and by the increase of decentralised production, resulting in a growing number of small and medium size "producers" and a lot of small size plant connected to the electricity grids. [1].

From a technical standpoint the production of intermittent renewable electricity and the increase of distributed generation systems cause unpredictable energy flows into the grid that requires control. The large-scale integration of renewable energy sources into the context of complex energy systems must meet the challenge of coordinating fluctuating and intermittent renewable energy productions with the rest of the energy system. In particular it is shown how the penetration of new renewable energies is limited at an upper level by technological considerations and it will be more sustainable if an integration of the various energy uses (thermal energy, mobility and electricity) will be considered [2-4].

Maintaining the balance between supply and demand in energy systems with large quantities of fluctuating renewable energy plants is a quite complex task. For this reason, the growing increase of penetration of RES must be joined with an optimization of the whole energy systems. This in order to permit an effective energy saving, otherwise the great effort for the promotion of those new energy systems will be not effective in order to provide the reduction of the dependence on fossil fuel resources and the reduction in carbon emissions. A possible way is the promotion of self consumption strategies; moreover several studies, like [5] have suggested the systematic use of battery storage co-located with solar photovoltaic (PV) systems.

In some European countries, the increase of intermittent renewable sources is particularly relevant (more than 30000 MW, installed in Italy nowadays, of PV plus Wind power systems) and it is required, for the aim of the grid stability, to develop structural strategies in order to meet this challenge. Due to the intermittent nature of RES, very little can be gained by means of an improved forecasting and by regulating the renewable source itself.

For the aforesaid reasons questions about the impacts and costs associated with maintaining grid stability are receiving growing attention. In order to bring about a substantial long-term penetration of distributed energy resources in Europe, it is necessary to address the key issues related to their integration into existing energy systems, in which a large variety of thermoelectric power plants is still present, so that a primary energy saving (PES) based on the use of fossil fuels will be obtained.

A crucial element is often to show coherent technical analyses of how renewable energy can be implemented, and what effects renewable energy has on other parts of the energy system. For this reason the penetration of RES must be encouraged with the perspective of the heat demand too. With regard to such recommendations, some conversion technologies such as heat pumps may contribute in a relevant way to improve the efficiency of the whole system and can be useful for a further increasing of penetration of RES.

Another important element is represented by the increase of the use of heat pumps (HP) both in the version of air source heat pump and geothermal heat pumps. HP using ground as source are particularly attractive both in the perspectives of their efficiency increase (COP is increasing from the available values of 3-4 up to values of 5-6), [6, 7] and because they permit a further integration of production of thermal energy and electricity.

Even if HP and in particular Ground Source Heat Pumps (GSHP) cost more to be installed than conventional systems, like condensing boilers, inclusion of technologies such as HP and GSHP can be relevant in order to add flexibility to the system [7] and to determine improvements in terms of general efficiency [8].

The use of heat pumps during the winter time contribute to shift a part of the energy demand satisfied with natural gas to the electricity sector and consequently to renewable energy, while during summer time it contribute to assist the operation of the cooling systems that in the last years, determine the peak of electricity demand, that mainly in some countries of southern Europe occurs in July from 11-13 a.m. In this way heat pumps increase the flexibility of the system because they can consume electricity at hours of excess production during summer time while in winter they can replace efficiently the heat production of boilers and CHP units for the residential sector.

Adding heat pumps to the energy systems means that they can be used instead of boilers so they permit an increase of electricity uses for heating purposes and a shift from the use of fossil fuels like natural gas to the use of electricity.

Moreover a new approach to the promotion of renewable energy is represented by the attempt of maximising the installation of systems for self supply use, limiting the impact on the electrical grid. For this reason it is important to consider the connection between the production of electricity and the use of thermal energy, [9-10].

The promotion of self-consumption policies is already available in Europe and has already been tested in Italy, just form the fifth energy bill – Vth Conto Energia – a specific self-consumption premium scheme which was very similar to the scheme introduced in Germany in 2011: this is an initial attempt to promote direct consumption schemes, featuring a mix of net-metering aspects (especially for grid costs) and self-consumption (for electricity costs) and the definition of new schemes for the self consumption is expected.

Other important topics considered in the literature are the development of multi-energy systems in buildings, that integrate different energy sources, at least one of which is renewable, in order to cover the thermal and electric loads of a building [11] and Net Zero Energy Buildings (NZEB) represented by systems that combines measures for reducing the energy demand and increasing the share of renewable energy in the energy systems. [12]

The main framework of a NZEB concept is the idea of a low-energy building that produces energy and interacts with the electrical grid. Such a building is conceived as energy-efficient building, equipped with energy efficient systems and effective insulation materials to curb the heating and electricity demand and with on-site renewable energy systems (typically solar thermal and PV systems). The energy generation over a year balances the energy use and the excess energy from renewables, which is not self-consumed, is exported to the grid [13]. This is considered in a series of recent papers both with a methodological perspective, [14, 15] and with respect to particular buildings [16]. The European Union's directive on the energy performance of buildings will lead to more local energy generation in the future and more energy efficient buildings. Solar energy is regarded as one of the most promising ways for local energy generation and solar assisted heat pump systems in particular the combination of a PV system and heat pump is considered the best alternative [17]. Many energy systems have already been developed including technical solutions and models. Most of them concentrate on the investigation of electricity supply and demand, but neglect or do not cover in detail the interaction of heat and electricity and the interaction of the systems with the electric grid. Moreover, there is a lack of studies from the perspective of the dynamic approach and the system integration.

Considering the previous argumentations, this paper investigates an integration strategy between (GSHP) and PV plants with the aim of evaluating the perspectives of this solution for increasing self-consumption policy within a residential building. In this case instead of setting up the PV system to feed the energy produced into the grid, the energy produced is primarily employed to supply the heat pump and the other domestic loads.

The perspective of this joint solution can be a method to superate the problem of the high running costs of ground-source heat pump (GSHP) systems, and the forthcoming unprofitability of feeding into the grid the electricity generated by small-sized photovoltaic (PV) arrays that risk to reduce the future developments of such a kind of systems. In particular the aim of the paper is to propose the results of an experimental analysis of a building in Pisa in the north of Tuscany, with typical temperate climate conditions. The geographic coordinates of the implementation site in Pisa are 43.66°N, at an altitude of 10 m above the sea level. The climatic profile is temperate with lowest temperatures reaching −2 °C in winter and warm summers with peak temperatures of 34-36 °C. The work done on this building before the installation of the new system has addressed the objective of reduction of the heat loss through the building's envelope.

In this building the existing heating system was replaced by means of a geothermal heat pump. In the meantime a PV plant has been installed sized with the objective of supplying the energy consumption of the geothermal heat pump and assisting the other distributed electricity consumption. The experimental analysis was carried out during one year in order to investigate all the possible operating conditions.

The objectives of the analysis are different: the first is to analyze the feasibility of a technical solution that permits a direct integration of energy production and consumption in a real context and to define the balance of production and consumption in the various periods of the year so that it can be analyzed the validity of such a kind of solution in connection with future further development of PV plants. Then an analysis of the operation of the two systems (Geothermal Heat Pump and Photovoltaic plant) is performed in order to investigate the real operating efficiencies of both and comparing the operating data with the expected ones. Finally some general indications about the perspective of development of such a kind of system and guidelines for the design are provided. It is clear that it is impossible that all the energy produced by PV modules can be directly consumed or stored in the building and a totally self supply architecture is very difficult but the idea developed in the paper is useful to understand the upper level of energy that could be fed into the grid in the various operating conditions during a year of operation.

2. System description: Ground Source Heat Pump (GSHP) assisted by a Photovoltaic (PV) generator

One of the methods to transform a complex energy system in order to increase the flexibility and the percentage of intermittent RES, like PV plants on a large scale, is to increase the demand of electricity and to promote the dissemination of self-consumption strategies of the energy produced. An interesting solution is the use of solar assisted Heat Pumps for heating and cooling purposes. During the last decade, a number of studies have been performed by various investigators in the design, modelling and testing of solar assisted heat pump systems [18]. But the use of solar energy is often proposed for the production of thermal energy and for the use in adsorption heat pumps. Unfortunately the technical solutions are not optimized. They have to be tailored for the specific case under analysis and they often require the utilization of consistent storage volumes. Moreover the joined operation of solar energy and heat pump does not permit a profitable use of energy during winter period.

Taking into account that two of the major issues concerning the microgeneration technologies are the ground source heat pumps (GSHP) and of small size PV plants and of the recent developments in terms of economic support polices has determined a growing use both of PV plants (determined by the effect of feed-in tariff) and HP (determined by the effect of fiscal incentives). [19-20]. It seems obvious to propose a possible integration among the two technologies.

This integration, proposed in [21], can contribute in the medium to long period, to a possible reduction of the use of conventional fossil fuels (like natural gas) for heating purposes and to a further increase of penetration of PV technology in the energy production systems. As observed, some European countries as Italy are interested by a meaningful growth of PV power plants, frequently installed on residential and commercial buildings and connected to the grid. The development of PV power plants has been a consequence of the feed-in tariff policy named "conto-energia", active in Italy from 2005 to 2014 (Table 1), [22].

Table 1. The development of PV plants in Italy [1]

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Number of plants	14	7467	32018	71256	155977	330306	478331	579524	648418
Power installed [MW]	7.2	86.7	432	1142	3470	12773	16420	18420	18609
Specific power [kW/plant]	512.5	11.6	13.5	16.0	22.2	38.7	34.3	31.5	28.7

As shown in Table 1, even if the average power of the single plant is decreased in the last years, a value well higher than the one typically required for a self consumption strategy can be observed: about 28.7 kW considering the whole PV systems installed in Italy at the end of 2014, this causing important unidirectional flows from the PV systems to the grid.

The PV technology is really interesting but considering the forthcoming unprofitability of feeding into the grid the electricity generated by small-size photovoltaic (PV) generator, a further development must be strictly connected with the promotion of self-consumption strategies of the energy produced. Investment in a PV system for a prevalent self-consumption will then be the only possible in the perspective of a further increase of penetration and self-consumption models are likely to emerge in the perspective of the smart house [23]. Another interesting technology developed in connection with residential system is the GSHP. Many studies used experimental and numerical simulations for evaluating the performance of the GSHP system have been recently proposed in the literature, both in the perspective of promoting high efficient solutions for building space conditioning and for integration in smart grids focusing the attention on the dynamics [24-25]. It is recognized that GSHP can determine good energy advantages for heating and cooling of residential and commercial buildings if compared with others systems, mainly in the perspective of future developments that will increase their COP at values quite higher than the actual level of 3-4. In the light of the above exposed considerations, supplying a HP or GSHP system with electricity locally produced by means of a microgeneration equipment becomes an attractive option. These systems must be designed in such a way that they can cope with the fluctuating and intermittent nature of renewable energy sources, especially with regard to the electricity supply. Unfortunately it is not easy to define the proper size of the system.

3. Experimental setup

The analyzed building is located in Pisa. Pisa is a town of in Tuscany (central Italy) and is characterized by a temperate climate. According to standard normalized data the annual solar irradiation corresponds to the value of 1500 kWh/m^2/yr.

The system object of the analysis is composed by a Ground Source Heat Pump (GSHP) assisted by a PV plant. The house is a typical medium-sized single-family house of 160 m^2 plain surface and an indoor volume of about 450 m^3. Some details of the building and of the two energy systems are shown in Fig. 1. The building typology was designed to be generic enough to enable a realistic situation typical of Tuscany. The type of the geothermal heat pump considered is a classic liquid-liquid Ground Source Heat Pump (GSHP). The heat pump system is coupled to two closed-loop vertical borehole Ground Heat Exchanger (GHE) of total depth of 60 m: in this way the total length of the GHE is approximately 240 m, so that it is possible, in case of the expected value of linear power rate of 50 W/m, to obtain a total heat power of about 11 kW.

The nominal electric power of the heat pump is 3.8 kW; the operating fluid is R-407 and the nominal COP is about 4 in heating mode and 3 in cooling mode. The temperatures in/out of the condenser are 35/30 °C and the evaporation temperature is 5 °C. Ground Source Heat Pump (GSHP) provides up to 14.4 kW of space heating for the entire building, and, through reverse cycle technology will also provide the cooling during summer. The PV system, of about 21.13 m^2 of total surface is composed of 17 modules organized in two arrays (9 modules in the south-est side with inclination angle of 24° with respect to the horizontal and 8 modules in the south-west side with an inclination of 21° with respect to the horizontal) is sized according to the maximum electric power of the HP.

The main characteristics and the nominal data of the PV system and the nominal data of the PV module are reported in Table 2 where the operating voltage and current at the maximum power V_{mpp} and I_{mp}, the short circuiting voltage V_{oc} and short circuiting current I_{sc}. As additional data it is possible to include the temperature coefficient of the module: considering the maximum output power P_{mpp} the value of minus 0.38%/°C is declared for the system if the operating temperature of the module is higher than 25°C. The nominal operating temperature of the module is declared to be 46 °C.

The PV is connected to the grid, in order to provide a minimum stabilization of the system; even if the production and consumption will be similar they are very far to be in phase also considering that other appliances consume electricity inside the house. As already mentioned, the 17 modules of the PV plant are arranged in two strings, one with 8 modules and the second with 9 modules. The interface between PV plant and the grid is obtained with two inverters, sized with a maximum capacity of 2kVA. A scheme of the complete experimental system is depicted in Fig. 2. Fig. 2 provides also that the systems are completed with measurement point of both temperature and humidity inside and outside the house. The temperature probes have an accuracy of 0.1 °C, while the humidity can be determined with 1% accuracy. Moreover the energy production of the PV system, the energy consumptions of the Ground Source Heat Pump separately and of the whole house can be measured separately. Experiments were conducted extensively starting from the middle of January till the end of the year. The GSHP system is programmed to maintain the indoor temperature around a well defined value: 19 °C during the heating period and 26 °C during the cooling period. The acquisition data system permits to evaluate the daily energy consumption of the heat pump, the daily energy production of the PV system, the daily energy consumption of additional power from the grid or the energy daily feed into the grid. Moreover temperature and humidity can be acquired during the whole day, using particular temperature probes connected to a data acquisition system. Both PV plant and GSHP are equipped with an independent energy meter in order to analyze the production and the consumption respectively, while a bi-directional energy meter is used, able to measure the energy flow to the grid in both directions, is also used: in this way the total energy consumption can be determined and the energy used for all the devices can be obtained for difference. All the data of temperature, humidity and energy flows are acquired and recorded at a time step of 15 minutes.

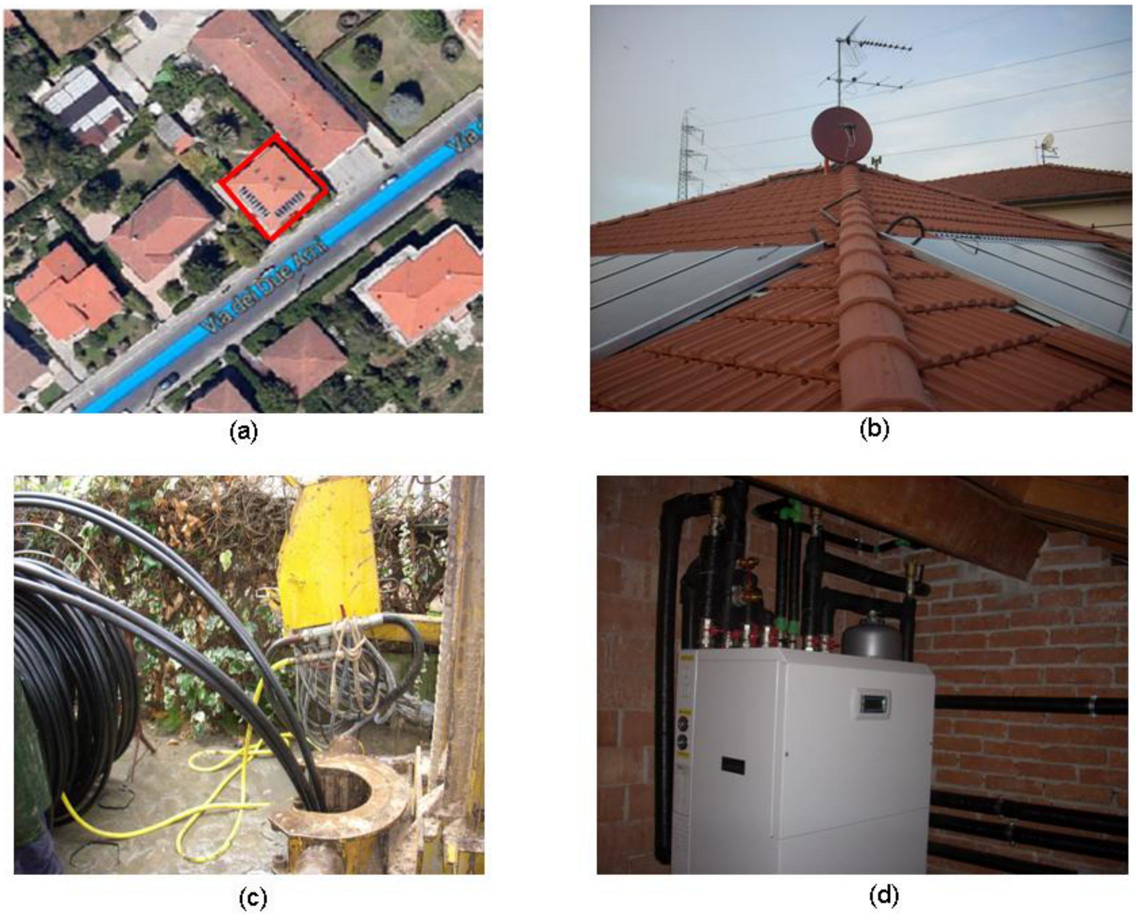

Fig. 1. Details of the experimental system: the building (a); the two strings PV plant (b); details of the borehole heat exchanger (c); the heat pump (d)

Table 2. Nominal data of the PV system and of the PV module (referred to STC: 25 °C and 1000 W/m^2)

Nominal Power	**Nominal Power per module**	**Area of module**	V_{mpp}	I_{mpp}	V_{oc}	I_{sc}	**Nominal efficiency**
3.74 kW	220 W	1.24 m^2	41.0 V	5.37 A	48.6 V	5.75 A	17%

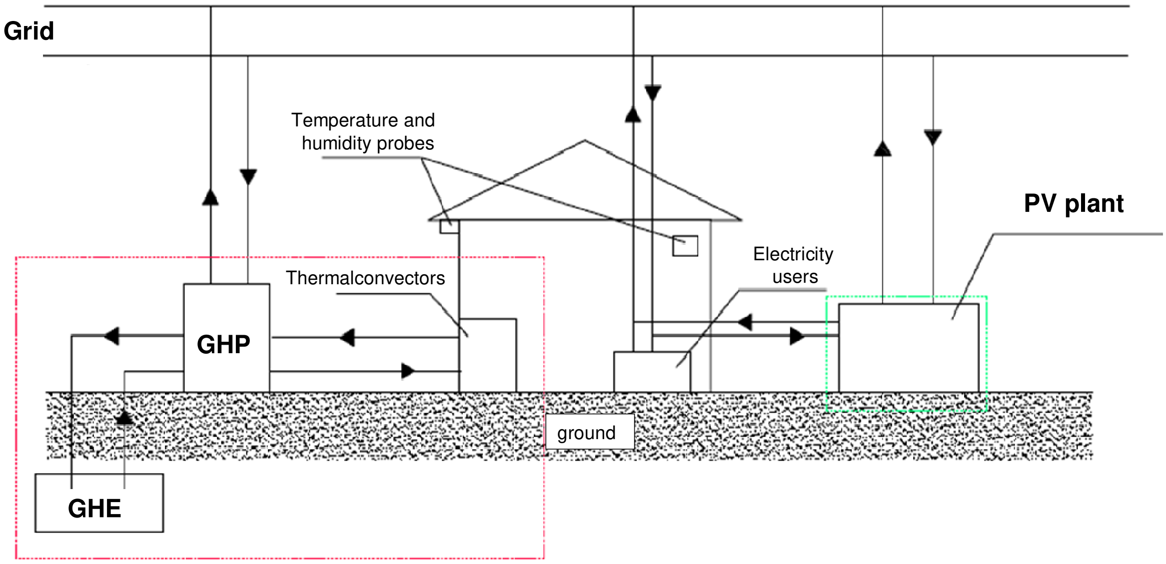

Fig. 2. A schematic description of the plant

4. Results

The first group of experimental results concerns an analysis of the operating mode of the system in real operating conditions: the period covered is between 14 of January and 31 of December.

Fig. 3 provides a comparison among the different energy components (energy produced by the PV plant, daily energy consumption, energy feed in and out to the grid) in the various days of the year from January to December.

From this plot it is possible to understand how the total energy consumption in the house, obtained as the sum of HP consumption and other household appliances taken into consideration stands in the range between 5 kWh/day up to 40-45 kWh/day during some particular days of winter time while the maximum energy produced with the PV plant is always below 22 kWh/day.

The GSHP operates from a minimum of 1 hour in some days in the mid season up to a maximum of 12 hours during some particular cold days in winter. As observed from the experimental data, only during summer time it is possible to think to a real self-supply strategy, and this is really true mainly in June and September, while in July and August the energy consumption is often well higher than the energy produced with the PV system, due to the high operating time in cooling mode of the heat pump.

Fig. 4 provides a comparison among the various electricity consumptions measured during the year. In particular, analyzing the energy consumption related to the GSHP and to the other electricity systems, it is possible to understand that the daily energy required for the operation of the GSHP has a maximum of the order of 30-35 kWh/day and this maximum occurs in heating mode. For this reason it is confirmed the idea that in this particular house and operating conditions (Pisa) the summer operation of a GSHP, from the standpoint of energy balance can be covered by means of a PV plant of the same size. If the data are analyzed in a more careful way a series of different observations can be carried on.

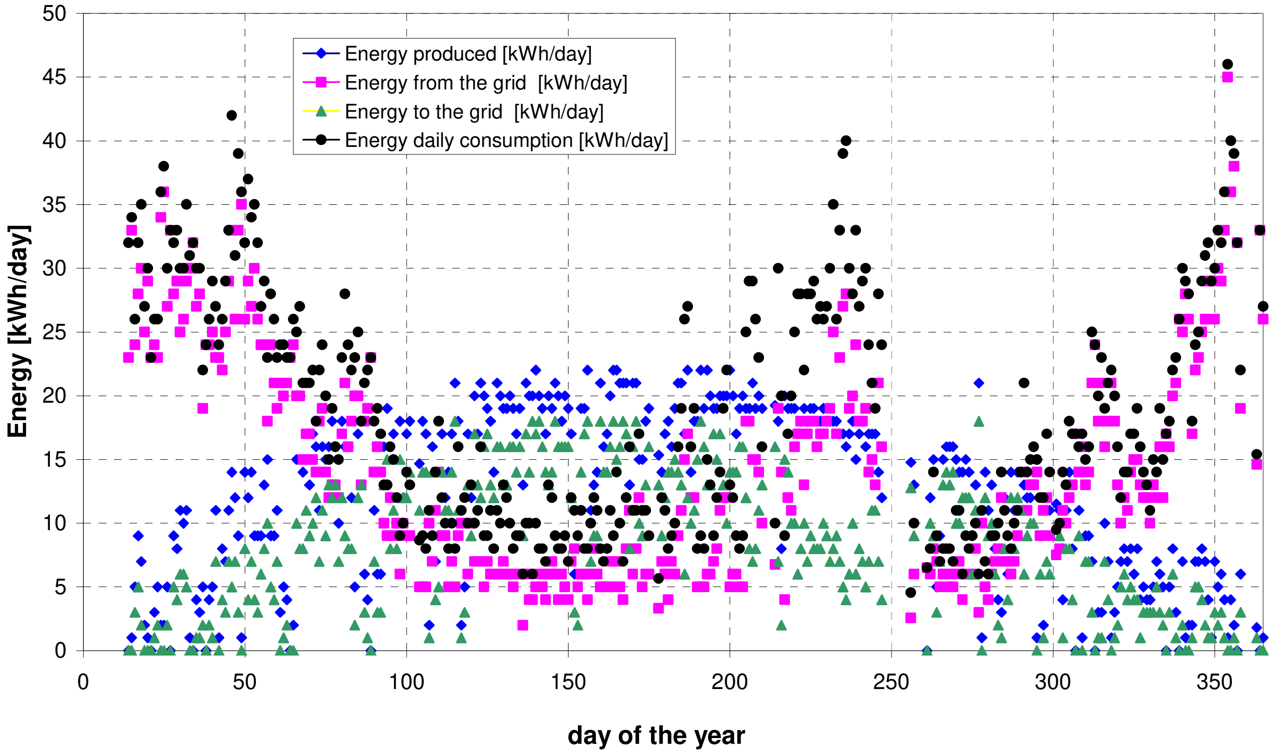

Fig. 3. A schematic plot of the various energy components (daily analysis)

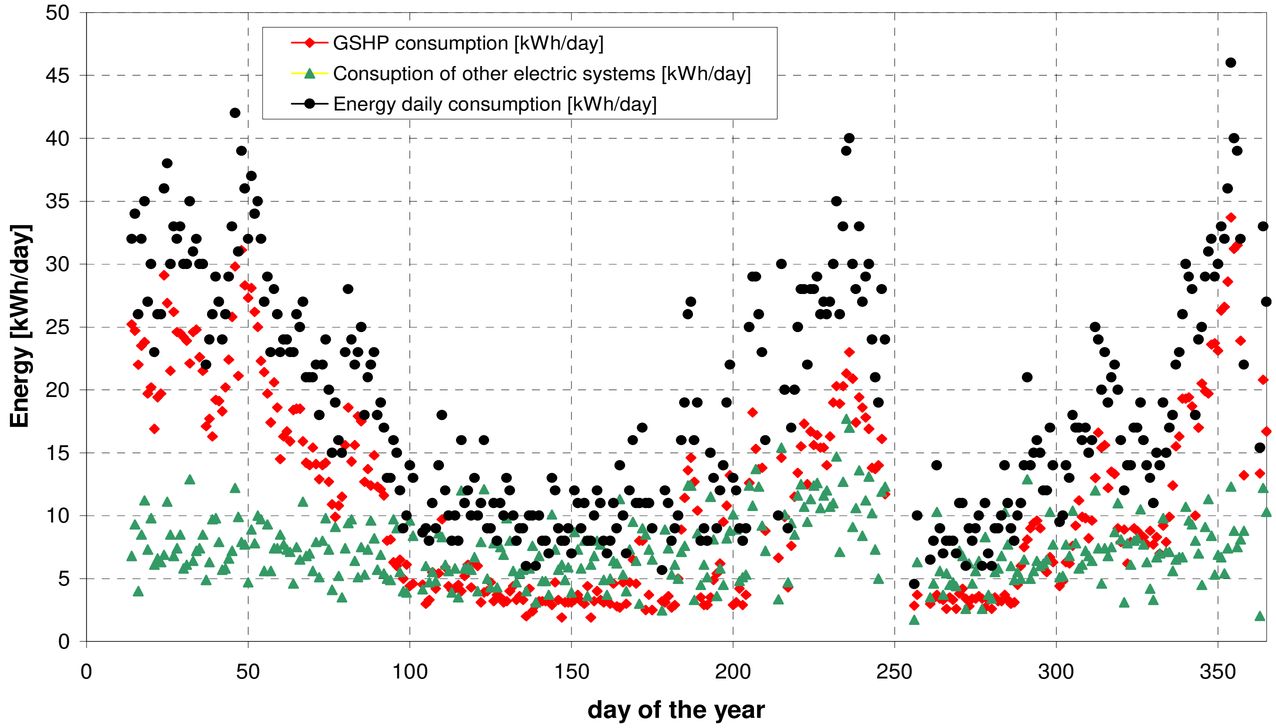

Fig. 4. A schematic plot of the various energy consumption data (daily analysis)

A brief consideration concerns the energy consumption of the heat pump during the heating period: also considering the maximum level of 30 kWh for day, an annual energy consumption of 13-14 kWh/m^2 can be obtained, value completely satisfactory that demonstrates the good energy performance of the house. An extended period of reduced activity of the GSHP (energy consumption below 5 kWh day) can be observed during the mid seasons, in spring and in autumn.

Considering the whole data reported in Figs. 3 and 4 it is possible to observe that in the considered experimental analysis, heating proves to be the most energy consuming operating mode, with daily peaks up to 33 kWh during the coldest period of the year. In summer, daily peaks are at least 70% lower than in winter. The plots of Fig. 5 report the annual energy consumptions profiles and the energy production profile of PV system.

Concerning the energy consumption it is possible to distinguish among total energy consumed, energy used for the operation of the geothermal heat pump and energy used for the operation of the other household appliance. If the energy used by the heat pump, considering both the heating and the cooling period, is about 4000 kWh for the whole year, the energy consumption of the household appliances is less below the value of 2500 kWh (corresponding to an average value of 7 kWh for each day). Further considerations on the sizing and on the design of the power system can be made by comparing the annual power consumption profile of the GSHP system with the cumulative production of the PV plant. Analyzing the data of Fig. 5 it is possible to understand that, considering the energy balance, the energy produced with the PV system is sufficient to fulfil the total electricity requirements of the GSHP during one year of operation, but the other energy has to be supplied from the grid.

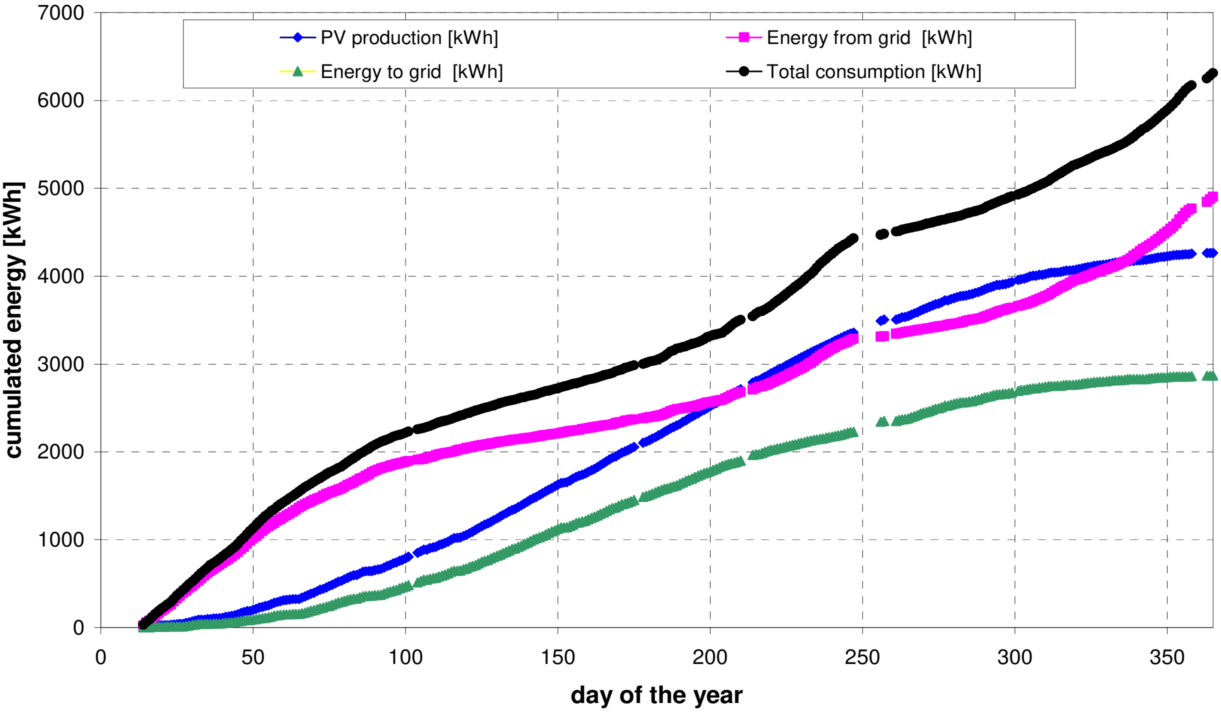

Fig. 5. A schematic plot of the various energy components (integral analysis)

5. Analysis of the data and discussion

Some general considerations on the system can be made by comparing the annual power consumption profile of the GSHP system with that of a PV plant and the seasonal data too. The first important element of the analysis is a comment about the size of PV power system. The value of 3.7 kW has been selected with the perspective of minimizing the energy exchanged with the grid. From the analysis of the data it is clear that a self-sufficient operating mode of the plant is not possible because a sensible grid assistance is necessary, mainly in the heating period (from October to March). Table 3 provides the cumulative data of the various energy components (total energy consumption, energy consumption of the heat pump, energy consumption for the other household applications and energy produced by the PV plant), grouped in the four different periods of the year. A balance of the energy produced is possible during the period from July to September, while during the mid season (April-July) the energy coming from the solar array is sufficient for supplying the consumption of the various household appliance, with a gain of about 500 kWh. However it is possible to observe that with this particular size of the plant, the use of the grid to feed into the produced energy in excess is always important and it is difficult to eliminate this. Considering the different months, like in Fig. 6, it is possible to observe that the balance is sometimes different and some months evidence more specific problems and a more careful consideration of the energy transfer between the plant and the grid.

Table 3. Energy balance of the plant in the various seasons.

Period	**Energy consumption of heat pump [kWh]**	**Energy consumption for household appliance [kWh]**	**Total energy consumption [kWh]**	**Total PV production [kWh]**
January-March	1499	579	2078	655
April-June	377	550	927	1436
July-September	796	652	1448	1399
October-December	1005	622	1627	580
TOT	3677	2403	6080	4070

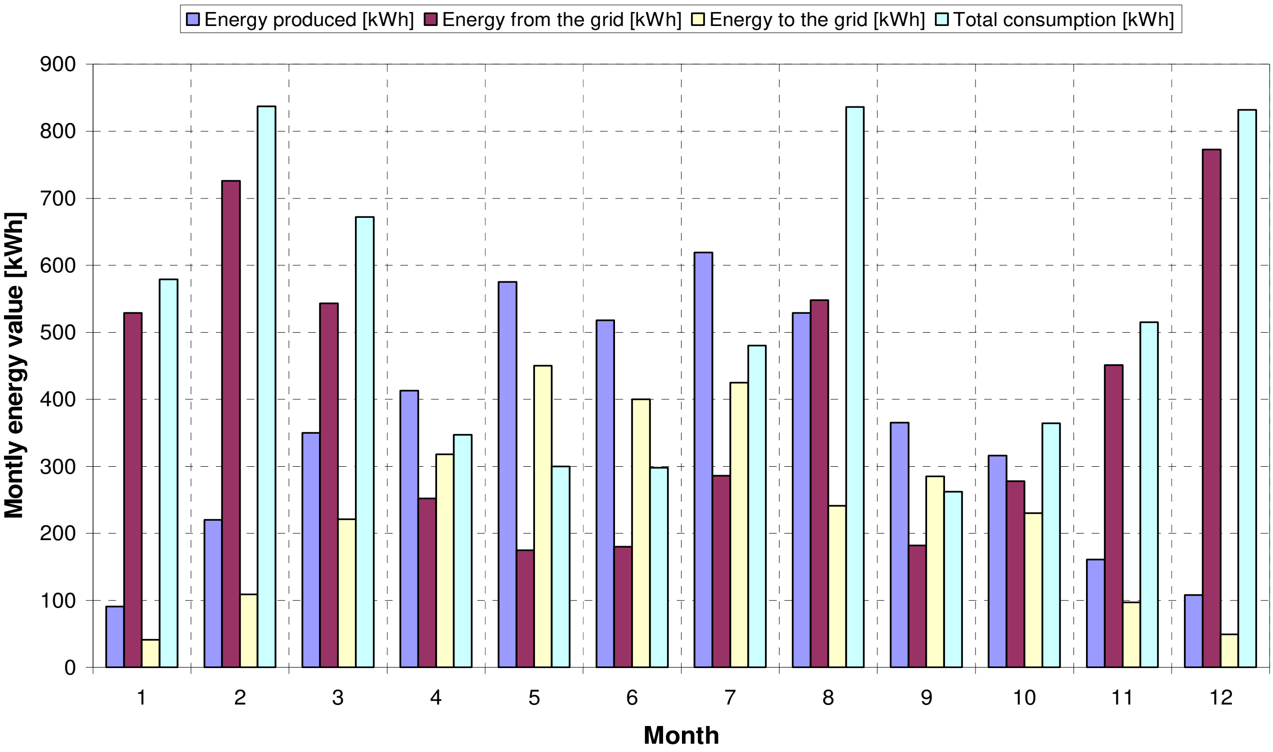

Fig. 6. Monthly cumulative values of the various energy components

The data of Fig. 6 show clearly how the energy flow to the grid is particularly relevant in the months characterized by a reduced functioning of the GSHP (April-July) ranging from a minimum of about 300 kWh to a maximum of 450 kWh for each month (about 10-15 kWh for each day). Other detailed analysis can concern the real operational efficiency of the two plants under analysis: the GSHP and the PV generation system.

5.1. *Detailed analysis of the operating mode of the GSHP: the operating COP*

Considering the recorded energy consumption data of GSHP, available for each day of the year, and the indoor and outdoor temperatures, it is possible to furnish a detailed analysis of the real operating mode of the heat pump. An estimation of the energy load required to maintain the imposed indoor temperature value can be estimated during the heating period as:

$$En_{th,h} = \bar{U} \cdot A \cdot \left(T_{in} - \bar{T}_{ext}\right) \cdot t - Q_{in.solar} \tag{1}$$

and during the cooling period as

$$En_{th,c} = \bar{U} \cdot A \cdot \left(\bar{T}_{ext} - T_{in}\right) \cdot t + Q_{in,solar} \tag{2}$$

in which $\bar{U}$ is an average value of the heat transfer coefficient, A the heat transfer surface of the whole building envelope, $\bar{T}_{ext}$ is an opportunely defined average external temperature and $Q_{in,solar}$ the energy gain from solar energy. The average temperature reaches the minimum values of -0.6 in a day of December and the value of 4.2 °C in the period from January to the end of March. During summer time the maximum of the average temperature was observed in two days of July (the 23rd and 24th) ant it was 29.4 °C. The value of the term $\bar{U} \cdot A$ has been estimated in this way: considering the electricity consumption of the heat pump and the outdoor temperature profile, a tentative value of the energy load has been established. From this value the average value of the heat transfer coefficient for the entire envelope of the building, $\bar{U}$, that considers internal and external heat transfer coefficients and thermal conductivity of the envelope, including walls doors, windows, roof and floor constructions and ventilation loss term, has been defined. This is estimated to be about 0.7 W/m^{2}K.

The value of the overall heat transfer coefficient estimated in this way is an ideal average value obtained in a single day, because it takes into account both the real heat transfer coefficient and the direct gain due to passive solar, but it appears to be quite reasonable considering the values available from the literature [26-27]. The ratio among the estimated required value of the energy load and the energy consumed by the heat pump permits to estimate an apparent COP of the GSHP, both for heating and cooling period as

$$COP_h = \frac{En_{th,h}}{En_{el}} \tag{3}$$

$$COP_c = \frac{En_{th,c}}{En_{el}} \tag{4}$$

Considering that the maximum available value of COP of the HP during the heating season is 4, this values has been attributed to the day in which the maximum operating performance have been identified and then the average heat transmittance ($\bar{U} \cdot A$) was redefined. With this value new estimation of the energy required for the heating season E_{th} has been carried out. Considering the values calculated above the same estimation can be operated for the summer period when the heat pump operates in cooling mode. Fig. 7 provides a comparison between the two values (energy consumed by the heat pump and energy theoretically required) for the heating period (for example between 14 of January and 31 of March). The estimation of the operating COP of the GSHP during the heating period is provided in Fig. 8. From Fig. 8 it is possible to observe while in real operating conditions the effective COP could be well lower than the declared value of 4 and in a lot of operating days the value of COP is lower than 2. In a lot of cases, especially during the mid-season it is important to underline that the intermittent activation of the heat pump causes slightly high peaks in electric power consumption and these values made partially explanation of the so low running values of COP. In a completely similar way it is possible to estimate the operating COP value during the cooling period. In this case it is possible to observe that COP range between values approaching the nominal value of 3 and values that are also below 1. The lower values are in general obtained in the days characterized by a reduced operating time of the GSHP. Fig. 9 reports the daily value of the operating COP in the two months of June and July and Fig. 10 the effective operating hours of the heat pump during the whole year.

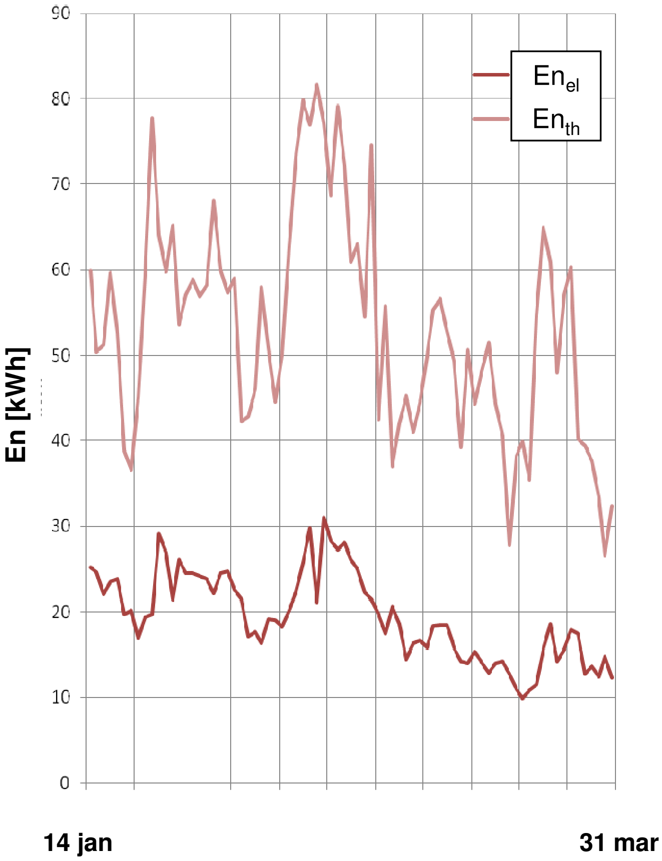

Fig. 7. Comparison between energy load and GSHP electricity consumption during the cold season

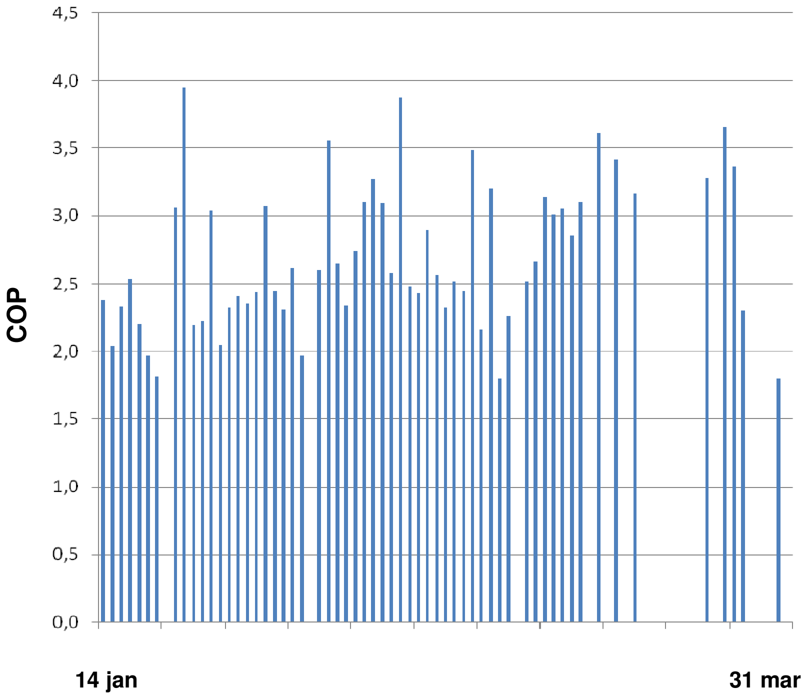

Fig. 8. Operating COP of the geothermal heat pump during the heating period

5.2. *Detailed analysis of the operation of PV system: estimation of the operating efficiency*

The data of the PV plant installed on the building are reported in Table 1. Considering the experimental data acquired, the total production is similar to the one theoretically expected and it can be estimated basing on the well known equations

$$E_{PV} = H_{SN} \cdot A_{pv} \cdot K_{shade} \cdot \eta_{PV} \cdot \eta_{BOS} \tag{5}$$

Because of the total surface of the two PV arrays is 21.13 m^2, the value for the specific annual solar irradiance H_{SN} of 1500 kWh/m^2 and the values of 0.99, 0.8 and 0.17 for the shading efficiency, for the efficiency of Balance of System and for the efficiency of the PV modules respectively, an expected value of the annual energy produced of about 4250 kWh is obtained, while the experimental value measured corresponds to 4070 kWh.

Considering that 13 days of January has been lost, the results obtained can be considered really good. The recorded operating data, joined with the data for the solar irradiation permits to estimate the operating efficiency of the plant defined as:

$$\eta = \eta_{PV} \cdot \eta_{BOS} \tag{6}$$

Fig. 11 provides the average data of the efficiency calculated. The efficiency of the PV system is calculated dividing the effective production, as can be deduced from Fig. 6 and the theoretical integral value of the energy radiation in Pisa observed during the corresponding month, obtained basing on the data acquired in a meteo experimental station in Pisa.

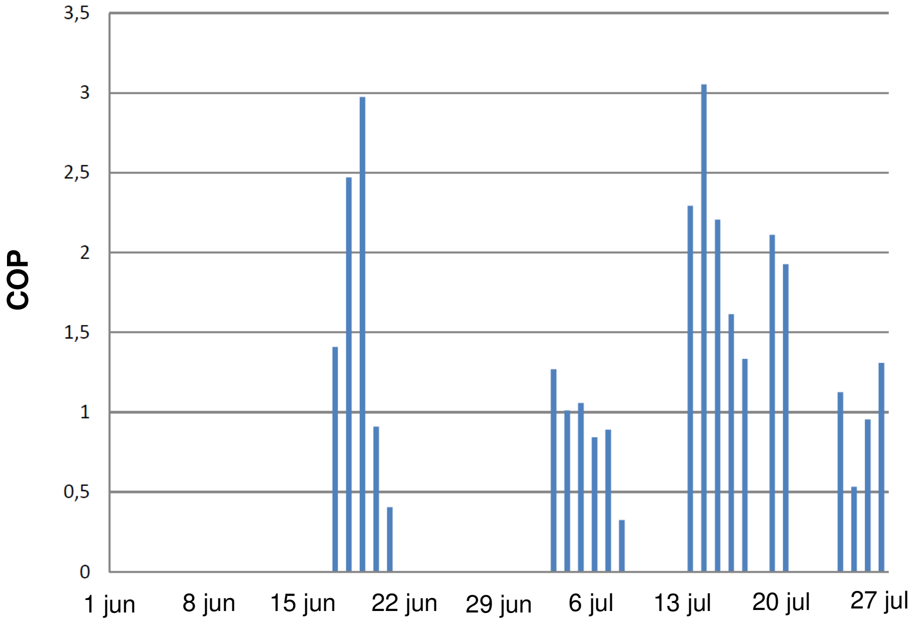

Fig. 9. Daily operating value of the COP of GSHP during the months of June and July

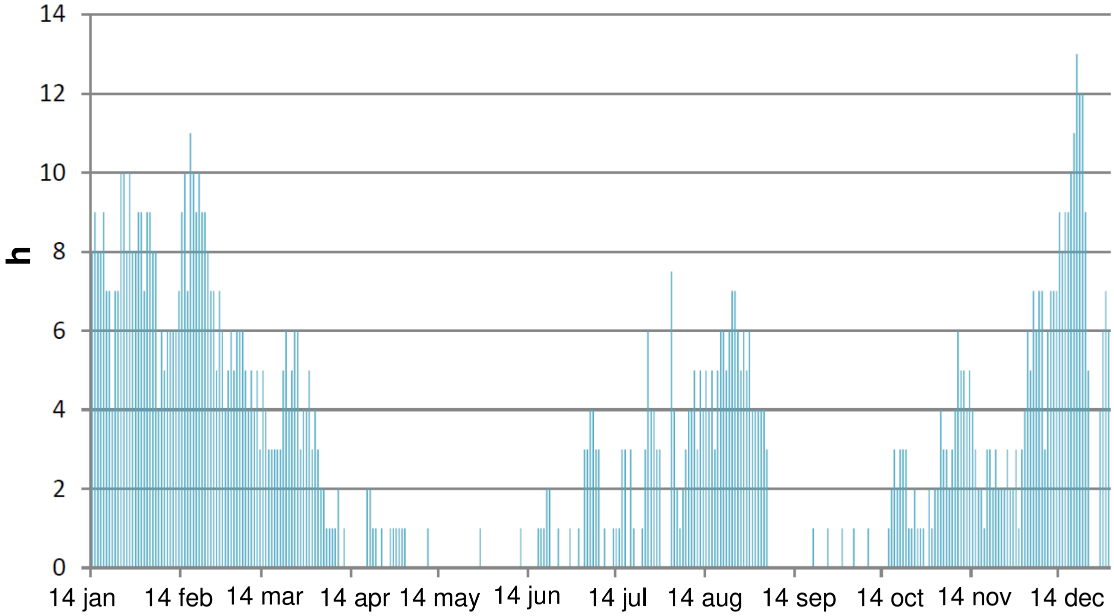

Fig. 10. Operating hours of the heat pump during the year

The value so calculated gives only a general indication on the real operating efficiency of the PV plant: a reduced value of the efficiency, as observed in September, can be caused both by the quite high temperature and by the growing number of cloudy days. Observing the data of Fig. 11 it is possible to observe that the estimated operating efficiency of the PV generation system stands in the range between 0.12 and 0.16. The maximum values of the efficiency are obtained in the mid season, while the average value obtained during the hot season is around 0.14. From this analysis it was confirmed that the maximum values for the efficiency of the PV system is obtained during the mid season, in particular in the months of February and October, when the intensity of solar radiation is quite high and the operating temperature of the modules is quite close to the value referred to Standard Test Conditions (25°C).

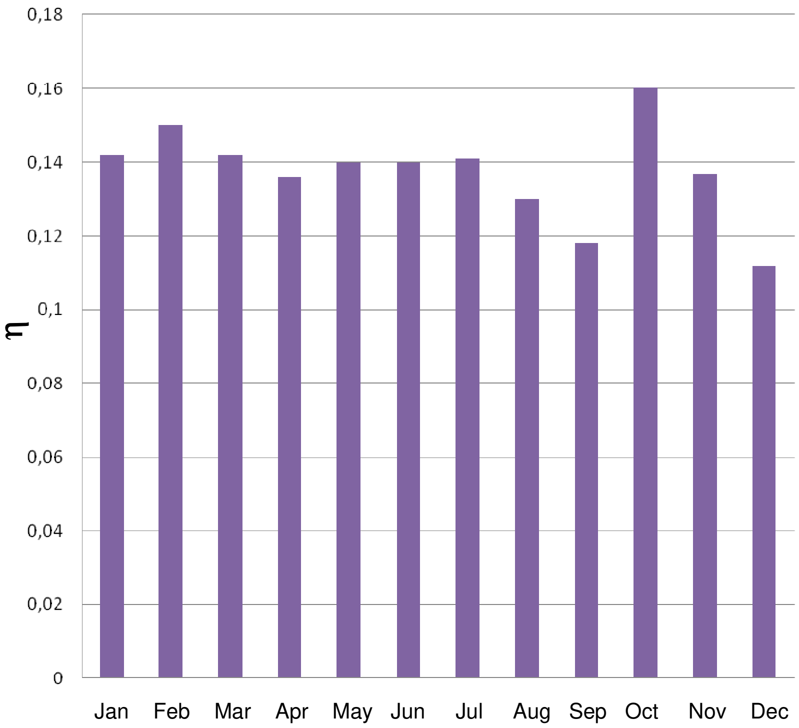

Fig. 11. PV generator efficiency under real conditions

5.3. *Discussion*

The particular solution proposed in the present paper, just considered in the past as one of the possible solutions in the field of net zero-energy building solutions, after the analysis conducted in real operating conditions show some interesting peculiarities but also some critical elements of discussion.

The solution proposed has been designed using the same power for the GSHP and for the PV plant. This particular choice has been done in order to have a global energy balance between energy produced and energy consumption. In this way, the nominal heat pump output is approximately 14.4 kW for 160 m^2, thus capable of delivering about 90 W/m^2 and about 30 W/m^3. Considering the particular climate conditions, this seems to be a very high power requirement. So the heat pump is appears to be oversized for the major part of the operating conditions. On the other hand the longest run during a day is 12 hours during the coldest day of the year which is quite short and the low COP values are probably a consequence of the oversized heat pump. Moreover the other appliances are arbitrarily utilized during the day. Though if the solution is interesting, the schemes proposed use in a quite relevant way the grid as energy buffer, to temporally decouple the energy generation and consumption. The data reported in Fig. 6 show clearly that the idea of zero-energy building has some intrinsic problems. Even if the energy balance is sometimes close to the parity, the experimental analysis of the systems demonstrates the relevance of the grid-connection.

Even if the case analyzed represents only one of the possible solutions for the promotion of further increase of PV, the impact on the electrical grid of solutions like the one proposed is not meaningful, mainly during the mid-seasons: in anycase, even if the energy balance between the energy produced and the energy consumed is close to zero it not possible to affirm that a solution like the one proposed could be really considered without impact on the global system.

The promotion of self-consumption strategies like the one proposed in the paper, and in general the use of heat pumps in connection with PV plants represents surely the new frontier for the future development of systems based on renewable energy; but the promotions of solutions like the one analyzed cannot neglect the consideration of the effects determined on the whole energy system.

Considering an economic perspective, the analysis of a plant like the one proposed taking into account only the value of the energy produced it could be very difficult to appreciate the possible convenience of a solution like the one proposed without a more general perspective: in this case the discussion could be shifted at a high level in order to define possible incentivation policies, based on different concepts with respect to those active is some European countries like Italy, till 2014, that determined benefits but also important drawbacks in the energy system [28-29] and more clearly focused on domestic systems, like proposed in [30].

It is opinion of the authors that to make this solution attractive both for the user and for the whole energy systems, in order to minimize the energy transfer to and from the grid, the introduction of a minimum storage capacity (estimated in the range between 200 and 400 kWh of storage capacity) would be required but the optimal solution should be properly discussed in terms of the logistics, demands and supply and overall system performance in a holistic manner.

Other opportunities concerns the possibility of exploring the performances of hybrid energy systems as those discussed in [31]. But it is clear that in this way the complexity of the plant increase furtherly the economic cost could be sensibly higher and the system embraces a paradigm typical of stand-alone systems.

6. Conclusions

In this paper the perspective of the possible development of a specific system that integrates a PV array with a GSHP system, proposed for building applications is analyzed and discussed. The aim of this system is to improve the sustainability of the GSHP system by maximizing the self-consumption all the energy generated by the solar PV array, installed on the same building served by the heat pump and to test a possible self-consumption strategy useful to permit a further penetration of PV systems in complex energy systems, like some European countries, characterized by an important penetration of intermittent renewables.

In particular the authors have arranged, tested and shown the operating data of a system that join a system for providing heating and cooling with a PV plants in a house located in Pisa (plane surface 150 m² and volume of 400 m^3). The plant is composed of a GSHP for house heating and cooling, assisted by a PV system. The nominal powers of the heat pump (electric) and of the PV plant considered for the experimental analysis are approximately the same and are selected in the range between 3.7 and 3.8 kW. The data acquired, during one year, in real operating conditions, of the plant demonstrates that even if terms of energy balance the energy consumed by the GSHP and the energy produced by the PV array are similar, the energy exchange with the electricity grid appears to be relevant, considering that the other household appliances also receive energy from the PV generator and that there is still much exchange with the grid. So we can conclude that it is really to obtain self-consumption schemes.

Moreover the data acquired are particularly interesting to analyze the real efficiency of photovoltaic modules in the various seasonal conditions, and the real operating COP of the GSHP. It is shown for example how the real operating COP of the geothermal heat pumps, comparing the total energy consumed and the thermal energy furnished, is often below the value of 2 while the nominal COP is declared between 3.5 and 4. The heat pump is oversized for the particular operating condition. As discussed in the paper the longest run during a day is 12 hours during the coldest day of the year - which is short, but in a lot of days, the heat pump operates for a really low number of hours (less than two). Considering a case like the one under analysis it is better to design heat pump in order to deliver about 80% of the design thermal power (about 3 kW) in order to obtain longer running periods and to increase the energy efficiency (operating COP). The low COP values obtained in some periods of the year, are probably a consequence of the oversizing of the heat pump. Moreover a more coordinate and optimal scheduling of the appliances would be required in order to have minor fluctuations of the power flow on demand side. The operating efficiency of PV system, nominally declared as 17% for the single module, ranges between the values of 12% and 16%; the maximum is available in February and October.

Considering all the data discussed and the elements introduced in the paper, it is important to highlight that all relevant data presented are strictly related to the particular building application and to the climate zone under investigation. It is clear that according to the location of the building to different energy use profile and to the different climate conditions during the year, the GSHP consumption and the PV generation profiles can vary significantly, along with the relative repartition of heating and cooling loads like the incidence of the different energy consumption. The effectiveness of the solution depends on the climate zone, on the relative repartition of the various loads and can be strongly influenced by the application of advanced control strategies and system optimization.

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Figures captions

Fig. 1. Details of the experimental system: the building (a); the two strings PV plant (b); details of the borehole heat exchanger (c); the heat pump (d)

Fig. 2. A schematic description of the plant

Fig. 3. A schematic plot of the various energy components (daily analysis)

Fig. 4. A schematic plot of the various energy consumption data (daily analysis)

Fig. 5. A schematic plot of the various energy components (integral analysis)

Fig. 6. Monthly integral values of the various energy components

Fig. 7. Comparison between energy load and GSHP electricity consumption during the cold season

Fig. 8. Operating COP of the geothermal heat pump during the heating period

Fig. 9. Daily operating value of the COP of GSHP during the months of June and July

Fig. 10. Operating hours of the heat pump during the year

Fig. 11. PV generator efficiency under real conditions