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To cite this article: Alessandro Franco *et al* 2021 *J. Phys.: Conf. Ser.* **1868** 012025

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Optimal sizing of an integrated energy system for a nearly zero-energy residential building

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Abstract. The paper analyzes the design of a typical solution for a smart energy system. It examines a particular plant, evaluating the integration of a Photovoltaic (PV) system and a Ground-Source Heat Pump (GSHP) for residential building service. The idea is to develop a system that maximizes self-consumption of the renewable energy generated by a small-sized solar array installed on the building. The case is analyzed starting from the results of a long-term experimental analysis of a real plant in Pisa. The analysis concerns the energy balance of the system during a year with a special attention on the operation of the two different systems, PV array and GSHP. Some indications on the possible optimum design of this solution are proposed and discussed and analyzed.

1. Introduction

The last fifteen years have been characterized by a relevant development of intermittent Renewable Energy Systems (RES), mainly photovoltaic (PV), and by an increase of the decentralized production, resulted in a growing number of small and medium size plants, often installed on buildings [1].

The problem of maintaining the balance between supply and demand in energy systems, in the presence of a large amount of fluctuating RES, is quite complex. For this reason, the growing penetration of RES has to be joined with an optimization of the whole energy systems, in order to permit an effective reduction of fossil fuel use. Without this, the great effort connected to the promotion of those new energy systems will be not effective in providing a reduction of the dependence on fossil fuel resources and in carbon dioxide emissions.

Several studies have shown how the penetration of RES, and in particular of PV plants, is limited at an upper level. A further increase of the level could be possible if the integration of the various energy uses (thermal, mobility and electrical) will be increased. In this perspective it is important the shift of thermal energy use from gas and fossil fuels to electricity. In this perspective, a relevant role will be played in residential buildings by a systematic use of Heat Pumps (HPs) for heating and cooling [2-4].

One of the authors of the paper has analyzed the problem for the Italian energy system, which was characterized by an important modification of the structure in the period from 2005 to 2020, as a consequence of the relevant increase RES energy production, and of the number of local energy producers [5]. Considering a complex energy system, one of the methods to increase the penetration of intermittent RES, as PV plants, stands really on the possibility of increasing the demand for consumption of electricity and on the promotion of self-consumption schemes.



Till some years ago, for all the electricity produced by means of renewable sources from small power-generating facilities, a form of priority dispatch has been granted either via a specific priority order in the dispatching methodology or via legal or regulatory requirements. However, in the next future it is not sure that it should be always maintained, and, in any case, it should be deemed to be compatible with the participation in the electricity market.

An important element in connection with the perspective of further increase of RES share in the energy systems is surely represented by the increase of the use of heat pumps (HP), both in the version of air-source and in the specific form of geothermal heat pumps. The simultaneous utilization of HP and small PV plants installed on the buildings yields a positive synergy, in the perspective of determining a shift from the use of fuel-based systems (as natural gas in Italy) to the use of electricity produced by means of renewable energy, as well as of a consistent reduction of local pollution and CO₂ emissions. This can guarantee the economical sustainability of the investment in renewable energy in the economic market without subsidiary mechanisms [6-7].

Considering HPs, they could be both in the version of Air Source and in the one of Ground Source.. In this last case, the use of the more stable seasonal temperature of ground-source heat pumps (GSHPs) offers, in principle, considerable opportunities for reducing global energy consumption, due to the perspective of obtaining higher efficiency level (COP can raise from the values of 3-4 to higher values), even if it makes the installation more complicated and significantly increases the investment costs [8-9]. However, the problem of the difference between the PV production and the energy use profile of the GSHP still remains, mainly during the cold season.

Anyway, the relevant promotion of integrated solutions of solar-assisted Heat Pumps (both of the air type and of the geothermal type) and a PV plant to support the system producing the electricity for supplying the HP contribute, in principle, to add flexibility to the system. In this case, a relevant problem is represented by the bidirectional energy flows on the external power grid, due the electricity exported to the grid from a renewable-based system and the electricity imported from the grid, in comparison to the electricity demand of a building. While this is a minor problem in case of public buildings, because the energy consumption is maximum during the day when maximum energy generation from the PV plant occurs, it is a relevant problem in case of residential buildings [10].

Moreover, if the building is equipped with PV modules, the use of an electric storage to mitigate the effects of the daily time span between the electrical production peak, occurring between 11 a.m. and 3 p.m., and the thermal power demand peak, occurring in the early morning or in the late evening, could be particularly important. A further increase of PV plant installation and of HP is expected in the next years for building services [11-12].

During the last years, a relevant number of studies by various investigators have been produced for designing, modelling and testing such a kind of solar-assisted heat pump systems and are available in the literature, mainly in the perspective of Smart Energy Systems that will consider as one of the main elements the development of near Zero Energy Buildings (ZEB) systems [13]. Many review articles have been published in recent years on the topic, considering the different system boundaries, the main performance indicators used for assessing energetic and economic optimization, as [14].

The possibility of experimentally monitoring the behavior of different types of building-plant systems that cover the most widespread typologies, such as residential buildings, or that are considered "strategic" by the various energy efficiency programs, such as office buildings, supermarkets and educational buildings, is of fundamental importance, in order to evaluate heat pump system performance in real operating conditions. Depending on the building typology and envelope characteristics, lay-out and use, it is important to properly select the size of each single component and the development of design methods for the design of such a kind of systems could be particularly relevant for engineers and designers. This sizing of PV and PV/T (Thermal) is considered in recent papers like [15], and it is based on technical and economic criteria. Only in occasional situations, the problem of the energy flows from and to the grid is considered [16]. Considering the above exposed scenario, the paper, starting from the analysis of the data acquired during the long-time experimental analysis of a real system, with a PV plant connected with a GSHP, analyzes the optimization of the fundamental plant's component with

emphasis on the specific problem of the energy flows to and from the power grid and suggests guidelines for an optimum design of the system under analysis, in order to increase the share of energy produced with the PV plant and directly used in the building. With the perspective of obtaining further increase of power produced with renewable energies, the problem considered is in particular the reduction of energy flow to the power grid, and the consideration of how a system like this can be designed in order to maximize the self-consumption and to minimize energy flows to the electrical grid, considering the possible introduction of a small-size storage system. Starting from the particular system under analysis, some general guidelines for the design of systems including PV plants, HP and storage systems are provided by the authors. Even if there are many sizing strategies in recent publications and technical guides for that purpose, the authors discuss the idea of developing a system that permits the maximum level of self consumption of the renewable energy generated by a small-sized PV solar array installed on the same building, introducing a constraint on the maximum amount of energy produced and not used in the building.

2. Experimental analysis of the PV-GHSP system

A method to transform a complex energy system for increasing its ability of introducing intermittent RES, as PV plants, is to increase the demand of electricity and promote self-consumption policies. An interesting solution is represented by the connection of PV plants with HPs for heating and cooling purposes in residential buildings. The idea of the plant is schematically provided in Fig. 1. 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, but the use of solar energy is often proposed for the production of thermal energy and the use in adsorption HP. The technical solutions considered have to be tailored for the specific case under analysis and it is often required the utilization of consistent storage volumes. Taking into account that two of the major issues concerning the microgeneration technologies are GSHPs and small-size PV systems, the recent developments in terms of economic support policies have determined a growing use of both of PV plants (determined by the effect of feed-in tariff) and HPs (determined by fiscal incentives). The tested experimental system is in Pisa and has floor surface of about 150 m² and a volume of 450 m³. The GSHP is of the "three circuits" type, with three different operating fluids: water for borehole heat exchanger, refrigerant and water for heat distribution in the house. Its nominal electric power is 3.8 kW with COP=3 in cooling mode and COP=4 in heating mode.

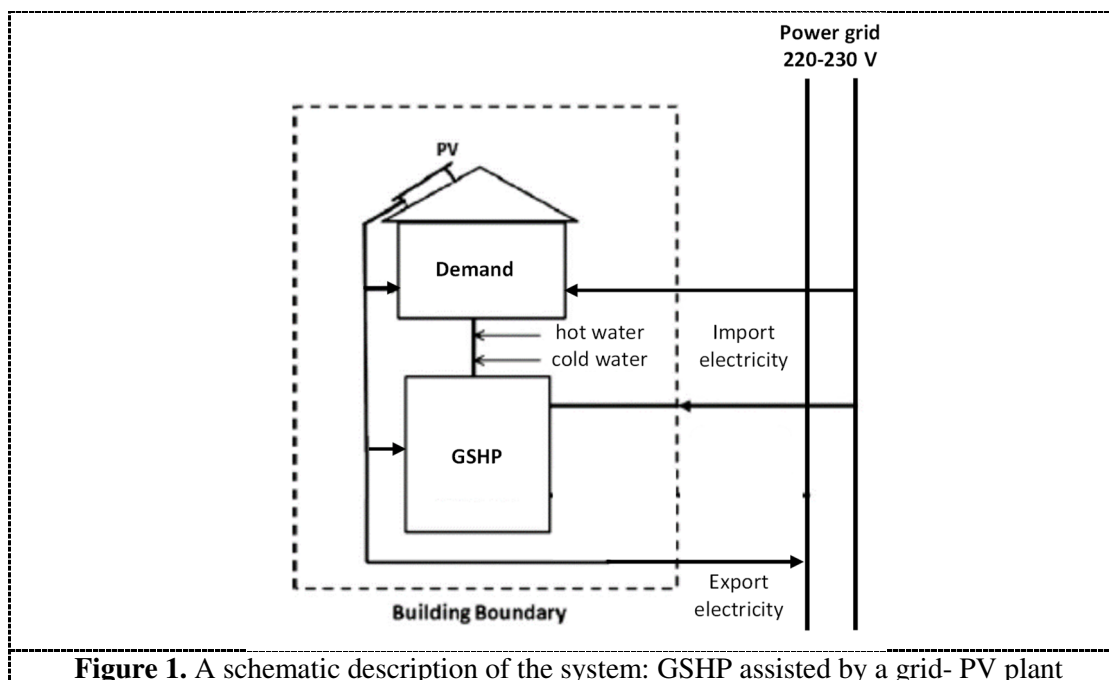


Figure 1. A schematic description of the system: GSHP assisted by a grid- PV plant

The plant is composed by a HP and ground probes, PV plant and thermal energy storage: depending on the building typology and envelope characteristics, lay-out, and uses, it is important to properly select the size of each component. If one of the main limitations of ASHPs is the fact that the thermal power delivery curve is opposite to environmental conditions and the maximum of photovoltaic (PV) electricity production occurs during the daytime, with higher ambient temperature, while there is no production in the evening. The use of the more stable seasonal temperature of the geothermal source offers considerable opportunities for reducing global energy use, even if it makes installation more complicated and significantly increases the investment costs.

The typical climatic conditions of Pisa are described in Fig. 2, for the heating period. In particular, Fig. 2 provides the probabilistic distribution of the external temperature in Pisa. The temperature is reported considering steps of 0.4 °C, while the number of hours during the cold season, characterized by a well-defined average temperature, is reported on the ordinate axis. A similar distribution can be obtained for the cooling phase, in general from 15 of May to 30 of September. The installed HP used is a commercial unit using R-407 as refrigerant fluid. Considering the data of the device.

Considering the operation of the HP, the following data can be evidenced: the condenser temperature is 35/30 °C, while the evaporator temperature is about 0 °C. The geothermal heat exchanger is of the borehole type, with a depth of 50 meters. The total length of the "borehole heat exchanger" is about 200 meters, corresponding to a maximum power of about 50 W/m. The PV system, is obtained using 17 modules, each one with a nominal power of 220 W; so, the total power of the plant is about 3.74 kW. The sizes of the GSHP and of the PV system have been selected using available commercial models, according to the following general criterion: to be suitable for operating so that, in the summer period, considering an energy balance, the PV plant is able to completely assist the operation of the GSHP (for cooling) and of the other electrical devices, because the energy produced is of the same amount of the energy required. The plant is analyzed in [4]. According to the schematization of Fig. 1, the system can measure the total energy from the power grid, E_{TOT} , corresponding to the whole energy used in the house, the energy used by the GSHP, E_{GSHP} , the energy produced by the PV plant, E_{PV} , and the amount of energy produced by the PV plant and exported to the power grid, E_{GRID} .

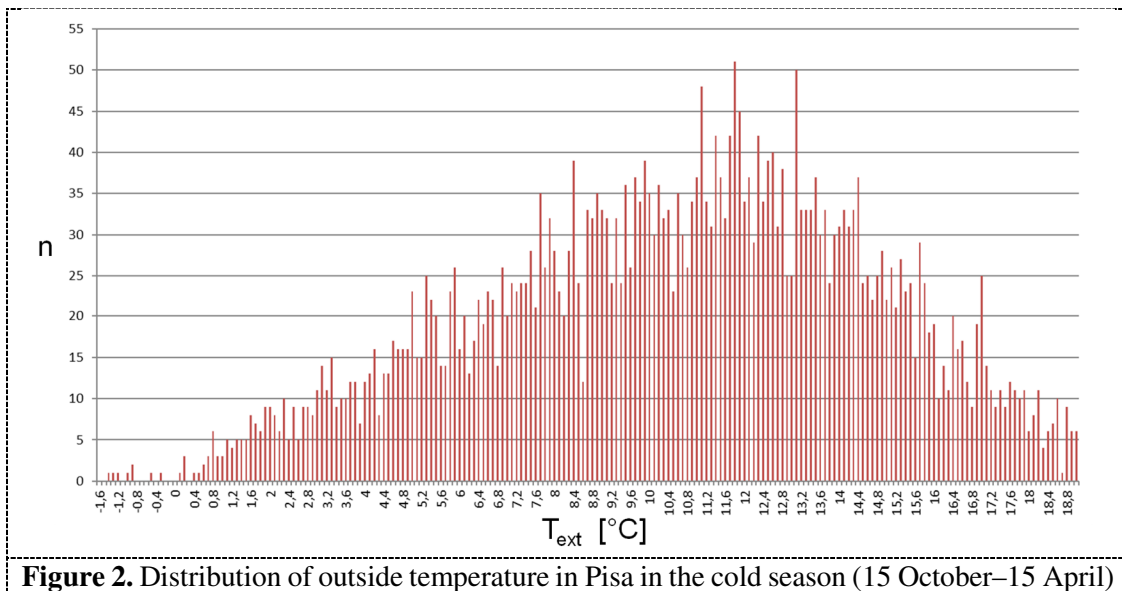


Figure 2. Distribution of outside temperature in Pisa in the cold season (15 October–15 April)

The energy produced with the PV plant can be estimated as the product of the specific production of 1 kW installed, function of the irradiation of the specific place, H_{SN} , (kWh/kW_p) and a balance of system efficiency, η_{BOS} , so that it is possible to write:

$$E_{PV} = (H_{SN} \cdot \eta_{BOS}) \cdot P_{PV} \quad (1)$$

in which P_{PV} is power of the PV plant. Considering the total energy used in the house, measured with an electronic counter, E_{TOT} , and the energy used by the GSHP, measured with a second electronic counter, E_{GHSP} , it is quite easy to evaluate the energy used by the other devices:

$$E_{DEV} = E_{TOT} - E_{GHSP} \quad (2)$$

Using the results of the measurements, it is possible to evaluate, for each time, the energy exchanged with the power grid, in order to understand how the system could be really close to the model of Zero Energy Building (ZEB), and what are the quantities of energy exported, E_{EXP} , or imported from the power grid, E_{IMP} , according to the definition given in the equations:

$$E_{EXP} = E_{PV} - E_{TOT} \geq 0 \quad (3)$$

$$E_{IMP} = E_{TOT} - E_{PV} \geq 0 \quad (4)$$

From the data acquired from the first electronic counter it is possible to estimate the energy produced with the PV plant and directly used in the building, E_d

$$E_d = E_{TOT} - E_{IMP} \geq 0 \quad (5)$$

and to define the share of the energy produced by the PV plant and directly used, in a given period of time, τ , introducing an index of direct utilization, I_U , as:

$$\frac{\sum_{\tau} E_d}{\sum_{\tau} E_{PV}} = I_U \quad (6)$$

Considering the data of the first year of operation (2009), the first objective is to verify if the sizes of the components of the system were correct. In principle, the sizing appeared to be correct, as evidenced in Table 1, in which the energy balance for each trimester of the year is considered. In summer, the total production of PV plant was not sufficient for supplying the total consumption of the house, even if only for a small amount (1399 kWh with respect to 1448 kWh). From the same table it appears how, although in the period from April to June the PV production is quite higher than the total energy consumption, in the other trimesters (Oct-Dec and Jan-Mar) the PV production is insufficient to assist the operation of the GSHP and of the other devices. To obtain a kind of parity, it could be necessary to oversize the power plant of a factor approximately 3, so installing a power higher than 10 kW; in this case, the energy exported to the grid would increase. The operation of the HP is described in Fig. 3. The electricity consumption ranges from a lower value of 2-3 kWh/day, typical of the mid-season, when it is used only for hot water production, up to values of 35 kWh/day in winter, and about 15-20 kWh/day in summer. A further analysis concerns the results obtained during a long-time monitoring activity of the system. After the first year of operation (2009), the data have been acquired during a period of five years, from 2013 to 2017 so that this data set could be considered representative of the real operation of the system. Table 2 permits to clearly evaluate the distribution of the various energy flows, in order to verify the weak points and the possible improvements that could be implemented to the system.

Table 1. Energy balance of the plant (year 2009).

Period	E_{GHSP} [kWh]	E_{DEV} [kWh]	E_{TOT} [kWh]	E_{PV} [kWh]
Jan-Mar	1658	671	2329	850
Apr-Jun	377	550	927	1436
Jul-Sep	796	652	1448	1399
Oct-Dec	1005	622	1627	580
TOT	3836	2495	6331	4265

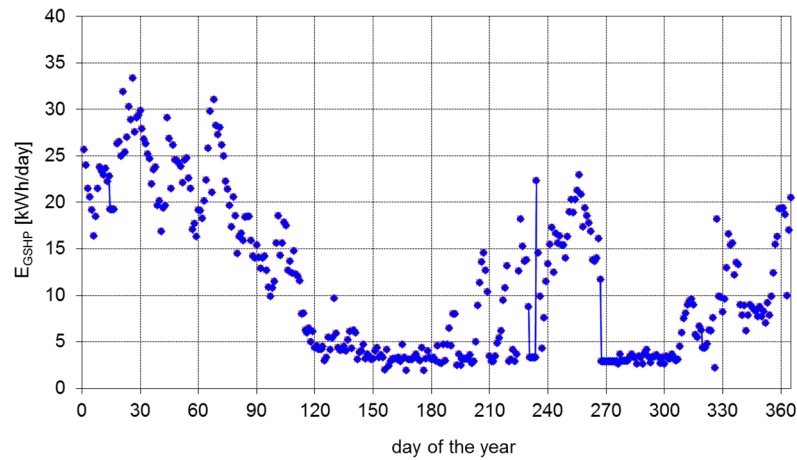


Figure 3. Daily energy consumption of the GSHP in a typical year of the monitoring period

The share of self-consumed energy with respect to the total PV production is around 30%.

Besides, during the cold season (mainly in the periods of December and January), the PV production is definitely insufficient for supporting the operation of the GSHP, while in summer time (from June to September), the production of PV is redundant. The behavior of the system during the mid-season, mainly in the months from February to May and in October and November is reported in Table 3. Even if the energy used by the GSHP and the energy produced by the PV array are similar, the exchange with the electricity grid appears to be relevant, considering that the other household appliances also receive energy from the PV plant and that there is still energy transfer to the grid. Considering the years from 2013 to 2017, the average values of energy exported to and imported from the grid in the various months are reported in Fig. 4. A further analysis tries to define optimization criteria based on the installation of an electrochemical storage and on the definition of an optimized size of HP and PV. The use of an electric storage mitigates the effects of the time span between the electrical production and the thermal power demand. From a critical analysis of the experimental data collected on the existing systems, combined with an optimum design strategy, it is possible to obtain guidelines for optimal combination between power of PV generators and energy storage systems (electrical and thermal) to define an appropriate size of various components of the system. Table 3 provides a summary of the electricity produced by PV plant, in the period 2013-2017 in comparison with the data of 2009, first year of operation. Concerning heat generation efficiency, the real operating COP of the GSHP, given by the thermal energy provided divided by the total electrical energy consumed, is often below 2, while the nominal COP is declared between 3 and 4. A good operation of the HP was evaluated during the very cold period, while in summer the COP value was a little bit lower than the nominal one (COP=3). During the heating phase, a monthly average power value was quite close to the nominal one, while in the cooling phase the HP works frequently in ON-OFF mode and transient conditions are not negligible.

Table 2. Annual energy flows of the plant and PV self-consumption results

	E_{pv} [kWh]	E_{IMP} [kWh]	E_{EXP} [kWh]	E_{GSHP} [kWh]	E_{TOT} [kWh]	E_{DEV} [kWh]	I_u [%]
2009	4265	4923	2857	3836	6331	2495	33.01
2013	3825	4518	2622	3370	5721	2351	31.45
2014	4059	4133	2982	2924	5210	2286	26.53
2015	3947	4971	2837	3685	6081	2396	28.12
2016	3957	4938	2804	3210	6091	2881	29.14
2017	4084	4510	2833	3382	5761	2379	30.63

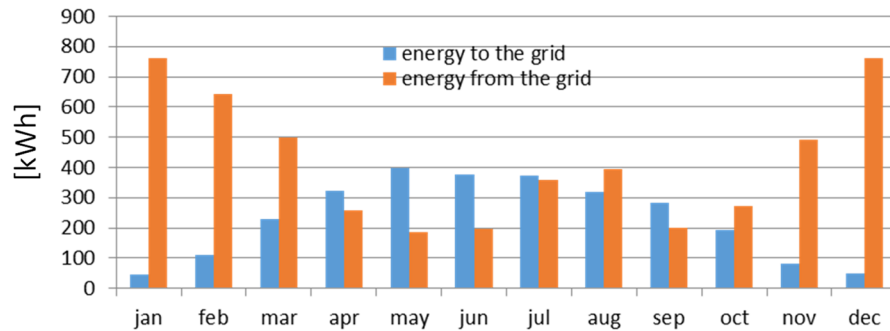


Figure 4: Energy from and to the grid in the various months (case of PV plant of 3.7 kW)

Table 3. PV plant production in the different months during the mid-season (data in kWh)

	February	March	April	May	October	November
2009	220	350	413	575	316	161
2013	221	335	403	487	240	160
2014	186	388	427	470	310	101
2015	210	312	445	582	256	111
2016	147	311	441	498	256	156
2017	184	413	469	458	313	163

3. The definition of a correct size of PV-HP system

The particular plant solution proposed in the paper, considered as one of the possible solutions for zero-energy building, after the analysis conducted in real operating conditions shows some points of interest and some drawbacks. The solution tested in the paper has been designed with the same values of power for the HP and for the PV. Though the solution appears interesting, the schemes proposed use in a quite relevant way the grid as energy buffer, to temporally decouple the energy generation and consumption, mainly during the mid-season. The plant was built while the incentive mechanism named "Conto Energia" was active in Italy. In this way the economic plan of the investment was very favored and oversizing of the plants was easily justified. Instead, in the current conditions, in order to be able to guarantee a reasonable payback time, the size of the photovoltaic system must be reduced. Furthermore, the sale of energy to the grid could also be penalized. In the present section, the system under analysis is modified with a different perspective. In particular, the objective is to maximize the energy production of the PV plant, but considering a constraint on the energy exported to the power grid.

3.1 Reduction of the size of the PV plant

The possibility of introducing an electrical storage system of appropriate size could be relevant in order to reduce the amount of energy exchanged with the electrical grid, mainly for the period of the year in which the production of energy given by the PV system and the energy consumption of the HP are approximately the same, a period which resulted straddling the two peaks in demand electricity of the building (one in winter and one in summer). Reducing the size of the plant, the amount of wasted energy, E_w , is reduced, but the size of the plant decreases too much. Table 4 summarizes the results obtained analyzing four different options. In the last case, case 4, the power of the PV plant is reduced at only 1.1 kW; the energy produced with the PV plant is approximately 1200 kWh, and the wasted energy is reduced to less than 10%, even if the energy imported from the grid is similar to the one of the reference case (5193 kWh with respect to 5021 kWh). But the size of PV plant is in this case really low!

A compromise could be achieved using 10 modules, of the same type as the previous ones, instead of 17, so with a PV peak power of 2.2 kW. In this way, the amount of the energy imported from the grid is approximately the same of the one observed in the reference case (case 0), while the wasted energy is of 1121

kWh instead of 2771 kWh. Fig. 5 provides the energy flows from and to the grid (or wasted) in the various months. A relevant percentage of self-consumption is obtained (36% in May).

Table 4. Waste energy with a reduced size of the PV plant

	P_{PV} [kW]	n° modules	E_{IMP} [kWh]	E_w [kWh]
Reference case	3.74	17	5021	2771
Case 1	2.2	10	5021	1121
Case 2	1.54	7	5042	435
Case 3	1.32	6	5107	263
Case 4	1.1	5	5193	114

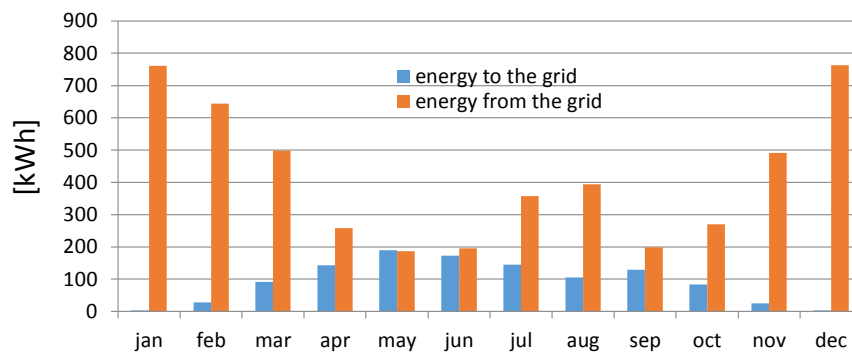


Figure 5: Energy from and to the grid in the various months (case of PV plant of peak power 2.2 kW)

3.2 Reduction of the size of the PV plant and use of an electrochemical storage system

The configuration of the plant analyzed in the previous section, characterized by a relevant reduction of the size of the PV plant, clearly shows the real problem connected with the development of such a kind of solution. In general, the amount of energy exchanged with the power grid is relevant and this condition remains with a reduction of the PV size too. A possible variation of the system could consist in the introduction of a storage system. A series of attempts have been made to define a correct size of the storage system. Table 5 proposes the energy flows in five additional cases. For example, just with the introduction of a storage system of 6 kWh/day capacity, the electricity transfer from the network decreases drastically, going from about 5000 kWh taken in one year to just 4000 kWh. In the month of May, a total detachment from the network was thus obtained, while in April, June, and September the dependence on it was small. Figure 6 provides the main data referred to Case 9 of Table 5. But with reference to the same Table 5, a PV plant of peak power 2.86 kW with storage system of 9 kWh reduce the level of energy not directly used in the house at a level of about 150 kWh.

Table 5. Energy imported from the grid and wasted in five different cases with storage system

	E_{IMP} [kWh]	E_w [kWh]	Storage [kWh/day]	P_{PV} [kW]	n° of modules
Case 5	2800	551	13	3.74	17
Case 6	3189	232	10	3.08	14
Case 7	3348	156	9	2.86	13
Case 8	3703	39	7	2.42	11
Case 9	3903	0	6	2.2	10

4. Guidelines for defining an optimal size of PV-HP plus storage system

As a result of the analysis proposed in the paper, the authors try to develop some general elements of discussion and criteria that would set guidelines for the design of systems of similar architecture, that is an integrated system, including a HP, a PV system, and storage systems (electrical and/or thermal).

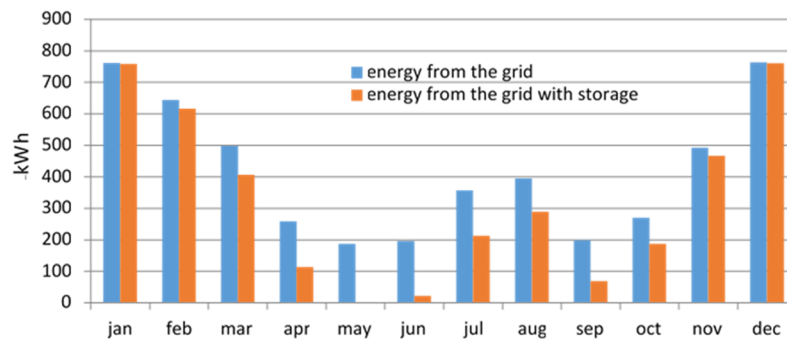


Figure 6. Energy from grid (PV plant of 2.2 kW) with a 6 kWh storage and without storage

Aware of the fact that to date a self-consistent solution is not easy to be defined, it is possible join all the elements considered, to suggest some criteria and guidelines.

A preliminary step is the definition of the transient thermal load of the building. It can be done by means of a dynamic simulation considering an overall heat transfer coefficient (UA , in W/K), which defines the type of building, a reference year of construction, and the climate (average hourly temperatures). This information permits to define an "average power" of the HP, so that the electricity needed to meet its thermal demand can be estimated. Once that capacity of the HP has been defined (also in accordance with advanced sizing criteria [17-18]), PV size can be defined. Three options can be considered:

- 1) the peak power of the PV plant is similar to the nominal power of the HP: the size of the heat pump needs to be based on the demand for thermal energy plus burdensome on the part of the building, and it depends on the period (it is necessary to define "standard" periods of heating and cooling);
- 2) the PV plant can be sized at about 70% of the peak power of the GSHP, in order to reduce the energy exported to the grid (wasted) without increasing energy imported to the grid;
- 3) an electrical storage of 3 kWh for each kW of PV is installed, in order to reduce at zero the energy flows to the grid, maximizing the self-consumption level.

The previous statements are relevant for the case under analysis. To discuss more general elements, it could be necessary to take into account the variation of solar radiation, the selected type of PV module (and its relative performances) and all the constraints. In general, two different optimization criteria can be considered. The first one leads to minimize "energy losses" by introducing an additional penalty to the "extra" energy produced by the modules, which cannot be directly used for the building; in this case, the minimization of the PV plant is pursued. An alternative criterion considers not relevant the energy losses and the overproduction of PV plant, depending on the cost of electricity.

In both cases, the definition of the size of the storage system appears to be particularly relevant. Considering that the months of April and May are those in which a high PV production is possible, the selection can be done considering to reduce to zero the value of the energy amount directed to the power grid in those months. The above-exposed considerations are primarily connected with the specific climatic condition under analysis. One could discuss about the change of the perspective in case of different climatic conditions, but the considerations will be similar to those exposed in the paper.

5. Conclusions

The possibility of monitoring the behavior of different types of building-plant systems in order to cover the most widespread typologies, is of fundamental importance in order to monitor the HP system performance in real conditions of use, as well as to be appropriately processed in order to make them usable for the validation of dynamic simulation models.

The paper has analyzed the real operation of a building-plant system, composed by a PV and a GSHP, joined to the other miscellaneous energy devices, along a period of nine years. The most relevant observations coming from the experimental analysis is the high amount of energy exchanged with the

power grid. A possible compromise can be obtained with a reduction of the PV plant size at about 70% of the peak power of the GSHP. The use of an electric storage to mitigate the effects of the time span between the electrical production peak and the thermal power demand peak seems particularly interesting. From the analysis it is possible to conclude that it is really difficult to obtain self-consumption schemes. The data acquired on the real system are particularly interesting to analyze the real efficiency of PV modules in the different seasonal conditions, and the real operating COP of GSHP.

Acknowledgments: The authors gratefully acknowledge the financial support of the Italian Ministry of Education, University and Research (MIUR), in the framework of the Research Project of Relevant National Interest (PRIN) “The energy FLEXibility of enhanced HEAT pumps for the next generation of sustainable buildings (FLEXHEAT)” (PRIN 2017, Sector PE8, Line A, Grant n. 33).

References

- [1] Terna Statistical data on electricity in Italy – 2006 to 2018: section Power Plants. Available online: http://www.terna.it/default/home_en/electric_system/statistical_data.aspx.
- [2] Lund H 2010, *Renewable Energy Systems The Choice and Modeling of 100% Renewable Solutions*, 3rd ed.; Elsevier.
- [3] Franco A and Salza P 2011, Strategies for optimal penetration of intermittent renewables in complex energy systems, *Renewable Energy* 36, 743-753.
- [4] Franco A and Fantozzi F 2016, Experimental analysis of a self consumption strategy for residential building: the integration of PV system and GHP, *Ren. Energy* 86, 1075-1085.
- [5] Antonelli M Desideri U and Franco A 2018, Effects of large scale penetration of renewables: The Italian case in the years 2008–2015, *Ren. and Sust. Energy Reviews* 81, 3090-3100.
- [6] Facci AL Krasteva VK Falcucci G and Ubertini S 2019, Smart integration of PV production, heat pump and thermal energy storage in residential applications, *Solar En* 192, 133–143.
- [7] Vaishak S and Bhale PV 2019, Photovoltaic/thermal-solar assisted heat pump system: current status and future prospects, *Solar Energy* 189, 268–284.
- [8] Fisher D and Madani H 2017, On HP in smart grids: a review, *Ren and Sust En Rev* 70, 342–357.
- [9] Ratman EL Weller SR and Kellett CM 2015, An optimization-based approach to scheduling residential battery storage with solar PV: assessing customer benefit, *Ren Energy* 75, 123-134.
- [10] Roselli C Diglio G Sasso M and Tariello F 2019, A novel energy index to assess the impact of a solar PV-based ground source heat pump on the power grid, *Ren Energy* 143, 488-500.
- [11] Carli D Ruggeri M Bottarelli M and Mazzer M 2013, Grid Assisted Photovoltaic Power Supply to Improve Self Sustainability of GSHP Systems. *Proc. of the 2013 IEEE Int. Conf. on Industrial Technology*, Cape Town, South Africa, 25-28 Feb 2013, 1579-1584.
- [12] Manfroi G Maistrello M and Tagliabue LC 2011, Synergy of Geothermal Heat Pumps and PV Plant for Buildings Block. *Proc. of the 2011 Int. Conf. on Clean Electrical Power (ICCEP)*, IEEE, Ischia, Italy, 14-16 June 2011, 466-473.
- [13] Testi D Schito E and Conti P 2016, Cost-optimal sizing of solar thermal and photovoltaic systems for the heating and cooling needs of a nearly Zero Energy Building: design methodology and model description, *Energy Procedia* 91, 517-527.
- [14] Poppi S Sommerfeldt N Bales C Madani H and Lundqvistb P 2018, Techno-economic review of solar heat pump systems for residential heating applications, *Ren and Sust En Rev* 81, 22–32.
- [15] Lazzarin R and Noro M 2020, Photovoltaic/Thermal (PV/T)/ground dual source HP: optimum energy and economic sizing based on performance analysis, *Ener & Build* 211, 109800.
- [16] Bahlawana H Morini M Pinelli M Poganietz W Spina P R and Venturini M 2019, Optimization of a hybrid energy plant by integrating the cumulative energy demand, *App En* 253, 113484.
- [17] Conti P Schito E and Testi D 2019, Cost-benefit analysis of hybrid photovoltaic/thermal collectors in a Nearly Zero-Energy Building, *Energies* 12(8), 1582.
- [18] Casarosa C Conti P Franco A Grassi W and Testi D 2014, Analysis of thermodynamic losses in GSHP and their influence on overall system performance, *Jour- of Physics*: 547(1), 012006.