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Dynamic Simulation of a Solar Electric Driven Heat Pump Integrated with Electric Storage for an Office Building Located in Southern Italy

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ABSTRACT

The paper examines a solar electric driven heat pump serving an office building located in southern Italy. To satisfy space heating and cooling demand a heat pump activated by electric energy available from solar photovoltaic plant equipped with an electric storage is here considered. Dynamic simulations to evaluate the thermo-economic performance of this system, varying photovoltaic peak power (4.5-7.5 kW) and electric battery capacity (3.2-9.6 kWh), are carried out. The proposed system achieves primary energy saving and equivalent dioxide carbon emission reduction up to about 82 % in comparison to the reference conventional system based on a natural gas fired boiler and an electric chiller. The results show that the solar energy system is more competitive when there is no battery storage and government incentives will be provided.

Keywords: Solar electric heat pump, Electric storage, Dynamic simulation.

1. INTRODUCTION

In European Union about 295 Mtoe, corresponding to 27% of final energy consumption in 2012, are due to space heating and cooling demand representing one of the greatest energy sector [1]. Developing a strategy to make heating and cooling more efficient and sustainable is a priority of EU. Different measures could be introduced in order to achieve this aim and the most common ones, also in existing building, are:

- renovation of opaque and transparent building envelope reducing transmittance;
- installing systems characterized by high energy conversion efficiency, such as cogenerator, gas fired gas condensing boiler, ground source heat pump (GSHP) and gas engine driven heat pump (GHP);
- solar thermal heating and cooling plant using solar thermal collectors (flat plat, evacuated tube) and thermally-activated heat pump [2];
- solar electric heating and cooling system [3]: solar photovoltaic (PV) collectors interacting with a reversible electric heat pump (EHP);
- electric heat pump assisted by solar thermal energy: thermal energy delivered by solar thermal collector is used to improve the performance of an EHP [4];
- hybrid systems combining renewable energy based and high energy conversion efficiency technologies [5][6].

Particularly interesting appear technologies that exploit solar source to satisfy heating and cooling demand.

In the recent years great attention has been focused on solar thermal systems and in particular on solar heating and cooling (SHC) systems integrating thermally-activated devices [7], such as absorption [8] and adsorption heat pumps [9], ejector systems [10], desiccant-based air handling unit [11] and evaporative cooling systems.

As stated by Ref. [12] systems based on solar thermal collectors can achieve interesting primary energy saving up to 67 %, even if investment costs need to be lower to make the technology suitable for the market [13].

Solar source could be also exploited for heating and cooling purpose introducing a reversible EHP interacting with a PV system. In Ref. [14] the authors reports a theoretical and experimental analysis on a system based on PV panels with a nominal power of 2.88 kW and electric storage with a capacity of 250 Ah interacting with a reversible air to water heat pump. The EHP has a nominal thermal power of 6 kW and satisfies space heating demand of a laboratory, located in Spain, supplying hot water to a radiant floor. On the basis of experimental data solar heating fraction achieve up to 90 %. In Ref. [15] the authors compare by means of TRNSYS the performance of solar heating and cooling systems based, respectively, on solar thermal collectors and PV panels used to satisfy energy demand of a small office building in two different European climates (Freiburg/Germany and Madrid/Spain). Varying solar collecting area the authors analyze through energy and economic indices the performance of the systems. Large collector areas achieve up to 40 % (Freiburg) and 60 % (Madrid) of primary energy saving both for the solar electrical system and the solar thermal system. The economic analysis shows that PV based system is ready for market while solar thermal based system needs improvements in terms of energy performance and also a low investment cost aiming a wide diffusion. Franco et al. in [16] considers a PV plant (3.7 kW of peak power) interacting with a GSHP serving cooling and heating demand of a single-family house of 160 m^2. The aim of the study is the optimization of the system increasing self-consumption of the electricity delivered by PV plant starting by experimental data. The analysis shows that the interaction with the external electric grid is high enough and the installation of an electric storage is recommended to reduce electricity sent to the grid. In [17] the authors analyze by means of TRNSYS software solar systems, based on solar thermal collectors, PV panels, electric batteries, and a GSHP, used to cover energy demand (electricity, domestic hot water, space heating and cooling) of residential buildings located in three different Italian cities. The solar based systems guarantee low energy consumption especially in places characterized by high solar radiation where the use of a quite small PV and solar thermal systems leads to high energy savings. Ref. [18] analyzed the electric load of a microgrid located in Meizhou Island (China), evaluating the introduction of a system based on a centralized PV plant, an electric storage and distributed air source heat pumps as heating and cooling system. The authors evaluate the energy management strategy based on a fuzzy logic algorithm to reduce the cost of the proposed system that consists of a PV peak power of 2.5 MW and 12 MWh of electric storage battery. Ren et al. in [19] assessed the impact PV plant varying peak power (1.5-5.5 kW), battery size (2-16 kWh), location (Townsville, Sydney and Melbourne, Australia), feed-in-tariff and application (old and new residential buildings). The results show that there is an increasing reduction in annual electricity drawn for the grid with the size of solar PV and battery storage. In [20] a residential solar cooling system is analyzed in three different climates (Madrid/Spain, Shanghai/China, and Brisbane/Australia) using TRNSYS. The proposed system satisfy cooling demand of residential building has a total floor area of 210 m^2 and is based on a PV plant and a chiller. This system is provided with either a cold storage, characterized by different phase–change materials, or an electric energy storage. These two configurations were compared in terms of primary energy saving to the case where no energy storage is provided. From the simulation it appears that the saving in terms of primary energy of cold storage based configuration is generally lower than that of the electric battery based plant storage. In [21] is reported an analysis aiming to increase the value of PV for the prosumers. In this paper different solutions were introduced to increase the flexibility of PV system output to balance energy demand by managing the operation of a GSHP, as well as the use of thermal and electric storages. This flexible residential energy system operates on the basis of cost-optimal and self-consumption maximizing control. The authors, starting by data available for a Finnish low-energy house, applied the optimization model obtaining interesting electricity cost savings between 13 % and 25 %, along with 8-88 % reduction in electricity fed to the grid.

The above reported literature is focused on existing works dealing with simulative or experimental analysis of solar heating and cooling systems, serving residential and office building, based on an electric activated heat pump interacting with PV field equipped with an electric storage. In this paper an energy, environmental and economic analysis of a solar heating and cooling system based on a PV plant, equipped with an electric storage, and a reversible EHP is considered. The proposed system satisfies space heating and cooling load of an office building located in southern Italy. The study was performed considering the introduction of an electric storage aiming the reduction of exported electricity to the grid.

2. USER AND BUILDING DESCRIPTION

The office building considered in this study has one floor with a flat roof, while the area and the volume are 200 m^2 and 600 m^3, respectively. The office occupancy, due to 13 working persons, is 8 hours per day divided during weekdays between 9:00 and 13:00 in the morning and between 14:00 and 18:00 in the afternoon. Furthermore the office is empty during weekends. Seated persons with very light writing, corresponding to 120 W (65 for sensible and 55 for latent heat) in terms of gain per person is here considered [22]. Heat gains for PCs, monitors and printers is constant during working hours and equal to 1.30 kW, value estimated on the basis of average power required per person [23]. The heating and cooling terminal units are fan-coils. Artificial lights require a specific electric power of 5 W per m^2. The building envelope characteristic, reported in Table 1, respects Italian legislation [24] that imposes limitations on transmittance for building renovation. The office location is Naples (Italy), characterized by 1034 heating degree days (HDD) and a latitude of 40° 51' 11.8584" N. The window solar factor (*g-value*) considered for the transparent components is 0.75.

Table 1. Main characteristics of building envelope

	Transmittance [W/m^2K]	Thermal mass [kg/m^2]
External vertical wall	0.40	373
Roof	0.38	322
Ground	0.42	689
Window	2.58	-

The heating load for domestic hot water is considered negligible. The heating period is from November 15th to March 31st while the set-point of air temperature room is 20.0 °C (+/-0.5 °C). Space heating system is activated during weekdays between 8:00 and 18:00, while during weekends is not active. The cooling period is from June 1st to September 30th with the same hours of occupancy, space cooling system activation hours and internal gain of heating period, while desired temperature is 26.0 °C (+/-0.5 °C).

Table 2. Heating and cooling demand

Heating period	Peak load [kW]	10.5
	Space heating demand [kWh]	4200
	Specific heating demand per area [kWh/m^2]	21.0
	Specific heating demand per volume [kWh/m^3]	7.00
Cooling period	Peak load [kW]	13.6
	Space cooling demand [kWh]	5245
	Specific cooling demand per area [kWh/m^2]	27.8
	Specific cooling demand per volume [kWh/m^3]	9.27

In Table 2 main data on heating and cooling demand on annual basis including internal gains (persons, artificial lights, solar radiation, personal computers, monitors, printers, etc.) and loads due to air infiltration and ventilation, are reported.

Cooling demand is higher than heating demand due to mild climate of Naples. As reported on Table 2 specific energy requirements are higher in cooling period. Furthermore the peak loads are 10.5 and 13.6 kW, respectively for heating and cooling period.

The specific electric annual demand, excluding HVAC (Heating and Ventilation Air Conditioning) requirements, is assumed equal to 52 kWh/m^2 per year according to an on-site analysis performed on electricity consumption in office buildings [25]. The electric load profile, Figure 1, is defined for two type days (weekday, weekend day) on the basis of Ref. [26].

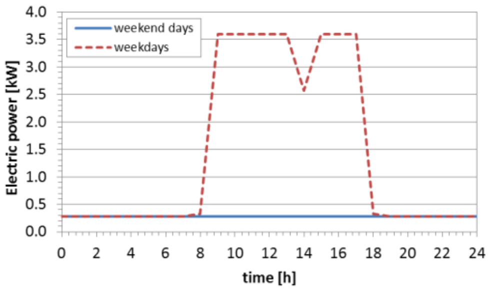

Figure 1. Electric load excluding HVAC

3. SYSTEM CONFIGURATION AND COMPONENTS

In order to satisfy space heating and cooling demand of the office a PV system, equipped with an electric storage, interacting with a reversible EHP is here considered as proposed system (PS). This system is based on a PV plant, located on the flat roof of the building, an inverter (INV), an electric storage (BAT) and a reversible EHP. The PV system can satisfy both electric requirements of the EHP and the end user (PCs, printers, lights, etc.). The system interacts in bidirectional way with the external grid and the electric battery.

The reference energy conversion system (CS, Conventional System) is based on:

• a boiler (B) fueled by natural gas in heating period with a thermal power of 24.0 kW and a thermal efficiency, η_{th}^{B}, of 90.2 %;

• an electric chiller (CH), with a nominal cooling power of 13.3 kW and an EER (Energy Efficiency Ratio) equal to 3.0;

• electric grid covers electric demand of the end user (lights, PCs, chiller, etc.). The average Italian electric grid efficiency (η_{el}^{PP}), equal to 65.5 %, includes the contribution of fossil fuel based thermo-electric power plant mix, the renewable based systems and also transmission and distribution grid losses [27]. This parameter is evaluated considering only primary energy input due to fossil fuel and excluding input primary energy contribution of renewable plants.

In Figure 2 and in Figure 3 heating and cooling operating modes both for proposed and conventional systems are reported.

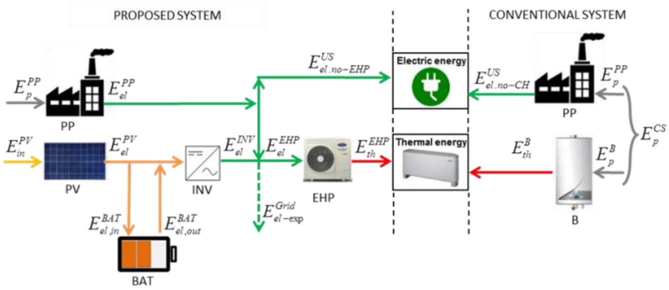

Figure 2. Solar PV based and conventional system in heating mode

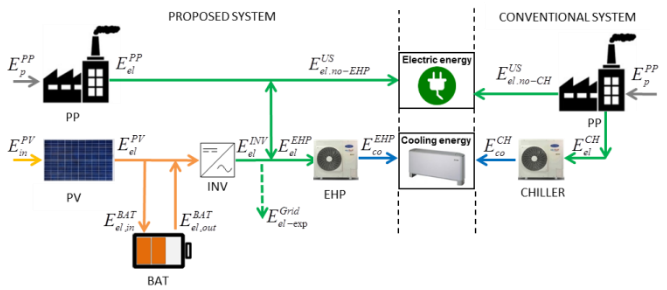

Figure 3. Solar PV based and conventional system in cooling mode

For the PS three different PV peak powers (4.5 kW, 6.0 kW and 7.5 kW) were considered. The PV panels face to south and their main characteristic are shown in Table 3 [28].

Table 3. PV panels characteristics at STC[1]

Peak power [W]	250
Solar panel efficiency [%]	15.28
Peak power voltage [V]	30.38
Peak power current [A]	8.29
Open circuit voltage, V_{oc} [V]	37.12
Short circuit current, I_{sc} [A]	8.76
Peak power temperature factor [%/K]	-0.42
Temp. coefficient V_{oc} [%/K]	-0.32
Temp. coefficient I_{sc} [%/K]	0.059
Gross area [m^2]	1.64

[1] Standard Test Conditions: air mass = 1.5; irradiance = 1000 W/m^2; cell temperature = 25 °C.

Table 4 shows the characteristic of the inverters, sized on the basis of different PV plants [29].

Table 4. Inverter characteristics

Nominal AC power [kW]	5.00	6.00	7.50
Nominal DC input power [kW]	5.15	6.20	7.65
Number of MPPT [-]	2	2	2
Nominal efficiency [%]	97.0	97.0	98.0
Weighted efficiency (EURO/CEC) [%]	96.4	96.4	97.5

The Li-Ion battery has an efficiency equal to 0.94 while the capacity ranges between 3.2 and 9.6 kWh [30].

In the following analysis a DOD (Depth of Discharge) equal to 90 % is considered. The cycle life considered for this component is higher than 6000 times (90 % DOD, 25 °C).

A reversible air to water heat pump is used to cover space heating and cooling demands, Table 5 [31]. The EHP delivers at nominal condition 14.1 kW of thermal power with a COP (Coefficient of Performance) of 3.19, and 13.3 kW of cooling power with an EER of 3.32.

Table 5. Nominal air to water heat pump data[2]

Heating mode	Thermal power [kW]	14.1
	Electric power input [kW]	4.42
	COP [-]	3.19
Cooling mode	Cooling power [kW]	13.3
	Electric power input [kW]	4.12
	EER [-]	3.32

[2] Nominal data according to EN 14511:2013 [32]

4. DESCRIPTION OF THE MODELS

Thermo-economic performance of proposed and conventional system are evaluated by means of TRNSYS software [33]. It is a very common software used for transient simulation, to evaluate the interaction between buildings and energy conversion systems based both on fossil fuel and renewable sources. It has a modular design and each component is simulated by a model included in a subroutine (called "type") available in specific libraries [33][34]. The different components can be linked to each other to create very complex systems. The models considered for the main components are briefly described in the following.

PV panels are simulated using *type 94*, [35], that is based on an equivalent "four-parameter" circuit model able to predict the current-voltage characteristics of a single module [36][37]. The input data to the model are taken from the manufacturer's PV data (see Table 2). The storage battery and its charge controller are simulated by means of *type 47*, considering Shepherd and Hyman battery model [38][39]. This model considers power exceeding the user load and in this case the battery is charged or electricity is directly sent to the grid if it electric storage is fully charged. The inverter is modeled by *type 48* that takes into account both direct current available from PV plant and electricity required by the user in order to manage the interaction with electric grid and battery. On the basis of a performance maps, EHP and CH are modelled by *type 941* and *type 655* [40], respectively. The boiler is evaluated, through a simplified model characterized by a constant thermal efficiency, using *type 6*. Finally the building is simulated by *type 56* that models the thermal behavior of a building having multiple thermal zones.

5. METHODOLOGY

In this paragraph an analysis of the performance of solar system considering the contribution of renewable source to cover space heating and cooling demand is reported. A further study is performed comparing the solar based system with the conventional system by means of energy, environmental and economic analysis.

5.1 Solar system analysis

One of the most important element to evaluate the performance of the solar based system is the global electric efficiency of solar system (SS), that depends on PV module efficiency, inverter efficiency and also by other BOS (Balance Of System) losses (reflection, dirt, PV cell temperature, wiring, mismatch, etc.). It achieves on yearly basis about 14.6 % for 4.5 kW and 6.0 kW while is little higher (14.7 %) for 7.5 kW without considering storage batteries. The efficiency reduces up to 14.4 % (4-5-6.0 kW) and 14.6 % (7.5 kW) including batteries with a storage capacity of 9.6 kWh.

Further useful parameters, that show the contribution of solar source to cover space heating and cooling demand of the user, are the heating (SF_{th}), the cooling (SF_{co}) and the total solar fraction (SF_{tot}). These indexes, typically used to evaluate the performance of solar thermal systems, are defined in Eq. (1), (2) and (3), [41]:

$$SF_{th} = \frac{E_{th}^{EHP,INV}}{E_{th}^{US}} \quad (1)$$

$$SF_{co} = \frac{E_{co}^{EHP,INV}}{E_{co}^{US}} \quad (2)$$

$$SF_{tot} = \frac{E_{th}^{EHP,INV} + E_{co}^{EHP,INV}}{E_{th}^{US} + E_{co}^{US}} \quad (3)$$

where $E_{th}^{EHP,INV}$ and $E_{co}^{EHP,INV}$ are, respectively, thermal and cooling energy available from EHP considering only the electricity contribution due to PV system. When available from PV electric energy is used to power, priority, the EHP. Furthermore space heating and cooling demands of the office are represented by E_{th}^{US} and E_{co}^{US}, respectively. For each configuration, in terms of PV peak power and storage battery, the best results are achieved by total solar fraction for a tilt angle of 29°. In Figure 4 and Figure 5 the heating and cooling solar fractions are shown as a function of battery storage and PV peak power for a tilt angle of 29°. SF_{th} increases with PV power and battery storage reducing the contribution by electric grid. Its maximum is equal to 0.38 for 7.5 kW of PV peak power and 9.6 kWh of storage battery capacity.

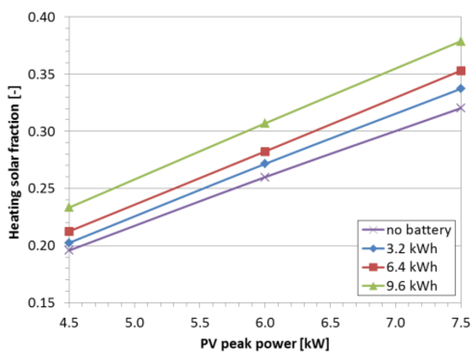

Figure 4. Heating solar fraction as a function of PV peak power and storage battery capacity

Similarly to SF_{th}, the parameter SF_{co} increases with PV power and storage capacity. It shows higher values than SF_{th} due to increased availability of solar radiation during summer period. Its value achieves 0.85 for 7.5 kW and 9.6 kWh.

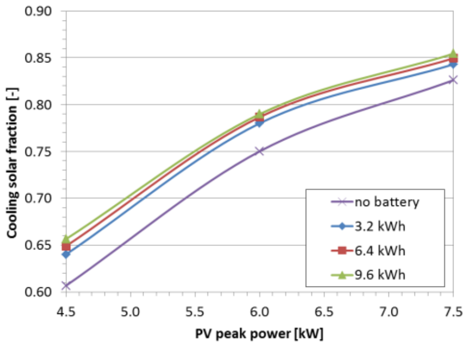

Figure 5. Cooling solar fraction as a function of PV peak power and storage battery capacity

Finally on annual basis also SF_{tot} increases with PV power and electric storage ranging between 0.43 (4.5 kW, no battery) and 0.65 (7.5 kW, 9.6 kWh storage capacity). In the best case, 65 % of space heating and cooling demand is satisfied by renewable energy, Figure 6.

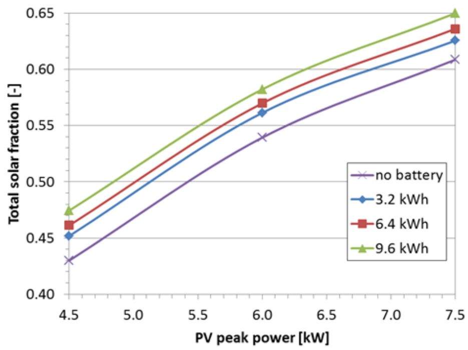

Figure 6. Total solar fraction as a function of PV peak power and storage battery capacity

Unfortunately, increasing the size of PV system renewable source can increase its contribution to solar heating and cooling demand, but also the percentage of electricity exported to the grid improves (see § 5.2.1).

5.2 Energy, environmental and economic analysis

The solar based system used to satisfy electric, heating and cooling demand of the office building is compared in terms of energy, environmental and economic analysis with a conventional system that consists of electric grid, a boiler and a chiller.

5.2.1 Energy analysis

The energy performance of the proposed system has been analyzed evaluating the index Fuel Energy Saving Ratio (*FESR*), that compares primary energy input related to fossil fuel of PS (E_p^{PS}) and CS (E_p^{CS}), as shown in Figure 2 and in Figure 3. *FESR* is defined as:

$$FESR = \frac{E_p^{CS} - E_p^{PS}}{E_p^{CS}} \tag{4}$$

where, with i = 1 (heating), 2 (cooling), 3 (intermediate):

$$E_p^{CS} = E_p^{PP} + E_p^{B} = \sum_{i=1}^{3}\left(\frac{E_{el}^{PP}}{\eta_{el}^{PP}}\right)_i + \frac{E_{th}^{B}}{\eta_{th}^{B}} = \sum_{i=1}^{3}\left(\frac{E_{el,no-CH}^{US}}{\eta_{el}^{PP}}\right)_i + \frac{E_{el,CH}^{US}}{\eta_{el}^{PP}} + \frac{E_{th}^{B}}{\eta_{th}^{B}} \tag{5}$$

$$E_p^{PS} = E_p^{PP} - E_p^{Grid} = \sum_{i=1}^{3}\left(\frac{E_{el}^{PP} - E_{el-exp}^{Grid}}{\eta_{el}^{PP}}\right)_i \tag{6}$$

Primary energy of CS, as shown in Eq. (5), depends on electric energy required by chiller, E_{el}^{CH}, pure electric load (lights, PCs, etc.), $E_{el,no-CH}^{US}$, thermal energy delivered by natural gas fired boiler, E_{th}^{B}, and reference efficiency parameters (η_{el}^{PP}, η_{th}^{B}).

A similar equation is introduced for PS, even if it depends on the electricity drawn from (E_{el}^{PP}) and exported to the grid (E_{el-exp}^{Grid}), which value is considered as a credit for primary energy evaluation. *FESR* has a negligible dependence from electric storage size and increases with PV peak power due to the greater availability of renewable electric energy, Table 6. It ranges between 54 % for 4.5 kW and 83 % for 7.5 kW for a tilt angle of 31°, which represents the angle that maximizes the performance of the system.

Table 6. FESR as a function of PV power and battery size

Peak power [kW]	4.5	6.0	7.5
FESR range [%]	54.1 – 53.7	68.0 – 67.4	82.6 – 81.9
Battery range [kWh]	0 – 9.6	0 – 9.6	0 – 9.6

The exported electricity to the grid due to PV plants needs to be limited to reduce different issues (voltage regulation, power quality, etc.). In this way it could be interesting to evaluate, on the basis of electric energy required by end-user, the configuration characterized by the lowest percentage of electric energy exported. Total electricity demand, including also EHP, for PS is 13.7 MWh/y corresponding to 68.5 kWh/m^2 per year. Considering the best configuration for each peak power (4.5-7.5 kW) and battery size (0-9.6 kWh) electric energy available from PV (tilt angle of 31°) is partly used (blue bar) by end-user and partly exported to the grid (green bar), Figure 7. In the same figure the electricity import is shown too (red bar).

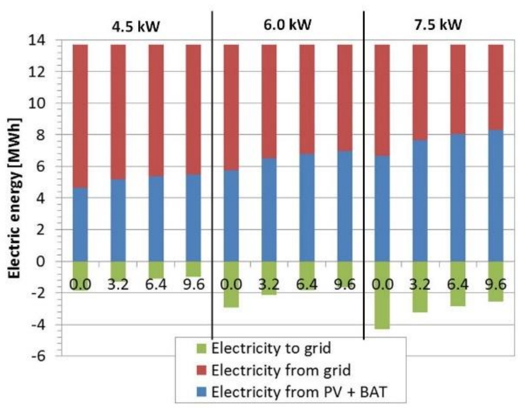

Figure 7. Electric energy distribution as a function of battery capacity and PV peak power for 31°

Two parameters could be considered to evaluate the self-consumption of PV electricity [42]:

- *s*: ratio between electric energy delivered through the inverter by PV or, if available, by batteries to end-user and the total one that it requires;
- *d*: ratio between electricity supplied by PV through the inverter or, if available, by batteries to end-user and the total one available from the inverter.

On Table 7 total solar radiation reaching PV panels, *s* and *d* indexes, and also electricity from INV are reported.

Table 7. Ratios to evaluate the use of electricity from PV

PV power [kW]	Battery capacity [kWh]	Total electricity from INV [MWh]	s [%]	d [%]
4.5	0	6.52	33.8	71.1
	3.2	6.48	37.7	79.8
	6.4	6.47	39.0	82.8
	9.6	6.46	40.0	84.8
6.0	0	8.69	42.0	66.3
	3.2	8.64	47.6	75.5
	6.4	8.62	49.6	78.8
	9.6	8.61	50.8	80.9
7.5	0	10.98	48.6	60.7
	3.2	10.92	55.9	70.2
	6.4	10.89	58.7	73.9
	9.6	10.87	60.6	76.5

Renewable electricity covering end-user's demand, represented by s index, increases with PV peak power and battery capacity achieving the best result of 60.6 % for 7.5 kW and 9.6 kWh. The fraction of PV electricity self-consumed, with respect to global production (index d), decreases with PV size while increases with battery storage. The solution characterized by the lower percentage of exported electricity, equal to 15.2 % (d = 84.8 %), is that one obtained for 4.5 kW and 9.6 kWh.

A further parameter that could be introduced to estimate the residual operating life of the batteries is n_c defined as the ratio between electric energy output from battery, $E_{el,out}^{BAT}$, and the net electric capacity of batteries, E_{el}^{BAT}, considering a DOD of 90%:

$$n_c = \frac{E_{el,out}^{BAT}}{E_{el}^{BAT}} \tag{7}$$

To understand the importance of the batteries could be evaluated the index *b*, defined as the ratio between electric energy from batteries and total electric energy required on annual basis by user (E_{el}^{US}):

$$b = \frac{E_{el,out}^{BAT}}{E_{el}^{US}} \tag{8}$$

Finally the index *f*, defined as the ratio between electric energy from batteries and renewable electric energy used to cover energy demand when solar system has no batteries, is introduced.

Table 8. Performance indexes for battery

PV power [kW]	Gross battery capacity [kWh]	n_c [-]	b [%]	f [%]
4.5	3.2	207	4.35	12.9
	6.4	139	5.83	17.2
	9.6	108	6.83	20.2
6.0	3.2	295	6.20	14.8
	6.4	201	8.44	20.1
	9.6	156	9.81	23.4
7.5	3.2	382	8.02	16.5
	6.4	264	11.1	22.8
	9.6	209	13.2	27.1

The results reported on Table 8 show low values of charge/discharge cycles per year for batteries with respect to maximum available. The configuration of the plant with 7.5 kW and an electric storage of 3.2 kWh allows to achieve an operating life of the battery of about 16 years considering 6000 operating cycles.

In the best case, the percentage of electric energy demand covered by batteries is low achieving 13.2 % thanks to a good agreement between electricity use and production.

Finally the increase of renewable electric energy usage due to batteries (index *f*), with respect to PV plant without these components, varies as a function of PV and battery size achieving 27.1 % for 7.5 kW and 9.6 kWh.

A further possibility, aiming the reduction of electricity exported to the grid, could be the introduction of mobile storage battery that could be represented by an electric vehicle [42].

5.2.2 Environmental analysis

A simplified environmental analysis, based on the evaluation of equivalent carbon dioxide emissions (CO_2) both for proposed (CO_2^{PS}) and reference (CO_2^{CS}) systems, is here considered. The CO_2 emissions for each system are evaluated by means of CO_2 emission factors. This factor for natural gas, β, is equal to 0.205 kg CO_2 for each kWh of primary energy related to the fuel. The CO_2 emission factor for the electricity drawn from the grid, α, is equal to 0.351 kg CO_2 for each kWh of electric energy and was estimated considering the contribution of the fossil fuel based thermo-electric and renewable plants [44] [45]. Similarly to *FESR*, ΔCO_2 is defined as:

$$\Delta CO_2 = \frac{CO_2^{CS} - CO_2^{PS}}{CO_2^{CS}} \tag{9}$$

where, with i = 1 (heating), 2 (cooling), 3 (intermediate):

$$CO_2^{CS} = CO_2^{PP} + CO_2^{B} = \alpha \cdot \sum_{i=1}^{3}\left(E_{el,no-CH}^{US}\right)_i + \alpha \cdot E_{el}^{CH} + \beta \cdot E_p^B \tag{10}$$

$$CO_2^{PS} = CO_2^{PP} - CO_2^{Grid} = \alpha \cdot \sum_{i=1}^{3}\left(E_{el}^{PP} - E_{el-exp}^{Grid}\right)_i \tag{11}$$

As stated by Eq. 11 equivalent CO_2 emission due to electricity exported to the grid (CO_2^{Grid}) is considered as a credit for CO_2^{PS} evaluation. ΔCO_2 has a behavior that is similar to *FESR* reaching a maximum for an angle of 31° for each peak power, Table 9.

Table 9. ΔCO_2 as a function of PV power (tilt angle 31°)

Peak power [kW]	4.5	6.0	7.5
ΔCO_2 range [%]	53.1 – 52.7	67.2 – 66.7	82.2 – 81.5
Battery range [kWh]	0 – 9.6	0 – 9.6	0 – 9.6

5.2.3 Economic analysis

The economic analysis was performed on the basis of investment and operating costs of proposed and conventional systems. In particular a specific natural gas cost, $c_{u,NG}$, equal to 0.90 €/Nm^3, a specific electricity price for electricity drawn from grid, $c_{u,el}$, of 0.20 €/kWh both for PS and CS is considered. Electricity exported to the grid is paid by a feed-in tariff, $c_{u,el\text{-}exp}$, equal to 0.11 €/kWh and an annual ordinary maintenance cost of 18.5 € per kW of PV peak power is introduced [46]. The specific investment cost of PS decreases with plant size and is in the range 2123 €/kW (4.5 kW) to 1926 €/kW (7.5 kW). It includes all PV plant components (inverter, panels, cables, etc.), flat roof PV frame, installation, transportation, design and 10% in terms of VAT. Finally a specific cost for battery equal to 780 € per kWh of electric capacity storage and an investment cost for EHP, IC^{EHP}, of 6217 € is added.

To study the economic feasibility of a solar electric heat pump system, different methods could be considered (net present value, internal rate of return, annualized life cycle cost, etc.), but in this paper is introduced a simplified analysis based on the simple payback period, *SPB*, defined as:

$$SPB = \frac{IC}{\sum_{j=1}^{N} F_j} \quad (12)$$

where

$$IC = IC^{SS} + IC^{EHP} + IC^{BAT} \quad (13)$$

$$F_j = \Delta OC_j = OC_j^{CS} - OC_j^{PS} \quad (14)$$

$$OC_j^{CS} = VO_{NG} \cdot c_{u,NG} + \left(E_{el}^{CH} + E_{el,no-CH}^{US}\right) \cdot c_{u,el} \quad (15)$$

$$OC_j^{PS} = E_{el}^{PP} \cdot c_{u,el} + OC_{man}^{PV} - E_{el-exp}^{Grid} \cdot c_{u,el-exp} \quad (16)$$

considering that:

- IC represents the investment cost of the proposed system (PV plant, EHP, batteries, …);
- IC^{SS} is the global investment cost of PV plant;
- IC^{BAT} is the investment cost of electric storage;
- F_j is the cash flow for a generic year j;
- OC_j^{PS} and OC_j^{CS} are the operating costs of the PS and CS;
- ΔOC_j is the difference in terms of operating costs between PS and CS;
- OC_{man}^{PV} is the maintenance cost for PV plant;
- VO_{NG} is the volume of natural gas used for boiler considering a lower heating value equal to 9.52 kWh/Nm^3.

Operating cost savings, ΔOC, due to introduction of PS increases with PV peak power and battery size achieving the maximum for a tilt angle of 31° for each configuration, Figure 8. The annual saving is in the range 1300 € (4.5 kW) - 2000 € (7.5 kW).

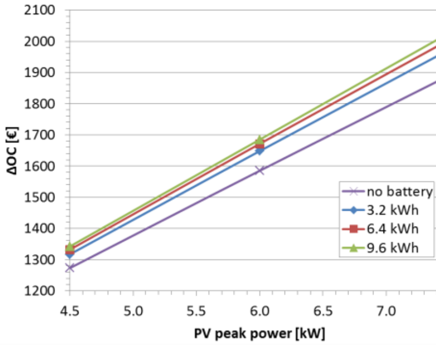

Figure 8. Annual operating costs difference as a function of PV power and battery

The operating costs for CS related to electricity, space heating and cooling demand are about 2965 € (2525 € for electricity and 440 € for natural gas). The evaluation of SPB could be based on two different scenarios:

- grid parity: characterized by an investment cost without any economic support;
- support action: Italian government gives incentives covering 50% of investment cost for PV, battery and EHP [47].

The economic analysis in presence of government support leads to interesting results with SPB lower than 9 years for each configuration achieving the worst results for 7.5 kW and 9.6 kWh, Figure 9.

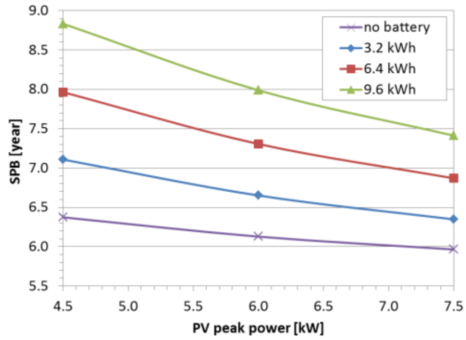

Figure 9. SPB as a function of PV peak power and electric storage

Comparing the results is clear that the SPB decreases with PV size while increases with electric battery capacity, due to high investment cost of this component. The price of electric storage needs, for this application, a further reduction when higher capacity batteries are considered.

The introduction of storage batteries could be more interesting for systems in which electric requirements of the user has a distribution that is different from office one.

A more detailed economic analysis needs to consider:

- the reduction of performance, and therefore the electric production, during the operating life of PV panels;
- the reduction of performance of batteries, their actual capacity (state of health) and operating life (about 12 years) [48];
- the operating life of the inverter that is lower than 15 years;
- the variation of feed-in tariff, and the electricity and natural gas unitary costs.

For the configuration characterized by lower electricity exported (4.5 kW, 9.6 kWh) and in presence of economic support action on investment cost a sensitivity analysis varying unitary electricity and natural gas costs both for proposed and conventional system is reported in

Figure **10**. SPB could be interesting achieving about 6 years only in case of high electricity and natural gas prices.

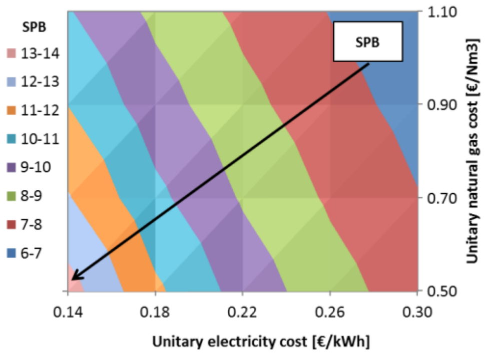

Figure 10. SPB as a function of unitary electricity and natural gas price for 4.5 kW and battery storage of 9.6 kWh

6. CONCLUSIONS

A solar electric heating and cooling plant, based on a reversible EHP interacting with PV field, to satisfy electric, thermal and cooling demand for an office building located in southern Italy is here considered.

Dynamic simulations are carried out to evaluate the energy, economic and environmental performance of the proposed system varying PV peak power and battery size. Yearly PV plant efficiency, including BOS losses, is higher than 14.4 % for a tilt angle of 31°.

Total solar fraction achieves 0.43 for 4.5 kW and 0.65 for 7.5 kW and 9.6 kWh of electric storage capacity, for a tilt angle of 29°. Energy and environmental analysis of proposed system show good and similar results, with respect to a reference energy conversion system consisting of a natural gas fired boiler and an electric chiller.

FESR and ΔCO_2 are always higher than 52 % with a maximum of about 82 % for 7.5 kW without batteries for a tilt angle of 31°.

Increasing the size of PV system, renewable electricity covering total demand achieves 60.6 % with battery (7.5 kW, 9.6 kWh), while the fraction exported increases up to 39.3 % for 7.5 kW and no batteries.

The economic analysis shows a reduction of operating costs even if investment costs, due to PV field, EHP and batteries, highlight the need of economic support action that could lead to interesting results for such application. A SPB lower than 9 years for each configuration considered could be achieved.

The introduction of batteries leads to a reduction of electricity exported to the grid even if there is an increase of SPB due to high investment cost of this component.

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NOMENCLATURE

AC	Alternate Current
B	Boiler
BAT	Battery
BOS	Balance Of System
c_u	Specific electricity cost/reward, €/kWh €/Nm^3
CH	Chiller
CO_2	Equivalent dioxide carbon emission, kg CO_2/y
COP	Coefficient Of Performance, -
CS	Conventional System
DC	Direct Current
DOD	Depth Of Discharge, %
E	Energy, kWh/y
EER	Energy Efficiency Ratio, -
EHP	Electric Heat Pump
F	Cash flow, €/y
FESR	Fuel Energy Saving Ratio, -
GHP	Gas engine driven Heat Pump
GSHP	Ground Source Heat Pump
HDD	Heating Degree Days
HVAC	Heating and Ventilation Air Conditioning
I	Current, A
IC	Investment Cost, €
INV	Inverter
MPPT	Maximum Power Point Tracker
OC	Operating Cost, €/y
PP	Power Plant
PS	Proposed System
PV	Photovoltaic
SF	Solar Fraction, -
SHC	Solar Heating and Cooling
SPB	Simple Pay Back, y
SS	Solar System
STC	Standard Test Conditions
US	End user
V	Voltage, V
VAT	Value-Added Tax, %
VO	Volume, Nm^3/y

Greek symbols

α	Emission factor for electricity, kg CO_2/kWh$_{el}$
β	Emission factor for natural gas, kg CO_2/kWh$_{Ep}$
η	Efficiency, -, %
Δ	Difference

Subscripts

co	cooling
el	electric
el,no-CH	electric excluding chiller
el,no-EHP	electric excluding EHP
el-exp	electric exported
man	maintenance
NG	Natural Gas
p	primary
th	thermal
tot	Total