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(Article begins on next page)

1
2 **Thermal Energy Storage Coupled with PV Panels for Demand**
3 **Side Management of Industrial Building Cooling Loads**

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10 **Abstract**

11 Due to their non-deterministic behaviour, renewable energies are defined as non-dispatchable energies and are largely
12 coupled with energy storage systems to overcome the problem of matching energy production and demand. Hence, in
13 the energy efficiency and conservation field there is growing interest towards energy storage systems, especially
14 when combined with the demand side management (DSM) concept, representing DSM the possibility of shaping end
15 user electricity consumption. In this work an existing installation of a thermal energy storage (TES) system coupled
16 with heat pumps in an industrial building is presented and a dynamic simulation model is built to represent its
17 behaviour. Simulations are performed to show the load shifting potential of such storage and costs and energy use are
18 assessed for different configurations, in order to evaluate the viability of this TES application. In particular the
19 demand side strategy considered is aimed at shifting energy demand for cooling to weekend daytime to recover
20 surplus PV electricity or otherwise to off peak hours to profit from lower electricity tariffs. It is found that the use of
21 TES implies increased energy demand, while costs can decrease when electricity tariffs with a considerable
22 difference between on peak and off peak rates are applied. Furthermore the integration with renewable sources for
23 electricity production, such as PV panels, makes the installation of TES economically interesting independently of the
24 electricity tariff in place. However the more relevant aspect for the overall economic feasibility of such installation is
25 the initial capital investment.

26
27
28 Keywords: thermal energy storage; dynamic simulation; demand side management; control strategy; buildings; PV panels.

29 **1. Introduction**

30 Climate change mitigation and environmental protection require the community to
31 increase the use of renewable energy and reduce fossil fuels dependence. Being the
32 building sector one of the most energy consuming worldwide, major efforts are
33 necessary to limit this growing energy demand, which accounts for approximately 40%
34 of global energy consumption [1]. In this context, heat pumps are considered a good
35 choice: large scale deployment of heat pumps (HP) is predicted to satisfy heating and

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1 cooling service requirements and to attain over 50% penetration by 2030 and over 75%
2 by 2050 [2]. Heat pumps are expected to become efficient devices to provide heating
3 and cooling in buildings, especially if coupled with the promising concept of demand
4 side management (DSM) [3].

5 Demand side management refers to all those actions aimed at changing electricity load
6 profiles to optimise the entire power system from generation to delivery to end use,
7 improving power efficiency and optimising resources allocation so as to allow a more
8 efficient use of electricity [4]. DSM can be implemented by means of, among others,
9 additional equipment that enables load shaping, such as thermal energy storage (TES)
10 [5]: a TES can be used for electric load management in buildings by shifting electric
11 heating and cooling demands e.g. from peak periods to off peak periods. During off
12 peak times, heating or cooling can be generated by grid electricity, stored in the thermal
13 energy device and then used during peak hours in order to flatten customers' load
14 profiles [6,7]. Studies on the use of thermal storage systems for electric demand side
15 management have been reviewed and the main findings are reported in the following.

16 TES has recently taken on an interesting role in the context of microgrids, thanks to its
17 contribution in controlling loads, as presented by Brahman et al. [8] who dealt with
18 thermal energy management in a residential energy hub, or as investigated by Comodi
19 et al. [9] who considered storing thermal solar energy to produce domestic hot water
20 (DHW) during day hours to be used during night time. Another interesting application
21 of TES in the DSM context is represented by its coupling with air conditioning in
22 buildings, where it can provide a spinning reserve on the demand side with minimal
23 changes to conventional operation and without sacrificing occupant thermal comfort
24 [10]. Upshaw et al. [11] presented a model for the evaluation of peak load reduction and
25 change in overall energy consumption for a residential air conditioning compressor with
26 and without condenser side thermal storage. In this study the thermal storage is used to
27 increase compressor efficiency by providing a low temperature heat sink for the
28 condenser. Palacio et al. [12] described a method to optimally allocate flexible cooling
29 loads with the goal for reducing power system costs by flattening system load,
30 increasing electric system load factor and reducing system ramping, while maintaining
31 thermal comfort.

32 The possibility of storing energy in a cheap way is extremely important and represents
33 one of the most promising methods for containing and reducing the costs of energy. In
34 particular, as far as the installation of heat pumps is concerned, it has been demonstrated
35 that coupling these systems with thermal energy storage units improves heat pump
36 efficiency and reduces heat pump size by decoupling energy generation from energy
37 distribution [13]. The performance obtained is also strictly related to the storage
38 medium considered [14].

39 Several studies have analysed the application of TES for demand side management of
40 thermal loads, using both external devices [15] or active and passive thermal energy
41 storages within building envelopes, without significantly affecting indoor thermal
42 comfort [16]. In particular, thermal energy storages for cooling application are
43 promising, since they have the potential to alter consumption dynamics, reduce energy

1 demand and cut the costs of air conditioning systems [17]. In fact, cold TES (CTES)
2 provides cooling capacity by extracting heat from a storage medium. It makes it
3 possible to reduce refrigeration plant capacity, which can be designed to operate at
4 optimum efficiency for most of its working time and generally with the use of smaller
5 air handling units [17]. TES is particularly interesting for those buildings where cooling
6 demand significantly contributes to energy bills. The effectiveness of TES application
7 depends on a number of factors, including i) the building air conditioning normal usage
8 pattern without TES (the average cooling load should be significantly lower than the
9 peak cooling load); ii) TES system design and operating strategies; iii) the incentives
10 available and/or rate structures by the utility supplying electricity [18,19].
11 TES can be economically competitive as its behaviour changes slowly and is mostly
12 predictable. Several studies have dealt with the economic feasibility of TES application
13 for DSM purposes, especially for cooling loads. Among others, Raham et al. [20]
14 analysed CTES technical and economical feasibility in Australian subtropical climate.
15 Their results show that full and partial chilled storage systems can save up to 61% and
16 50% of the electricity cost required for cooling, respectively, when compared with
17 conventional systems. Rismanchi et al. [21] developed a computer model to determine
18 the potential energy savings of implementing CTES systems in Malaysia. They
19 concluded that, although the use of CTES systems cannot reduce total energy
20 consumption considerably (with a load levelling storage strategy, the overall energy
21 usage was almost 4% lower than that of the non storage system), they have several
22 outstanding benefits, for example they allow cost saving, grid system balancing,
23 reduction of overall fuel consumption in power plants and, consequently, reduction of
24 total carbon footprint. Ruddell et al. [22] simulated the air conditioning portion of
25 electric demand during a summertime heat wave in Phoenix metropolitan area and its
26 shift to off peak hours using distributed thermal storage technology. They assessed the
27 necessary aggregated thermal storage capacity and operating hours required to reduce
28 peak load and evaluated gross electric energy cost savings. They concluded that it
29 would take between 10 to 20 years to reach the necessary level of CTES market
30 penetration and a gross electricity cost saving of \$2.47 per day for a residential retail
31 customer would be possible (with a 17.6 kWh CTES system installed). Similarly,
32 Sabate et al. [23] studied how to optimise the performance of a district cooling network
33 consisting of a number of electric chillers and a thermal energy storage (TES) tank.
34 In particular office buildings are ideal for DSM purposes, because of their shorter
35 occupancy periods. Moreover, especially in the industrial sector, the possibility of
36 shifting electric consumption to times of lower prices is of paramount importance. In
37 fact, most electric energy is consumed during daytime, when the price is typically
38 higher than night time. Puchegger [24] considered industrial buildings and analysed
39 their DSM potential, which can be reached by means of storage systems or by PV
40 panels, in order to shift demand away from peak hours. Whereas, Ostermann et al [25],
41 assessed that, by using PCM (phase change materials) in office buildings, the energy
42 consumption can be annually reduced by about 142 kWh for their case study when
43 storing cold during summer nights (free cooling) and heat during winter days (free

1 heating).

2 This work, too, focuses on the benefits of using a TES system coupled with heat pumps
3 to produce the heating and cooling load of a real factory in Italy. Thus the paper deals
4 with the load behaviour of the industrial sector and its potential to use demand side
5 management. In particular the purpose of the paper is to point out whether the
6 installation of a TES is viable in the Italian mild climate. It is shown that the present
7 Italian electricity tariff structure does not sufficiently reward the off peak use of
8 electricity, making the application of a thermal energy storage for load shifting hardly
9 convenient. Therefore, considering a microgrid context, the role of demand side
10 management strategies for the full integration of photovoltaic (PV) panels is discussed.
11 Other studies have dealt with similar topics. For example, Li et al. [26] explored
12 efficient integration approaches of photovoltaic thermal systems, HVAC (heating
13 ventilation and air conditioning) systems and thermal storage devices to enable optimal
14 collection and utilisation of solar energy in high performance buildings. PV panels are
15 used to drive both the air handling unit (AHU) and the heat pump, coupled with the
16 TES. The TES tank can reduce the electric energy consumption of the heat pump by
17 34.5%. While the work by Korkas et al. [27] presented load management of HVACs,
18 achieved by regulating set points and fan speed, so as to apply DSM strategies and
19 match electric energy demand and PV electricity production in an intelligent microgrid.
20 Conversely in this paper, the use of PV panels electricity to drive the HP for recharging
21 the TES, rather than for supplying the building, is analysed. PV panels and heat pumps
22 coupling is aimed at exploiting the PV overproduction (especially during weekends)
23 that is not consumed for the working activities in the factory, thus increasing PV
24 electricity self-consumption. This can produce a benefit both for the end user, which can
25 reduce energy costs, and for the grid, which does not have to cope with the injection of
26 non-deterministic renewable electricity. The novel contribution of this work lays mainly
27 in the analysis of such integration of TES and PV in order to improve the overall system
28 performance. In particular an in-depth study of the operation of the system in cooling
29 mode (i.e. when PV production is higher) is conducted by means of dynamic
30 simulations. The paper outline is as follows. Firstly the real installation under study
31 (section 2.1) and then the related simulation model with its main assumptions (section
32 2.2) are presented. Secondly, after a preliminary analysis of the actual yearly energy
33 performance of the building considered (section 3.1), the operational behaviour of the
34 system is evaluated for different TES setting configurations by means of dynamic
35 simulations (section 3.3) with a model tested through experimental data (section 3.2).
36 Lastly, an economic assessment of the TES installation and operation is performed
37 (section 3.4).

38 **2. Methods**

39 A real case study, represented by a factory in a town in central Italy, was considered. As
40 a first step the real yearly total PV electricity production was analysed in order to assess
41 the actual building needs and PV overproduction available. Secondly, a simulation

1 model both for the building and the heating/cooling system (production units and
2 emission system) was set up using a dynamic simulation software, TRNSYS [28]. The
3 model was first tested by means of experimental data available and then run with the
4 aim of evaluating in detail the operation of TES during the working week by varying the
5 minimum temperature set-point. The purpose of the dynamic study was to analyse the
6 electric energy use breakdown of the system and identify the best operative
7 configuration. In this paper only the cooling operation of the system was considered,
8 because in summer surplus PV electricity production is higher (as better explained in
9 section 3.1). Finally an economic analysis for the evaluation of the operational electric
10 energy costs due to the HVAC during the working week and the potential savings in
11 comparison with the case without TES was performed. The payback period (PBP) of the
12 installation was also evaluated.

13 2.1 The sample case

14 The factory, “Leaf Lab”, which is owned by the Italian company Loccioni Group, is a
15 two-storey building consisting of two distinct areas: the factory (total area of about 2400
16 m²) in the inner part of the building and the offices (total area of about 5200 m²) placed
17 all around it (Figure 1). Such building was constructed following environment-friendly
18 concepts and it is equipped with modern technologies. The main thermo-physical
19 properties of the building envelope are listed in Table 1. The building is located in a
20 town in central Italy (coordinates: 43°28'58.29" N, 13°04'09.48" E).

21

Table 1. Building envelope properties.

Test Building	U value [W/(m ² K)]
External wall	0.216
Internal wall	0.508
Roof	0.316
Windows	1.29÷1.88

22



23

24

Figure 1. Photograph of the Leaf Lab building.

1 The HVAC system is composed of chilled beams and air handling units as emission
2 systems and of three water-to-water heat pumps (HP1, HP2, HP3) as production units.
3 The AHUs are used for the whole building, including factory and offices, while the
4 chilled beams are used for the offices only. Both the system can work together or
5 separately. Two of the heat pumps (HP2, HP3), which have a nominal cooling capacity
6 of 280 kW each (when supplying water at 7°C), are used for the AHUs [29]. The
7 smaller heat pump (HP1) has a cooling capacity of 150 kW (when supplying water at
8 15°C) and is used for the chilled beams only [30]. Their capacity can be regulated
9 according to the cooling demand by varying the load at 20-40-60-80-100% of the total
10 capacity and the supply temperature ranges between 5-15°C. The water source for the
11 heat pumps is represented by a well at a constant year-round temperature of about 13°C.
12 The water from the well can also supply the chilled beams directly in passive cooling
13 mode for reduced cooling demands.

14 An insulated concrete water tank of 460 m³ is used as thermal storage. It has a
15 rectangular base and its dimensions are 12.3x11x3.4 m. Each wall has a thickness of
16 0.25 m and is insulated by means of 0.16 m of xps polyfoam c350 (thermal conductivity
17 0.032W/mK) [31]. The tank is buried below the ground to reduce heat losses as much as
18 possible. In summer the storage tank can be charged by the heat pumps (HP2, HP3)
19 outside the working hours (when PV electricity is available or during off peak hours, as
20 better explained in the following) and it can supply then cold water to the AHUs when
21 cooling is required during the working hours.

22 Moreover, the building is provided with a PV system, with a nominal power of 236.5
23 kW to cover the electricity demand for the working activities in the factory. The tank
24 was originally installed to store water for fire protection purposes. It was then adapted
25 to be used as a TES with the idea to recover PV electricity during weekends, when the
26 factory electric demand is negligible, as thermal energy. In this way it is possible to
27 increase the self-consumption and profitability of such renewable electricity, reducing
28 the quantity sold to the grid.

29 **2.2 The simulation model**

30 A simulation model of the case study building was performed with TRNSYS. A
31 conceptual schematic of the TRNSYS model is shown in Figure 2.

32

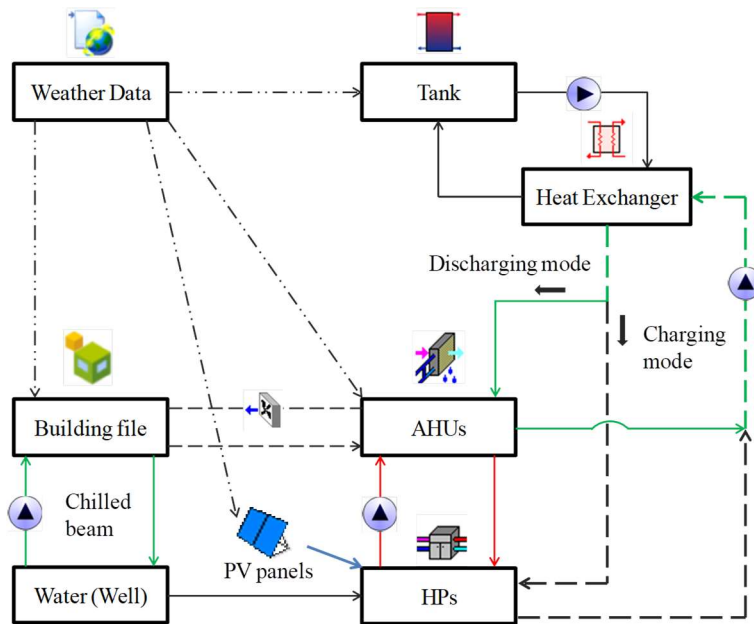


Figure 2. Simplified schematic of the simulation model in TRNSYS.

Only the main components of the cooling production and distribution system are represented on the basis of data from manufacturers. Chilled beams are assumed to work always in passive cooling mode, supplied by well water at 13°C. The building is divided into 4 zones (2 zones for the offices and 2 zones for the factory, one of each on every single floor) and the influences on the cooling loads of internal and external gains are taken into account. In particular, the occupation rate of the building is assumed to be equal to 20 m² per person in the offices and 50 m² per person in the factory from Monday to Friday 8:00 am to 17:00 pm. The load of a computer is 140 W and the number of computers is the same as that of the occupants. The total heat gain of artificial lighting is 10 W/m², which includes 40% convective part. Infiltration of peripheral zone is modelled as a constant air flow of 0.5 ACH (air changes per hour). Indoor air temperature set-point is 24°C (±2°C). The annual weather data file for Ancona (Italy) was used for the simulations. A time step of 15 minutes was considered.

The model can work in three different configurations, according to building and tank needs:

- (i) charging mode: heat pumps charging the tank;
- (ii) tank discharging mode: tank discharging its energy to the building;
- (iii) HP discharging mode: heat pumps providing energy to the building when the tank temperature is too high to preserve internal comfort.

The idea behind the simulations was to charge the storage outside the working hours in order to use as much PV overproduction as possible, i.e. the PV electricity which is not consumed by the factory and which is otherwise sold to the grid. Assuming that the tank is mainly recharged during the weekend by means of the heat pumps driven by surplus

1 PV electricity and that such thermal energy is then used during the working days, the
2 basic time period considered in the analysis is a week, to represent both charging and
3 discharging phase. The simulations were performed for both the hottest and the typical
4 summer weeks, representing respectively the highest cooling demand and the average
5 cooling demand in summer season. The simulation strategy is summarised as follows:

- 6 • It is assumed that, at the starting time, the tank is completely charged and its
7 temperature corresponds to the minimum temperature set-point. Several operational
8 configurations of the tank are considered, namely with the following minimum
9 temperature set-points: 5°C, 7°C, 10°C, 12°C, 15°C.
- 10 • During the week the tank temperature can rise till it guarantees internal comfort
11 when the temperature goes above 18°C, the tank is no longer able to provide cooling
12 to the building (as demonstrated in [32]) and the HPs step in to supply the building
13 directly.
- 14 • At the end of the simulated period, the tank has to be completely charged again and it
15 has to reach the minimum temperature set-point, so that it is completely charged and
16 ready to work the following week.
- 17 • During weekdays the charging mode is possible only when the tank temperature is
18 above 16.5°C and only outside the working hours (the system cannot charge the tank
19 and provide cooling to the building at the same time). The charging is preferably
20 performed during weekend daytime (6:00 am to 7:00 pm). This charging strategy is
21 aimed at trying to recover any available PV electricity or at least exploiting lower
22 grid electricity prices. In fact, the Italian electricity tariff considered is time based.
23 Thus, whether the surplus PV production is not enough to complete the tank
24 charging, this setting makes it possible also to reduce HVAC energy costs by means
25 of demand load shifting to off peak hours.

26 The Italian tariffs taken as reference in this evaluation are: 0.149 €/kWh during off peak
27 time (from 8:00 pm to 8:00 am during week days and during weekends) and 0.164
28 €/kWh during on peak time (from 8:00 am to 8:00 pm during week days), taxes
29 included [33]. For comparison also a different tariff structure with a lower ratio between
30 off peak and on peak price (50%, i.e. on peak tariff 0.164€/kWh and off peak tariff
31 0.082 €/kWh, as, for example, in the existing Chinese tariff scheme) was also
32 considered to assess weekly HVAC operational energy costs with load shifting.

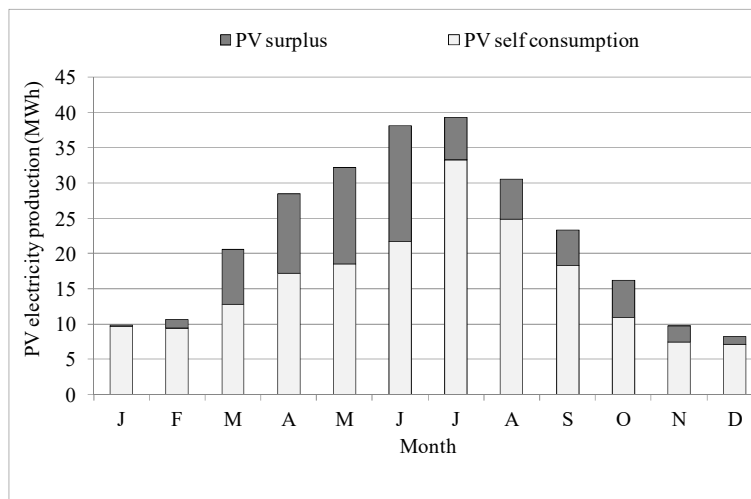
33 The results obtained were compared to a reference case consisting of the same HVAC
34 system without the thermal energy storage to find energy use breakdown and costs of
35 the two configurations and to assess the possible operational profitability of TES
36 application.

37 **3. Results and discussions**

38 **3.1 Analysis of the existing installation**

39 The "Leaf Lab" building was designed in the framework of the microgrid concept, like
40 the residential building "Leaf House" presented in another work [9]. The PV panel

1 installation to cover the building electricity demand and the interest in load shifting to
 2 increase the self-consumption of the electric energy produced are of paramount
 3 importance in a microgrid. Figure 3 shows the monthly PV electricity production
 4 referred to the period from September 2014 to August 2015. The part directly used for
 5 the working activities in the building, self-consumption, is represented vs the surplus
 6 electricity. The latter could be partly recovered for TES charging (see Eq.1 below),
 7 while the rest is sold to the grid. The surplus PV production is due to its not
 8 simultaneity with the building needs (especially outside the working hours). The share
 9 of PV electricity production that could be recovered during weekends is about 24% of
 10 the total PV production and about 85% of the surplus PV electricity. Therefore, it is
 11 worth considering to store such energy for a later use. Storage in the form of thermal
 12 energy to satisfy the building thermal demand for the HVAC system was deemed to be
 13 an interesting option, as thermal load shifting is one of the best known DSM strategies.
 14 Furthermore, thanks to the increased self-consumption of PV production, also the grid
 15 benefits from reduced injection of electricity with a non-deterministic behaviour.
 16



17
 18 Figure 3. Total PV electricity production, divided between self-consumption and surplus PV electricity, in
 19 a year.

20
 21 Given the tank volume of 460 m³ in the existing installation and the operative
 22 temperature difference of 5°C (corresponding to a thermal energy stored of about Q_{th}=
 23 2600 kWh_{th}), assuming an average coefficient of performance COP=5 of the heat pumps
 24 and a recovery efficiency of the tank, ε_{cp}, of 0.85^{†1}, the maximum PV electricity

^{†1} The COP was obtained by measuring the performance of the heat pumps during real operation, while the tank recovery efficiency was assessed by calculating the ratio between the energy recovered from and the energy supplied to the tank during real charging-discharging processes (the value obtained is in agreement with data from literature [36]). It is reasonably assumed that the charging process and discharging process contribute equally to the total tank recovery efficiency.

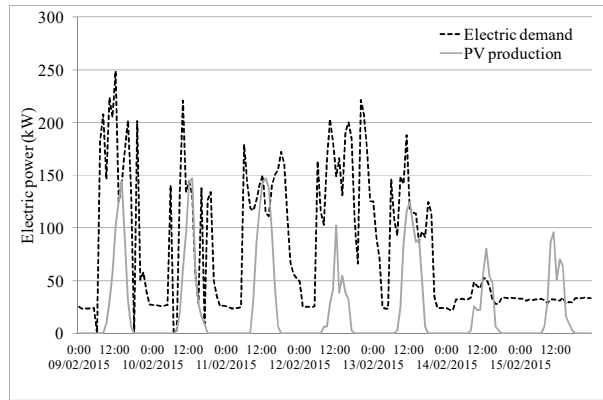
1 recoverable by means of the tank was assessed at about 600 kWh_{el} per week by means
2 of (Eq.1).

$$E_{cp} = \frac{Q_{th}}{\varepsilon_{cp}^{1/2} \cdot COP} \quad (1)$$

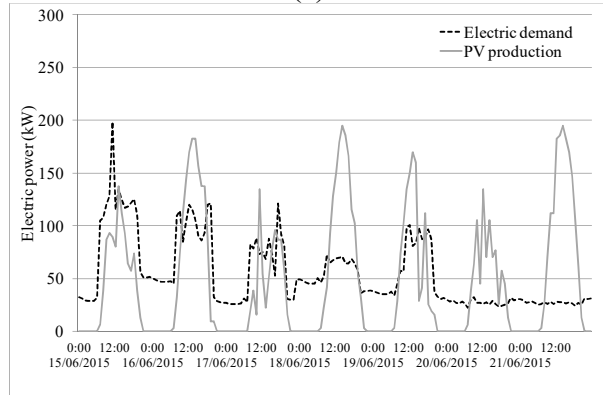
3
4
5
6 Such electricity can be compared with the surplus PV electricity available during
7 weekends, then the monthly PV electricity recoverable with the TES can be determined.
8 The latter (monthly PV electricity recovered) can be used to supply the heat pumps and
9 store thermal energy in the tank, rather than being sold to the grid. Given the building
10 energy demand assessed, the thermal energy stored can be completely consumed during
11 the working weeks considered (see section 3.3).

12 On the basis of the PV electricity production during the year, it is evident that the PV
13 surplus energy is higher during spring and summer season. This is also confirmed by
14 Figure 4, where the total electric power demand and PV electric power are shown for a
15 typical winter (Figure 4a) and summer week (Figure 4b). Therefore this study was
16 focused only on the analysis of cooling loads.

17



(a)



(b)

18 Figure 4. Total electric power demand and PV electric power production during a typical winter (a) and
19 summer (b) week.

3.2 Comparison of the model with experimental data

In order to verify the reliability of the results obtained with the simulation model, a comparison with experimental data available was performed. In particular, Figure 5 shows the behaviour of the system during the charging process. Experimental data were collected during a weekend in July 2014 from 7:00 pm on a Friday onwards, and during this testing phase the tank temperature varied in the range 28°C to 10°C^{‡2}. As it can be seen in Figure 5, the trend of the tank water temperature and of the heat pump power consumption assessed with the simulation fits pretty well with the experimental results. The mean absolute percentage error (MAPE) between simulated and experimental values is 5% for the HP power, 1% for the outlet tank temperature and 16% for the inlet tank temperature. Only the last error is relevant and represents the existing gap between the two inlet tank temperatures (simulated and experimental), especially at the beginning of the charging phase (the initial difference is about 6°C, then it decreases to less than 0.5°C), influenced by the starting conditions assumed in the components of the model that may not coincide with reality. However, the difference existing between experimental and simulated data is acceptable for the purposes of this work, which aims at implementing demand side management strategies and comparing the operational behaviour of different tank configurations.

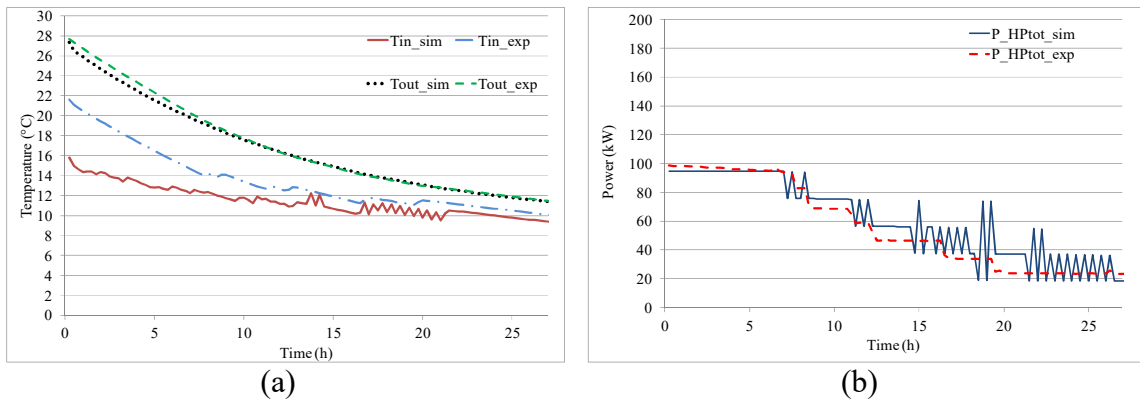
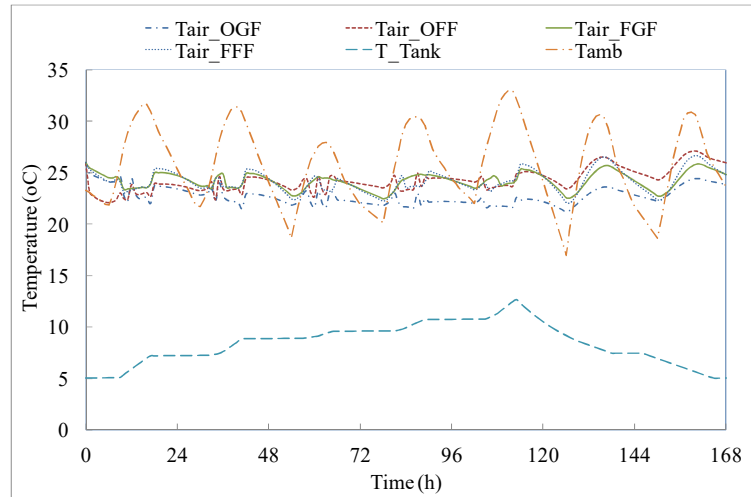


Figure 5. Comparison between experimental and simulated values of tank temperature (a) and HP power consumption (b) during the charging process. T_{in_sim} and T_{in_exp} represent the tank inlet temperatures simulated with the model and measured during the experimental testing phase, respectively. T_{out_sim} and T_{out_exp} are, respectively, the tank simulated and experimental outlet temperatures. P_{HPtot_sim} and P_{HPtot_exp} are, respectively, the simulated and experimental total power consumption by heat pumps. Note that the heat pump power trend (Figure 5b) follows the control strategy described in section 2.1: the capacity is lowered when the cooling demand decreases (i.e. when the HP evaporator inlet temperature is lower).

3.3 Analysis of the system performance

^{‡2} This testing phase represents a first attempt to charge the tank and does not correspond to real operation. The TES, in fact, is not currently working, but it is used only for experimental tests.

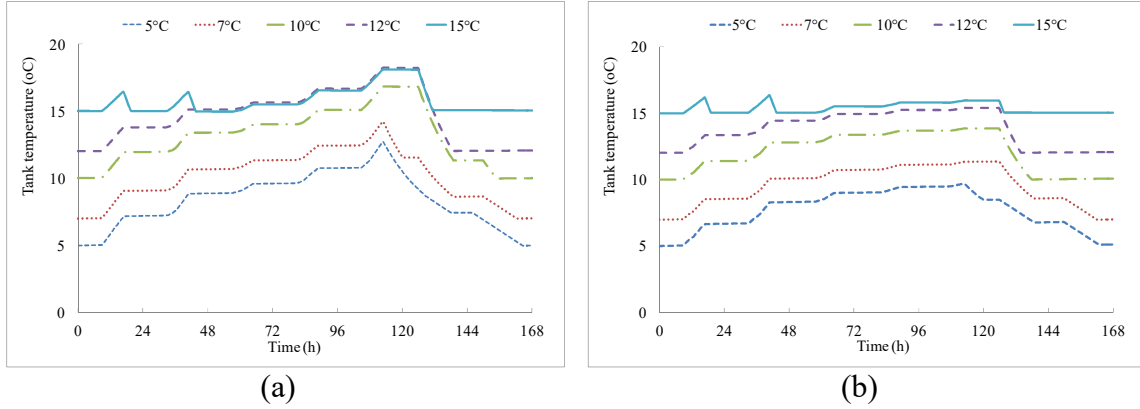
1 The main purpose of the dynamic simulations was to compare different tank operational
 2 strategies in terms of energy use breakdown and analyse the tank charging. The latter is
 3 aimed at increasing the use of PV electricity and reducing the use of heat pumps during
 4 peak hours when electricity price is higher, without influencing the internal comfort of
 5 the rooms. In Figure 6 the building and tank temperatures (for the tank set-point at 5°C)
 6 during the hottest week are shown. The cooling system is automatically switched on
 7 during the working hours when the indoor temperature is higher than 24°C. The AHU is
 8 served by the tank thus making the tank temperature rises accordingly. In this case the
 9 highest tank temperature is 12°C (it changes case by case according to configuration
 10 constraints). The tank needs to be recharged during weekend and brought back to its
 11 initial set point of 5°C at the end of the week (so that is ready for the following week).
 12



13
 14
 15 Figure 6. Trend of the tank temperature and the air temperature in the building zones (OGF-offices
 16 ground floor; OFF-offices first floor; FGF- factory ground floor; FFF-factory first floor) during the
 17 hottest summer week (Note that 0 h corresponds with 0 am of Monday).
 18

19 In order to reduce storage energy demand and heat losses, the tank temperature during
 20 the whole week should be as high as possible, consistently with the fact that the cooling
 21 demand of the building must be met anyway. For this reason different minimum tank
 22 temperature set-points were investigated: 5°C, 7°C, 10°C, 12°C, 15°C. Figure 7 shows
 23 the tank temperature trend during the hottest (Figure 7a) and the typical (Figure 7b)
 24 summer weeks. The tank temperature increases when the tank discharges to the AHUs
 25 and decreases when the tank is charged by the heat pumps. Only when it is really
 26 needed (i.e. to accomplish the two constraints of thermal comfort and final tank
 27 temperature set-point), the tank is recharged and every time, at the end of the period, the
 28 tank initial temperature (set-point) is restored in order to be ready for the following
 29 week. Considering that the system cannot charge the tank and provide cooling to the
 30 building at the same time, the charging process needs to be performed outside the
 31 factory working hours, i.e. during weekends or during weekday nights. Moreover, as

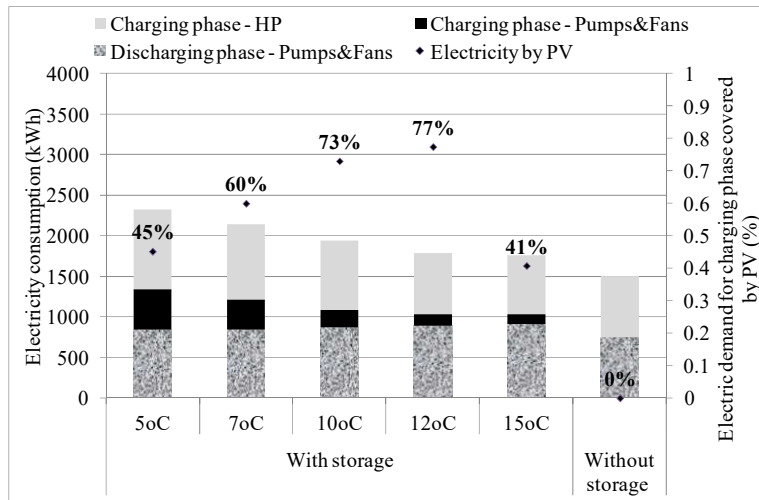
1 explained in section 2.2, in order to increase the recovery of surplus PV production and
 2 reduce charging costs, priority for charging was given to weekend daytime (6:00 am -
 3 7:00 pm), when the PV electricity is not used for the working activities in the factory, or
 4 to hours with off peak rates if necessary. All the configurations analysed make it
 5 possible to keep the internal temperature in thermal comfort condition ($<26^{\circ}\text{C}$ during
 6 working hours). During these simulations the HPs never step in to supply cooling
 7 directly to the building.



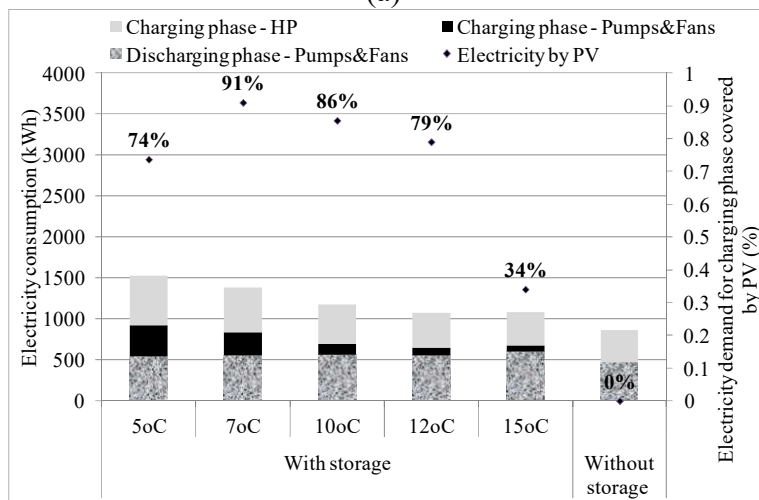
9
 10 Figure 7. Trend of the tank temperature with different minimum set points during the operation in (a) the
 11 hottest week and in (b) the typical week.

12
 13 For the purpose of assessing the best operational configuration of the tank and the
 14 viability of its application, HVAC energy use and related electricity costs (reported in
 15 the next section 3.3) were evaluated for the two weeks under consideration. During the
 16 discharging phase, electricity is consumed by circulator pumps and AHU fans only
 17 while the heat pumps are switched off. Whereas, during the charging phase, the heat
 18 pumps charge the tank and circulator pumps are needed to transfer heat to the tank. In
 19 Figure 8 the energy use breakdown is reported. It is evident that the tank charging phase
 20 (outside working hours) is generally more energy demanding than the corresponding
 21 tank discharging phase (during working hours), except for the case with higher tank
 22 temperature set-points (as further discussed below). Circulator pumps and AHU fans
 23 require a considerable amount of energy, comparable with the energy demand of the
 24 HPs (in the configuration without tank, for example, the two contributions are almost
 25 the same). Furthermore, the installation of the tank always increases energy demand if
 26 compared with the normal operation without the tank, mainly due to the additional
 27 circulator pumps needed in the system configuration. Moreover, the presence of the
 28 TES can cause heat losses in the process of transferring and storing energy in the tank.
 29 As expected, a higher tank temperature set-point reduces tank charging energy use,
 30 while it increases the discharging energy, because the HVAC system works with higher
 31 temperatures and needs to be switched on for a longer period of time in order to keep
 32 the internal building temperatures in the comfort range. Simulation results show that the

1 best trade-off between these two opposite trends is provided by the tank set-point of
 2 12°C which has the lowest total energy use among the configurations with the tank (20%
 3 higher than the energy consumption for the case without the tank).
 4



(a)

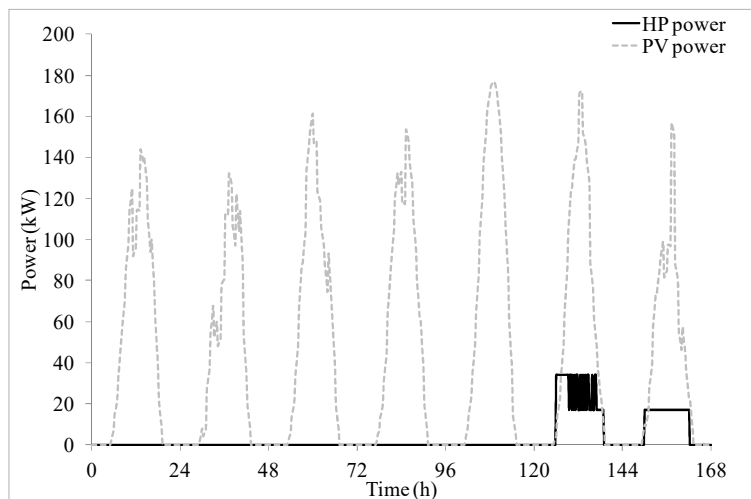


(b)

5
 6 Figure 8. HVAC electric energy use breakdown (due to heat pumps or pumps and fans) for all the
 7 configurations analysed with and without storage divided by operational mode (tank charging or tank
 8 discharging) for the hottest (a) and typical (b) summer weeks. The percentage of the electric demand for
 9 the charging phase provided by PV panels is also reported.

10
 11 Figure 8 also shows the part of energy demand that can be covered by PV panels
 12 (mainly during weekends, as previously explained), as predicted by simulations. This
 13 configuration makes it possible to exploit the PV production in the most economical
 14 way, being self-consumption more convenient than selling the PV overproduction to the
 15 grid (PV electricity selling price is 0.045 €/kWh [34]). The percentage of the electric

1 demand necessary for the tank charging process that can be covered by the surplus PV
 2 electricity is not constant and depends on several aspects, such as: the total electricity
 3 required for the charging phase, the duration of the charging phase, the control strategy
 4 of the heat pumps that determines the power trend, the simultaneousness of heat pump
 5 power demand and PV power production. Thus, for example, when the tank temperature
 6 minimum set point is 5°C, the charging process is more energy demanding (due mainly
 7 to lower COP of the HP for lower supply temperatures) and, consequently, longer.
 8 Therefore, the weekend daytime and its available PV production are not sufficient to
 9 complete the charging process and also night time hours need to be used. Whereas,
 10 when the tank temperature minimum set point is 15°C, the tank needs to be charged also
 11 during week days outside the working hours to have enough thermal energy stored for
 12 the rest of the week. As a result, the percentage of energy demand covered by PV panels
 13 is reduced. The case with the tank temperature minimum set point of 7°C for the typical
 14 week has the highest surplus PV production recovered, because the weekend daytime is
 15 sufficient to complete the charging process and generally the HP power is lower than
 16 the PV power (see Figure 9). In these simulations the charging strategy was assumed to
 17 be the same for all the configurations in order to compare results obtained. Nevertheless,
 18 once the tank minimum temperature set-point for the tank operation is chosen, the
 19 charging strategy and, especially the HP control strategy during tank cooling, could be
 20 optimised to further maximise surplus PV electricity use.
 21



22
 23 Figure 9. Power trend of the HPs and PV panels during the tank charging process with a tank minimum
 24 temperature set-point of 7°C for the typical week.

25

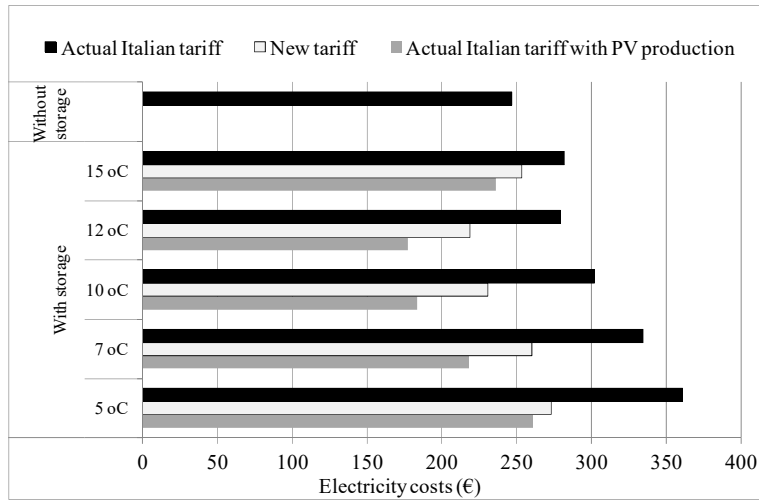
26 3.4 Economic evaluations

27 In this section an attempt to evaluate the economic impact of the TES for the case under
 28 consideration is presented. First the HVAC operational electric energy costs and then
 29 the payback period due to the TES use are evaluated.

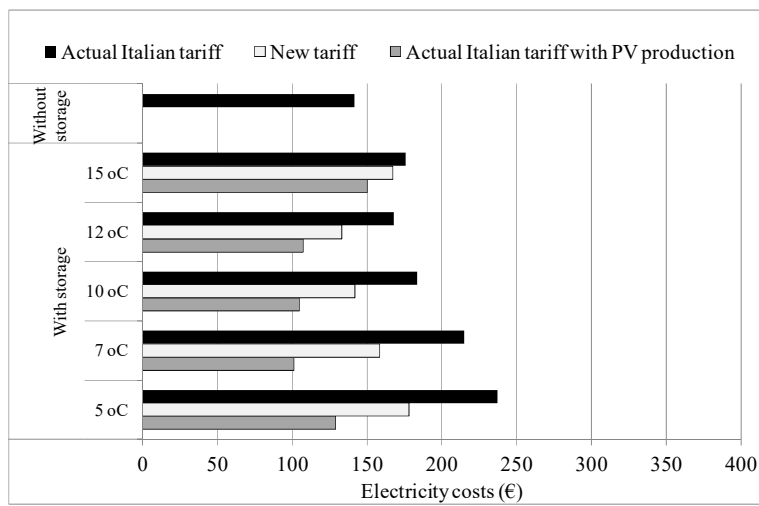
30 As previously mentioned, even if the installation of the tank requires more energy
 31 consumption during operation, its application could be economically convenient thanks

1 to the integration with PV and by shifting the load to off peak hours when the electricity
2 tariff is lower. By means of the dynamic simulations described in the previous
3 paragraph (section 3.3), the HVAC operational electric energy costs were assessed for
4 the case without TES and for the case with TES, in both the situations when it is
5 possible to recover the surplus PV electricity and when, instead, the electricity is totally
6 bought from the grid during off peak hours. In the latter scenario two tariff structures
7 were considered: (i) the existing Italian tariffs, characterised by a price ratio between off
8 peak time and on peak time tariffs of about 90%, (ii) a new tariff characterised by a
9 price ratio between off peak time and on peak time tariffs of about 50%. The results are
10 reported in Figure 10. It is evident that, considering the actual Italian tariff structure,
11 there is no economic convenience in installing a TES, unless the PV electricity is used
12 to cover the tank charging energy demand. This is due to the high price ratio of off peak
13 time and on peak time tariffs, because the small difference between the two tariffs
14 reduces the convenience of shifting the loads. When, however, the electricity price
15 difference between peak and off peak time is considerable, the use of the tank turns out
16 to be convenient, also without self producing the necessary charging energy by means
17 of PV. This is confirmed by the results obtained with the new tariff considered (50%
18 price ratio), which reduces operational electric energy costs compared with the
19 reference case without the tank in almost all the configurations, even if costs slightly
20 decrease. For sake of completeness a sensitivity analysis on the basis of the price ratio
21 between off peak time and on peak time tariffs was also performed. It was obtained that,
22 for the hottest week for example, a ratio of at least 37% is necessary in order to have
23 lower operational electric energy costs than the threshold of the reference case in all the
24 configurations analysed. While a ratio of 69% is sufficient to reduce, under the same
25 threshold, the costs of the best case in terms of energy performance (i.e. 12°C, see
26 section 3.3). Furthermore, thanks to the positive contribution of PV overproduction, the
27 HVAC electric energy costs can be reduced by up to 30% of the costs in the reference
28 case. The maximum cost reduction is achieved when the energy demand covered by PV
29 during charging process is higher (i.e 12°C in the hottest week and 7°C in the typical
30 week, as shown in Figure 8).

31



(a)



(b)

1
 2 Figure 10. HVAC operational electricity costs for all the tank configurations analysed and for the
 3 reference system without storage, both considering the actual Italian electricity tariff structure, accounting
 4 or not accounting the energy for the charging process provided by PV panels, and a new tariff structure
 5 with a ratio between off peak and on peak price of 50% for the hottest week (a) and the typical week (b).
 6

7 The previous analysis describes only the tank operational condition, nevertheless, the
 8 initial tank charging process from ambient temperature to minimum set point was also
 9 simulated and the corresponding energy consumption was accounted for. This process
 10 happens only once at the beginning of the summer season and a starting temperature of
 11 the tank of 21.5°C was assumed, assessed as the average of the ambient temperature in
 12 the three days preceding the starting of summer season. The charging process lasts
 13 about 58 hours for the case with the minimum tank temperature set-point of 5°C, 43
 14 hours for 7°C, 24 hours for 10°C, 17 hours for 12°C and 10 hours for 15°C. Thus, the

PV electricity produced during a weekend could be used to provide most of the necessary load (Table 2). Even the charging process could be performed in more than one weekend only during daytime and the energy costs would be completely cancelled out. Consequently, the first charging energy consumption has a negligible influence on the feasibility evaluation of the tank application during the whole season.

Table 2. Energy use from the grid (accounted for the PV electricity contribution during a weekend) and costs for the first charging process of the tank.

	5°C	7°C	10°C	12°C	15°C
Energy use (kWh)	1840.66	1248.43	836.91	288.78	265.75
Energy cost (€)	274.26	186.02	124.70	43.03	39.60

In order to complete the economic analysis, the simple payback period for the installation of the TES used to recover surplus PV production during weekends was evaluated (Eq. 2). Calculations are based on data for yearly PV recoverable electricity with the considered TES assessed in section 3.1. The value of the investment (CI) is estimated on the basis of data from literature. The report [35] states that the cost of a complete system for sensible heat storage ranges between 0.1-10 €/kWh of the storage capacity depending on the size, application, thermal insulation technology, charging and discharging equipment and operation costs. TES systems for sensible heat are rather inexpensive as they basically consist of a simple tank for the storage medium and the equipment for charging/discharging operations. Storage media are relatively cheap, however tank thermal insulation may be an important cost element. Whereas in another study by DeForest et al. [36], a capital factor of 30 €/kWh_{th}, linearly growing with system size, based on values from real projects, is reported. The operational cost savings (AS) in (Eq. 2) account for the avoided purchase from the grid of the electricity to supply the heat pumps during the working hours at on peak price ($c_{pp}=0.164$ €/kWh), thanks to the thermal energy stored in the TES during weekends.

$$PBP = \frac{CI}{AS} \quad (2)$$

The operational costs savings are calculated through (Eq. 3).

$$AS = \eta_c \cdot (C_{pg,pp} - R_{sg}) + (1 - \eta_c) \cdot (C_{pg,pp} - C_{pg,op}) \quad (3)$$

$$C_{pg,pp} = E_{cp} \cdot \varepsilon_{cp} \cdot c_{pp} \quad (4)$$

$$R_{sg} = E_{cp} \cdot p_{sp} \quad (5)$$

$$C_{pg,op} = E_{cp} \cdot c_{op} \quad (6)$$

1
2 where $C_{pg,pp}$ is the cost of electricity purchased from the grid at on peak price to drive
3 the HPs in the configuration without tank (Eq. 4), R_{sg} the revenue for selling to the grid
4 the recovered PV electricity (Eq. 5), $C_{pg,op}$ the cost of electricity purchased from the grid
5 at off peak price for tank charging process (Eq. 6), E_{cp} the electric energy for tank
6 charging process, η_c a contemporary factor between HP energy demand and PV
7 production, ε_{cp} the recovery efficiency of the tank, c_{pp} the electricity on peak cost, c_{op}
8 the electricity off peak cost and p_{sp} the PV electricity selling price to the grid.
9 The first term of (Eq. 3) represents the savings achievable by supplying cooling to the
10 building through the TES, charged with PV electricity, instead of directly using the HP,
11 driven with the electricity from the grid. The revenue that could be obtained by selling
12 that PV electricity to the grid (rewarded with the selling price of $p_{sp}=0.045$ €/kWh),
13 rather than self-consuming it, was subtracted. On the basis of the results in section 3.3,
14 it was assumed, on average, that 80% (η_c) of the electricity for the charging process is
15 covered by PV panels and 20% by the grid at off peak price ($c_{op}=0.149$ €/kWh). The
16 second term of (Eq. 3) represents the savings achievable by exploiting the difference
17 between on peak and off peak electricity price, thanks to the load shifting operated by
18 the tank. It is worth noting that the second term does not always lead to actual savings
19 (as demonstrated also by results in Figure 10): the off peak price needs to be sufficiently
20 lower than the on peak price so as to compensate the energy use increase due to the
21 TES. If this condition is not verified, (Eq. 3) clearly shows that shifting the cooling load
22 to off peak price hours is not convenient (the second term of the equation is negative)
23 and it would be better charging the tank only when the surplus PV electricity is
24 available.
25 Therefore, assuming a capital factor of 10 €/kWh_{th} [35], the payback period of the TES
26 installation to recover the surplus PV electricity is of about 16 years. Whereas, with the
27 capital factor suggested by DeForest et al. [36] the payback period increases to 47 years,
28 making the installation no longer attractive. In this case, if the contemporary factor η_c
29 could be increased to 100%, thanks to an optimized HP control strategy during charging
30 that allows it to be driven only by PV electricity, the PBP would decrease to 37 years.
31 Moreover it has to be noted that in this analysis the simple payback time was assessed.
32 In case of taking into account also the time value of money, risks, financing, the period
33 to recover the initial investment would be also longer. For example, with an interest rate
34 of 3% [36], the PBP with a capital factor of 10 €/kWh_{th} would increase to 23 years,
35 while with a capital factor of 30 €/kWh_{th} it could also be four times the simple PBP
36 value. It is evident that these results depend on the parameters assumed in the
37 calculations and they show, as expected, that the PBP is long and obviously strictly
38 related to the amount of PV electricity recovered and, mainly, to the capital cost factor
39 used. In order to have a simple PBP lower than 10 years, for the configuration and
40 assumptions made in this analysis, the capital factor should be lower than 6 €/kWh_{th}.
41 Nevertheless, in industrial buildings storage tanks with other purposes, such as fire risk
42 protection in this case, can be found which could be adapted also for thermal
43 application, considerably reducing the impact of the initial investment. Eventually,

1 being such systems able to avoid the injection of a non-deterministic renewable
2 electricity into the grid, it could be in the interest of the utility to provide incentives to
3 spread the introduction of energy storage systems to increase the self-consumption of
4 PV distributed generation. Anyway such figures can help to provide an order of
5 magnitude of realisation costs, but an in-depth analysis about this issue is out of the
6 scope of this paper.

7 **4. Conclusions**

8 The performance of an industrial building using a thermal storage tank coupled with
9 heat pumps was studied for the summer cooling period by means of dynamic
10 simulations. The purpose of the analysis was to evaluate the viability of the TES
11 installation aimed at recovering surplus PV electricity during weekends, thus different
12 operational configurations were considered and energy use and costs were assessed. As
13 expected, it was found that the tank always increases energy use. Moreover, it is better
14 to keep tank temperature as high as possible and allow the recharging process only
15 when it is strictly necessary to guarantee internal thermal comfort, because in this way
16 charging energy use and losses are reduced. However, as the opposite trend, a higher
17 tank temperature produces higher energy use for the energy discharging phase, therefore
18 a good trade-off between the energy necessary to charge the tank and the energy
19 required to provide cooling to the building needs to be found when the tank temperature
20 set point is decided. Nevertheless an economic advantage (even if limited) is possible
21 when the load is shifted to weekends to recover PV electricity or to off peak hours, if
22 the off peak electricity tariff is considerable lower than the on peak tariff (with a ratio
23 between off peak and on peak electricity price of 50%). In particular, the possibility of
24 employing electricity which is self-produced by PV panels makes this application
25 profitable whatever the electricity tariff structure in place is. However, as it could be
26 expected, the economic feasibility of TES installation is strictly related to capital costs
27 which, if considerably high, make the payback period of the project too long for such
28 kind of investments.

29 **Acknowledgements**

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33 about their *Leaf Lab* and allowed us to study their plant.

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1 Figure captions:
2 (all figures to be printed in black and white)
3
4 Figure 1. Photograph of the Leaf Lab building.
5 Figure 2. Simplified schematic of the simulation model in TRNSYS.
6 Figure 3. Total PV electricity production, divided between self-consumption and
7 surplus PV electricity, in a year.
8 Figure 4. Total electric power demand and PV electric power production during a
9 typical winter (a) and summer (b) week.
10 Figure 5. Comparison between experimental and simulated values of tank temperature
11 (a) and HP power consumption (b) during the charging process. T_{in_sim} and T_{in_exp}
12 represent the tank inlet temperatures simulated with the model and measured during the
13 experimental testing phase, respectively. T_{out_sim} and T_{out_exp} are, respectively, the
14 tank simulated and experimental outlet temperatures. P_{HPtot_sim} and P_{HPtot_exp}
15 are, respectively, the simulated and experimental total power consumption by heat
16 pumps. Note that the heat pump power trend (Figure 5b) follows the control strategy
17 described in section 2.1: the capacity is lowered when the cooling demand decreases (i.e.
18 when the HP evaporator inlet temperature is lower).
19 Figure 6. Trend of the tank temperature and the air temperature in the building zones
20 (OGF-offices ground floor; OFF-offices first floor; FGF- factory ground floor; FFF-
21 factory first floor) during the hottest summer week (Note that 0 h corresponds with 0 am
22 of Monday).
23 Figure 7. Trend of the tank temperature with different minimum set points during the
24 operation in (a) the hottest week and in (b) the typical week.
25 Figure 8. HVAC electric energy use breakdown (due to heat pumps or pumps and fans)
26 for all the configurations analysed with and without storage divided by operational
27 mode (tank charging or tank discharging) for the hottest (a) and typical (b) summer
28 week. The percentage of the electric demand for the charging phase provided by PV
29 panels is also reported.
30 Figure 9. Power trend of the HPs and PV panels during the tank charging process with a
31 tank minimum temperature set-point of 7°C for the typical week.
32 Figure 10. HVAC operational electricity costs for all the tank configurations analysed
33 and for the reference system without storage, both considering the actual Italian
34 electricity tariff structure, accounting or not accounting the energy for the charging
35 process provided by PV panels, and a new tariff structure with a ratio between off peak
36 and on peak price of 50% for the hottest week (a) and the typical week (b).
37
38

1 Table captions:

2

3 Table 1. Building envelope properties.

4 Table 2. Energy use from the grid (accounted for the PV electricity contribution during
5 a weekend) and costs for the first charging process of the tank.

6

1 Table 1. Building envelope properties.

Test Building	U value [W/(m ² K)]
External wall	0.216
Internal wall	0.508
Roof	0.316
Windows	1.29÷1.88

2

3

1 Table 2. Energy use from the grid (accounted for the PV electricity contribution during
2 a weekend) and costs for the tank first charging process.

	5°C	7°C	10°C	12°C	15°C
Energy use (kWh)	1840.66	1248.43	836.91	288.78	265.75
Energy cost (€)	274.26	186.02	124.70	43.03	39.60

3