Thermal energy storage coupled with PV panels for demand side management of industrial building cooling loads

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

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Abstract

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

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

1. Introduction

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

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

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

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

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

Several studies have analysed the application of TES for demand side management of thermal loads, using both external devices [15] or active and passive thermal energy storages within building envelopes, without significantly affecting indoor thermal comfort [16]. In particular, thermal energy storages for cooling application are promising, since they have the potential to alter consumption dynamics, reduce energy demand and cut the costs of air conditioning systems [17]. In fact, cold TES (CTES) provides cooling capacity by extracting heat from a storage medium. It makes it possible to reduce refrigeration plant capacity, which can be designed to operate at optimum efficiency for most of its working time and generally with the use of smaller air handling units [17]. TES is particularly interesting for those buildings where cooling demand significantly contributes to energy bills. The effectiveness of TES application depends on a number of factors, including i) the building air conditioning normal usage pattern without TES (the average cooling load should be significantly lower than the peak cooling load); ii) TES system design and operating strategies; iii) the incentives available and/or rate structures by the utility supplying electricity [18,19].

TES can be economically competitive as its behaviour changes slowly and is mostly predictable. Several studies have dealt with the economic feasibility of TES application for DSM purposes, especially for cooling loads. Among others, Raham et al. [20] analysed CTES technical and economical feasibility in Australian subtropical climate. Their results show that full and partial chilled storage systems can save up to 61% and 50% of the electricity cost required for cooling, respectively, when compared with conventional systems. Rismanchi et al. [21] developed a computer model to determine the potential energy savings of implementing CTES systems in Malaysia. They concluded that, although the use of CTES systems cannot reduce total energy consumption considerably (with a load levelling storage strategy, the overall energy usage was almost 4% lower than that of the non storage system), they have several outstanding benefits, for example they allow cost saving, grid system balancing, reduction of overall fuel consumption in power plants and, consequently, reduction of total carbon footprint. Ruddell et al. [22] simulated the air conditioning portion of electric demand during a summertime heat wave in Phoenix metropolitan area and its shift to off peak hours using distributed thermal storage technology. They assessed the necessary aggregated thermal storage capacity and operating hours required to reduce peak load and evaluated gross electric energy cost savings. They concluded that it would take between 10 to 20 years to reach the necessary level of CTES market penetration and a gross electricity cost saving of $2.47 per day for a residential retail customer would be possible (with a 17.6 kWh CTES system installed). Similarly, Sabate et al. [23] studied how to optimise the performance of a district cooling network consisting of a number of electric chillers and a thermal energy storage (TES) tank.

In particular office buildings are ideal for DSM purposes, because of their shorter occupancy periods. Moreover, especially in the industrial sector, the possibility of shifting electric consumption to times of lower prices is of paramount importance. In fact, most electric energy is consumed during daytime, when the price is typically higher than night time. Puchegger [24] considered industrial buildings and analysed their DSM potential, which can be reached by means of storage systems or by PV panels, in order to shift demand away from peak hours. Whereas, Ostermann et al [25], assessed that, by using PCM (phase change materials) in office buildings, the energy consumption can be annually reduced by about 142 kWh for their case study when storing cold during summer nights (free cooling) and heat during winter days (free heating).

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

2. Methods

A real case study, represented by a factory in a town in central Italy, was considered. As a first step the real yearly total PV electricity production was analysed in order to assess the actual building needs and PV overproduction available. Secondly, a simulation model both for the building and the heating/cooling system (production units and emission system) was set up using a dynamic simulation software, TRNSYS [28]. The model was first tested by means of experimental data available and then run with the aim of evaluating in detail the operation of TES during the working week by varying the minimum temperature set-point. The purpose of the dynamic study was to analyse the electric energy use breakdown of the system and identify the best operative configuration. In this paper only the cooling operation of the system was considered, because in summer surplus PV electricity production is higher (as better explained in section 3.1). Finally an economic analysis for the evaluation of the operational electric energy costs due to the HVAC during the working week and the potential savings in comparison with the case without TES was performed. The payback period (PBP) of the installation was also evaluated.

2.1 The sample case

The factory, “Leaf Lab”, which is owned by the Italian company Loccioni Group, is a two-storey building consisting of two distinct areas: the factory (total area of about 2400 m^2) in the inner part of the building and the offices (total area of about 5200 m^2) placed all around it (Figure 1). Such building was constructed following environment-friendly concepts and it is equipped with modern technologies. The main thermo-physical properties of the building envelope are listed in Table 1. The building is located in a town in central Italy (coordinates: 43°28'58.29" N, 13°04'09.48" E).

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

Figure 1. Photograph of the Leaf Lab building.

The HVAC system is composed of chilled beams and air handling units as emission systems and of three water-to-water heat pumps (HP1, HP2, HP3) as production units. The AHUs are used for the whole building, including factory and offices, while the chilled beams are used for the offices only. Both the system can work together or separately. Two of the heat pumps (HP2, HP3), which have a nominal cooling capacity of 280 kW each (when supplying water at 7°C), are used for the AHUs [29]. The smaller heat pump (HP1) has a cooling capacity of 150 kW (when supplying water at 15°C) and is used for the chilled beams only [30]. Their capacity can be regulated according to the cooling demand by varying the load at 20-40-60-80-100% of the total capacity and the supply temperature ranges between 5-15°C. The water source for the heat pumps is represented by a well at a constant year-round temperature of about 13°C. The water from the well can also supply the chilled beams directly in passive cooling mode for reduced cooling demands.
An insulated concrete water tank of 460 m^3 is used as thermal storage. It has a rectangular base and its dimensions are 12.3x11x3.4 m. Each wall has a thickness of 0.25 m and is insulated by means of 0.16 m of xps polyfoam c350 (thermal conductivity 0.032W/mK) [31]. The tank is buried below the ground to reduce heat losses as much as possible. In summer the storage tank can be charged by the heat pumps (HP2, HP3) outside the working hours (when PV electricity is available or during off peak hours, as better explained in the following) and it can supply then cold water to the AHUs when cooling is required during the working hours.
Moreover, the building is provided with a PV system, with a nominal power of 236.5 kW to cover the electricity demand for the working activities in the factory. The tank was originally installed to store water for fire protection purposes. It was then adapted to be used as a TES with the idea to recover PV electricity during weekends, when the factory electric demand is negligible, as thermal energy. In this way it is possible to increase the self-consumption and profitability of such renewable electricity, reducing the quantity sold to the grid.

2.2 The simulation model

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

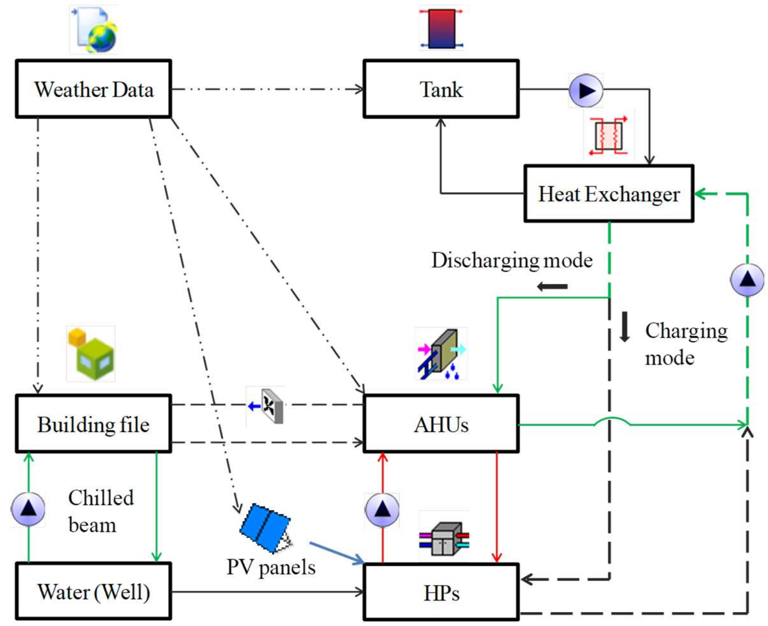


Figure 2. Simplified schematic of the simulation model in TRNSYS.

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 m^2 per person in the offices and 50 m^2 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/m^2, 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

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

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

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

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

3. Results and discussions

3.1 Analysis of the existing installation

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

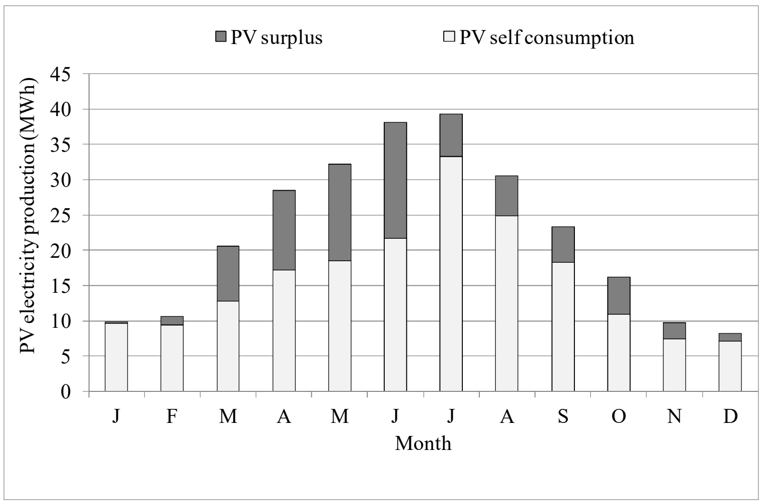


Figure 3. Total PV electricity production, divided between self-consumption and surplus PV electricity, in a year.

Given the tank volume of 460 m^3 in the existing installation and the operative temperature difference of 5°C (corresponding to a thermal energy stored of about Q_{th}= 2600 kWh_{th}), assuming an average coefficient of performance COP=5 of the heat pumps and a recovery efficiency of the tank, ε_{cp}, of 0.85[†1], the maximum PV electricity

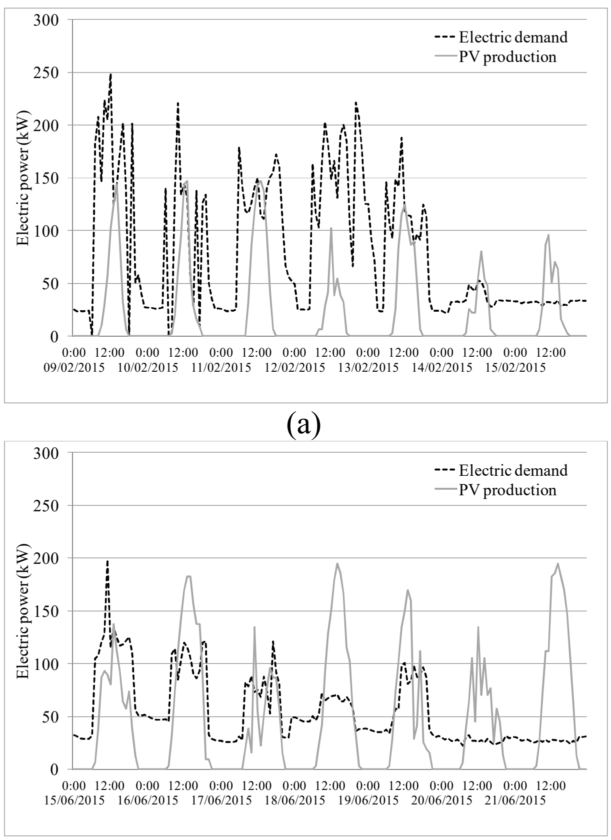
† [1] The COP was obtained by measuring the performance of the heat pumps during real operation, while the tank recovery efficiency was assessed by calculating the ratio between the energy recovered from and the energy supplied to the tank during real charging-discharging processes (the value obtained 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.

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

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

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

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

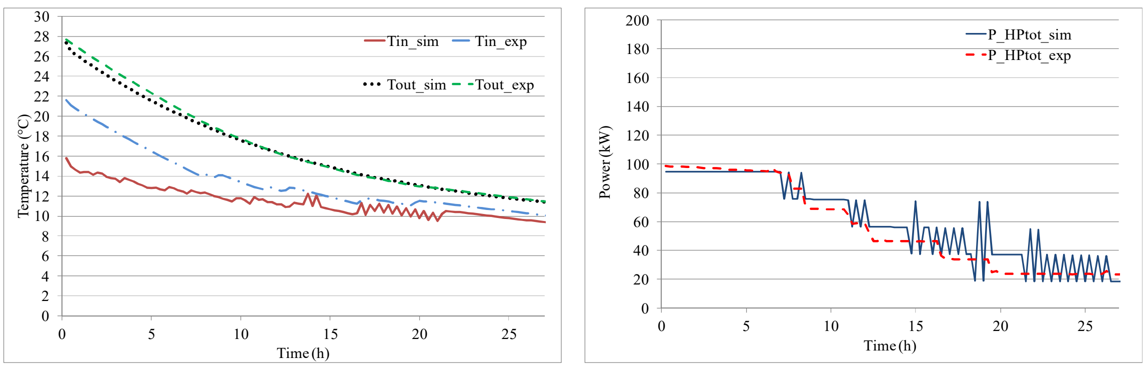


(b)

Figure 4. Total electric power demand and PV electric power production during a typical winter (a) and 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.



(a) (b)

Figure 5. Comparison between experimental and simulated values of tank temperature (a) and HP power consumption (b) during the charging process. Tin_sim and Tin_exp represent the tank inlet temperatures simulated with the model and measured during the experimental testing phase, respectively. Tout_sim and Tout_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.

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

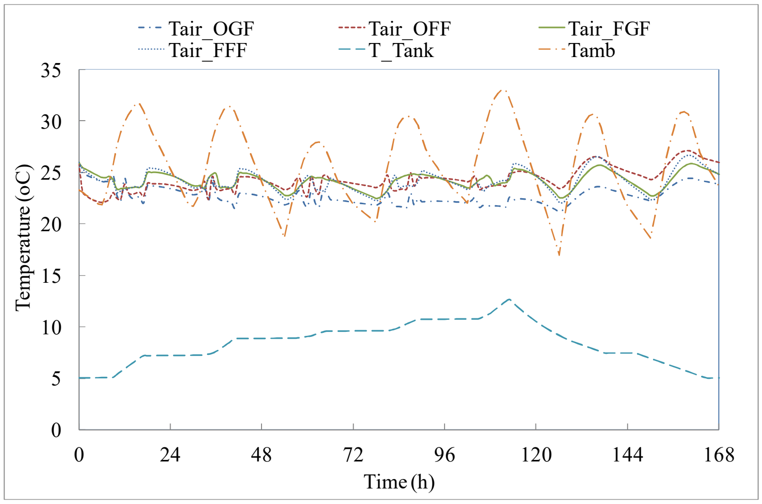


Figure 6. Trend of the tank temperature and the air temperature in the building zones (OGF-offices ground floor; OFF-offices first floor; FGF- factory ground floor; FFF-factory first floor) during the hottest summer week (Note that 0 h corresponds with 0 am of Monday).

In order to reduce storage energy demand and heat losses, the tank temperature during the whole week should be as high as possible, consistently with the fact that the cooling demand of the building must be met anyway. For this reason different minimum tank temperature set-points were investigated: 5°C, 7°C, 10°C, 12°C, 15°C. Figure 7 shows the tank temperature trend during the hottest (Figure 7a) and the typical (Figure 7b) summer weeks. The tank temperature increases when the tank discharges to the AHUs and decreases when the tank is charged by the heat pumps. Only when it is really needed (i.e. to accomplish the two constraints of thermal comfort and final tank temperature set-point), the tank is recharged and every time, at the end of the period, the tank initial temperature (set-point) is restored in order to be ready for the following week. Considering that the system cannot charge the tank and provide cooling to the building at the same time, the charging process needs to be performed outside the factory working hours, i.e. during weekends or during weekday nights. Moreover, as explained in section 2.2, in order to increase the recovery of surplus PV production and reduce charging costs, priority for charging was given to weekend daytime (6:00 am - 7:00 pm), when the PV electricity is not used for the working activities in the factory, or to hours with off peak rates if necessary. All the configurations analysed make it possible to keep the internal temperature in thermal comfort condition (<26°C during working hours). During these simulations the HPs never step in to supply cooling directly to the building.

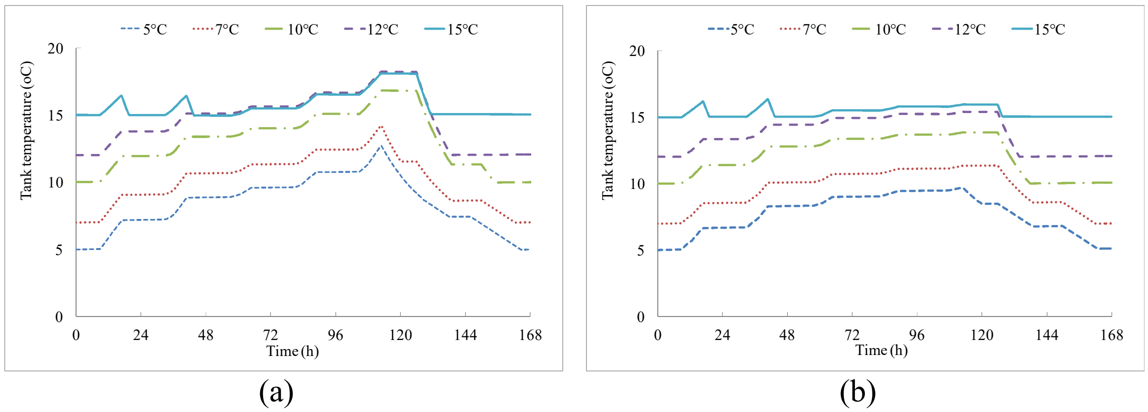
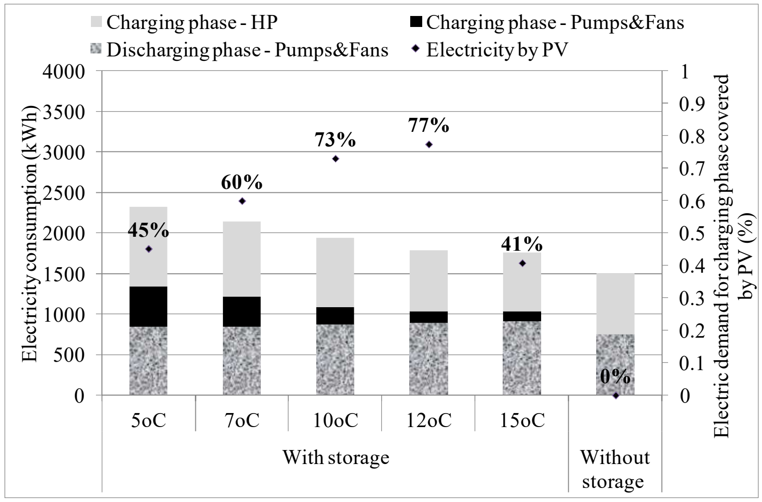
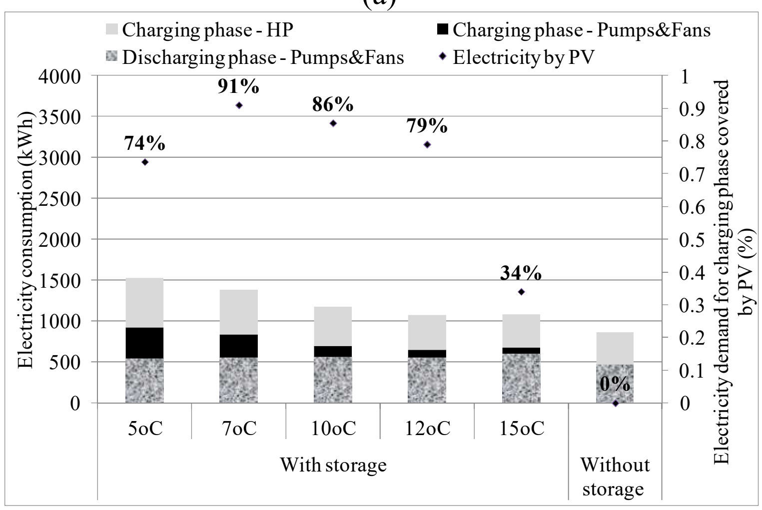


Figure 7. Trend of the tank temperature with different minimum set points during the operation in (a) the hottest week and in (b) the typical week.

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



(a)



(b)

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

Figure 8 also shows the part of energy demand that can be covered by PV panels (mainly during weekends, as previously explained), as predicted by simulations. This configuration makes it possible to exploit the PV production in the most economical way, being self-consumption more convenient than selling the PV overproduction to the grid (PV electricity selling price is 0.045 €/kWh [34]). The percentage of the electric demand necessary for the tank charging process that can be covered by the surplus PV electricity is not constant and depends on several aspects, such as: the total electricity required for the charging phase, the duration of the charging phase, the control strategy of the heat pumps that determines the power trend, the simultaneousness of heat pump power demand and PV power production. Thus, for example, when the tank temperature minimum set point is 5°C, the charging process is more energy demanding (due mainly to lower COP of the HP for lower supply temperatures) and, consequently, longer. Therefore, the weekend daytime and its available PV production are not sufficient to complete the charging process and also night time hours need to be used. Whereas, when the tank temperature minimum set point is 15°C, the tank needs to be charged also during week days outside the working hours to have enough thermal energy stored for the rest of the week. As a result, the percentage of energy demand covered by PV panels is reduced. The case with the tank temperature minimum set point of 7°C for the typical week has the highest surplus PV production recovered, because the weekend daytime is sufficient to complete the charging process and generally the HP power is lower than the PV power (see Figure 9). In these simulations the charging strategy was assumed to be the same for all the configurations in order to compare results obtained. Nevertheless, once the tank minimum temperature set-point for the tank operation is chosen, the charging strategy and, especially the HP control strategy during tank cooling, could be optimised to further maximise surplus PV electricity use.

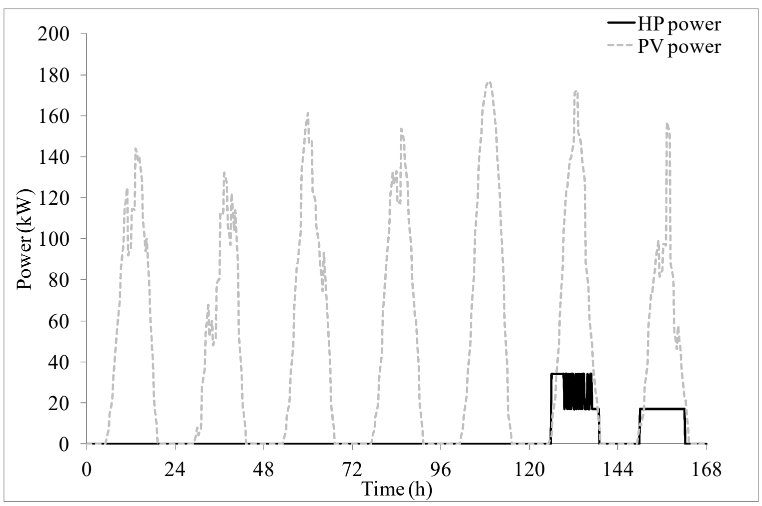
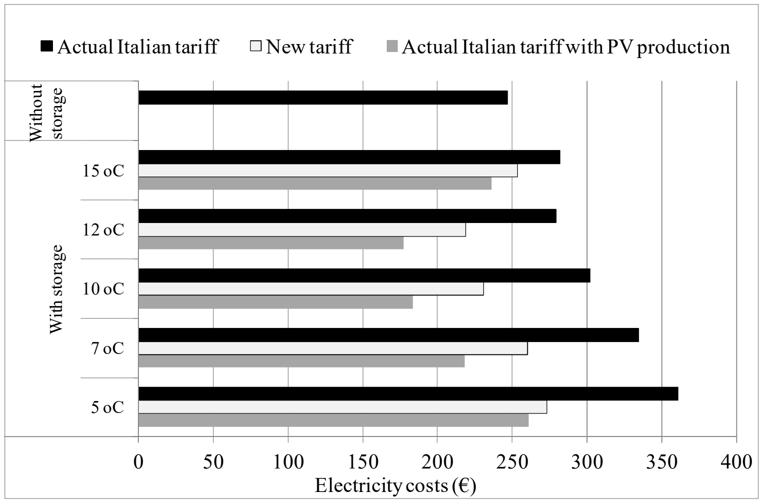


Figure 9. Power trend of the HPs and PV panels during the tank charging process with a tank minimum temperature set-point of 7°C for the typical week.

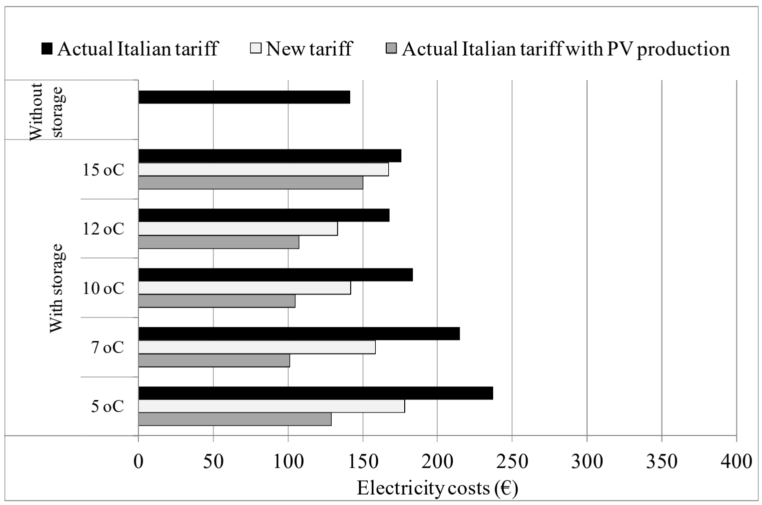
3.4 Economic evaluations

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

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



(a)



(b)

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

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

$$PBP = \frac{CI}{AS} \tag{2}$$

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

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

$$C_{pg,pp} = E_{cp} \cdot \varepsilon_{cp} \cdot \; c_{pp} \tag{4}$$

$$R_{sg} =\cdot E_{cp} \cdot p_{sp} \tag{5}$$

$$C_{pg,op} =\cdot E_{cp} \cdot c_{op} \tag{6}$$

where $C_{pg,pp}$ is the cost of electricity purchased from the grid at on peak price to drive the HPs in the configuration without tank (Eq. 4), R_{sg} the revenue for selling to the grid the recovered PV electricity (Eq. 5), $C_{pg,op}$ the cost of electricity purchased from the grid at off peak price for tank charging process (Eq. 6), E_{cp} the electric energy for tank charging process, η_c a contemporary factor between HP energy demand and PV production, ε_{cp} the recovery efficiency of the tank, c_{pp} the electricity on peak cost, c_{op} the electricity off peak cost and p_{sp} the PV electricity selling price to the grid.

The first term of (Eq. 3) represents the savings achievable by supplying cooling to the building through the TES, charged with PV electricity, instead of directly using the HP, driven with the electricity from the grid. The revenue that could be obtained by selling that PV electricity to the grid (rewarded with the selling price of p_{sp}=0.045 €/kWh), rather than self-consuming it, was subtracted. On the basis of the results in section 3.3, it was assumed, on average, that 80% (η_c) of the electricity for the charging process is covered by PV panels and 20% by the grid at off peak price (c_{op}=0.149 €/kWh). The second term of (Eq. 3) represents the savings achievable by exploiting the difference between on peak and off peak electricity price, thanks to the load shifting operated by the tank. It is worth noting that the second term does not always lead to actual savings (as demonstrated also by results in Figure 10): the off peak price needs to be sufficiently lower than the on peak price so as to compensate the energy use increase due to the TES. If this condition is not verified, (Eq. 3) clearly shows that shifting the cooling load to off peak price hours is not convenient (the second term of the equation is negative) and it would be better charging the tank only when the surplus PV electricity is available.

Therefore, assuming a capital factor of 10 €/kWh$_{th}$ [35], the payback period of the TES installation to recover the surplus PV electricity is of about 16 years. Whereas, with the capital factor suggested by DeForest et al. [36] the payback period increases to 47 years, making the installation no longer attractive. In this case, if the contemporary factor η_c could be increased to 100%, thanks to an optimized HP control strategy during charging that allows it to be driven only by PV electricity, the PBP would decrease to 37 years. Moreover it has to be noted that in this analysis the simple payback time was assessed. In case of taking into account also the time value of money, risks, financing, the period to recover the initial investment would be also longer. For example, with an interest rate of 3% [36], the PBP with a capital factor of 10 €/kWh$_{th}$ would increase to 23 years, while with a capital factor of 30 €/kWh$_{th}$ it could also be four times the simple PBP value. It is evident that these results depend on the parameters assumed in the calculations and they show, as expected, that the PBP is long and obviously strictly related to the amount of PV electricity recovered and, mainly, to the capital cost factor used. In order to have a simple PBP lower than 10 years, for the configuration and assumptions made in this analysis, the capital factor should be lower than 6 €/kWh$_{th}$. Nevertheless, in industrial buildings storage tanks with other purposes, such as fire risk protection in this case, can be found which could be adapted also for thermal application, considerably reducing the impact of the initial investment. Eventually, being such systems able to avoid the injection of a non-deterministic renewable electricity into the grid, it could be in the interest of the utility to provide incentives to spread the introduction of energy storage systems to increase the self-consumption of PV distributed generation. Anyway such figures can help to provide an order of magnitude of realisation costs, but an in-depth analysis about this issue is out of the scope of this paper.

4. Conclusions

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

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Figure captions:
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Figure 1. Photograph of the Leaf Lab building.
Figure 2. Simplified schematic of the simulation model in TRNSYS.
Figure 3. Total PV electricity production, divided between self-consumption and surplus PV electricity, in a year.
Figure 4. Total electric power demand and PV electric power production during a typical winter (a) and summer (b) week.
Figure 5. Comparison between experimental and simulated values of tank temperature (a) and HP power consumption (b) during the charging process. Tin_sim and Tin_exp represent the tank inlet temperatures simulated with the model and measured during the experimental testing phase, respectively. Tout_sim and Tout_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).
Figure 6. Trend of the tank temperature and the air temperature in the building zones (OGF-offices ground floor; OFF-offices first floor; FGF- factory ground floor; FFF-factory first floor) during the hottest summer week (Note that 0 h corresponds with 0 am of Monday).
Figure 7. Trend of the tank temperature with different minimum set points during the operation in (a) the hottest week and in (b) the typical week.
Figure 8. HVAC electric energy use breakdown (due to heat pumps or pumps and fans) for all the configurations analysed with and without storage divided by operational mode (tank charging or tank discharging) for the hottest (a) and typical (b) summer week. The percentage of the electric demand for the charging phase provided by PV panels is also reported.
Figure 9. Power trend of the HPs and PV panels during the tank charging process with a tank minimum temperature set-point of 7°C for the typical week.
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Table captions:

Table 1. Building envelope properties.
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.

Table 1. Building envelope properties.

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

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

	5ºC	7ºC	10ºC	12ºC	15ºC
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