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"Demand Side Management in the built environment by means of heat pumps"

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Abstract

Il Demand Side Management (DSM) raggruppa un insieme di pratiche ed attività progettate per influenzare la domanda energetica di un consumatore in termini di tempo e/o distribuzione con il fine di individuare come utilizzare l'energia elettrica in modo più efficiente. Il DSM diminuisce il costo per il soddisfacimento della richiesta del consumatore in termini energetici tramite investimenti in efficienza energetica e in gestione dei carichi del consumatore, fornendo flessibilità e riconfigurando il mercato dell'elettricità. Gli obiettivi del DSM sono vari ed includono la diminuzione delle emissioni di CO_2 nonché un uso più efficiente di energia, inoltre le misure del DSM mirano ad instaurare un sistema più stabile di tariffazione elettrica. Un altro fondamentale obiettivo del DSM è la gestione dei carichi elettrici, ovvero dei profili di carico del consumatore. Le combinazioni tra i profili di carico sono molte e svariate, tra le categorie più impiegate troviamo il Load Shifting ed il Peak Clipping poiché sono di semplice applicazione e realizzazione, inoltre non richiedono l'impiego di tecnologie avanzate. Per questo motivo, questi due profili di carico sono stati i più indagati nei lavori presentati nel manoscritto. Tra le opportunità più interessanti dell'applicazione del DSM troviamo l'impiego di tali strategie nei dispositivi elettrici, per citarne uno tra tanti, nel campo delle pompe di calore. Il modo più promettente di combinare queste due realtà consiste nell'applicare strategie di *load management*. A tal fine, ci si serve di strumenti in grado di consentire la gestione dei carichi energetici: tra i tanti, uno dei più validi è sicuramente lo stoccaggio di energia termica (TES). Nei programmi di DSM, il TES viene impiegato in modo da spostare la richiesta per il riscaldamento/raffrescamento dai periodi di maggiore richiesta (on-peak) notoriamente più gravosi a livello economico, ai periodi di bassa richiesta (off-peak) dove solitamente la tariffa oraria è più conveniente. L'impiego dei TES nel DSM aggiunge flessibilità alla gestione dei carichi energetici come ampliamente dimostrato da un vasto numero di lavori in letteratura ed è il nostro campo di ricerca. La novità di quanto qui presentato consiste nell'applicazione delle strategie di DSM al settore dell'edilizia residenziale ed industriale, nello specifico applicando il DSM a casi reali nei quali fossero integrate energie rinnovabili. Si parte dal ricostruire il caso reale in un ambiente di simulazione dinamica per simularne il comportamento sul lungo periodo. I modelli di simulazione sono stati progettati per studiare l'integrazione delle strategie di DSM negli edifici e per analizzare gli effetti dei carichi termici sui consumi elettrici e sulle prestazioni degli involucri. I risultati avuti confermano come le strategie di DSM possano agire positivamente sulle prestazioni degli edifici e dell'intero sistema, incrementandone flessibilità ed efficienza energetica. Inoltre, tali strategie di DSM hanno influito sulla riduzione dei consumi energetici e delle bollette elettriche dei casi studiati, soprattutto qualora siano in atto tariffe elettriche che variano su scala oraria, tutto ciò senza intaccare il comfort interno degli edifici e degli occupanti. Le strategie di DSM risultano essere economicamente vantaggiose qualora vengano integrati sistemi di stoccaggio di energia termica; questi permettono di spostare la richiesta energetica nelle fasce orarie di bassa tariffazione, andando ad attivarsi nei periodi di on-peak, ovvero quando il costo dell'elettricità è più alto. I lavori presentati dimostrano come lo stoccaggio non sia sempre la soluzione energeticamente più vantaggiosa poiché questi necessita di cariche preventive e successive scariche che vanno ad influire sui consumi. Tuttavia, lo stoccaggio permette di allontanare i consumi dai periodi di on-peak e quando presenti delle strategie di DSM, viene confermato come lo stoccaggio sia di aiuto nella riduzione dei costi. Nei lavori viene dimostrato come un contesto Cinese di tariffazione elettrica possa rendere lo stoccaggio un'applicazione di successo, questo poiché i prezzi durante l'off-peak sono sensibilmente più bassi dei prezzi della fascia on-peak. Inoltre, si dimostra come misure semplici di DSM siano solitamente sufficienti a migliorare l'efficienza energetica, questo è dovuto al fatto che il settore edilizio non ha bisogno di grandi stravolgimenti qualora siano impiegate tariffe variabili su scala oraria e soprattutto energie rinnovabili.

Abstract

Demand side management (DSM) consists in a set of practices and activities designed to affect the amount or timing of customers' energy demand in order to use electricity more efficiently. DSM decreases the cost of meeting the customers' increasing energy demand by means of an investment in end-use energy efficiency and load management. As a result, this allows for an increased flexibility in the power generating systems and thus improving the energy supply balance in the network and reshaping the electricity market. DSM brings along a variety of advantages including the decrease of CO_2 emissions and a development of a more efficient use of energy. Furthermore, DSM also allows for greater stability in the electricity prices for all market players. The load management is one of DSM objectives, this means changing the customers' load profiles in a more efficient way. Among the broad variety of load shape profile combinations, Load Shifting and Peak Clipping are the most widely used demand patterns. This is mainly attributed to the fact that they are relatively quick and easy to perform without the requirement for a significantly advanced technology. Both demand patterns have been particularly researched in the presented works. Interesting opportunities come from the use of DSM strategies for the management of electric devices. A very promising combination is when the heat pumps operate according to DSM strategies, more precisely when load management is applied. Such a DSM strategy can be implemented by means of additional equipment that enables load shaping, among all, thermal energy storage (TES) is a valid tool. In DSM program, a TES can be used for electric load management in buildings by shifting electrical heating and cooling demands e.g. from peak periods to off peak periods. The application of TES in DSM can thus add flexibility to the energy management as shown in the various works considered in this study's literature review. With respect to previous studies, the novelty of this work lies in the application of DSM real existing cases within the building sector which also integrate renewable energy sources into the system. Initially, reliable experimental data from realistic experimental campaigns was consulted. Subsequently, simulation models were built in order to closely represent the true behavior recorded in each of the studied experimental campaigns. The purpose of such simulation models was to study the integration of DSM strategies in the built environment and to analyze the effect of the thermal loads on the electricity consumption as well as the building energy performances in the long run. Results from this work confirm how DSM strategies can positively impact on the buildings' and systems' performances as they help increasing energy efficiency and system flexibility. Moreover, the application of DSM has proven to reduce the energy consumption of the presented cases and the electricity bills, particularly when dynamic electricity tariffs are implemented. The DSM measures turn out to be economically feasible when integrated with TES system which allows for the electric consumption demand to be shifted to time of cheaper electricity prices. This research study also illustrates how a TES system is not necessarily always the best solution in terms of energy consumption as it requires an initial charging and subsequent discharging, thus requesting energy to the whole system. However, such a measure helps smoothen out the overall electricity consumption patterns as it reduces the peak period electricity demand as it offsets such a demand to the off-peak period when cheaper tariffs are in operation. This research study demonstrates how a Chinese tariffs context can be successful for the TES application as the off-peak electricity tariff is considerable lower than the on peak tariff. Simple DSM measures are often enough to significantly improve energy efficiency. Furthermore, the building sector does not necessitate an extreme overturning if renewable energy or dynamic taxation are implemented.

Introduction

Environmental protection and sustainable development have recently become of paramount importance due to the scarcity of resources, supply problems and global warming effects. Climate change mitigation requires the community to increase the use of renewable energy and reduce its dependence on fossil fuels. The building sector is internationally recognized as one of the most energy consuming sectors amounting to approximately 40% of the global energy consumption. Major efforts are necessary in order to limit this growing energy demand.

In this context, heat pumps represent the link between thermal loads and the electricity, providing a sustainable solution to generate heat for new and existing building stock.

Furthermore, heat pumps can play a fundamental role in achieving the established 2020 environmental targets by reshaping and reducing energy consumption at all stages in the energy system; for this reason, they 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). DSM refers to practices and activities intended to change the load profiles to optimize the entire power system from generation to delivery to final customers, allowing a more efficient use of electricity and adding flexibility to the grid. The potential importance of DSM programs is that they can be an effective way to achieve sustainable development and help energy consumption reduction in buildings when altering the load pattern through the use of incentives, grants and benefits.

The aims of DSM are diverse and include the decrease of CO_2 emissions, lowering the cost of electricity, establishing a more reliable power supply and reducing energy consumption.

The DSM concept has been introduced in response to the rise of energy cost and in response to the potential problems of global warming. DSM can be considered as one of the most practical policy tools for balancing economic growth and environmental preservation available at present. In particular, DSM can be implemented by means of additional equipment that enables load shaping, among all, thermal energy storage (TES) is a valid tool.

TES allows the decoupling between heat generation and the energy demand, being the key for the thermal demand of a building which is usually not very flexible, especially if thermal insulation properties are not good. This is why TES is gaining more attention and it is evident that it will play a central role for the heat pump's ability to meet the power system needs, especially if variable electricity prices (thus, DSM measures) are in operation as they can influence heat pump behavior.

In DSM program, 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. In fact, 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. Effective thermal energy storage in buildings can severely impact on DSM mechanisms if properly designed.

The scope of this PhD thesis is to investigate on the application of the DSM on the building sector, with the aim of improving energy efficiency and adding flexibility to the power system in terms of matching demand and supply in the network. To do so, dynamic simulations tools have been used to have accurate predictions on the building's performances.

The building response has been investigated for the most representative cases, in particular real cases and experimental data has been handled and this has given reliability and actuality to our research. Experimental data has been used to build the simulation models via dynamic simulation tools and to validate the designed models, and this has been carried out by comparing the results from calculated models to the real available data. These simulated models have been created for studying the integration of DSM strategies in the built environment and to analyze the effect of the thermal loads on the electricity consumption and on the building energy performances in the long run.

The reliability of the building' simulated model depends on the accuracy of the variables that has been used (materials' characteristics, system components' information, …) but also on the effectiveness of the designed solutions.
The first step for a genuine model lies in its validation via experimental measures or data.
The validation process aims to minimize the deviation between the experimental measures and the calculated outputs from the model, and this is usually performed through the adjustment of each of the parameters.
Input parameters considered as inaccurate are adjusted to obtain a combination that guarantees the best approximation in terms of thermal building's and system's behavior.
DSM methods turned out to be a good opportunity to apply thermal energy storage to decouple the temporal link between the energy supply and demand, enabling them to be shifted in time and above all, allowing the penetration of the heat pumps. The new applied system contributes to reduce energy consumption, costs and preserves the thermal indoor comfort of the studied building cases, obtained through reductions on thermal and electrical loads.
The focus is constantly on the Italian electricity market that has been deeply investigated during these years, thanks to the cooperation with Italian industrial companies, but with a careful glance to the Chinese market too. Chinese market has been chosen as DSM has become very popular during last 10 years and still is a topic of great interest in China.
The remainder of this manuscript is organized as follows.

Chapter 1 is considered as the state of the art of the Demand Side Management topic and introduces its definition, measures and methods. In this chapter the evolution of DSM is explained and a thorough literature review is presented. The most representative works are illustrated for a better comprehension of the DSM field and to define the boundary and novelty of our work.

Chapter 2 presents an existing installation of a CO_2 heat pump in a domestic application that has been implemented in a dynamic simulation tool. The model is set up for heating, cooling and hot water production in order to evaluate possible implementation of demand side management (DSM) control strategies, with a specific focus on load management. DSM methods are tested and the overall performance such as thermal comfort and energy consumption of the system in heating mode are analyzed and the possible beneficial effects are assessed.

Chapter 3 illustrates an existing installation of a thermal energy storage (TES) system coupled with heat pumps in an industrial building. Once again, a dynamic simulation model is built to represent the behavior of the whole productive and emissive system and to show the load shifting potential of the thermal energy storage. Costs and energy use are assessed in order to evaluate the viability of the TES application for each configuration.
The novel contribution of this work lays mainly in the analysis of the integration of TES with photovoltaic panels in order to improve the overall system performance and to investigate on the economic assessment of the TES installation.

Chapter 4 leaves out of consideration DSM topic and focuses on a two-stage air source heat pump performance, installed in the Green Energy Laboratory. The performance analysis is pursued by means of an experimental campaign coupled with the Response Surface Methodology (RSM); RSM has been applied with the aim of extending the data sample as some of the experimental data had to be rejected due to the sensors' inaccuracy problems experienced during the tests. By means of RSM, it was possible to highlight which parameters affect mostly the HP performance and to draw curves showing the relationship between power consumption and COP, supply water temperature and ambient temperature, in order to highlight the best system configuration in terms of efficiency. Also, an optimal configuration of the system that can allow thermal comfort in the rooms, minimizing the HP power consumption, was assessed.

Appendix A illustrates a part of the PhD works that moves away from heat pump investigation and deals with Thermal Conductivity (λ). The aim of this part of the research was to investigate an equation for the calculation of the Thermal conductivity knowing a small number of physical properties of a specific material. This research has been the subject of two international publications as new equations on Thermal conductivity have been detected.
Starting from a literature review, a database consisting in 136 compounds have been created and for each compound physical properties and experimental data are provided. The new Thermal conductivity definition aims to minimize the deviation between the collected experimental data and the predicted based upon this new equation. In both papers, a new and simple method has been developed for the calculation of thermal conductivity and clear improvements in its calculation, with respect to other existing correlating equations, have been assessed.

1. Demand side Management (DSM)

1.1. DSM definition

Demand side management is a set of practices and activities designed to affect the amount or timing of customers' energy demand in order to use electricity most efficiently, this means focusing on changing the load profile, reducing both customer demand and energy consumption during peak times and aiming to optimize the entire power system from generation to delivery, to end use [1]. DSM decreases the cost of meeting customers' increasing energy demand by means of an investment in end-use energy efficiency and load management [2]. As a result, this allows for an increased flexibility in the power generating systems and thus improving the energy supply balance in the network and reshaping the electricity market.

Aims of DSM are diverse and encompass more than electricity market only, for instance socio-economic issues are implied, which are the decrease of CO_2 emissions and a development of a more efficient use of energy, but also contribute to a more stable electricity prices for market players. From the end user point of view, DSM aims at lowering the cost of electricity, establishing a more reliable power supply and reducing energy consumption. Starting from such aims, benefits are very promising. These are the reduction in need for new power plant and in dependency on foreign expensive imports of fuels consequently. Moreover, DSM can benefit in reducing air pollution and emissions and reducing in peak power prices for electricity.

Since mid-1980s the concept of DSM has been of primarily importance for achieve sustainable development and energy efficient topics. It has been introduced in response of the rise of energy cost, in light of energy conservation and in response to the potential problems of global warming. DSM can be considered as the most practical policy tools for balancing economic growth and environmental preservation available at present.

Looking back on DSM’s earlier definition by Gellings, who is the very first presenter of DSM, there are five main elements of demand side management, as explained in his books [3,4], considered to be a masterpiece for who is approaching this topic.

The first and introducing element is to set objectives: the first step in demand side management is to set objectives, which could be reducing energy needs, reducing dependence on foreign imports or improving customer relations. Another level of this planning process is to put these objectives into operation with the aim of guiding the policymakers to specific actions. Designated objectives are translated into demand-pattern changes or load-shape changes.

Among the broad variety of load shape profile combinations, six cases are considered to be the most significant. These are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape, shown in Figure 1. These six ways of managing the load can be combined among them for a more efficient solution.

a) *Peak Clipping* (or the reduction of the peak demand) is considered as the reduction of peak load by using direct load control. Direct load control is usually practiced by direct utility control of service and customers' appliances. Direct load control can be used to reduce operating cost and dependence on critical fuels by economic dispatch.
b) *Valley filling* is the second classic form of load management and applies to both gas and electric systems. It consists in increasing demand at off-peak. Valley filling includes building off-peak loads. If priced off-peak are added properly, the average price decreases. Valley filling can be performed in several ways, the most popular is the thermal energy storage that can serve loads usually provided by fossil fuels (water heating and/or space heating).
c) *Load Shifting* is another classic form of load management and also applies to both gas and electric systems. It consists in shifting loads

from on-peak to off-peak periods. It can be performed by using thermal storage and customer load shifting.

d) *Strategic Conservation* is directed to the end use consumption. It is not directly included in load management and it is a change that reflects a modification of the load shape involving a reduction in consumption and a change in the pattern of use. It can be performed by weatherization and equipment efficiency improvement.

e) *Strategic Load Growth* refers to an increase in demand beyond the valley filling described previously. Load growth may include electrification as electric vehicles, industrial process heating, and automation that have a potential in increasing the electric energy intensity of the industrial sector. Strategic Load Growth and Strategic Conservation have effects on the value of energy and not directly on consumption rates as the remaining ways that modify instead the load curve and smooth out the demand from peak hours avoiding coincidence of loads.

f) *Flexible Load Shape* is related to electric system reliability. Load shape can be flexible if customers agree in variations in quality of service in exchange for various incentives. The programs can involve interruptible or curtailable load, integrated energy management systems or individual customer load control devices.

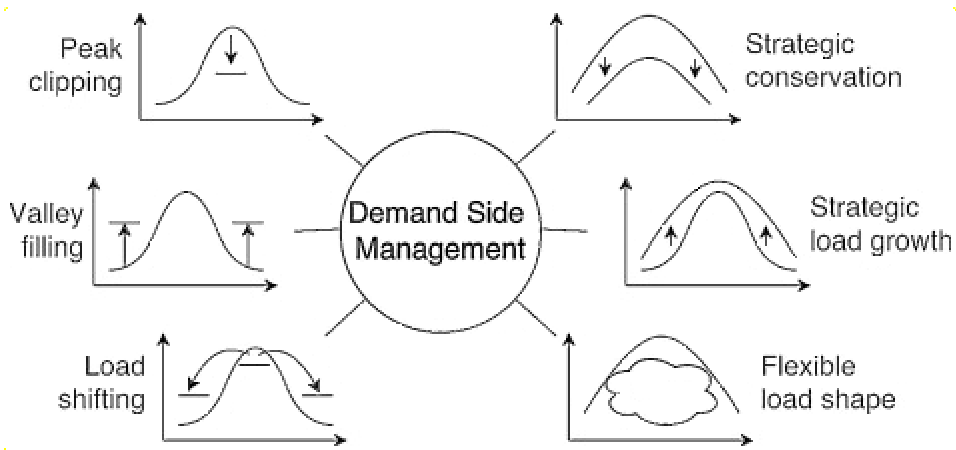


Figure 1 – Demand Side Management categories [3,4]

Load Shifting and Peak Clipping are the most widely used demand patterns. This is mainly attributed to the fact that they are relatively quick and easy to perform without the requirement for a significantly advanced technology. Both demand patterns have been particularly researched in the presented works. In this manuscript, the use of DSM will be further explained.

The second element of demand side management is to identify alternatives that provide cost-effective services to the customers. The first thing to do is to identify the end uses whose peak load and energy consumption characteristics match the requirements of the load-shape objectives established before. Once done this, appropriate technology alternatives for each target end use are chosen. When completed, this analysis (both cost-benefits and environmental-benefits) provides a rank of DSM alternatives.

The third element of demand side management is to evaluate and select programs with the aim of identifying the most efficient alternatives to pursue. A supplier-customer relationship is fundamental for pursuing beneficial results even though these two members act independently while changing the load pattern.

The fourth element of demand side management is to implement programs. Implementation stage aims to design the program for specific end-use applications and to promote it through advertisement activities. Program management is required to ensure efficient implementation.

The fifth and last element of demand side management is to monitor the programs with the aim of identify deviations from expected performance and to improve the process. This monitoring can be useful to investigate customer behaviour and utilities system impacts and to achieve the desired load change.
Gellings' definition and organization [3,4] can be considered as a "cornerstone" in DSM concept, however early DSM programs were operated

by utilities and from their specific point of view. It is important to stress that the motivation behind the implementation of DSM is clearly different for each involved parties. For utilities companies, the reduction or the shift of customer's energy demand could mean avoiding or postpone the need for investments in new power plant, transmission and distribution network. For customers, DSM offers the opportunity to reduce their energy bills through efficiency measures.

Utilities should be one of the key driving forces behind DSM implementation by motivating customers in using energy efficiently, reducing their energy demand and thus their energy costs [5].

To have a more realistic vision of what DSM is, different measures of DSM are described. These are able to meet utilities and customers' needs.

1.2. DSM measures and methods

Utilities try to encourage end users to alter their demand pattern, this is generally accomplished through positive tariff incentives allowing customers to schedule demand activities at a time that will reduce their energy costs. This in turn helps the utilities by moving the demand away from the peak period.

The main types of DSM activities may be classified in three different measures: Energy Reduction Programs, Load Management Programs, Load Growth and Conservation Programs [5,6].

Energy reduction programs reduce the general load level on the network and reduce peak demand. Its main aim is to reduce the demand through a more efficient process, buildings and equipment. It involves typical energy reduction measures such as energy saving tips for the existing housekeeping items (boilers, steam systems, lightning, etc), variable speed drives, preventive maintenance and implementing buildings equipment which reduce both demand and greenhouse gas emissions.

Load management programs are based on a contract signed by the end users and consist in interrupting particular loads with or without notifying the customers of the action, while they can continue in their use of energy. Sometimes the customers can act independently in response to specific request for load reduction or to electricity prices.

Load management techniques are:

i) Load levelling: these technologies are used to smooth out the peaks and dips in energy demand by reducing consumption at peak times which is peak shaving, increasing it during off-peak times which is valley filling, or shifting the load from peak to off-peak periods to maximize the use of efficient generation and reduce the need of energy. Classic forms of load levelling were discussed by Gellings [3,4] and represented in Figure 1.

ii) Load control: this is performed by "switching" on/off the end users' load. Energy management control systems (EMCSs) can be used to switch electrical equipment on or off for load leveling purposes. Some of these devices enable direct off-site control of user equipment performed by the utility. It is applied to heating, cooling, ventilation and lighting loads. Energy storage devices located on the customer's side of the meter can be used to shift the timing of energy consumption.

iii) Tariff incentives and penalties: this is performed by the utilities with the aim of suggesting a load energy pattern to the customers in exchange for tariff incentives and better price-rate. This category that encompasses Time of use and Real Time pricing will be further discussed.

Load Growth and Conservation programs aim to improve customer productivity and environmental issues while increasing the sale of power for the utilities. These programs include strategic load growth consisting in increase demand beyond the valley filling described previously. Conservation results in a reduction in sales as well as a change in the pattern of use.

Another important classification of DSM, or more specifically of Demand Response (DR), can be performed on the methods for influencing the rate of consumption. They belong to direct control of equipment and indirect influence on customers' behavior performed through prices. These two categories are carried out by means of two programs:

- Price-based programs
- Incentive-based programs

These mechanisms are highly interconnected and complementary. They are mentioned in the most part of Demand Response review I've read and considered to be the most promising for a broad uptake of DSM and DR itself.

Price-based programs consist in a change of the load patterns performed by the end users in response to a change in electricity price. This means that the electricity prices are dynamic and change during the day, reflecting the availability of electricity in real time [8,9,10]. The end user consumes energy during periods with low tariffs to obtain reduction in electricity bills, thus always having a choice in the load pattern.

Some dynamic pricing mechanisms are illustrated in Figure 2 and explained below:

- ✓ Time of use tariff (TOU): this is the simplest and most common form of dynamic pricing; it involves charging higher prices for peak electricity as a way to shift demand to off-peak periods. Tariffs are charged based on the time electricity is used and users can achieve financial benefits if they consume away from the peak period [7,9,11]. This tariff usually leads to a permanent change in consumption patterns.
- ✓ Real Time pricing (RTP) or Dynamic Pricing: this tariff varies continuously during the day based on the utility's load, directly reflecting the wholesale price of electricity. The customers are informed about the changes in price usually one day ahead (on hourly predictions and experience) so they can plan to reduce demand to respond the supply [7,9,12].

- ✓ Critical Peak pricing (CPP): it is a relative new form of pricing and it occurs when the utility faces critical events like the high wholesale price of electricity or any power network emergency; in this particular time period there is a high rise in the price. A warning signals is sent to to consumers alerting them to a critical-peak period. Usually, the price spread between day time and critical peak time is set large enough to further foster load reductions [11,13].
- ✓ Peak time rebate: in critical events described before in CPP, the utility asks to the customers to reduce the load below a "baseline load curve", it offers rebates in return for the load reduction. If the customer manages to stay below this baseline, the price of electricity remains the same [9,14].
- ✓ Variable Peak pricing: in this tariff the electricity rates are high only for the peak hours in a day. In case of specific events, the peak price goes higher than the normal peak price based on real time conditions [9,15].
- ✓ Extreme Day pricing: in this tariff the rates are similar to CPP, with an exception for some critical days, during which the price remains high for all the 24 h. The critical days are notified to the customers on day ahead the event [9,15].
- ✓ Extreme Day CPP: here the rates are similar to CPP on critical days, for the rest of the time-based tariffs do not exist [9,15].
- ✓ Inclining block rate: this tariff applies an increasing price at the increase in the electricity consumption, so the user is recommended to reduce the average consumption. A lower price compared to fixed price should be charged for the first blocks that refer to the first kWh consumed. Above a determined threshold, a higher price is set [13].

Combining several of these instruments would bring to real results.

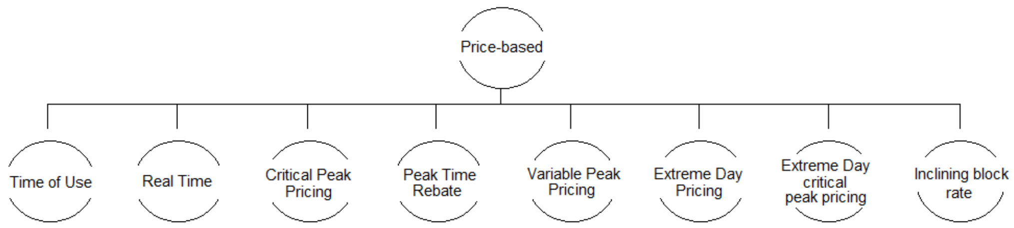


Figure 2 – Price-based mechanisms [9]

Incentive-based programs are mostly performed by the utilities. Utilities directly control the end user's load pattern once the end user agrees on conferring the whole load control in light of incentives. Moreover, the consumer can limit the use of electricity. Opposed to the price-based programs, users' consumption is directly limited. Users who agree to participate in such programs but do not respond, would incur in penalties according to the agreements.

Different types of incentives are presented in [9,11,12] and in Figure 3:

- ✓ Direct load control (DLC): a utility controls the customer's equipment remotely and the customer is incentivized for it. The customer enrolls to the program and the utility installs a control device on electrical equipment through which the utility shuts down or cycles the appliance on short notice, in exchange for incentives or bill credit.
- ✓ Interruptible/curtailable rates: this program consists in an agreement between a customer and the utility. A customer agrees to meet his energy demands at a particular time through his own ways of power generation (which can be CHP, storage batteries, solar power etc.), when there is peak demand for the utility. In response to a notice from system operator, the customer may shift loads to some generator or stored energy device within 30 to 60 minutes after being notified by the utility. The customer gets discount rates or bill credit or other concessions from the utility.
- ✓ Emergency Demand Response programs: here customers are incentivized for curtailing loads during a utility declared emergency when there is a reserve shortfall but the curtailment is voluntary. The

programs provide incentive payments to customers for reducing load, but customers can choose to give up the payment and not curtail when notified without penalty.

- ✓ Capacity Market Programs: in this program customers commit to provide pre-evaluated load reductions when system contingencies take place. The customers receive guaranteed payments for this commitment and are penalized if load reduction is not observed.
- ✓ Demand bidding and buyback programs: The customers are allowed to bid for curtailing loads in wholesale and retail electric markets. If customers bid but do not then reduce their load, they are subject to a penalty. This is usually for large consumers.
- ✓ Ancillary Services Market Programs: here customers can bid for load curtailment in ISO/RTO markets. If the bid is accepted, customers are incentivized at market price for their obligation to be on standby. When a load reduction is required, these customers are asked for curtailment and get paid.

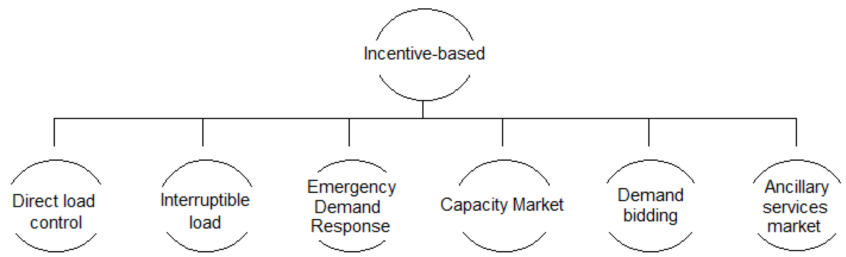


Figure 3 – Incentive-based mechanisms [9]

The illustrated frame of DSM topic has been accomplished through last 30 years and it is possible to trace each single stage of the process by recollecting the wide literature.

1.3. DSM evolution

Going back on DSM evolution, the concept of DSM grew in the USA in the 1980s and 1990s thanks to Gellings [3,4] as quoted before, and by 1995 a huge number of programs conducted by utilities has involved participants all over the world, even if DSM did not achieve the same interest or success in Europe as it did in the USA.
A renewed interest in DSM spread across the world in 2000s and 2010s as a result of climate change and energy security issues coming to the forefront of the political agenda. This is in contrast to the predictions of Gellings who argued that the development of DSM in developed countries would continue to decline.
An interesting temporal and spatial observation is that North American countries dominated the literature in the 1970s–1990s, European countries were prominent in the literature in the 1990s–2010s, and more recently Asian countries, notably China, South Korea, India and Thailand, are beginning to receive greater attention [16].
Nowadays, the potential of DSM varies from country to country as the electricity market is wide and different. For this thesis, two different market has been mostly investigated, these are the European, especially the Italian, and the Chinese market that will be briefly discussed.
Focusing on European countries, the Council of the European Union is in the process of drafting a directive on Energy Efficiency Demand Side Management; this directive would require each member state to achieve a minimum level of energy efficiency improvements through DSM programs. Each state would be free to determine which policy mechanisms to adopt to meet these levels. The target includes a recommended minimum level of investment for DSM programs from each member state of 2% of the total net revenue in that member state from electricity and natural gas sales to final customers. The DSM program investments must be additional to energy efficiency activities financed from the state budget. The member states

should also support the development of a market for DSM services [17]. Table 1 provides a forecast of DR settlement from now on.

Briefly, technological progress of European countries is moving toward providing the tools for DR by allowing customers to participate in the electric market. The European Commission has set energy and environmental goals for 2020 through the Third Climate and energy package. Studies on the economic potential of DSM and DR in Europe have focused on individual countries, looking at pilot studies in order to understand the economic potential associated to these activities. These studies estimate different levels of peak reductions in different European countries thanks to DSM and DR [18]. For instance, when looking at DR in Italy, most of the work focus on smart metering: Italy is the European country with the highest penetration of advanced electricity meters with about 90% of overall meters already installed.

Table 1 – DR forecast in UCTE countries (GW) [19]

Country	2013	2015	2020
Italy	4	4	4
France	3	3	3
Spain	2.5	2.7	3
Netherlands	1.1	1.25	1.5
Greece	0.8	1	1.3
Germany	0.4	0.5	0.05
Belgium	0.2	0.2	0.2
Hungary	0.08	0.1	0.2
Montenegro	0.05	0.05	0.05
Luxemburg	0.02	0.02	0.02
UCTE countries	12.15	12.82	13.32

Throwing an eye on the Chinese market, it is clear how DSM has a central role nowadays.

DSM was introduced into China at the beginning of the 1990s, before which traditional load management had been focused on power rationing during peak periods. Generally, the development of DSM programs in China can be divided into three stages: DSM before the Electric Power System Reform (1991–2002), DSM after the Electric Power System Reform (2002–2005) and DSM centring on energy conservation and emission reduction (the eleventh five-year-plan period (2005–2010) and the 12th five-year-plan period (2010–2015)) [20].

Focusing on the third stage, on August 31 of 2011, the State Council promulgated “The Integrated Program for Energy Saving during the 12th five-year-plan period”. According to China’s 12th Five-Year Plan, non-fossil fuel generation should account for 11.4% and 20% of the total primary energy consumption by 2015 and 2020 respectively [21].

According to the program, it is important to emphasize the development of supporting policies and to propose the implementation of comprehensive pilot programs in cities, promoting the energy efficiency of power plants. DSM can be implemented effectively with all of these measures [20,22].

Basically, policies and regulations implemented since now indicate that the government has been promoting the development of DSM programs, and DSM now has become an important type of energy resource to achieve the goal of energy conservation and emissions reduction. However, despite Chinese government’s efforts, the picture is uneven across provinces and there is no clear reinforced policy for its broad uptake.

According to the author Yongzhen Yu [23], the most important reason disabling DSM is the lack of long-term, stable and gradually increasing funds to flow into DSM projects, which is the bottleneck of DSM development in China.

Compared to other countries, the funding for DSM in China is very little, moreover the most part of Chinese regions has not established special DSM funds. To solve this problem, the governments would need to redesign the whole policy framework and play a stronger role to improve DSM and energy efficiency. Stable predictable funding mechanisms allow DSM programs to be planned and implemented [23]. It is time for China to develop a definite target and timetable to develop DSM, also relative policy outline in the near, medium and long term future are needed [23]. Cooperation among utilities, governments, customers are seen as measures to speed up the implementation of DSM programs.

Given the complicated electricity system of China, it is not easy to coordinate the Chinese sustainable energy development strategy. However, China newly established National Energy Commission (NEC), the highest level nationwide energy policy-making and coordination organization, which would be very helpful in integrating DSM into the current electricity system reform [24].

1.4. DSM applications

In the past, DSM programs have focused more on the management of electricity demand, however DSM includes non-electric energy measures also. Gellings' definition quoted above mainly focuses on load shapes and does not directly include current world policy priorities to reduce overall energy consumption and CO_2 emissions. Eissa [25] states that the goal of DSM should be to reduce energy demand and shift patterns of consumption to help distribute the demand over the day. Eissa's definition (described in Figure 4) is broad and includes both actions and implementers, this underlines how important is to involve the whole society in DSM strategies.

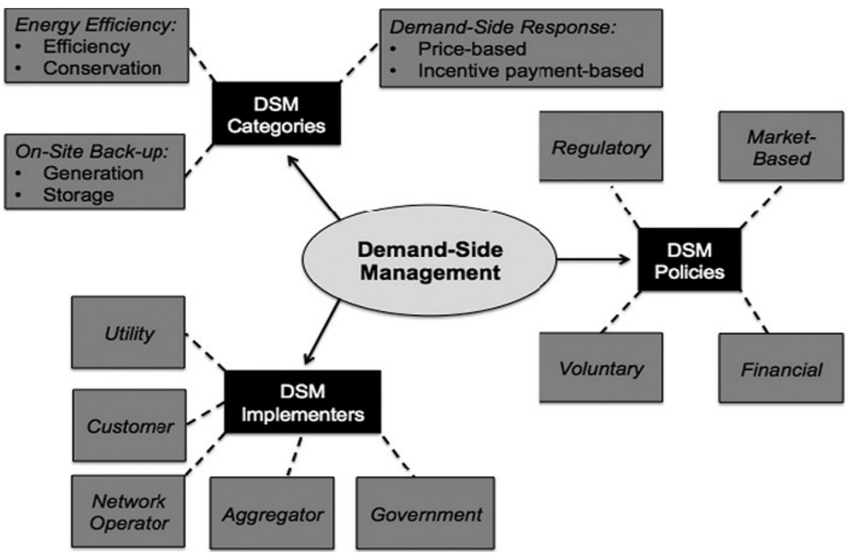


Figure 4 – Actions and technologies of DSM [16,25]

Also, as well explained by Warren [16], the definitions of DSM can vary in what they include or exclude.
DSM is applied to wide cases in literature, some authors use the definition of DSM as that of Smart grids [26,27,28] considered to be a key feature of future energy scenarios as they align energy generation and demand and can change the electric usage by responding to DR measures.
Also, most of the time DSM is overlapped to Demand Response [9,29,30,31] implying the response of the end users to price change and the smoothing of the demand away from the peak period, even though DSM already comprises DR measures, as explained before.
In some publications, DSM is combined with photovoltaic or solar collector systems as in the case of [32] where optimum panel plant configurations are found for each price strategies by varying solar-related design parameters.
Some other works simply refer to DSM as a measure for reducing energy demand at peak times [33] by using timer or as in [34] where automatic controllers are applied to reduce the energy request of the electrical equipment.
Interesting opportunities come from the use of DSM strategies for the management of electric devices. A very promising combination is when the heat pumps operate according to DSM strategies, more precisely when load management is applied.
In [35] the potential of the DSM strategies using heat pump combined with the building mass thermal storage (BMTS) is presented. This work explores the possibilities of load shifting in residential buildings by using the thermal mass of the building with the aim of postponing the heat demand for a certain period, unfortunately DSM strategies are listed but not investigated. For instance, the author shows how load shifting can be successfully applied during the transition period (where less energy is required from the building) but does not propose any analysis on such transition period.
A similar work [36] investigates on the impacts of DSM on BMTS as well. In this paper the building' storage capacity is improved by means of a phase change materials (PCM) built structures. The author shows how the

application of PCM in building environments enables the thermal storage of the building and allows some reduction in the overall electrical energy consumption if peak load shifting is applied but the presented analysis is carried out during a too high temperature to be a winter operation so it is clear that PCM only couldn't be enough for a very cold period and a thermal storage would be necessary to ease the implementation of DSM.

The application of thermal storage systems (TES) in DSM can add flexibility to the energy management as shown in a great number of works in the literature and it is our field of study.

The considered research approach closely looks at various thermal storage investigations carried out between the years 2000-2010. Thermal energy storage was widely used in buildings to shift on-peak load to off-peak hour during this period. A good review on this topic can be found in [37] where the principal peak demand management are illustrated; Figure 5 shows the classification of methods for peak demand management in buildings, divided in three main categories being the Load shedding, the Load shifting and other methods that are not included in the first two.

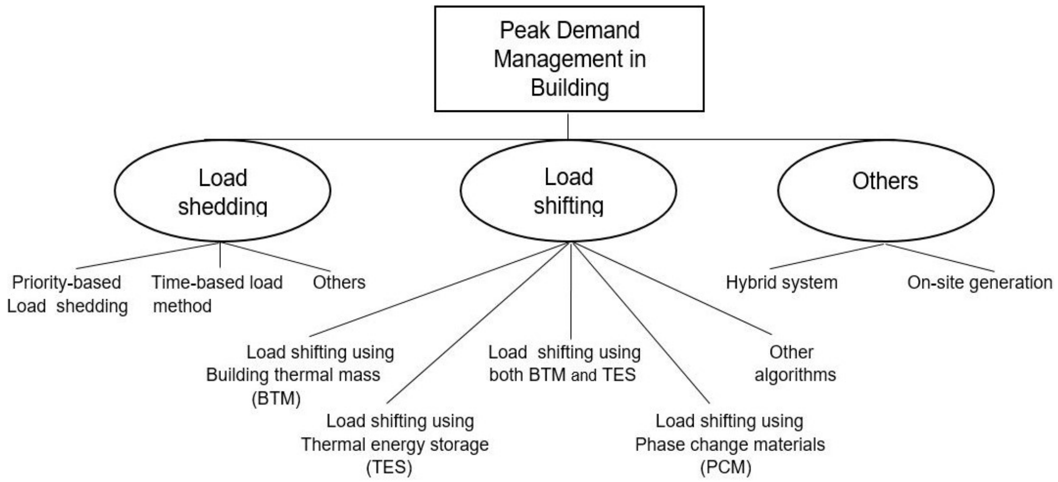


Figure 5 – Classification of peak demand management in buildings [37]

The present research collocates in the second category (Load shifting), for instance in the presented works load shifting using a thermal energy storage (TES) while heat pumps are in operation is investigated.

It is now important to compare relevant works connected to TES while combined to heat pump systems for a better understanding of what will be presented in this thesis.

In [38] a typical ambient air to water heat pump system in a single-family house has been examined concerning the impact of DSM providing control. The simulated scenarios differ from each other in terms of control strategies, dimension of the buffer storage and the heat pump. The authors explain how studied strategies can have a positive impact on smoothing the demand away from the peak; however, all the investigated smart controls cause an increase in the overall energy consumption if compared to the case scenario. This is due to a decrease of the heat pump efficiency and the increase of the storage losses as the studied case consists in enlarging the buffer storage and sometimes the heat pump capacity.

An increase in the energy consumption can happen while energy storages are applied for the reasons explained above but it is auspicial to contain it; if the increase is consistent, applied strategies have to be changed and new one should be investigated. Also in [39] energy consumption increase occurs. In this work a lab test setup is built to examine the potential of a heat pump for DR purposes. A market based multi-agent systems is developed to control the heat pump with the aim of limiting the peak power demands of the building and to maximize the self-consumption of the locally produced electricity. Two type of energy sources are studied which are a photovoltaic installation and a small wind turbine to help the exploitation of renewable sources. However, the result is that the heat pump consumes more energy than the reference case (8-12% more) due to the ON/OFF frequency of the system. This happens because the ultimate goal is to reduce the under-voltage problems avoiding the request to occur at the same time and this is important for DSM request but it has to be accomplished without penalizing energy consumption and costs, being remarkably important targets, as will be discussed in our works. Also, energy consumption and cost reductions can be fulfilled if renewable energy sources are integrated in the system and contribute to balance the energy demand. In [40] renewable sources have an important role in the generation system as they are sized to get about 75% of the total HVAC system energy consumption on 100% of the total energy requirement of the studied ZEB (zero energy building). A simulation model of this ZEB is performed with the integration of the PV panels in the storage tank. Plus, three different strategies based on electricity prices are performed with the aim of maximize the PV production (Type A, B, C) and investigate on the better strategy; in this analysis, the size of the water storage varies to identify possible improvements in DR measures as we also did (in Chapter 2) with a main difference being the validation of the simulated model that has not been performed here by the authors. However, the performed simulations, even if not validated, show how a proper control strategy make it possible to achieve relevant money savings and high degree of energy self-consumption, opening the field for further investigations. A very good work that demonstrates to be complete as it integrates renewable systems to a storage tank can be found in [41]. Here a heat pump system coupled with two storages, one for domestic hot water, the other for heating, is presented. Different configurations of these storages are investigated, as in the previous work [40], with the purpose of finding the best solution. A control strategy is performed according to the dynamic electricity pricing that adapts the heat pump control and/or the tank charging process to respond to the price incentives. The best configuration is identified: while the parallel hydraulic integration by four-pipe connections leads to an overconsumption which is hardly financially compensated by the use of dynamic tariffs, the parallel two-pipe configuration offers the largest cost savings for the consumer and the load shifting potential. Even though energy savings are assessed, cost are not investigated; the analysis turned out to be purely qualitative but not quantitative as the analysis we have pursued in our works, where energy consumption reductions are translated into cost savings.

Table 2 shows the most representative works found in the literature, these are the closest to the topics of the PhD. Contents and limitations are indicated for a better comprehension of the state of the art and for understanding the novelty of the work that will be further explained in this and future chapters.

Table 2 – Most representative work on Demand side Management (DSM) and Demand response (DR) found in literature.

Author(s)	Ref	Year	Type of study			Topic	Conclusions	Limitations
			Simulated/ numerical	Experimental	Review, other			
L. Gelazanskas, K. A.A. Gamage	[8]	2014	✓			DSM review, novel electricity demand control technique using real-time pricing, enabling user side load control	More effective balance between supply and demand side and improving in system's efficiency	Real time price could create higher peaks in demand at different time; model mismatch, a very accurate representation of model is needed.
J.Thakur, B. Chakraborty	[9]	2016	✓			Simulations for a price based and incentive based mechanisms to evaluate DR and DSM potential for residential consumers	Financial benefits and efficient usage of resources for the consumers if DSM strategies are applied	Technological improvements are needed, plus the target cannot be fulfilled if customers are not well aware of the project
C.Bergaentzlé, C.Clastres et al	[13]	2014			✓	Provide recommendations for the instruments to be used to prompt DR, maximizing energy and environmental efficiencies of various countries	Different DSM models which should be deployed depending on the specific generation mix in any given country are presented, it is discussed how DSM improves the flexibility and reliability of the energy system	-
J. Torriti, M.G. Hassan et al	[18]	2010			✓	These studies estimate different levels of peak reductions in different European countries thanks to DSM and DR	Reasons and limitations for the uptake of the DSM are explained	-
C.Ellerbrok	[35]	2014	✓			The potential of the DSM strategies using heat pump combined with the building mass thermal storage (BMTS) is presented; possibilities of load shifting in residential buildings by using the thermal mass of the building are presented to postpone the heat demand for a certain period	The variation heating curve correction achieve a higher thermal comfort and greater balancing power potential if low tariff hours appear in night times; the variation pulse width modulation attains better results if low tariff hours are appearing in daytime	DSM strategies are listed but not investigated
W.A. Qureshi, N.K.C. Nair et al	[36]	2011	✓			The building' storage capacity is improved by means of a phase change materials (PCM) built structures, the author shows how the application of PCM in building environments enables the thermal storage of the building and allows reduction in the energy consumption if peak load shifting is applied	Using PCM has potential significant advantages from space heating viewpoint such as peak load shifting, energy conversion, reduction in electricity consumption bills through RTP (real time price) tariff and reduction in the overall electrical energy consumption	The analysis is carried out during a too high temperature to be a winter operation
D.Günther, J.Wapler et al	[38]	2014	✓			A typical ambient air to water heat pump system in a single-family house has been examined concerning the impact of DSM providing control; the simulated scenarios differ in terms of control strategies, dimension of the buffer storage and the heat pump.	The investigated strategies have a positive impact on smoothing the demand away from the peak	All the investigated smart controls cause an increase in the overall energy consumption if compared to the case scenario

D.Vanhoudt, D.Geysen et al	[39]	2014	✓	✓	Lab test setup is built to examine the potential of a heat pump for DR purposes and a market based multi-agent systems is developed to control the heat pump for limiting the peak power demands	Current heat pump controller is able to shave the power consumption peaks of the building and the active control of the heat pump can diminish extra investment costs for grid reinforcement	Increase in the energy consumption while applying DSM strategies
L.Schibuola, M.Scarpa et al	[40]	2015	✓	✓	A simulation model of a zero-energy building is performed with the integration of the PV panels and a storage tank; 3 different strategies based on electricity prices are performed to maximize the PV production and investigate on the better strategy	A proper control strategy make it possible to achieve relevant money savings and high degree of energy self-consumption	Simulation model is not validated.
E.Georges , P.Garsoux et al	[41]	2016	✓	✓	Potential of DSM in a residential building equipped with heat pumps and thermal storage for both space heating and DHW are investigated. Control strategy in response to dynamic electricity pricing is presented.	Peak demand increases are observed with large penetration rate of heat pumps. A coordination mechanism between consumers allows to reduce peak demand increase without significantly impacting the cost savings for the end-users	Energy savings are assessed but costs are not investigated
F.Sehar, M.Pipattanasomporn et al.	[42]	2017	✓		Total building performance is assessed to define a method to determine the DR potential of a building and to identify the amount of electrical demand that can be shifted in time	Building's peak demand reduction potential as a result of performing DR to maximize building's economic benefits while maintaining occupant thermal and lighting needs	Renewable sources are not applied, nor thermal energy storage
M.Puchegger	[43]	2015	✓		Optimizing the control of electric equipment and reduce the annual cost dealing with their potential to use DSM to optimize load behavior	Electrical consumers are identified and 3 types of load distribution are investigated with the aim of pointing out the more efficient solution	Lack of thermal storage integration
N.DeForest, G.Mendes et al	[44]	2013	✓		Different configurations of thermal energy storage are investigated to formulate a system capable of finding the best technical features of a thermal storage. Annual energy requirements are used to determine system cost feasibility, payback periods and customer savings under local utility tariffs	A storage tank is identified in terms of capacity and DSM strategy according to the investigated locations.	
J.Abedin, S.Firth,et al	[45]	2013	✓		The behavior of a building with a without a retrofit action is simulated with the aim of comparing the two conditions when demand shifting is applied.	The investigated storage tank can help to smooth the demand (without affecting indoor thermal comfort) if the building has a proper thermal performance insulation.	No renewable sources are investigated and no economic evaluations are performed; storage proposed capacity is too big for a residential application

The novelty of the present work lies in the application of DSM real existing cases within the building sector which also integrate renewable energy sources into the system. Renewable sources are of paramount importance in this works as they help to reduce energy consumption and costs and contribute to balance the supply and the demand.

Initially, reliable experimental data from realistic experimental campaigns was consulted. Real experimental data contribute in a second step to the accuracy of the designed models. These models are built inside a dynamic simulation tool and this is performed in order to closely represent the true behavior recorded in each of the studied experimental campaigns. The purpose of such simulation models is to study the integration of DSM strategies in the built environment and to analyze the effect of the thermal loads on the electricity consumption as well as the building energy performances in the long run.

The reliability of such building simulation models depends on the accuracy of the considered variables (i.e. materials' characteristics, system components' information, etc…) as well as the effectiveness of the designed solutions.

Using dynamic building modeling, the presented research aims to provide an insight into the energy performance and the thermal transient response of the studied cases. The building response has been studied for the most representative cases with the aim of investigating on the best solutions. A validation of the simulation models has always been carried out by comparing the available real data to the results from the building performance simulations.

The main focus of the research is the integration of DSM strategies in the building sector to analyze the effect of thermal loads on the electricity consumption. The analysis is performed without sacrificing occupants' thermal comfort and with the purpose of minimizing the overall operating cost through reducing peak demand. Therefore, peak demand management is usually performed to reduce the demand during the on-peak time which results in substantial saving of peak demand costs and in smoothing the demand away from the peak hours for distributing it over the day. Spreading the energy demand over the day will require the heating system to operate at different

times. The price difference is a direct incentive which encourages consumers to alter their load profiles using DSM measures such as load shedding, load shifting and so on. These management methods turned out to be a great opportunity to apply thermal energy storage to decouple the temporal link between the energy supply and demand, enabling them to be shifted in time.
Successful deployment of thermal energy storage becomes critical to ensure an important penetration of heat pumps, without which domestic decarbonization target would become unachievable.
The final outputs of the entire process are the investigation on the energy consumption, the cost of such strategies and the thermal comfort of the building, obtained through reductions on thermal/electrical loads when required. These results have been pursued with a more innovative approach that is the combination of a series of tools which are the simulation models to represent DSM strategies and the implementation of thermal energy storage but also renewable sources as photovoltaics panels and heat pumps.
To have a quick overview of the entire research process, Figure 6 is presented. FIGURE 6 summarizes the research methods that will be presented in this manuscript and illustrates how the INPUTS (in green) are elaborated to become the OUTPUTS (in light blue).

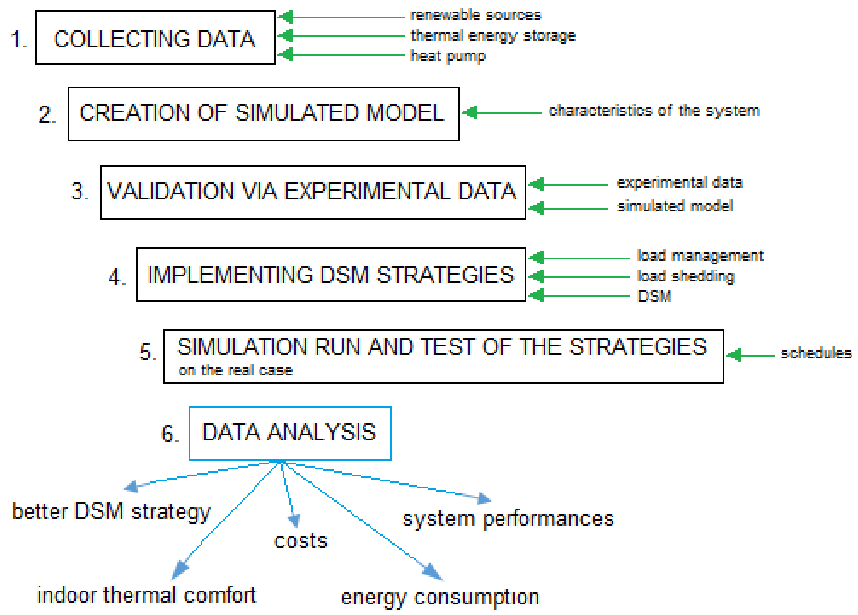


Figure 6 – Simplification of the research process.

2. Simulation and performance analysis of a CO2 heat pump for residential application performing DSM strategies

2.1. Introduction

The work described in this chapter has been presented to the 11th IIR (International Institute of Refrigeration) Gustav Lorentzen Conference on Natural Refrigerants held in Hangzhou on August 2014 [46]. In this paper an existing installation of a CO_2 heat pump in a domestic application is presented. A dynamic simulation of the building's emission and production system is set up for heating, cooling and hot water production in order to evaluate possible implementation of demand side management (DSM) control strategies. DSM methods are tested and the possible beneficial effects are analyzed.

CO_2 is one of the few natural refrigerants neither flammable nor toxic; it is inexpensive, easily available and does not affect the global environment as many other refrigerants do. Several studies have investigated the use of CO_2 as working fluid in heat pumps (HP) for tap water production [47-50], highlighting a good performance against traditional refrigerants. As far as HVAC coupling is concerned, CO_2 heat pumps are particularly interesting for high supply temperature systems and for combined heating and cooling applications [51].

In this study a hybrid CO_2 heat pump is coupled with an absorption chiller powered by solar energy for residential application. In previous works the cooling performance of such a system was analyzed [51-53] while in operation inside a real apartment in Minhang campus of Shanghai Jiao Tong University. Here, instead, the heating mode is taken into account and particularly the energy consumption of the heat pump and the internal thermal comfort are analyzed when demand side management (DSM) strategies are in action.

DSM programs can be an effective way to achieve sustainable development and help energy consumption reduction in buildings that account for approximately 40% of global energy consumption [54,55]. Above all the countries, China is the largest consumer in residential building energy use and the third in commercial building energy use [56] and this trend in Chinese buildings will not stop anytime soon [57]. Hence, improving energy efficiency and energy conservation in buildings has become of paramount importance for the reduction of carbon dioxide (CO_2) emissions.
This chapter focuses on load management of a CO_2 heat pump used in a residential application. Several demand-side strategies are performed by means of a dynamic simulation model with the aim of analyzing the overall performance (i.e. thermal comfort and energy consumption) of the system in heating mode.

2.2. Case study and model description

A simulation was implemented to point out the behavior and performance of the heat pump combined with DSM strategies by means of a case study. The dynamic simulation tool used is TRNSYS [58]. The DSM strategies that has been investigated are (i) a peak shaving strategy and (ii) a night load shifting strategy.
The case study is represented by an apartment inside the Green Energy Laboratory in Minhang campus (Figure 7a) at Shanghai Jiao Tong University in Shanghai (PRC). The total area of the apartment is 90 m^2, consisting of a 19.2 m^2 bedroom A, a 16m^2 bedroom B, a 46.8 m^2 living room with open kitchen, a 5 m^2 bathroom and a 3 m^2 storage room (Figure 7b). The total windows area is 27.84 m^2. The north, south and east building sides are exterior walls, while the west side is adjacent to another apartment. The overall heat transfer coefficients of the building envelop are listed in Table 3.
The heating production system for the apartment is a CO_2 heat pump, producing both space heating and domestic hot water (DHW), stored into a

thermally stratified water storage tank (0.3 m^3). The emission system in the apartment is represented by fan coil units (FCU) provided in each room.

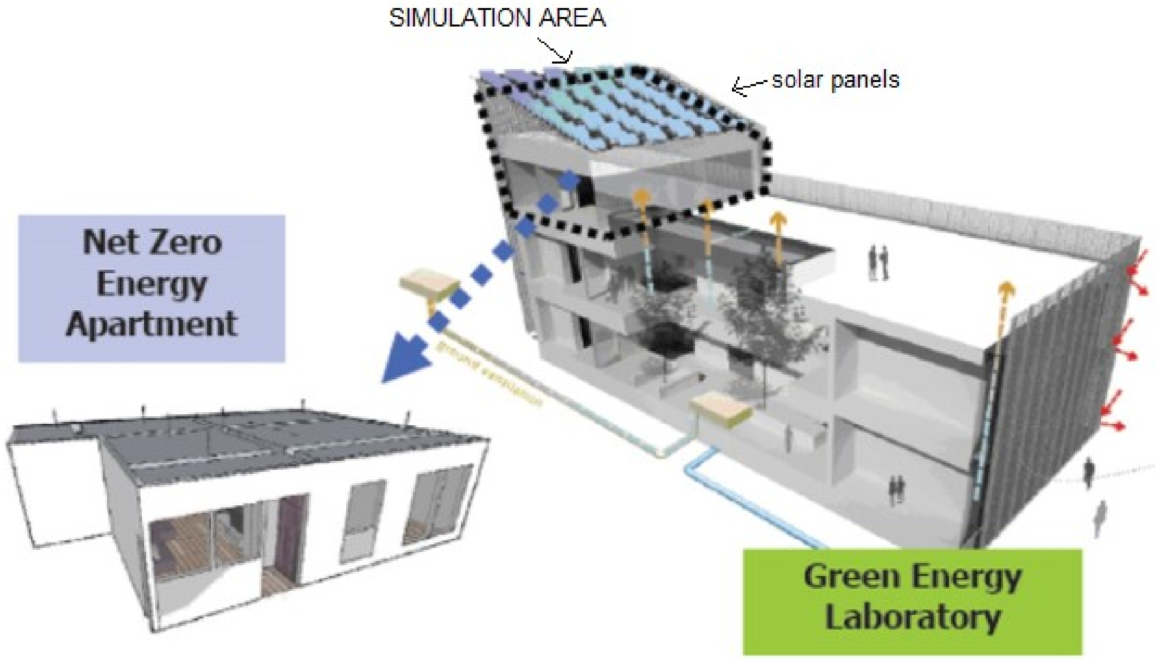


Figure 7a – Apartment in Green Energy Laboratory (case study) [51].

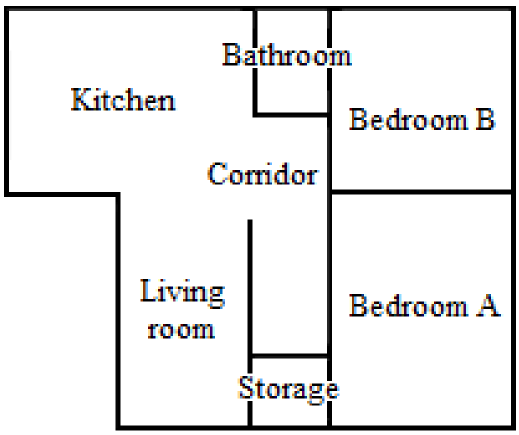


Figure 7b – Plant of the apartment (case study) [46].

Table 3 – Thermophysical properties of the case study [46].

Test Building	U value [W/m^2K]	G value [-]
Roof	0.34	-

Exterior wall	0.57	-
Interior wall	0.92	-
Floor	1.08	-
Window	2.83	0.62

Figure 8 shows the schematic diagram of the TRNSYS model. The heat pump is switched on/off based on the thermal energy storage (TES) tank temperature that has to be kept between 45 and 50°C. Heating is provided to the apartment in order to maintain the internal temperature at the set point (i.e. 20-22°C for 24h in Bedroom A and B and 18-20°C from 8 am to 9 pm in the living room). The weather file for Shanghai of a typical year used in TRNSYS is from METEONORM [59].

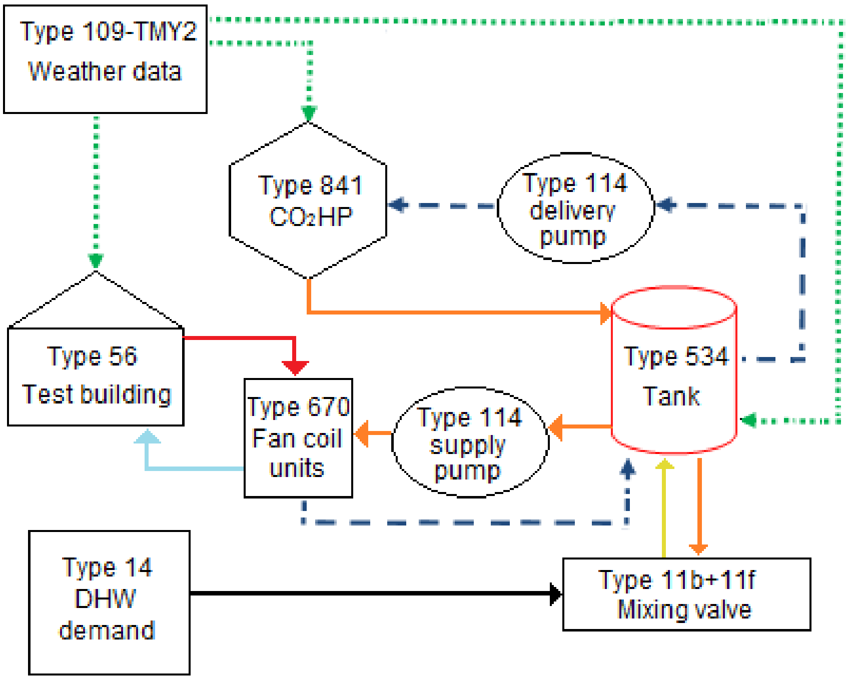


Figure 8 – Simulation model on Trnsys [46].

A specific simulation module (Type 841) was developed to represent the CO_2 HP, based on a series of real test data showing a maximum heating power of 5 kW and cooling power of 4 kW [6]. Figure 9 shows the performance curve versus ambient temperature of the CO_2 HP with a fixed inlet/outlet water temperature of 40°C and 50.5°C respectively. The COP of the CO_2 HP can still reach 2.2 even when the ambient temperature is -12°C, while the maximum value is always below 3.

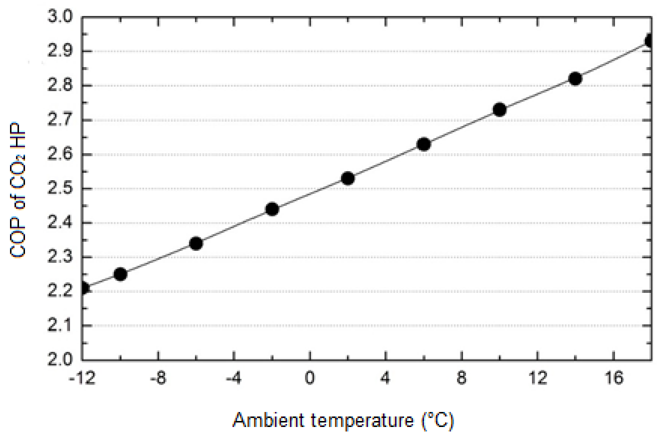


Figure 9 – Performance curve of CO_2 HP [46].

Type 534 was chosen to simulate the water tank with an immersed coiled tube. The tank loss coefficient is set to 0.8 W/(m^2·K). The DHW demand profile used in the simulation is represented in Figure 10, which was obtained by real test data for a family of three people in Shanghai [53]. The DHW supply temperature is set at 40°C.

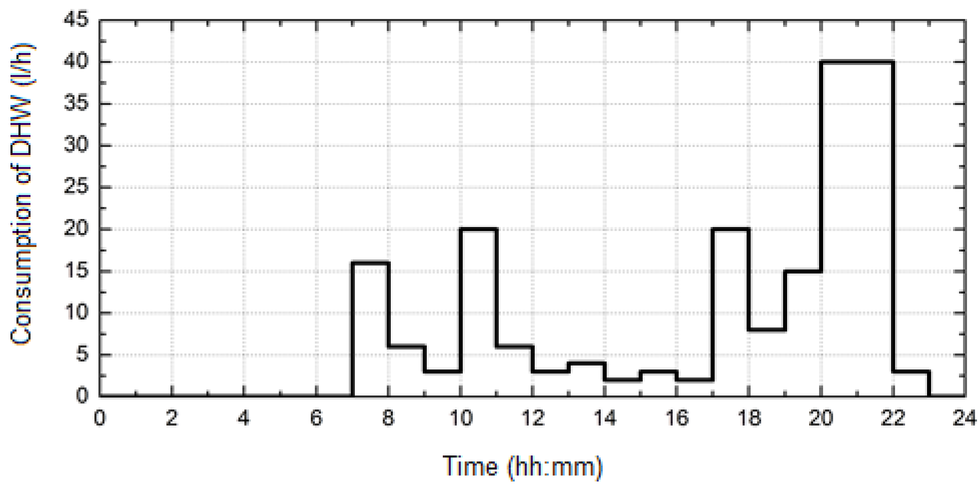


Figure 10 – Domestic hot water consumption profile [46].

The model was thoroughly validated for the cooling mode [51-53], here the comparison between simulated and experimental data during a typical winter day in heating mode is reported. During the testing phase the average value of ambient temperature was 4.8°C, while the room temperature in all the three rooms was set to 22°C. In particular, Figure 11 shows the electric power consumption (left axis) of the heat pump measured and calculated: the maximum difference recorded is of about 4% and it seems that the model tends to overestimates the power consumption. Thus, also for the COP (Figure 11 on the right axis) a good fit between experiments and simulations is achieved (even if the simulation cannot reproduce exactly the fluctuations of real data due to the model simplifications).

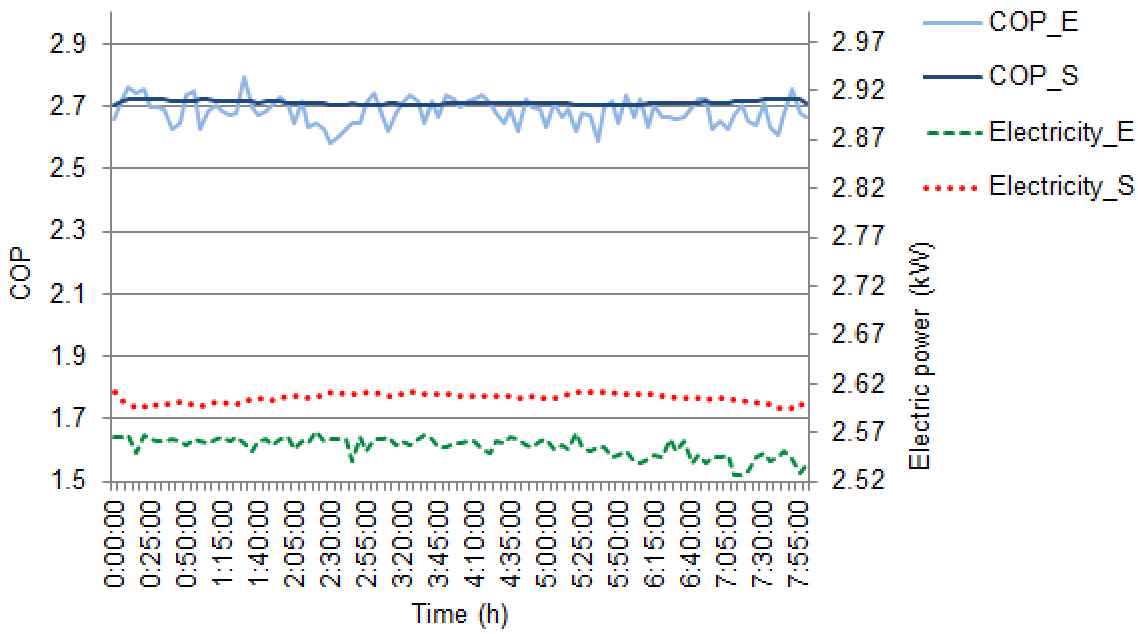


Figure 11 – Comparison between Experimental (E) and Simulated (S) data on COP (left) and power consumption(right) of heat pump in heating mode [46].

The DSM strategies considered in this work are peak shaving (PS) and load shifting (LS) strategies:

- Peak shaving is one of the most relevant strategies for the grid, consisting in moving the electricity consumption in order to cut the peaks

(Figure 12). In this case, the peak shaving strategy is in action from 9 am to 12 am and from 4 pm to 7 pm. During this period the heat pump is switched off while it works in the remaining hours.

- The load shifting strategy, instead, involves shifting loads from on-peak to off-peak periods (Figure 12). In our case, we considered a night load shifting strategy, consisting in switching off the heat pump from 8 am till 8 pm.

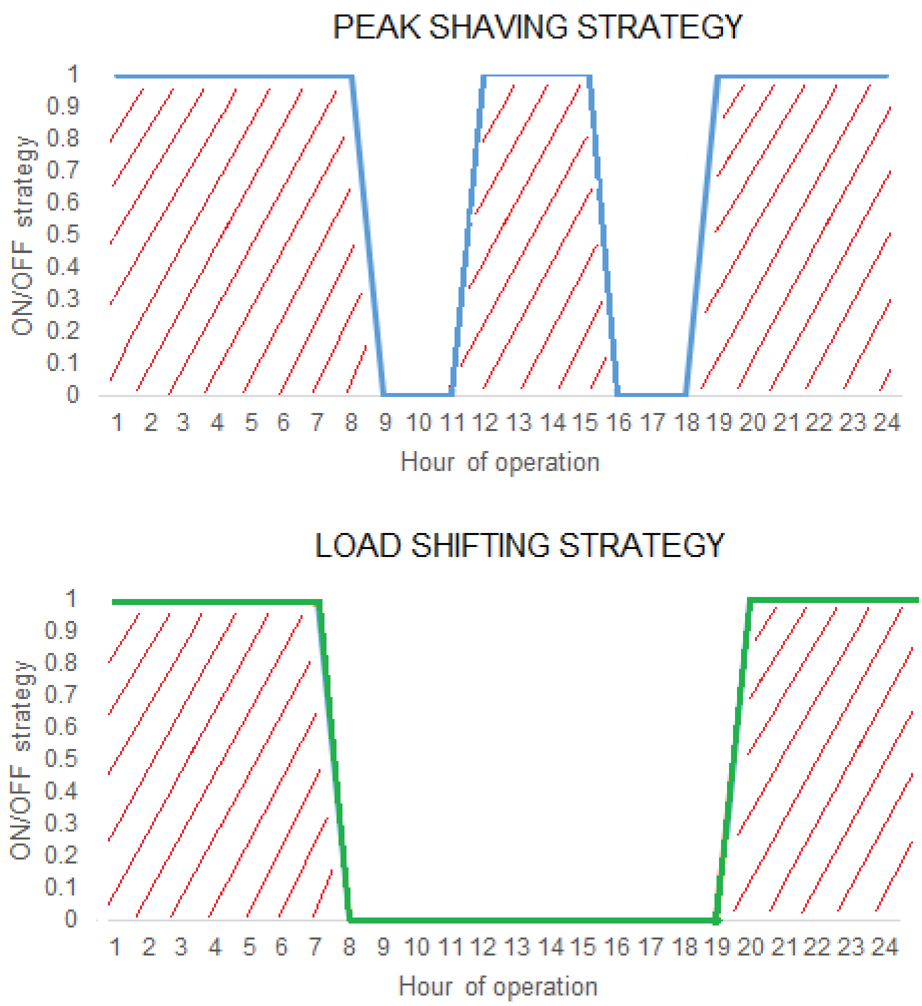


Figure 12 – DSM strategies: peak shaving (clipping) on the left side and load shifting on the right side.

In order to increase the building thermal storage to satisfy the flexibility requested by the grid, the storage tank size was increased from 0.3 m^3 to 0.5

m^3 and 1 m^3. Simulations were performed for several cases, combining the different storage sizes with the DSM strategies and the results were compared with the reference configuration with no DSM strategy in action (NO DSM). The heating period considered in the analysis goes from November to February (2888 h of simulation with a time step of 2 minutes).

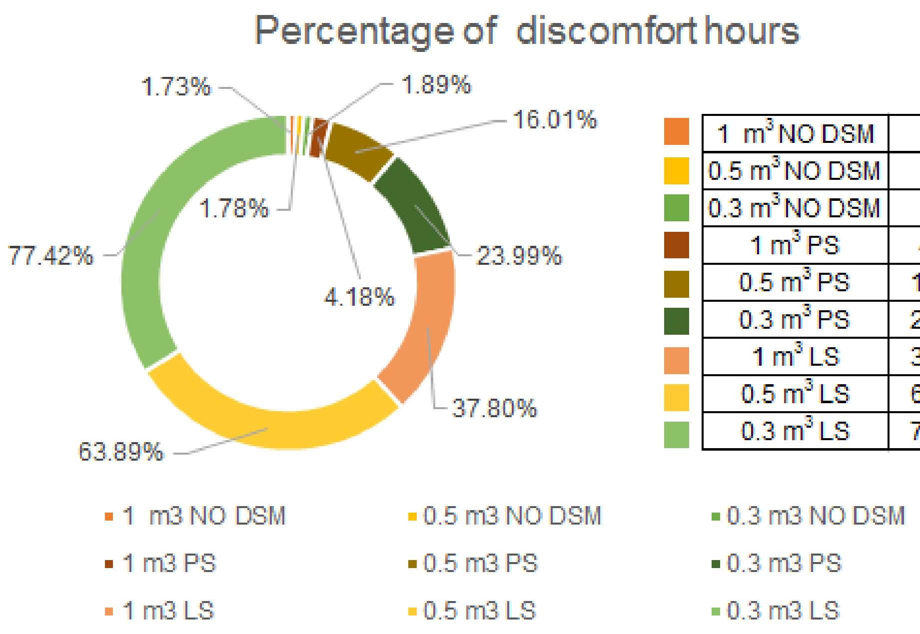
2.3. Results and discussion

In this section, main results of the performed simulations are reported (Table 4). The discomfort hours were calculated: there is underheating when the internal temperature is below 18°C, while there is overheating if the internal temperature is above 26°C. The percentage of the discomfort hours over the total number of the operative hours was assessed and if it is lower than 10%, the control strategy can be judged feasible. Moreover, the total electricity consumption (including the energy demand of heat pump, pumps and fan coil units) was evaluated together with the average coefficient of performance for the heating period.

Table 4 – Simulation results for the different configurations and DSM strategies [46]

	Max discomfort hours	Percentage of discomfort hours	Electricity consumption	Average COP
	[h]	(%)	[kWh]	
0.3 m^3 NO DSM	29.4	1.89	3620	2.63
0.3 m^3 PS	374.3	23.99	3360	2.77
0.3 m^3 LS	1207.8	77.42	2750	2.76
0.5 m^3 NO DSM	27.8	1.78	3660	2.61
0.5 m^3 PS	249.7	16.01	3440	2.75
0.5 m^3 LS	996.7	63.89	2910	2.79
1 m^3 NO DSM	27.0	1.73	3730	2.61
1 m^3 PS	65.2	4.18	3600	2.71
1 m^3 LS	589.7	37.80	3200	2.82

In Table 4 the maximum discomfort hours for the building are summarized (they always refer to the living room that has the worst thermal performance due to its heating schedule). It can be noticed that when the peak shaving strategy is in action the storage tank available in the reference configuration (0.3 m^3) is not enough to guarantee all the flexibility requested by the grid and a 1 m^3 storage tank is necessary to keep the discomfort hours below the 10% of the total operative hours. In the case of the load shifting strategy, instead, not even the largest storage size here evaluated is enough to maintain the internal temperature in the comfort range, because of the long period when the plant is forced to stay off, meaning that the energy demand for space heating cannot be satisfied. Figure 13 shows the percentage of discomfort hours for each strategy.



1 m^3 NO DSM	1.73%
0.5 m^3 NO DSM	1.78%
0.3 m^3 NO DSM	1.89%
1 m^3 PS	4.18%
0.5 m^3 PS	16.01%
0.3 m^3 PS	23.99%
1 m^3 LS	37.80%
0.5 m^3 LS	63.89%
0.3 m^3 LS	77.42%

Figure 13 – Discomfort hours for each strategy.

Figure 14 shows the temperature inside the building (in the living room and in room A) and the water temperature inside the tank during a PS strategy: it is evident how the energy stored into the 0.3 m^3 tank is not enough, thus the building temperature goes below the underheating set point during the peak shaving period (Figure 14a). With the 1 m³ tank this issue is overcome and the tank temperature remains warm enough to comply with building energy demand (Figure 14b). Figure 15, instead, represents the DHW supply temperature and it is evident that during a PS strategy such temperature drops below the set-point (40°C) both with a 0.3 m³ (Figure 15a) and with a 1 m³ tank (Figure 15b). This means that the DSM strategy cannot be addressed to space heating and DHW demand at the same time, because the system does not have enough thermal flexibility.

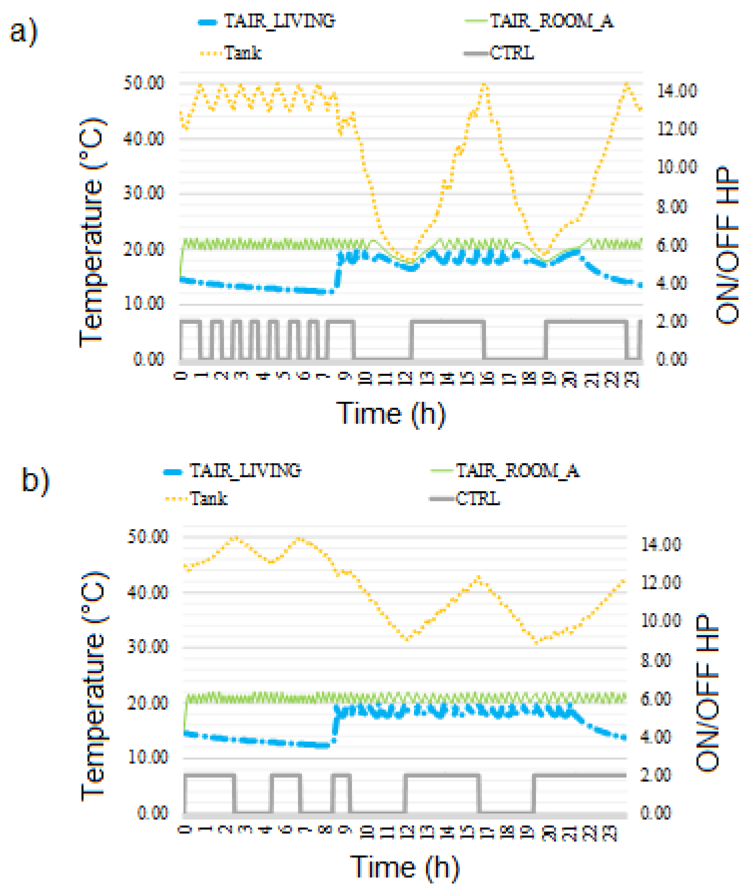


Figure 14 – Building temperature (Tair_living, Tair_room_A) and storage tank temperature trend during a PS strategy for a 0.3 m³ (a) or a 1 m³ storage tank (b) [46].

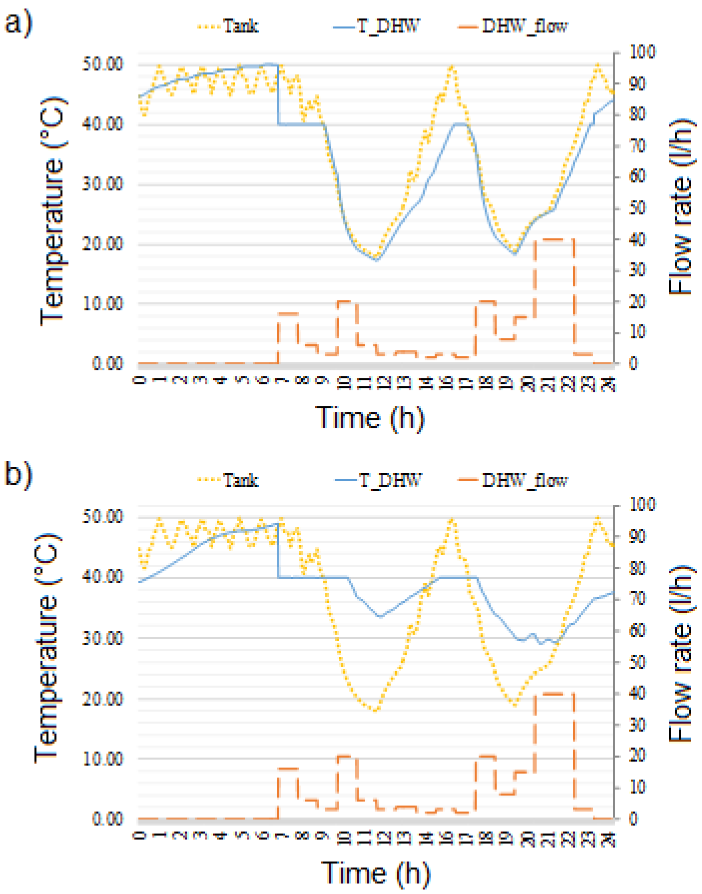


Figure 15 – DHW supply temperature and flow rate (T_{DHW}, DHW_{flow}) and storage tank temperature (Tank) trend during PS strategy for a 0.3 m^3 (a) or a 1 m^3 storage tank (b) [46].

As far as the heat pump performance is concerned, the energy consumption when the DSM strategies are in action is lower, given the storage size, because the working hours are reduced (see Figure 16).

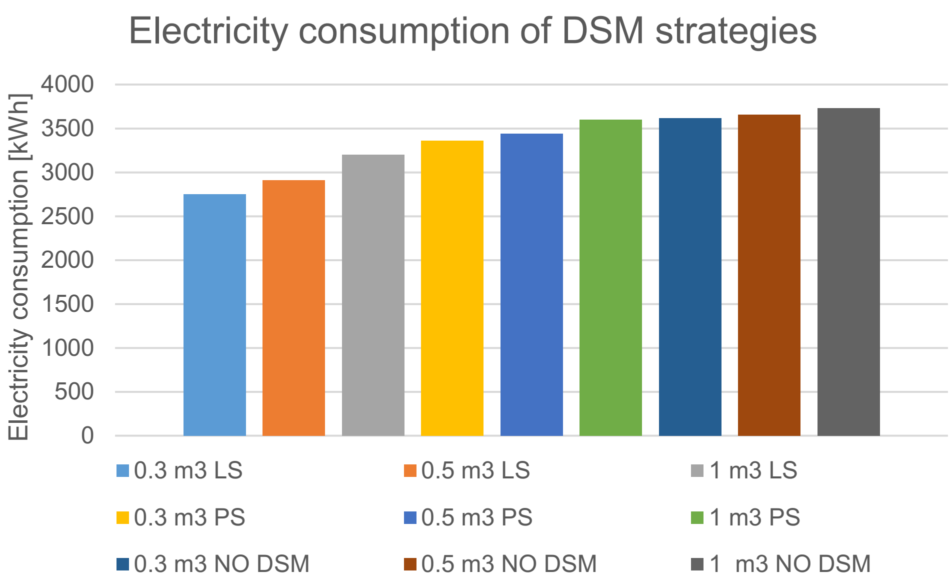


Figure 16 – Electricity consumption for each DSM strategy and base case.

Consequently, considering that, outside the peak hours, the electricity price is generally cheaper, a reduced energy bill can be achieved, as will be further explained. Comparing instead the energy consumption for the same DSM strategy but varying the storage size, as expected, the consumption is higher in presence of bigger storage tanks for the increased energy losses in the system and also the COP slightly decreases.

According to Chinese electricity tariffs for residential sector, the night operation is significantly cheaper, for instance the price from 8 pm to 8 am is 0.307 ¥ (off-peak), while from 8 am to 8 pm is 0.617 ¥ (on-peak), which is twice of the off-peak price. In Table 5 a comparison between the tank charging (for each capacity, 0.3 m^3, 0.5 m^3 and 1 m^3) for a normal operation during on-peak price and for a night operation during off-peak price is presented.

As showed, if the system works in the on-peak time the cost is more than doubled comparing to the off-peak load shifting strategy cost, identifying a substantial saving for the end user, especially if the strategy is applied on the long run.

Table 5 – Cost of each strategy in ¥ and the equivalent in €.

	Strategy	Energy consumption [kWh]	Price in ¥	Price in €
DSM	0.3 m^3 LS	2750	844.25	114.06
	0.5 m^3 LS	2910	893.37	120.69
	1 m^3 LS	3200	982.4	132.72
NO DSM	0.3 m^3 NO DSM	3620	2233.54	301.75
	0.5 m^3 NO DSM	3660	2258.22	305.09
	1 m^3 NO DSM	3730	2301.41	310.92

2.4. Conclusions

This chapter shows the behavior of a CO_2 heat pump when producing space heating and domestic hot water for a residential application. The considered heat pump has a COP always lower than 3. The introduction of two DSM strategies was evaluated: a peak shaving strategy and a load shifting strategy. The simulation results showed that it is possible to apply a peak shaving strategy to the heat pump operation, while maintaining the internal comfort of the building by increasing the storage tank size up to 1 m^3. However, it is not possible to maintain the DHW supply temperature to the requested set point, thus a contemporary application of this DSM strategy both for space heating and domestic hot water is not feasible. The load shifting strategy, instead, is not even suitable for space heating, because it asks for much more flexibility than that available in the system. The implementation of the peak shaving strategy is interesting (when the internal comfort is guaranteed), because it allows to reduce the energy consumption and consequently the energy bill as presented. The energy performance of the heat pump is slightly affected by such strategies.

3. Integration of PV panels in an industrial building coupled with thermal energy storage for demand side purpose

3.1. Introduction

The contents described in this chapter have been published before [60] and are the result of a full year cooperation between Università Politecnica delle Marche, Shanghai Jiao Tong University and an Italian company called Loccioni. 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 behavior. Simulations are performed to show the load shifting potential of such storage and costs and energy use are assessed in order to evaluate the viability of this TES application for different configurations. In particular, the demand side strategy considered aims 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. In this context, heat pumps are considered a good choice: large scale deployment of heat pumps (HP) is predicted to satisfy heating and cooling service requirements and to attain over 50% penetration by 2030 and over 75% by 2050, especially if coupled with the promising concept of demand side management (DSM) [61]. DSM can be implemented by means of, among others, additional equipment that enables load shaping, such as thermal energy storage (TES) [62]: 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 [63,64].

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. [65] who dealt with thermal energy management in a residential energy hub, or as investigated by Comodi et al. [66] 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 [67]. Upshaw et al. [68] 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. [69] 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 [70]. The performance obtained is also strictly related to the storage medium considered [71].

Several studies have analyzed the application of TES for demand side management of thermal loads, using both external devices [72] or active and passive thermal energy storages within building envelopes, without significantly affecting indoor thermal comfort [45]. 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 [73]. 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 [73].

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 [74,75]. TES can be economically competitive as its behavior 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. [76] analyzed CTES technical and economic 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. [77] 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. [78] 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 and 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 kW h CTES system installed). Similarly, Sabate et al. [79] studied how to optimize 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 [43] considered industrial buildings and analyzed 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 [80], assessed that, by using PCM (phase change materials) in office buildings, the energy consumption can be annually reduced by about 142 kW h 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. It deals with the load behavior of the industrial sector and its potential to use demand side management. In particular, the purpose of this work 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. [81] explored efficient integration approaches of photovoltaic thermal systems, HVAC (heating ventilation and air conditioning) systems and thermal storage devices to enable optimal collection and utilization 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. [82] 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 work, the use of PV panels electricity to drive the HP for recharging the TES, rather than for supplying the building, is analyzed. 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 nondeterministic 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 chapter outline is as follows. Firstly, the real installation under study (Section 3.2.1) and then the related simulation model with its main assumptions (Section 3.2.2) are presented. Secondly, after a preliminary analysis of the actual yearly energy performance of the building considered (Section 3.3.1), the operational behavior of the system is evaluated for different TES setting configurations by means of dynamic simulations (Section 3.3.3) with a model tested through experimental data (Section 3.3.2). Lastly, an economic assessment of the TES installation and operation is performed (Section 3.4).

3.2. 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 [58]. 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 analyze the electric energy use breakdown of the system and identify the best operative configuration.
In this work only the cooling operation of the system was considered, because in summer surplus PV electricity production is higher (as better explained in Section 3.3.1). 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.

3.2.1. 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 (Fig. 17). 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 6. The building is located in a town in central Italy (coordinates: 43°28’58.29” N, 13°04’09.48” E).

Figure 17 – Photo of the Leaf Lab building.

Table 6 – Building envelope properties [60].

Test building	U value [W/(m2 K)]
External wall	0.216
Internal wall	0.508
Roof	0.316
Windows	1.29–1.88

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 [83]. 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 [84]. 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 and 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 12.3 x 11 x 3.4 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 0.032 W/m K) [85]. 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.

3.2.2. 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 18.
Only the main components of the cooling production and distribution system are represented on the basis of data from manufacturers.

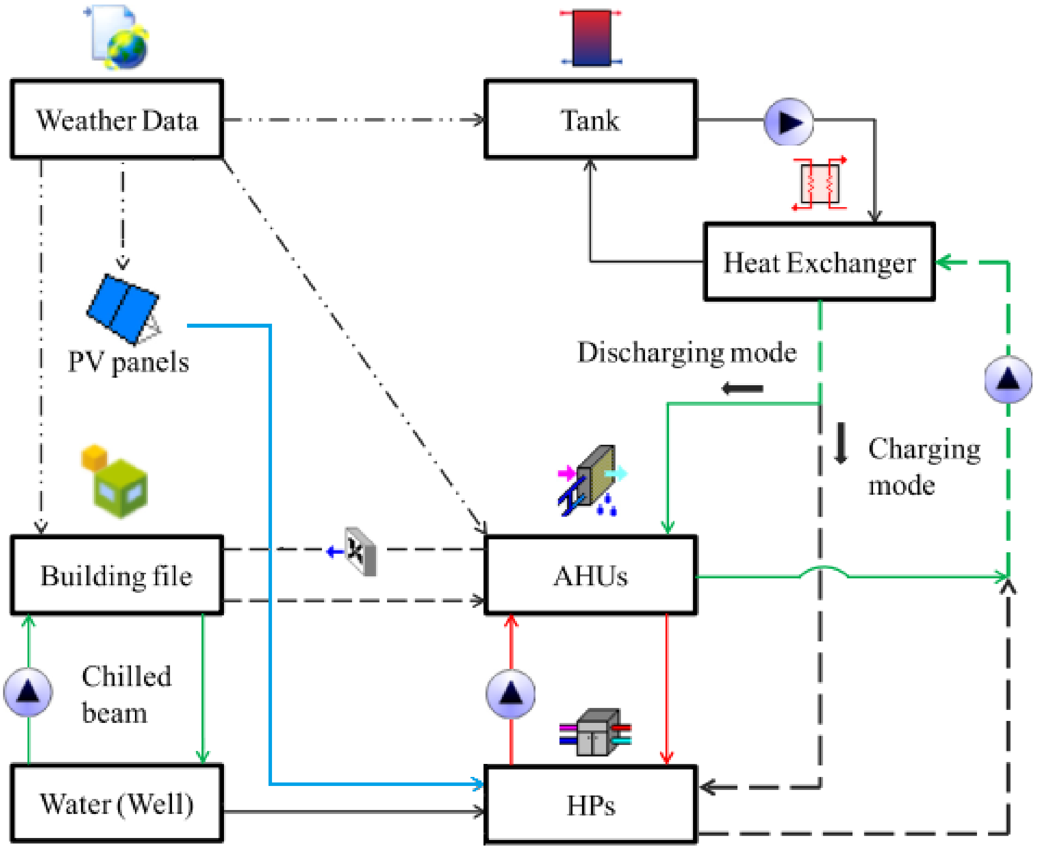


Figure 18 – Simplified schematic of the simulation model in TRNSYS [60].

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 min was considered.

The model can work in three different configurations (as shown in Figure 19), 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.

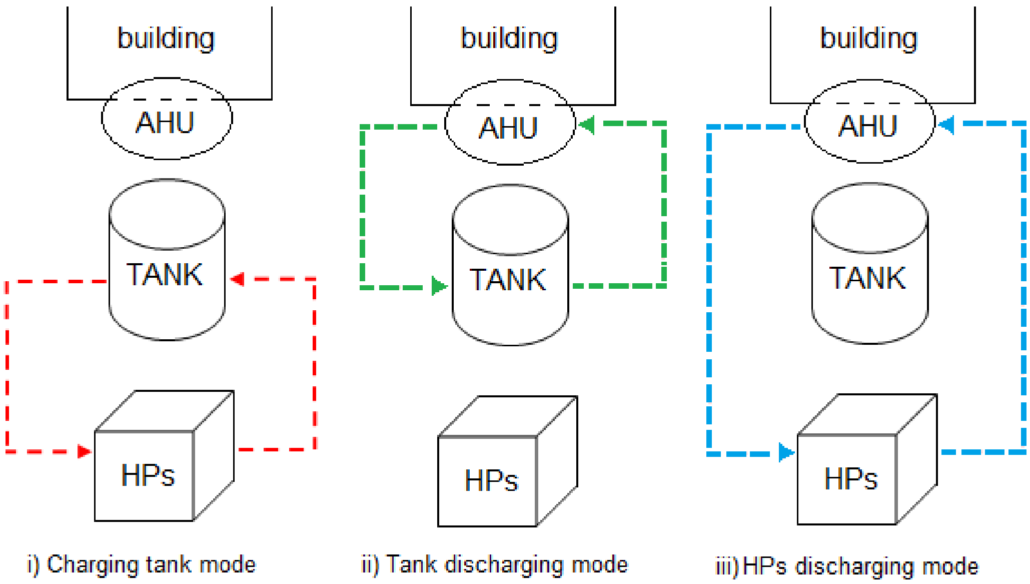


Figure 19 – Operational mode of each configuration of the system, charging and discharging processes.

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 summarized 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 [86]) and the HPs step into 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 €/kW h during off peak time (from 8:00 pm to 8:00 am during week days and during weekends) and 0.164 €/kW h during on peak time (from 8:00 am to 8:00 pm during week days), taxes included [87]. 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 €/kW h and off peak tariff 0.082 €/kW h, 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.

3.3. Results and discussion

3.3.1. 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 [66]. 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 20 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 nondeterministic behavior.

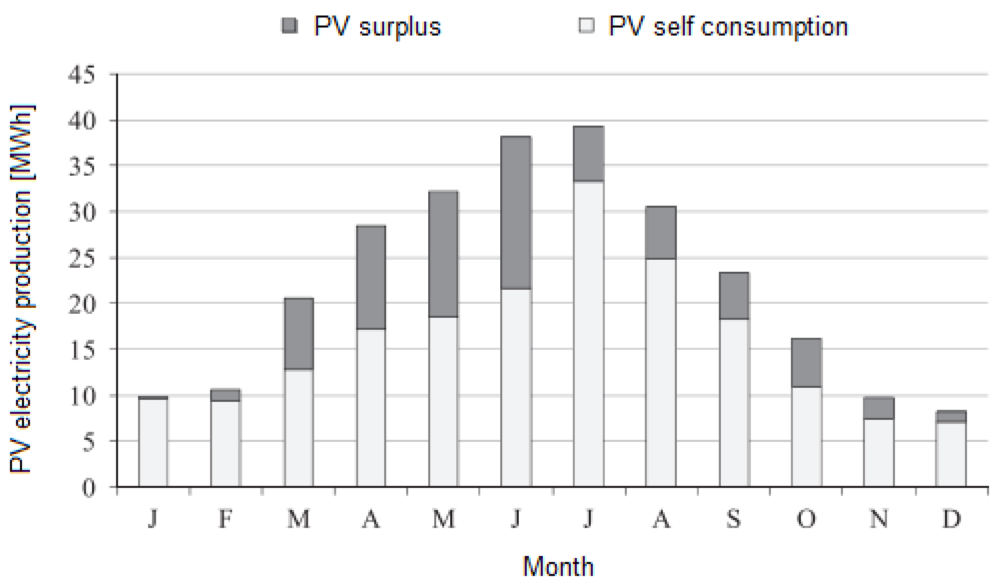


Figure 20 – Total PV electricity production, divided between self-consumption and surplus PV electricity, in a year [60].

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

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

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.

[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 [90]). It is reasonably assumed that the charging process and discharging process contribute equally to the total tank recovery efficiency.

Given the building energy demand assessed, the thermal energy stored can be completely consumed during the working weeks considered (see Section 3.3.3). 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 21, where the total electric power demand and PV electric power are shown for a typical winter (Fig. 21a) and summer week (Fig. 21b). Therefore, this study was focused only on the analysis of cooling loads.

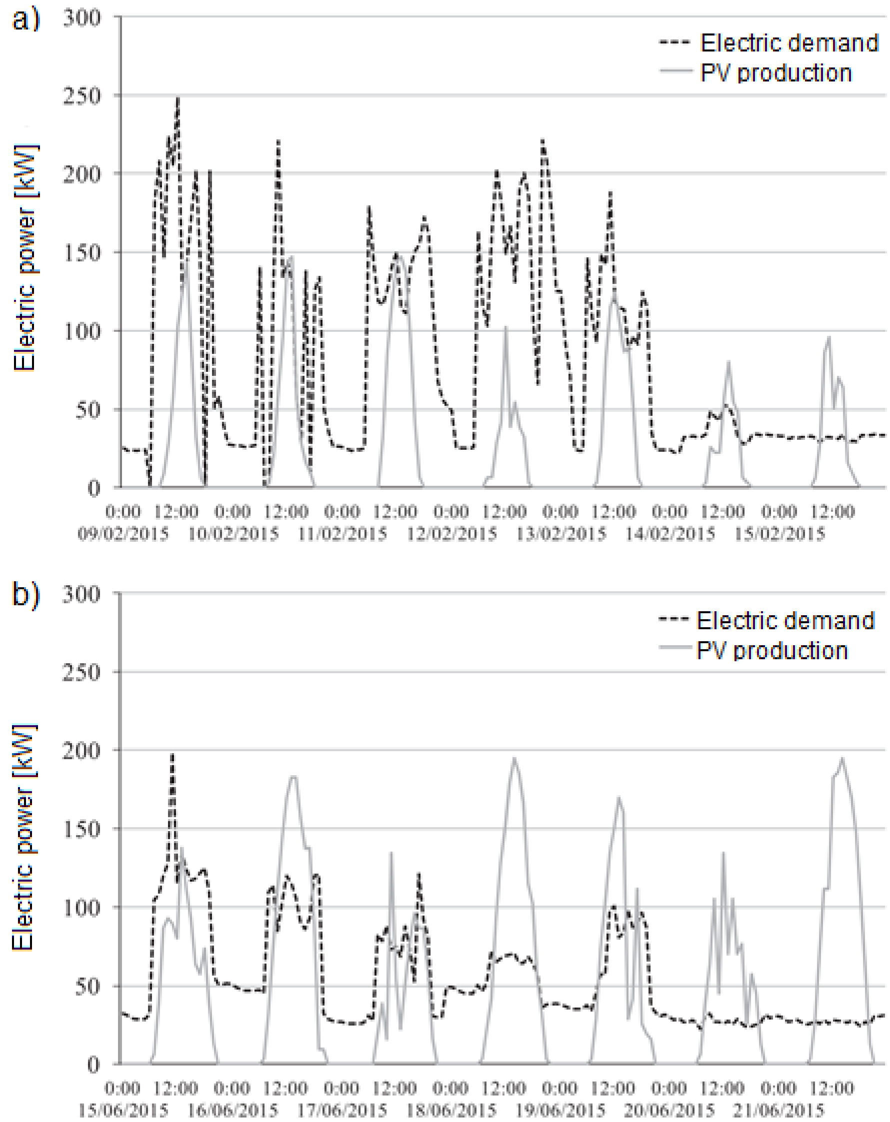


Figure 21 – Total electric power demand and PV electric power production during a typical winter (a) and summer (b) week [60].

3.3.2. 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 22 shows the behavior 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 28–10°C[2].

As it can be seen in Figure 22, 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 behavior of different tank configurations.

[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.

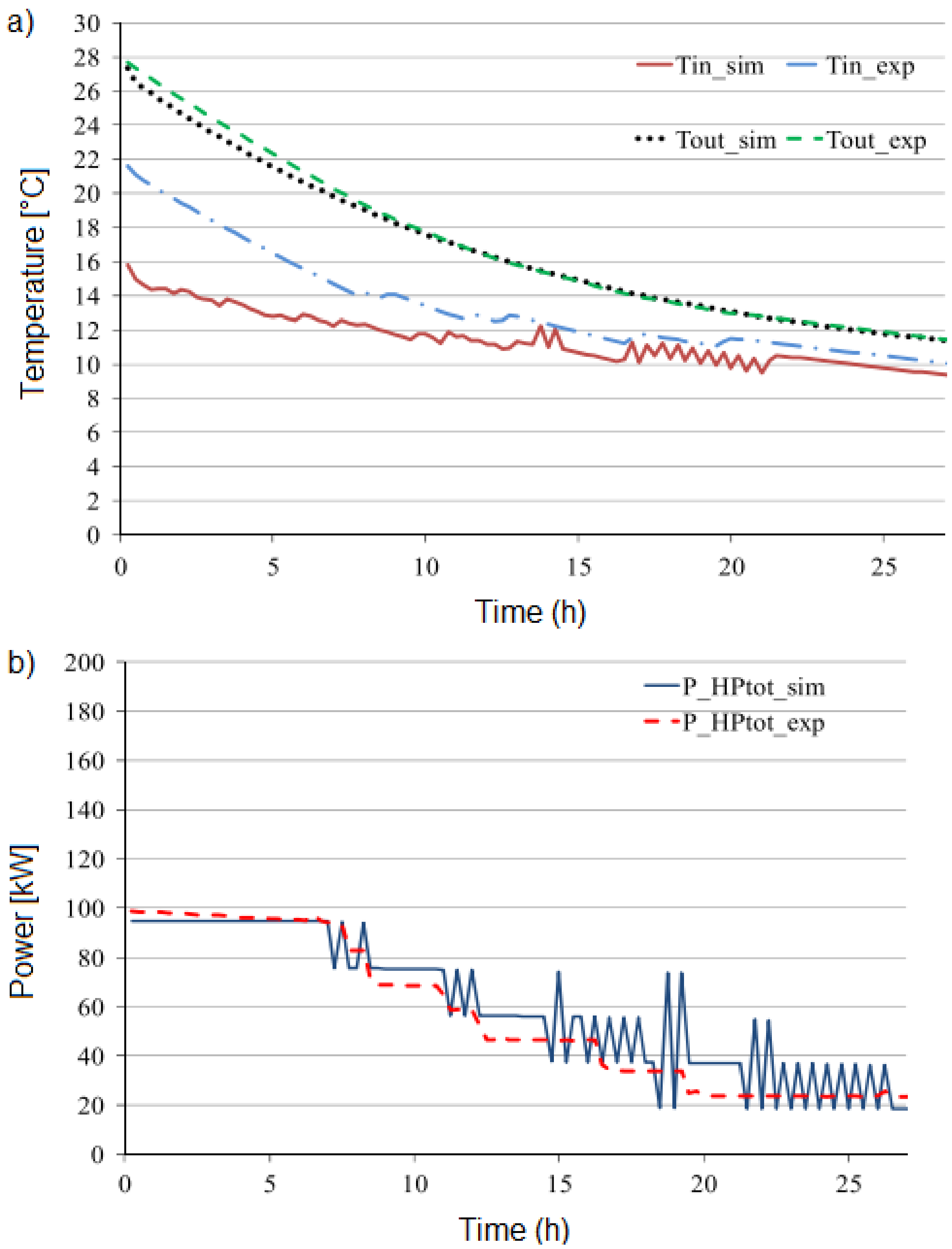


Figure 22 – Comparison between experimental and simulated values of tank temperature (a) and HP power consumption (b) during the charging process. Tin_sim and Tin_exp represent the tank inlet temperatures simulated with the model and measured during the experimental testing phase, respectively. Tout_sim 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 22b) follows the control strategy described in Section 3.2.1: the capacity is lowered when the cooling demand decreases (i.e. when the HP evaporator inlet temperature is lower) [60].

3.3.3. Analysis of the system performance

The main purpose of the dynamic simulations was to compare different tank operational strategies in terms of energy use breakdown and analyze the tank charging. The latter 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 33 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.

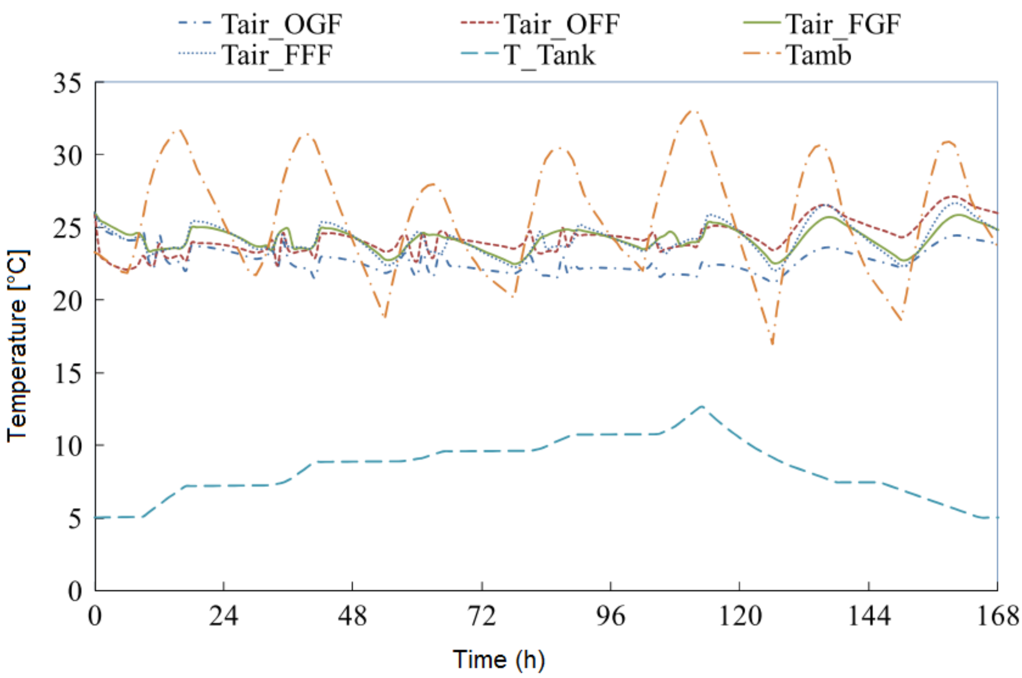


Figure 23 – Trend of the tank temperature and the air temperature in the building zones (OGF-offices ground floor; OFF-offices first floor; FGF- factory ground floor; FFF- factory first floor) during the hottest summer week (note that 0 h corresponds with 0 am of Monday) [60].

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).

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 24 shows the tank temperature trend during the hottest (a) and the typical (b) summer weeks.

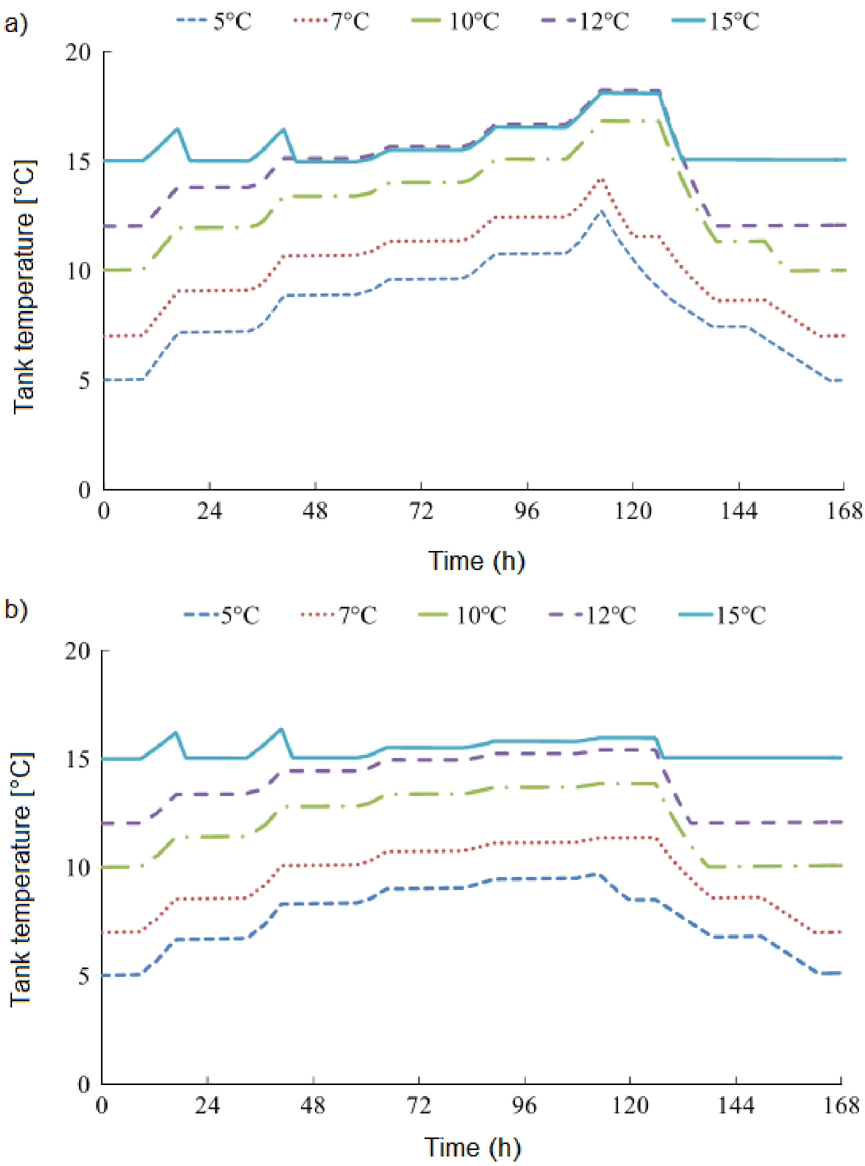
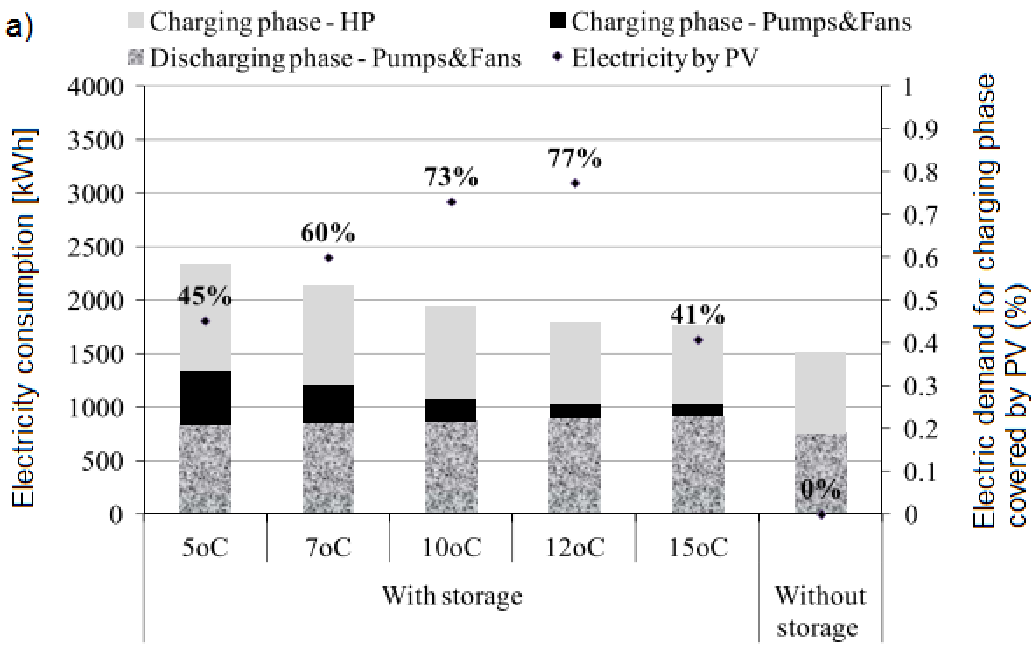


Figure 24 – Trend of the tank temperature with different minimum set points during th operation in (a) the hottest week and in (b) the typical week [60].

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 3.2.2, 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 analyzed configurations make it possible to keep the internal temperature in thermal comfort condition (<26°C during working hours). During these simulations, the HPs never step into supply cooling directly to the building.
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 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 25 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.



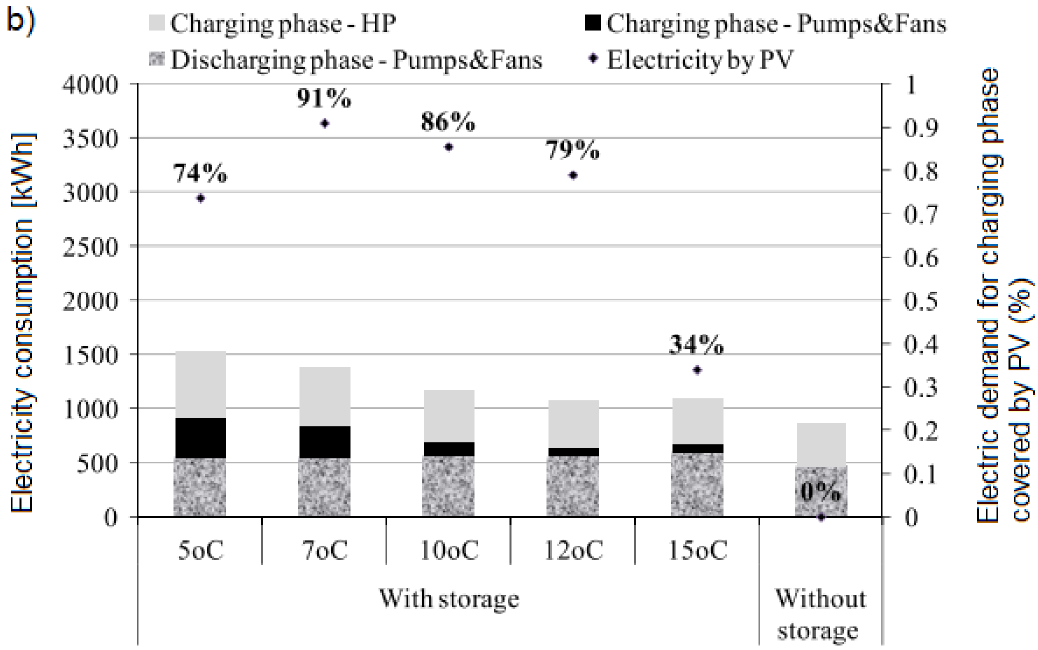


Figure 25 – HVAC electric energy use breakdown (due to heat pumps or pumps and fans for all the configurations analyzed with and without storage divided by operational mode (tank charging or tank discharging) for the hottest (a) and typical (b) summer weeks. The percentage of the electric demand for the charging phase provided by PV panels is also reported [60].

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). Figure 25 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 €/kW h [88]). 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 (mainly due 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 26). 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 optimized to further maximize surplus PV electricity use.

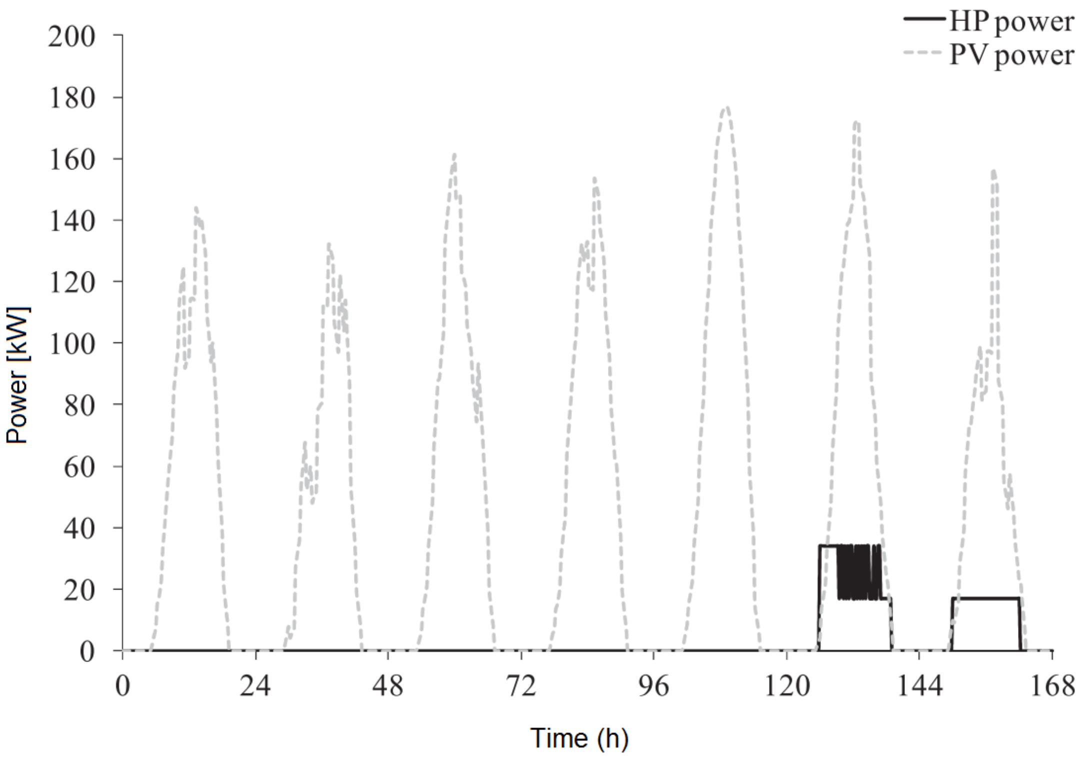


Figure 26 – Power trend of the HPs and PV panels during the tank charging process with a tank minimum temperature set-point of 7°C for the typical week [60].

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 3.3.3), 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, characterized by a price ratio between off peak time and on peak time tariffs of about 90%, (ii) a new tariff characterized by a price ratio between off peak time and on peak time tariffs of about 50%. The results are reported in Figure 27. 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.

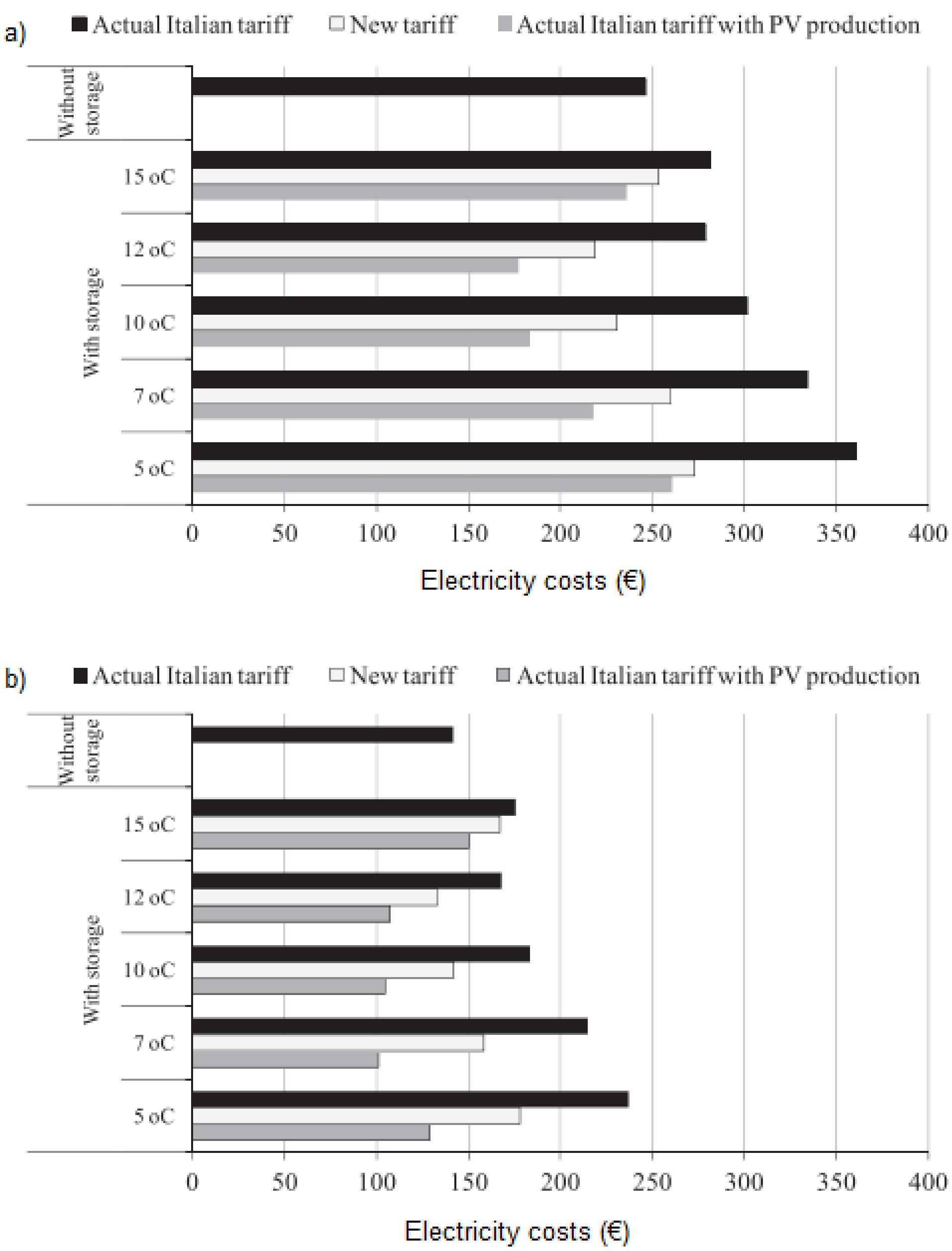


Figure 27 – HVAC operational electricity costs for all the tank configurations analyzed and for the reference system without storage, both considering the actual Italian electricity tariff structure, accounting or not accounting the energy for the charging process provided by PV panels, and a new tariff structure with a ratio between off peak and on peak price of 50% for the hottest week (a) and the typical week (b) [60].

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 analyzed. 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 3.3.3). 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 25).

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 h for the case with the minimum tank temperature set-point of 5°C, 43 h for 7°C, 24 h for 10°C, 17 h for 12°C and 10 h for 15°C. Thus, the PV electricity produced during a weekend could be used to provide most of the necessary load (Table 7).

Table 7 – Energy use from the grid (accounted for the PV electricity contribution during a weekend) and costs for the tank first charging process [60].

	5°C	7°C	10°C	12°C	15°C
Energy use (kW h)	1841	1248	837	289	266
Energy cost (€)	274	186	125	43	40

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. 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 3.3.1.

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

The value of the investment (CI) is estimated on the basis of data from literature. The report [89] states that the cost of a complete system for sensible heat storage ranges between 0.1 and 10 €/kW h 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. [90], a capital factor of 30 €/kW h_{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 €/kW h), thanks to the thermal energy stored in the TES during weekends.
The operational costs savings are calculated through (Eq. (3)).

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

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

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

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

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 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 €/kW h), rather than self-consuming it, was subtracted. On the basis of the results in Section 3.3.3, 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 €/kW h). 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 27): 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 €/kW h_{th} [89], 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. [90] the payback period increases to 47 years, making the installation no longer attractive. In this case, if the contemporary factor gc 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% [90], the PBP with a capital factor of 10 €/kW h_{th} would increase to 23 years, while with a capital factor of 30 €/kW h_{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 €/kW h_{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 nondeterministic 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 realization costs, but an in-depth analysis about this issue is out of the scope of this work.

3.5. 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.

4. Air source heat pump performance investigation by means of a response surface methodology

4.1. Introduction

This work has been conducted together with PhD students from Shanghai Jiao Tong University, it is the result of a year experimental data campaign and related elaboration and has been presented to the 8th International Conference on Applied Energy (ICAE) held in Beijing on October 2016 [91].
It aims at investigating on the performance of a two-stage air source heat pump (ASHP) installed in the Green Energy Laboratory; DSM measures are not investigated in this work.
Experimental data were collected in winter mode. Due to the scarcity of reliable experimental data, a response surface methodology (RSM) was applied with the aim of extending the data sample. The new database was analyzed to point out the performance of the ASHP by varying the supply water temperature to the indoor terminals in different ambient conditions. It was possible to draw curves showing the relationship between ASHP performance (power consumption and COP), supply water temperature and ambient temperature.
ASHP can be combined with different indoor terminals of HVAC systems in buildings. Capacity control of the ASHP is needed to reduce power consumption and enhance system performance, as presented by Xue et al. [92], where the capacity of the heat pump (HP) is modified to match the energy demand by means of the compressor load regulation. Similarly, Safa et al. [93] show that for a two-stage variable capacity ASHP the performance can be improved if a reduction in operating cyclic time and speed of the device is applied. Another important parameter to be adjusted and controlled during HP

operation is the supply water temperature of the heat pump as it can increase the heat pump performance, as stated by Gao et al. in [94].

As said, the performance of a two-stage ASHP unit (with two compressors running contemporary or individually) is presented while it is operated with several supply water temperatures, under variable outside ambient temperature and with different indoor temperature set-points.

RSM is applied to extend the available sample [95] and to determine the relationships between inputs and outputs of the ASHP system in order to highlight the best system configuration in terms of efficiency.

4.2. Methodology

The studied ASHP was operated in a test rig. The experimental data were previously analyzed, some of them were dismissed for inaccuracy issues, and therefore the remaining data have been used to perform the response surface methodology in order to draw conclusions about the system performance and optimization. The system setup and the test room are described below, together with the RSM basic theory.

4.2.1. Lab room and experimental setup

The test room is an experimental system built inside the Green Energy Laboratory (GEL) in Minhang campus owned by Shanghai Jiao Tong University. This room is equipped with a two-stage air to water heat pump, providing both heating and cooling, coupled with ceiling and floor fan coil units (FCU) and radiant floor (heating only) as indoor terminals, as shown in Figure 28 (a).

Figure 28 – a) Schematic of the different indoor terminals in the test room; b) Investigated rooms in GEL during experiments.

The air source heat pump serves the test room and 4 other rooms in GEL (figure 28 (b)), for a total area of 292 m^2. The heating capacity of the ASHP is 39.5 kW with a nominal power of 12.2 kW (each compressor is about 6 kW). The user can set the supply water temperature and the indoor room temperature. The HP runs until both set points are reached. The capacity of the HP varies accordingly: for a big heating request the two compressors work together, for smaller requests only one compressor runs. During the tests the three types of terminals were operated one by one under different conditions and only in heating mode.

Table 8 provides the specifications of the measurement equipment: flow meters records the water flow rate that supplies the indoor terminals, thermal resistance measures the temperature in the hydronic water circuit, temperature loggers are used for measuring the rooms and ambient temperatures and current transformers are needed for the energy consumption calculation.

Table 8 – Thermophysical properties of the case study [91].

Sensor	Number	Measurement range	Uncertainty
Flow meters	4	0-40 m^3/h	5%
Thermal resistance	8	0-100°C	3%
Temperature logger	20	0-100°C	5%
Current transformers	3	0-50 A	5%

All the signals from the sensors are connected to a data acquisition system and collected in an excel file to be elaborated afterward. The configuration of the experimental setup during the tests is presented in Table 9. The tests were run during November 2014.

Table 9 – Experimental setup description [91].

Test	Supply water temperature	Running indoor terminal	Hours of operation
1	30°C	Fan coil	27
2	35°C	Fan coil	22
3	40°C	Fan coil	24
4	45°C	Fan coil	25
5	35°C	Floor heating	24
6	40°C	Floor heating	23
7	45°C	Floor heating	24
8	30°C	Ceiling fan coil	24
9	35°C	Ceiling fan coil	24
10	40°C	Ceiling fan coil	24
11	45°C	Ceiling fan coil	20

Some of the experimental data had to be rejected because of sensors inaccuracy experienced during the tests. The scarcity of the collected data is the main reason behind the use of the response surface methodology (RSM) explained below. In this work, only the tests using fan coil as indoor terminals are considered.

4.2.2. Response surface methodology

The RSM is a modeling approach to determine the relationship between various process parameters (inputs) and responses (outputs). One of the advantages of the RSM is that it reduces the experimental costs, while allowing to have a lot of data useful for system optimization [96]. In the current study RSM was applied to extend the available experimental data to be used to identify the optimal configuration of the design parameters affecting the performance of the ASHP. ModeFRONTIER™ [97] software was used to perform the RSM. A variety of algorithms can be selected, the best choice for our case study turned out to be the Polynomial Singular Value Decomposition. The selected polynomial degree is the 4th degree as it produced the most reliable set of data. In the performed analysis, the ambient temperature, the supply water temperature and the total water flow rate were assumed as inputs, while the indoor temperature of the rooms, the return water temperature of the HP and the power consumption of the HP were considered as outputs. As shown later, the ambient temperature and the supply water temperature are the parameters mainly affecting the results.

4.3. Results

In this section the experimental data collected when the fan coils were used as indoor terminals are illustrated together with results from their elaboration. Figure 29 shows the duration curve of the HP power consumption during the tests performed with different supply water temperatures set-points (namely

30°C, 35°C, 40°C, 45°C, see Table 2). It is evident that for higher supply water temperatures the two HP compressors run together for a longer time at about 12 kW. Instead, at lower supply water temperatures there is only one compressor working at about 6 kW for most part of the time. The HP worked for a shorter number of hours during the test with the supply temperature at 35°C and it is visible in Figure 29 (power consumption is zero for a longer period compared to the other curves).

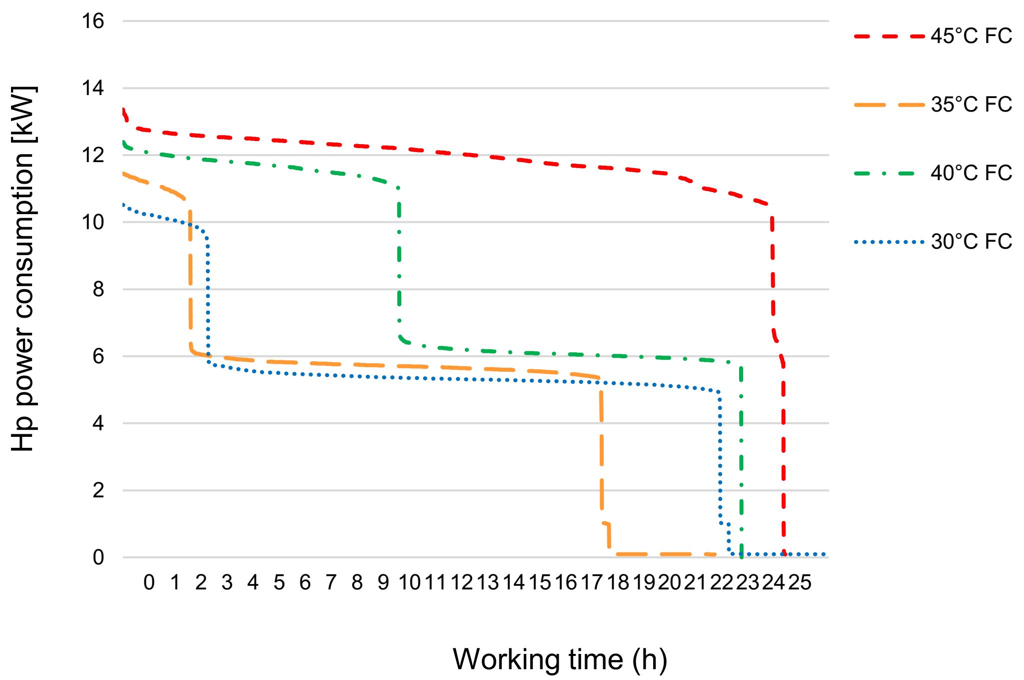


Figure 29 – ASHP operation time while running fan coils as indoor terminals. [91].

The first performed analysis aimed at identifying the correlation between input and output parameters. For quantifying such a correlation, Pearson coefficient was used. This can vary between -1 and 1: positive values indicate a concordant increase, vice-versa for negative values; for no correlation or a weak correlation, the coefficient is close to 0. It was found out that the most important parameters affecting the ASHP performance were the ambient temperature and much more the supply water temperature (Figure 30). The increase in the latter one produces a consistent increase in the power consumption. The correlation between the ambient temperature and the room temperatures (in the graph room 106 is the test room in Figure 28 (b) on the ground floor, while room 205 is a first floor room) was found to be strictly related to the room orientation. The influence of the supply water temperature is also linked to the distribution of the fan coil terminals in the room.

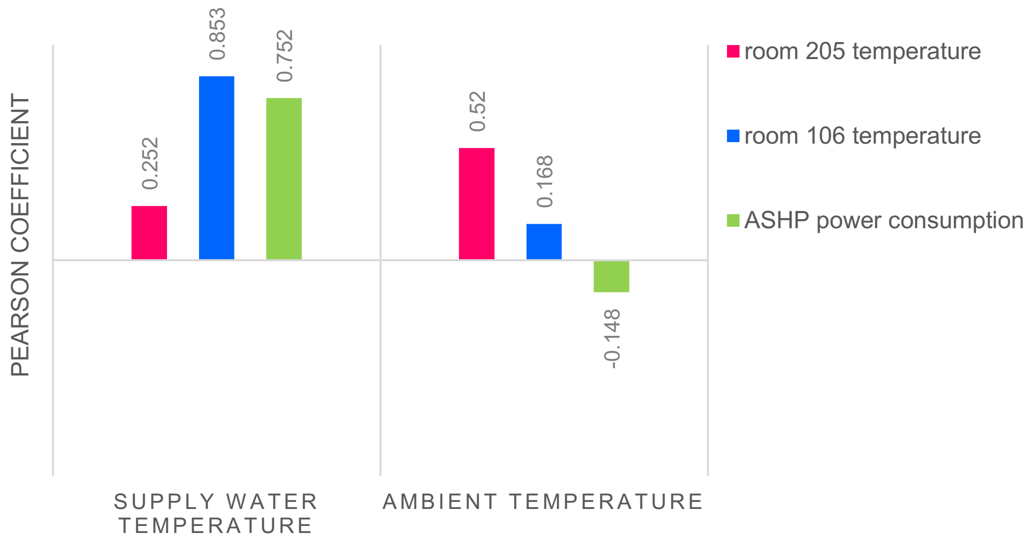


Figure 30 – Pearson coefficient between inputs and outputs of the system [91].

The RSM is applied starting from selected experimental data and the virtual generated sample has been used to analyze the dependency of the HP performance on the above-mentioned input parameters. Figure 31 shows that when the supply water temperature set point is higher, then the HP needs to run at maximum power even when the ambient temperature is warmer (about 15°C). Figure 32, instead, highlights a linear increase of the HP power consumption when the supply water temperature increases and confirms that higher supply water temperature forces the unit to work at full load even when the ambient temperature increases.

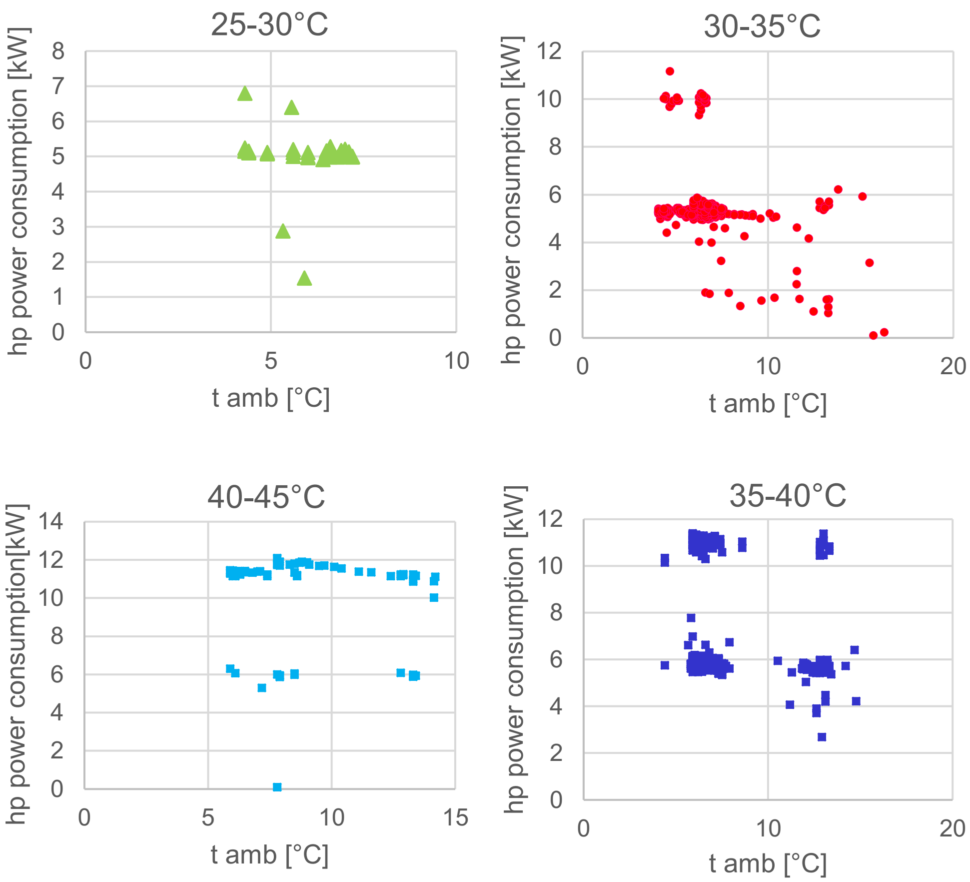


Figure 31 – Relationship between the HP power consumption and the ambient temperature by varying the supply water temperature [91].

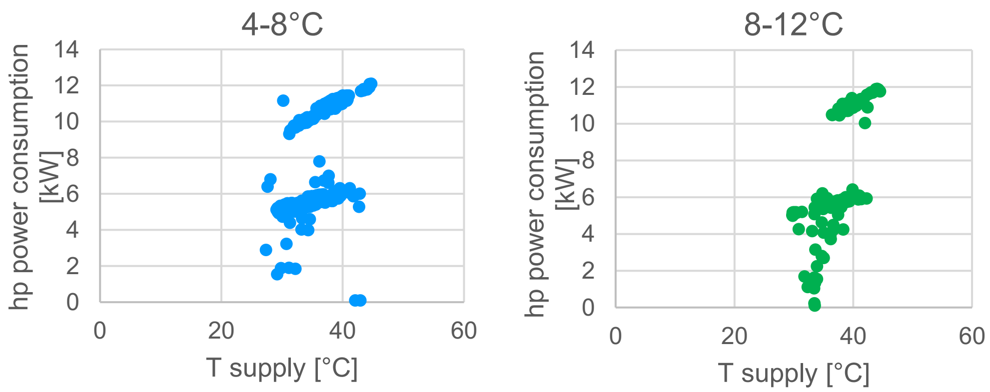


Figure 32 – Relationship between the HP power consumption and the supply water temperature by varying the ambient temperature [91].

Figure 33 (a,b) represents the coefficient of performance (COP) of the HP. It is evident the strong correlation with the supply water temperature that makes it decrease from around 3 to 1 when the supply water temperature increases, depending also on the ambient temperature.

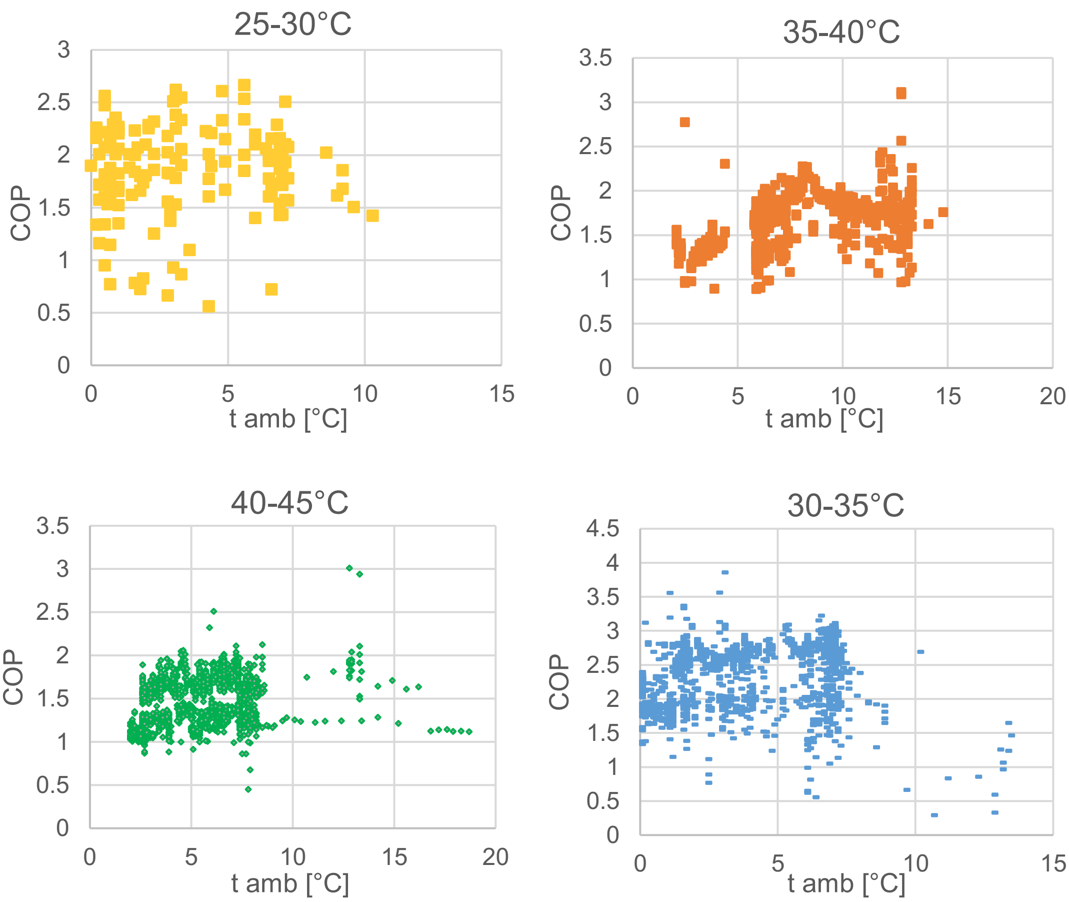
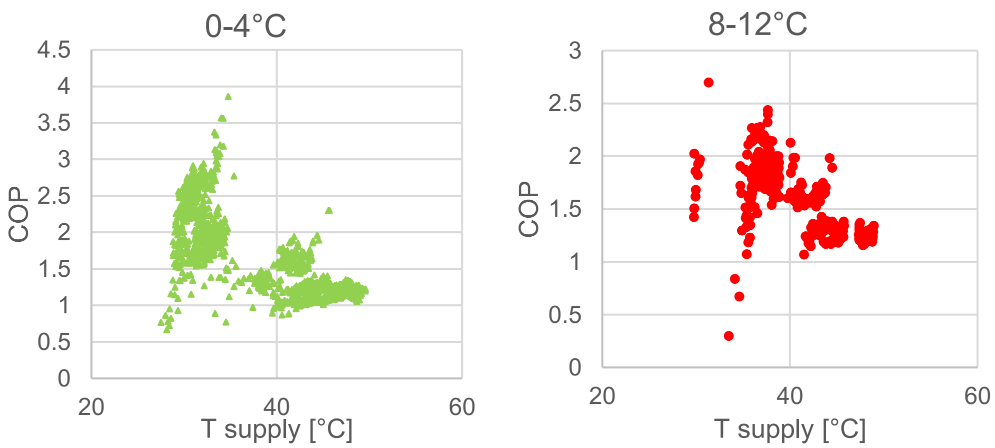


Figure 33 a – Relationship between the COP and the ambient temperature by varying the supply water temperature [91].



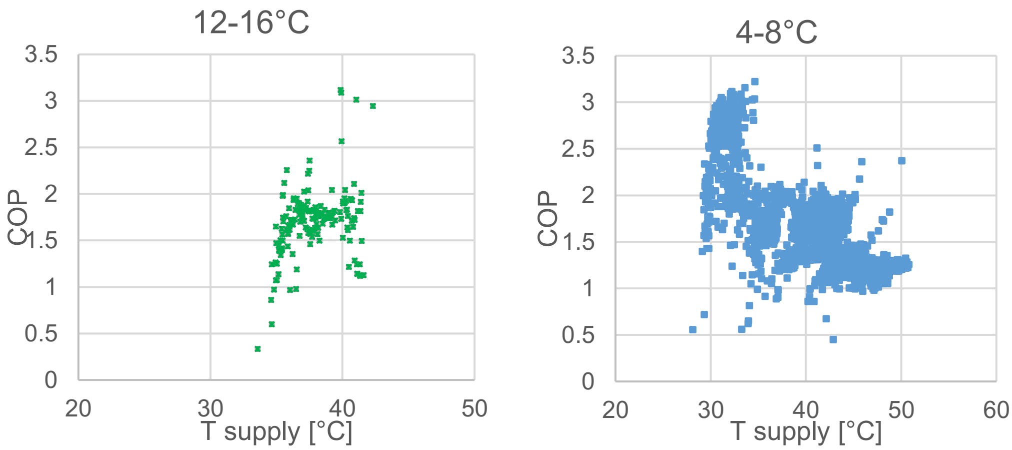


Figure 33 b – Relationship between the COP and the supply water temperature by varying the ambient temperature [91].

Furthermore, an optimization of the system was performed and the configuration that minimizes the power consumption of the HP while maintaining the internal comfort at 20°C (± 1°C) was assessed to be: 30°C for the supply water temperature and 2.4 m^3h^{-1} for the supply water flow rate, thus the HP consumption is about 5 kW when the ambient temperature is about 10°C.

4.4. Conclusions

In this work a performance analysis of an air source heat pump was performed by means of an experimental campaign coupled with the response surface methodology. RSM was useful for enlarging the data sample, as some of the experimental data had to be rejected for sensors inaccuracy problems experienced during the tests. By means of RSM, it was possible to highlight which parameters affect mostly the HP performance: namely the ambient temperature and much more the supply water temperature. Indeed, an increase in supply water temperature produces a consistent increase in the HP power consumption. It was shown that the increase of the supply water temperature from 25°C to 45°C causes a decrease of the heat pump COP from 3 to 1, depending also on the ambient temperature. An optimal configuration of the system that can allow thermal comfort in the rooms, minimizing the HP power consumption, was assessed: being the supply water temperature 30°C and the supply water flow rate 2.4 m^3h^{-1}, the HP consumption was found to be about 5 kW at an ambient temperature of 10°C.

Conclusions

The European community has established energy and environmental targets for 2020. Moreover, it is anticipated that further targets will follow suit in subsequent years.

The idea of an integrated and dynamic energy market is growing strong and reflects the EU's will to promote Demand side management (DSM) measures together with other aspects related to this topic.

Results from this work confirm how DSM strategies can positively impact on the buildings' and systems' performances as they help increasing energy efficiency and system flexibility. Moreover, the application of DSM measures has proven to reduce the energy consumption of the presented cases and the electricity bills, particularly when dynamic electricity tariffs are in operation. Furthermore it is seen how such beneficial measures are capable of preserving the buildings' thermal indoor comfort.

Apart from the tariffs' structure in place, the possibility of employing electricity which is self-produced by renewable sources such as Photovoltaic panels (as in Chapter 3) makes DSM combined to the thermal storage more profitable.

The correlation of the energy system with the building generates a complex array of variables, thus it is crucial to investigate on which DSM strategy can really benefit in terms of efficiency and energy consumption.

The DSM measures turn out to be economically feasible when integrated with Thermal energy storage (TES). TES allows the electricity consumption demand during on peak period to be shifted to the off-peak period when electricity costs are cheaper. This tool introduces flexibility to the demand side of the building, reducing the request to the conventional electricity equipment without affecting the end user's internal comfort.

The performed investigation on TES shows how thermal energy storage is not always the best solution in terms of energy consumption as it has to be preventively charged (this requests energy to the productive system) and discharged afterwards (this requests energy to the distribution system).

However, such a measure helps smoothen out the consumptions during the peak period and allows for the consumers to benefit of the cheaper tariffs available during the off-peak period (DSM strategies), thus helping to reduce the electricity costs. The study illustrates how a Chinese tariffs context can be successful for the TES application as the off-peak electricity tariff is considerable lower than the on peak tariff, with

$$\frac{offpeak}{onpeak} = 50\% .$$

Among the important achieved results of TES application, it has been proven how it is better to keep the tank temperature as closest as possible to the system's operational designed temperature so as to allow the recharging process only when strictly necessary in order to ensure internal thermal comfort. This method helps reducing losses of the tank and the charging energy use.

To make load management (load shifting, load shaping, …) an interesting topic, governmental authorities should implement dynamic electricity taxations that allow the commitment of the end users to be active players in the electric system. In fact, it is agreed that electricity tariffs' elasticity could be an efficient measure for the implementation of DSM and to achieve EU's energy objectives.

Furthermore, consumer educational programs related to DSM should be developed so as to reduce or change the load electricity patterns of such stakeholders in households and thus increase consumer awareness.

Simple DSM measures are often enough to significantly improve energy efficiency, besides building sector does not need an extreme overturning if renewable energy (such as Photovoltaics, as demonstrated in Chapter 3) or dynamic taxation are implemented.

In this light, combining DSM strategy as load management to other DSM strategy as dynamic electricity prices (time of use, real time pricing, critical peak pricing, …) could be an efficient measure to reach the set European Commission's goals.

Consequently, future works will focus on the DSM strategies coupled together with the aim of identifying the strength of each of the solution and to overcome their limitations by investigating on the best ways to combine them.
Moreover, identifying the interactive components of DSM needed for interfacing with the smart grids will be part of further investigations, being the energy efficiency measures and the control of the electric production a very important aspect of this topic, as well as in the DSM.
To conclude, the electricity tariffs become of paramount importance as they can bring cost saving on the user's bills when DSM is applied and when the off-peak tariff is convenient, as said before. Plus, the described situation improves when an incentive based mechanism is applied to motivate the final users and to increase the flexibility of the energy system. Such incentives, as said, have to be of an economic kind but must also include educational programs to let consumers be aware of how even an easy and small part of DSM such as energy reduction programs can help energy efficiency whilst reducing their energy bills.

Appendix A. Thermal conductivity of organic compounds using corresponding states principles

i) General overview

This Appendix is a brief introduction to another topic I've been working on during my PhD which is the Thermal Conductivity (λ) and even if it moves away from DSM and heat pumps topics, it will be presented to have a complete overview of what has been done in these three years.
The aim of the research was to investigate an equation for the calculation of the Thermal conductivity knowing a small number of physical properties of a specific material. The researched equation must be simple, accurate and able to estimate a result which is the closest to the experimental data. Several equations have been detected and are object of two international publications [98,99].
Here, the setup approach, the two abstracts and part of the results will be presented to have a quick view of the work.
In these papers, two different equations have been spotted, the first one applies to the following families of materials: refrigerants, alkanes, alkenes, aromatics, cycloalkanes, cycloalkenes, ethers, esters, ketones, carboxylic acids, and alcohols, while the second equation is addressed to the refrigerants only and aims to be more accurate than the equation proposed in [98].
In order to provide a reliable database of the thermal conductivity for pure compounds, a careful literature survey is performed. After this, the available data of the experimental thermal conductivity were collected and selected. The database consists of 136 compounds, for each one physical properties and experimental data are provided.
Afterwards, a factor analysis is performed to understand the relationships among variables and to assess the importance of each variables for the

thermal conductivity. It analyzes relationships among large numbers of variables in order to obtain a smaller number of factors. In this way, having a smaller number of variables, theory development and testing are easier.
After that, according to the literature review, already existing Thermal conductivity equations are identified. These equations are needed for comparing them to new one; to test the goodness of the new equation, the deviations between the predictions and the experimental data of each of the equation are compared.
In both papers, a new and simple method was developed for the calculation of thermal conductivity; clear improvements in the thermal conductivity calculation, with respect to other existing correlating equations, have been assessed.
Part of the results will be here presented.
With regards to [98], the proposed equation is

$$\frac{\lambda}{\lambda_0} = a + b \cdot T_r + c \cdot \Delta h_{fus} + d \cdot \omega + (\frac{e}{M})^f$$

where T_r is the reduced temperature [K], Δh_{fus} is the enthalpy of fusion at melting point [J $kmol^{-1}$], ω is the acentric factor and M is the molecular mass [kmol kg^{-1}]; the coefficients are equal to

a = -0.5694

b = -0.1436

c = 5.4893 x 10^{-10} [kmol J^{-1}]

d = 0.0508

e = 1 [kg $kmol^{-1}$]

f = 0.0622,

λ_0 = 1 [W mK^{-1}]

The presented equation, in spite of its simplicity, showed a high quality of data representation. Deviations of the new equation is compared to the deviations from the existing equations found in the literature (see [98]). Table 10 shows the deviation of the new equation.

Table 10. Deviations between experimental and calculated thermal conductivities [98].

Fluid	Deviations of the proposed equation	Total number of points	Total number of compounds
Alcohols	7.7	775	20
Alkanes	5.4	1025	20
Alkenes	3	135	7
Aromatic	3.4	414	8
Carboxylic acids	9.8	318	11
Cycloalkanes	3.4	35	3
Cycloalkenes	3.3	10	1
Esters	8.1	236	12
Ethers	5.4	111	5
Ketones	6.1	185	7
Refrigerants	9.2	1340	37
Average	7.1	-	-

Speaking of the equation for the refrigerants [99], this family has shown a very high deviation for every tested equation, thus showing possible margin of improvement, probably because the behavior of the associated compounds is quite different from non-polar compounds. For this reason, a new equation has been presented; Table 11 shows the deviations of the specific refrigerant equation compared to the equation presented in [98].

Table 11. Deviations between experimental and calculated thermal conductivities for equation in [98] and [99].

Fluid	Deviation [98]	Deviation [99]
R10	3.3	1.8
R11	16.4	2.2
R12	11.2	3.9
R12B	10.2	3.4
R13	11.3	5.7
R13B	8.7	3.5
R14	9.4	2
R20	17.4	2.9
R21	9.8	4.7
R22	15.7	6.2
R23	5.3	5.9
R30	8	3.8

R31	8.5	19.1
R32	12.9	8.3
R112	5.5	2
R113	10.9	9.8
R114	9.9	7.9
R114B	18.2	7.3
R115	6.8	2.1
R116	2.2	6.6
R123	5.1	2.4
R123a	11	1.6
R124	19.6	2.6
R125	28.2	4.5
R130	22.4	2.7
R133a	19.4	11.7
R134a	5.1	3.2
R141b	10.1	5
R142b	2.3	2.4
R143a	13.6	8.4
R150	10.1	12
R150B2	25.1	1.5
R152a	8.7	8.7
R160B1	14.8	1.7
R218	3.2	16.7
R236fa	11.1	14.7
R280	15	1.6
R280B1fb	7.4	1.1
R365mfc	4.4	11.9
R1234ze(E)	12.4	3
R1234yf	23.3	5.4
Total	11.1	4.9

The equation presented in [99] is thus recommended for the calculation of the refrigerant family whenever possible, the equation in [98] represents a valid choice for all other cases.

ii) A new equation for the thermal conductivity of organic compounds

ABSTRACT: This work presents a wide literature survey of the available data of the experimental thermal conductivity data of organic liquids. The

experimental data were collected for 136 compounds belonging to the following families: refrigerants, alkanes, alkenes, aromatics, cycloalkanes, cycloalkenes, ethers, esters, ketones, carboxylic acids, and alcohols. The experimental data were regressed with the most reliable semi-empirical correlating methods existing in the literature and a reliable set of 4,584 experimental data was finally selected. The influence of several physical parameters on the thermal conductivity calculation is discussed and a new equation to represent the thermal conductivity of organic liquids at atmospheric pressure for temperatures below normal boiling point and at saturation for temperatures above the normal boiling point is presented. To minimize the deviation between the predictions and the experimental data and to find the optimal coefficients for the proposed equation, a statistical analysis was performed. The resulting equation is simple and is able to predict the thermal conductivities with low deviations for the major part of the collected data for the studied families.

ii) Correlations of thermal conductivity for liquid refrigerants at atmospheric pressure or near saturation

ABSTRACT: A previously proposed general correlation relating thermal conductivity to reduced temperature is improved by the complete characterization of the refrigerant family. A total of 41 fluids and 1372 experimental points were considered. After analyzing the statistical effects, a new simple empirical correlation to represent the thermal conductivity of refrigerants is presented as a function of reduced temperature, molecular mass, acentric factor, and critical pressure. This equation gives an AAD ¼ 6.5%. The influence of the dipole moment is also discussed and a slightly more complex equation, with an AAD ¼ 6.1%, is presented. The refrigerants were then divided into four subgroups according to the different chemical halogen forming the compounds, and analyzed separately. To minimize the deviation between predicted and experimental data and to find the optimal

coefficients for each family, a non-linear regression was performed. In this way, an AAD ¼ 4.9% was obtained.

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