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Storing energy for cooling demand management in tropical climates: a techno-economic comparison between different energy storage technologies

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Nomenclature

CAPEX	Capital cost (*$*)
C_{cycle}	Cost per cycle *($/cycle*)
$CE_{2charge}$	Cooling energy to be charged (*kWh*)
CE_{demand}	Cooling energy demand (*kWh*)
C_{eu}	Cost per energy unit (*$/kWh*)
c_{lp}	specific heat in liquid phase (*kJ/kg K*)
COP	Coefficient of Performance
C_p	specific heat of the storage medium (*kJ/kg K*)
C_{pu}	Cost per power unit (*$/kW*)
c_{sp}	specific heat in solid phase (*kJ/kg K*)
Cycles	Lifespan in cycles
Econ_savings	Economic savings (*$*)
El_{daily}	Daily electricity consumption (*kWh*)
EN_{char}	Energy spend to charge the storage (*kWh*)
EN_{dis}	Useful energy discharged (*kWh*)
L	latent heat of fusion (*kJ/kg)*
m	mass of the storage medium (*kg*)
NODY	number of operative days per year
OPT	off peak tariff (*$*)
PBP	Payback period
P_{req}	Power requirement (*kW*)
PT	Peak Tariff ($)
Q	total amount of energy accumulated during charging/discharging operation (*kJ*)
$SE_{capacity}$	Storage energy capacity (*kWh*)
T_1	initial temperature (^oC)
T_2	final temperature (^oC)
T_m	melting temperature (^oC)
V	volume of the storage medium's container (m^3)
W_c	Electrical power required during the liquefaction process by a LAES (*kW*)
W_{cold}	Cooling power obtained during the discharge process by a LAES (*kW*)
W_e	Electrical power obtained during the discharge process by a LAES (*kW*)
ΔT	temperature variation of the storage medium (*K*)
ρ	density of the storage medium (kg/m^3)
η_{sto}	Energy storage efficiency
η_{total}	LAES total efficiency

Highlights

- Techno-economic evaluation of energy storage solutions for cooling applications
- Comparison between five energy storage (EES, SHTES, PCM, CAES, LAES) is performed
- Qualitative and quantitative performance parameters were used for the analysis
- LAES/PCM can be valid alternatives to more established technologies EES, SHTES, CAES
- Tariffs, price arbitrage and investment cost play a key role in energy storage spread

Keywords:

Cold Thermal Energy Storage, Liquid air Energy storage (LAES), Phase change materials, Compressed air energy storage (CAES), Li-Ion batteries, hot and tropical climates

Abstract

This paper addresses the role of energy storage in cooling applications. Cold energy storage technologies addressed are: Li-Ion batteries (Li-Ion EES), sensible heat thermal energy storage(SHTES); phase change material(PCM TES), compressed air energy storage(CAES) and liquid air energy storage(LAES). Batteries and CAES are electrical storage systems which run the cooling systems; SHTES and PCM TES are thermal storage systems which directly store cold energy; LAES is assessed as an hybrid storage system which provides both electricity (for cooling) and cold energy. A hybrid quantitative-qualitative comparison is presented. Quantitative comparison was investigated for different sizes of daily cooling energy demand and three different tariff scenarios. A techno-economic analysis was performed to show the suitability of the different storage systems at different scales. Three parameters were used (Pay-back period, Savings-per-energy-unit and levelized-cost-of-energy) to analyze and compare the different scenarios.The qualitative analysis was based on five comparison criteria (Complexity, Technology Readiness Level, Sustainability, Flexibility and Safety). Results showed the importance of weighing the pros and cons of each technology to select a suitable cold energy storage system. Techno-economic analysis highlighted the fundamental role of tariff scenario: a greater difference between peak and off-peak electricity tariff leads to a shorter payback period of each technology.

1. Introduction

Warming of the climate system is unequivocal. Each of the last three decades has been successively warmer than any preceding decade since 1850, and the concentration of Greenhouse Gases (GHG) have increased [1]. Demand for cold is booming, due to structural economic growth in developing economies – where the middle class is projected to grow 3 billion by 2030 [2] and the impact of global warming. For example, the IPCC calculates that global air conditioner energy demand will grow from nearly 300TWh in 2000, to about 4,000 TWh in 2050 and more than 10,000 TWh in 2100, of which about 75% is due to rising incomes in developing countries and 25% due to climate change [3]. The raise for cooling demand represents a challenge for existing electrical networks and future smart grids since it contributes to electricity peak demand. In this context cold energy storage can play an important role in shaving the peak demand burdening the electrical grid. Indeed, cold energy storage can be used to develop demand side management strategies able to shift the load from peak to off-peak hours (thus exploiting potential for price arbitrage) even in presence of renewable energy production [4]. Demand side management is a mean to increase the overall efficiency of the entire electricity network - from generation to the end use - which consists of optimizing the allocation of resources, limiting the peak demand and shaping the demand depending on the necessity of the grid [5]. This study aims to investigate five energy storage technologies applied to cooling demand management applications and to provide a comparison among them. The technologies taken into account are: Li-Ion Electrical Energy Storage (Li-Ion EES), chilled water Sensible Heat Thermal Energy Storage (SHTES), Phase Change Material Thermal Energy Storage (PCM TES), Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES). Among the five types of storage considered here, two are electrical storage devices (Li-Ion EES, CAES), two are thermal energy storage devices (SHTES, PCM TES) and the last one (LAES) can be considered as a hybrid storage system producing both cooling and power. Since this paper only addresses cold energy, the electrical storage devices (that is Li-Ion EES, CAES and LAES) are investigated as a reserve of electricity solely serving the purpose of driving a chiller unit of the cooling system (refer to Fig. 1.a), without any opportunity to use the electricity stored for any other purpose. On the other hand, since the TES systems (SHTES and PCM) are capable to directly serve a certain cooling energy demand, they are included between the chiller unit and the cooling energy demand, as shown in Figure 1.b.

Figure 1

With respect to the existing literature, this paper presents some elements of novelty. First of all, according to the literature review and in the authors knowledge, this paper is the first to compare these five energy storage technologies that differ for both technical aspects and readiness level with respect to a specific application that is the cooling demand management. The assessment is carried out under a holistic point of view, taking into account both a quantitative and a qualitative analysis. The quantitative analysis is mainly techno-economic; it refers to cooling demand management application in tropical and equatorial climates and it aims at providing both information on the role of peak and off-peak tariff in price arbitrage demand side management strategies and an order of magnitude of the main economic key performance indicators (PBP, capital costs and energy savings achievable). With respect to the qualitative analysis, the literature review highlighted, for each technology, the main pros and cons under different prospectives. Most of the authors debate the same engineering and environmental aspects, addressing them accordingly to their research background and sensibility. Different studies proposed similar approaches combining economic and environmental analysis [6]. Petrillo et al. [7] proposed a model which combines the point of view of multiple stakeholders, focusing on the environmental, social and economic dimension of sustainability. Also

Chong et al. [8] tried to propose a comparison of different storage techonologies using a mix of qualitative and quantitative criteria; in particular, they proposed so called decision matrixes that weight the different technology depending on the following criteria: capital cost, durability, response time, efficiency, specific energy/power and ease of implementation. Nevertheless, these works left out from their investigation some aspects discussed by other authors with respect to the same energy storage technology. With respect to the existing literature on energy storage, this work proposes five comparison criteria (complexity, technology readiness level, environmental footprint, flexibility and safety) that, in the author intention, is an attempt to summarize and include all the qualitative aspects discussed in literature improving the qualitative criteria already proposed.

The paper is organized as follows: section 2 presents the methodology applied to carry out both the techno-economic and the qualitative analysis (an in depth analysis of the different energy storage technology considered, highlighting the working principles, the possible applications, the main strengths points and weaknesses is also provided); section 3 presents the results and finally, section 4 presents the conclusions of the work.

2. Materials and methods

2.1 Techno-economic analysis and description of the case study

One of the purposes of this work is to carry out a techno-economic analysis in order to assess different energy storage systems for cooling energy service and provide a comparison. Of the five technologies under study, Li-Ion EES and SHTES are market established; PCM TES and CAES are technically proven, even though there are not as many real applications; LAES is a novel concept that is attracting interest from the scientific community and industry, since it is able to produce both electricity and cooling energy (Combined Cooling and Power: CCP) concurrently. The results of the techno-economic analysis depend on the energy demand, tariff scenarios, storage technologies and, most importantly, the investment costs.

Case study

The study refers to the climate of Singapore but it can be considered relevant for all the tropical and equatorial climates. Indeed, Singapore lies just north of the Equator and its tropical climate is characterised by uniform temperature and pressure, high humidity and abundant rainfall. It does not have a distinct wet or dry season: rainfall maximum occurs in December and April while the drier months are usually in February and July. Daily temperature usually ranges between a minimum of 23-26°C and a maximum of 31-34°C with extremes of minimum of 19.4°C and maximum of 36°C. With regards to ambient relative humidity (R.H.), the daily R.H. spans between ≈90% (and above) in the early morning and ≈60 % in the mid-afternoon; the mean value is ≈84% but during prolonged heavy rain, relative humidity often reaches 100 %. In this context, featured by a small temperature range during the day, also chiller plants work with almost constant perfomance all over the day as demonstrated by the graphs reported in Figure 2, where the hourly COP (measured in September 2015) of an actual water cooled chiller plant installed in Nanyang Technological University campus in Singapore [9] is reported as an example. Figure 2 shows the one-month trend of the COP of a water compression chiller in NTU campus in Singapore: throughout the 30 days the COP of the vapour compression chiller is almost constant during day-night operation. Moreover, the outdoor temperature being equal, the COP slightly differs as a consequence of different load operation: indeed, most of cooling plants are equipped with several chillers of different sizes managed in order to satisfy different load operation by maintaining a high COP. In Appendix, more information about the measurement and monitoring system used to collect data in Figure 2 are provided.

Figure 2

With regard to the energy demand, three different scenarios have been considered (which also correspond to three different cooling energy demands) in order to provide a fair comparison between all the technologies included in this paper:

- Demand scenario A (small scale): 1 MWh_c of daily cooling energy demand, suitable for large residential applications;
- Demand scenario B (Medium scale): 10 MWh_c of daily cooling energy demand, suitable for commercial-industrial buildings;
- Demand scenario C (Large scale): 500 MWh_c of daily cooling energy demand, suitable for very large district cooling applications.

1, 10 and 500 MWh_c represent the amount of cooling energy that the storage systems have to manage on a daily basis, considering a single cycle of charge/discharge per day and 300 days of cooling per year. The demand scenario C was chosen considering a possible cooling energy demand for large district cooling networks in tropical climates. As an example, in Singapore the “Marina Bay Business District” has a district cooling network served by two chiller plants whose nominal total size is 337 MWh_c [10].

The number of operating days was chosen considering the typical cooling operating days in a hot climate. Figure 3, shows the daily cooling load profile considered in the paper: a minimum base load is considered during night operation; then a pre-cooling operation is considered (5.00-8.00 am) before full load operation starting at 9.00 and lasting until 6.00 pm when the cooling load profile lowers progressively down to the night time base load at 10.00 pm.

Figure 3

Parameters for the techno-economic analysis

The main parameters utilized in the techno-economic analysis are: *storage energy capacity, energy storage efficiency*, *daily electricity consumption, power requirement, capital costs, cost per cycle, economic savings, savings per energy unit (specific savings) and payback period*.

A deterministic model was developed to simulate the behaviour of the storage. The purpose of the model is to evaluate the amount of electrical energy consumed to charge the storage unit when in operation. The first step consists of defining the amount of energy to be stored depending on the type of storage and on the action to be implemented (e.g. building cooling).

The ***storage Energy capacity*** **($SE_{capacity}$, kWh)** defines the amount of energy that the storage system has to store in order to manage the daily cooling energy demand. In the case of electric storage devices, energy storage capacity corresponds to the electrical energy to be stored in order to drive the chillers that satisfy the final user cooling energy demand. In the case of thermal storage, the storage energy capacity corresponds to the cooling energy demand that can directly be served for the final user to satisfy its cooling needs. In section 2.3, the storage Energy capacity is defined with detail for each cooling storage device.

The ***Energy storage efficiency*** represents the charge/discharge efficiency of the storage technology. It is also called round trip efficiency and it is calculated as:

$$\eta_{sto} = \frac{EN_{dis}}{EN_{char}} \qquad \textit{Equation 1}$$

In this work, the storage efficiency is approximated as a constant parameter, evaluated by considering the daily average charging, discharging and storing losses. The steady-state model does not account for the change in external conditions (e.g. temperature, humidity) that, in the real case, would affect the storage efficiency hour by hour.

The ***Daily electricity consumption*** **(kWhe)** represents the estimated electrical energy necessary to charge the storage system for its daily cycle. It is a function of: i) the Storage energy capacity, expressed in electric kWh; ii) the round trip efficiency of the storage technology and iii) the COP of the chillers serving the cooling system. This parameter is used to compare the energy conversion efficiency of different technologies. In section 2.3, the daily electricity consumption is defined in detail for each cooling storage device.

The ***Power requirement*** **(kW)** defines the size of the different storage power converting components needed for both charge and discharge operations. Each energy storage technology has its own power converting components: an inverter in the case of Li-Ion EES; a heat pump in the case of thermal energy storage, a compressor (during charge operations) and a turbine (during discharge operations) for CAES. The power requirement is calculated as the Daily electricity consumption divided by the number of discharging hours; this paper considers 8 discharging hours during peak time while the charging phase occurs off peak hours.

Capital cost ($) of each energy storage technology is function of both the costs per energy and power unit [11]. When assessing the capital cost relatively to a storage technology, three different cost components can be distinguished [12]: the costs related to the actual energy storing element, the power conversion system (PCS) and the "balance of plant" (BOP). The costs related to the energy storing elements depend on both the technology in use and the storage Energy Capacity: they are usually expressed in $/kWh. On the other hand, the power conversion systems consist of all the electrical components that are necessary to convert electricity from AC to DC (and back) making the storage interact with the grid: these costs are usually expressed in $/kW. BOP costs are relative to all the additional assets, services and equipment that are required to deploy the storage. As an example, the HVAC equipment, the maintenance devices and the mechanical structures are considered within the balance of plant. This cost component is really variable from application to application and it is the hardest one to evaluate. Equation 2 summarizes these three cost components: the first term refers to the energy contribution (cost per energy unit), while the latter refers to the power contribution (cost per power unit).

$$\boldsymbol{CAPEX = SE_{capacity} \cdot C_{eu} + P_{req} \cdot C_{pu}} \qquad \textbf{\textit{Equation 2}}$$

In particular, equation 2 approximates the relation between costs and size with a linear function. Since some of the technologies considered in this study have not achieved market readiness, the figures for the prices provided from manufacturers and/or literature can be considered more as an estimate rather than actual market price. For this reason, once calculated the capital cost with Equation 2, the techno-economic analysis is carried out also considering a ±20% error margin on the capital cost estimation, in order to consider the uncertainties in capital cost.

Storage technologies generate savings by exploiting the variability of energy rates and they are usually used to perform demand side management strategy that involves shifting of energy demand from peak to off-peak hours of the day. Indeed, with a flat electric tariff, storage technologies would not generate any savings but on the contrary would be more expensive since they lead to higher energy consumption by introducing inefficiency in the system. Thus, it is necessary to establish a tariff scheme. A tariff scheme is usually composed by the following components: power rate, energy rate, taxes and presence of possible incentives. This paper does not take into account possible incentives and it considers all the components of the tariff scheme as constant; the only variable is the energy rate that is varied between peak and off peak periods. The study was parameterized according to three tariff scenarios, based on different peak-off peak energy rates: tariff scenario 1 (TS1), scenario 2 (TS2) and scenario 3 (TS3) in which the off peak rate corresponds to 25%, 50% and 75% of the peak rate respectively. The peak energy price was fixed to 0.13 $ which represents the average electricity price for tertiary consumers in Singapore in 2016 [13].

Economic savings **($)** are calculated as the difference between the yearly operating costs with and without the storage. When evaluating the yearly operating cost, the energy quantity to shift per day, the storage efficiency, the spread between peak-off-peak tariffs and the number of operative days per year are taken into account.

$$\mathrm{Econ}_{\mathrm{savings}} = \left(\frac{\mathrm{ENdis}}{COP} \cdot PT - \mathrm{ENchar} \ \cdot OPT\right) \cdot NODY$$ *Equation 3*

Savings per energy unit **($/kWh$_c$)** are obtained by dividing the *Economic savings* for the cooling energy actually provided by the system to the final user; this parameter is a measure of the effectiveness of the system used.

Payback period **(years)** represents the main parameter that needs to be assessed to determine the feasibility of an investment; it is calculated by dividing the capital cost for the annual economic savings.

$$\boldsymbol{PBP} = \frac{\boldsymbol{CAPEX}}{\boldsymbol{Econ\_savings}}$$ *Equation 4*

Levelized Cost Of Energy – LCOE - ($/kWh) is defined as the average cost per kWh of useful energy produced by the system. It is calculated by considering all the costs and revenues associated with the system during its lifetime. Since this study is focussed on analysing the benefits of integrating storage technologies with existing cooling systems, only the relative savings between the scenarios with and without the storage systems have been considered. In contrast to the Savings per energy unit, this parameter considers the number of cycles that the storage system is supposed to carry out. Thus, the levelized cost of energy represents an interesting benchmark, normalizing the savings obtainable using a certain technology by the amount of energy that the system is able to deliver during its lifetime. A positive levelized cost of energy means that 1 kWh of cooling energy produced by the scenario investigated is more expensive than the base case with no storage. On the contrary, a negative levelized cost of energy means that by introducing that particular storage technology is possible to reduce the cost of energy for the system.

$$\boldsymbol{LCOE} = \frac{\boldsymbol{CAPEX - Savings\ per\ energy\ unit}}{\boldsymbol{CE_{demand} * Cycles}}$$ ***Equation 5***

2.2 Qualitative comparison criteria

In order to critically compare the characteristics of the storage systems, it is important to define the criteria which can be applied to compare the different technologies and which go beyond pure techno-economic analysis. In fact, while the techno-economic analysis provides quantitative information, the proposed criteria serve to provide qualitative information, useful to get an idea of the potential of each technology and to help defining its optimal exploitation.

Five different criteria are proposed in this paper and for each one of them a score is assigned from 1 to 3.

1. ***Complexity****:* it is an indicator of the challenges related with the integration and control aspects of the storage system; this criterion takes into account the typology and number of components, control systems, maintenance and reliability. The scores go from the easier (1) to the more complex (3).
2. ***Technology Readiness Level (TRL):*** TRL is a metric to estimate technology maturity. It is based on a scale from 1 to 9, from the least to the most mature technology [14] [15]. In the case of TRL, the proposed scores in this paper,1 to 3, correspond to *Early Research Stage* (TRL 1-3), *Advanced Research Stage – Pilot Testing* (TRL 4-7) and *Ready to Market* (TRL 8-9), respectively.
3. ***Environmental footprint:*** this is an indicator of the environmental impact of the storage technology; this is evaluated by assessing the whole life cycle, from the manufacturing to the disposal of each system. In addition to this, the *environmental footprint* also includes the climate change potential, human toxicity, particulate matter formation and fossil resource depletion; the higher the score, the cleaner the technology.
4. ***Flexibility****:* each storage technology is more suitable for specific applications, which can be classified in: Power generation, Transmission and distribution, Energy service and Renewable energy related [16]. The more flexible the technology is, the wider the field of application, thus the market potential. This paper mainly focuses on load shifting applications. The higher the score, the more flexible the technology.
5. ***Safety:*** the growth potential of storage technologies is also tied-up with their safety. This aspect becomes significantly important the closer the storage device gets to the point of demand. Safety depends on several aspects: the toxicity of the storage medium, high working pressure, chemical reactions, and potential of electrical shocks, fire or explosions. The higher the score, the safer the technology.

The five criteria have been defined condensing a wide range of considerations coming from review papers and from each technology's specific literature. As an example, papers in the literature relative to CAES systems focuses on the technical selling point of the technologies as well as on the critical challenges, like the lack of off the shelf machinery available and the geological restriction for underground systems [17]

[18]. The technology readiness level reflects the first consideration, while the latter one influences the Flexibility index.

2.3 Storage technologies description and modelling

For each energy storage technology considered in this paper, every subsection provides a brief description of the working principles, the state of the art, the classification, applications, R&D status and future challenges.

2.3.1 Lithium-Ion EES (Li-Ion EES)

In Li-Ion batteries, the cathode is made of a lithium metal oxide, while the anode is made of graphitic carbon. The main advantages of Li-Ion EES compared with other battery technologies are: high energy density (up to 200 Wh/kg), high overall efficiency (85-95%), long expected lifetime (up to 10000 cycles for specific chemistries), milliseconds response time and low self-discharge per day (0.1-0.3%) [11]. Moreover, Li-Ion batteries require low maintenance (no scheduled cycling, no memory issues) [19]. These characteristics make Li-Ion technology suitable for a wide range of applications, going from few kW-hours batteries up to MW-hours systems [20]. Li-Ion batteries are technically developed and commercially available, however some critical issues still have to be overcome: high investment costs [11] and potential dangerousness in some challenging scenarios. Rosenwater et al. [21] classify the hazardous conditions into five categories: voltage, arc-flash/blast potential, fire potential, vented gas combustibility potential and vented gas toxicity. Degradation is another important aspect to take into consideration; in fact, energy capacity tends to decrease along over a lifecycle of the battery due to electrochemical reactions that increase the internal resistance of the system. As per the environmental impact of Li-Ion EES, three different life stages must be taken into consideration: *productio*n, *use* and *end-of-life* [22]. Oliveira et al. [23] shows that, during the production stage, the positive electrode production and the manufacturing process are the most expensive items; during use stage the environmental performance is strongly dependent by the efficiency of the storage system and to the primary energy mix; the end-of-life is characterized by the recycling possibilities, which can reduce both the environmental footprint and the continuous need for raw materials. Currently R&D is working on: increasing safety and efficiency, recycling of components, definition of universal standardization procedures and quality control protocols to establish technology benchmarks [20] .

At the present time, one of the biggest drawbacks for Li-Ion EES is the high capital cost. The diffusion of electrical vehicles is pushing the market for Li-Ion batteries to new limits: an increase in the demand of batteries will eventually trigger a reduction in manufacturing costs. In 2015 the Citi Group, one of the biggest American multinational banking and financial services corporation, estimated a reduction in the investment cost for Li-Ion EES, down to 230 $/kWh in the next 7-8 years [24]. If this trend is confirmed, Li-

Ion EES will become competitive with the other technologies also from the economic point of view, making them a good solution for demand management in cooling applications.

In this paper, Li-Ion EES system is considered as an electric storage that only serves the cooling system. More in particular, the Li-Ion EES system is charged during off-peak hours and it discharges during peak-hours to drive the chiller unit. Once the amount of cooling energy to be provided by the storage system is defined, the storage energy capacity, that is the amount of useful electric energy to be stored, is calculated as:

$$\boldsymbol{SE_{capacity}}[\boldsymbol{kWh_e}] = \frac{\boldsymbol{CE_{demand}}[\boldsymbol{kWh_c}]}{\boldsymbol{COP}} \qquad \textbf{Equation 6}$$

The Daily electricity consumption is then calculated as:

$$\boldsymbol{El_{daily}}[\boldsymbol{kWh_e}] = \frac{\boldsymbol{SE_{capacity}}}{\boldsymbol{\eta_{sto}}} \qquad \textbf{Equation 7}$$

Table 1 reports the techno-economic value ranges of Li-Ion EES available in the market.

Table 1

2.3.2 Thermal Energy Storage (TES)

Thermal Energy Storage (TES) allows energy storage in the form of thermal energy by heating or cooling a storage medium. TES can be designed to work on daily, weekly or even seasonal basis. TES have been exploited for demand management applications (peak shaving, energy shifting), to enhance the operating efficiency of an energy conversion system working under unsteady conditions, or to store excess renewable energy. TES can be used both as centralized (district heating/cooling, large industrial plants, renewable power plants) and/or distributed solutions (heating and cooling for domestic and commercial buildings). The power capacity of TES systems ranges from kW to several MW. Depending on the technology and application, thermal energy can be stored at temperatures spanning from -40 °C to more than 400 °C [26]. Three different TES systems can be identified:

1) Sensible Heat Thermal Energy Storage (SHTES) that use the heat capacity of the storage materials.
2) Latent Heat Thermal Energy Storage (PCM TES) that use the latent heat of storage materials during phase transition (i.e. charging/discharging phases) between two states (e.g. gas-liquid or solid-liquid).
3) Thermo-Chemical Storage (TCS) systems that use reversible chemical processes as charging/discharging mechanism.

The two main aspects to consider, when sizing TES, are: the ratio between the maximum and the average thermal load; the local electricity tariff, in terms of energy and power rates[27] [9]. TES has already been recognized as a viable option for applications aimed to increase the efficiency of industrial processes, to integrate conventional thermal conversion machines (combustion engines, steam/gas turbines, ORC) [28] and as an energy management device, applied to single buildings or district heating/cooling networks [29]. As per this paper, TCS will not be investigated; the reason being that TCS systems are still in early research stage (low-to-medium TRL) with several engineering aspects which need to be addressed before commercialization: material selection, heat transfer characteristics, safety.

In this paper, TES system is thought as a reserve of cooling energy. In particular, TES charges during off-peak hours and it discharges during peak-hours to provide the cooling energy to the final user. For TES the Storage energy capacity ($\boldsymbol{SE_{capacity}}$) corresponds to the useful cooling energy demand ($\boldsymbol{CE_{demand}}$) to be provided by the storage system. The gross cooling capacity to be charged ($\boldsymbol{CE_{2charge}}$) is a function of the TES efficiency ($\boldsymbol{\eta_{sto}}$):

$$\boldsymbol{CE_{2charge}} = \frac{\boldsymbol{CE_{demand}}}{\boldsymbol{\eta_{sto}}} \qquad \textbf{Equation 8}$$

The daily electricity consumption can be calculated as:

$$\boldsymbol{El_{daily}} = \frac{\boldsymbol{CE_{2charge}}}{\boldsymbol{COP}} \qquad \textbf{Equation 9}$$

2.3.2.1 Sensible heat thermal energy storage (SHTES)

Sensible heat thermal energy storage (SHTES) is a mature technology, since it has been commercially available for many years in both domestic and industrial applications. The amount of energy stored in SHTES is proportional to the temperature difference between the initial and final state, the mass of the storage medium and its heat capacity (equation 10) [30].

$$\boldsymbol{Q = m\, c_p\, \Delta T = \rho\, c_p V\, \Delta T} \qquad \textbf{Equation 10}$$

This paper will mainly focus on the most common SHTES technology, the *chilled water thermal energy storage systems*, also called CTES. CTES is typically used for daily cycling demand management applications, as both centralized and distributed solution: cold energy is produced during off peak periods of the electrical demand, stored within a tank, and then withdrawn in times of demand. The storage medium is water at atmospheric pressure; operating with a temperature difference of 5°C (temperature ranges between 7°C when fully charged and 12°C when fully discharged). The overall efficiency of thermal storages ranges between 50-90% [26], depending on many aspects such as the insulation material, the water diffusion mechanism inside the vessel and the charging/discharging mechanisms (pumps, heat exchanger); Figure 4 shows a typical scheme for a water CTES.

By using water as storage medium, CTES become relatively cheap; the investment cost mainly depends on the size, the application, the charging/discharging equipment and the tank thermal insulation. DeForest et al. [27] estimate a cost per energy unit of 31 $/kWh based on real project quotations, linearly growing with size. SHTES systems are reliable, durable (they can work for more than 30 years depending on the management strategy and the operating conditions [26]) and easy to integrate with existing HVAC plants. Moreover, they are also safe during operations since they do not have risks derived from the use of toxic materials or pressurized equipment. The main downside of SHTES is the low energy density (10-60 Wh/kg [26]). This limits the range of feasible applications to small and mid-scale size: space requirements represent a significant constraint when designing HVAC plants, especially for urban networks, and for large energy demands to handle would result in high storage tank volumes [20].

Table 2 reports the techno-economic value ranges of SHTES available in the market. In the techno-economic analysis, a comprehensive cost per energy unit value, presented in [27], will be considered.

Table 2

2.3.2.2 Phase Change Materials Thermal Energy Storage (PCM TES)

In PCM TES, the storage capacity significantly increases allowing a compact TES to be used where space is a constraint. Oró et al. [31] has summarized a list of 88 low-temperature PCMs including commercially available PCMs and their properties. The latent heat of fusion of PCMs is at least 20 times that of chilled water's heat capacity (about 4 kJ/kg) with water (or ice) with the highest latent heat of fusion at 333.5 kJ/kg at 0^{o}C. Calmac, Evapco and ice-energy are examples of commercialized companies that are based on ice PCM TES to provide cooling for buildings and other refrigeration needs by making use of off-peak electricity to produce ice [32] [33] [34]. However, ice based TES systems are limited to a range of operating (discharge) temperatures (0-4 ^{o}C) that limits their ability to meet a larger range of cooling applications. Moreover, according to Dincer [35], PCMs with low melting temperature (7-10 ^{o}C) are described to be more suitable to work with standard air-conditioning than ice based storage systems (1 to 3 ^{o}C). Thus, for a comparison with chilled water SHTES and other types of cold energy storage technologies covered in this paper, an eutectic salts PCM storage system operating at 8^{o}C will be considered. The amount of energy accumulated (for PCM storage) is described in the equation below.

$$\boldsymbol{Q = m\,(c_{sp}(T_m - T_1) + L\; +\; c_{lp}(T_2 - T_m))} \qquad \textbf{Equation 11}$$

Equation 11 assumes that the operating range allows the material to melt completely; the initial and final temperatures, T_1 and T_2, depend on the design of the chiller system that is used to charge the PCMs. The storage capacity is even higher if the systems are designed to operate within a certain temperature range where the heat capacities, before and after melting, are taken into consideration. Eutectic salts for PCM TES are the most commonly investigated systems due to their higher latent heat of fusion when compared with other categories of PCMs [36]. The charging mechanism of a PCM TES is similar to the chilled water storage system and standard chillers can be used. Evaporator temperature remains constant due to the minimum range of operating temperatures required in PCM TES. Well established PCM TES technologies have a range of temperatures and applications from -33 ^{o}C to 27 ^{o}C by using eutectic salt PCMs [37]. PCMs are selected firstly based on two factors: the phase change temperature (i.e. melting temperature, T_m) and latent heat of fusion that will determine the operating point and the storage density. Other material properties that determine the selection process are minimal super-cooling, high thermal conductivity, low environmental toxicity and low cost; a list of considerations has been well covered in several reviews on PCMs [31, 36]. Li Gang et al. [38] provided a good review of cold PCMs for air conditioning applications where a wide range of PCMs with melting temperature between 6-14 ^{o}C.

In Table 3, a list of highly potential PCMs to meet cooling demand is compiled. A commercialized salt hydrate PlusICE S8 with relatively high volumetric heat capacity was selected for PCM TES. The cost of PlusICE S8 is around 2.18 $/kg. Another reason for selecting eutectic salt based PCM is that, other than ice storage and chilled water, eutectic salt is considered a relatively mature aspect of PCM TES [39].

Table 3

In PCM TES, the material is encapsulated in plastic containers that are stacked in the storage tank through which heat transfer fluids (e.g. water) is circulated [44]. During off-peak hours or using renewable energy sources, the system's chiller may supply cooled water of 4 to 5 ^{o}C that is pumped into the storage tanks to freeze the PCMs at 8^{o}C (charge mode). When there is high cooling demand during peak hours, the PCM is allowed to melt, and the water is pumped from the tank at about 10 to 12^{o}C through the cooling system's chilled water circuit (discharge mode). The main disadvantage is that the discharge temperature is higher which accomplishes less building dehumidification [35].

PCM TES efficiency is reported in the range of 75-90% [26] that includes the efficiency of ice and PCM TES. In a recent case study [44] of a small scale comparison between chilled water and eutectic salt storage system, it was found that the efficiency of the PCM tank (67-73%) was not as high as the water tank (83%) but the actual supplied cold (kWh) was higher. Given the same volume, the PCM tank was able to store 35% more cold than a water tank, but with a significant longer charging time. Thus, PCM TES needs to charge/discharge more quickly in order to meet power demand that considers energy extraction and storage per amount of time as key parameters. Other notable drawbacks relating to PCM storage include cost and energy density. Ice is undoubtedly the cheapest PCM but is limited by its freezing temperature. PCM storage has to be better integrated with the building's initial design for better efficiency and can reduce its space outlay if the storage was built underground with the space above the storage used for other purposes. There is notable R&D in phase change materials and PCM TES from academia and companies. Several active enterprises founded the quality association PCM in 2004 and since then, more quality indicators and standard measurement techniques have been listed [45]. One of the key challenges is to improve the low thermal conductivity of many PCMs which affects the charge/discharge time. Conductive nano-materials and additives, optimization of heat exchangers and multistage storage design were proposed [46, 47, 48]. Other studies aim to assess the sustainability of building materials, most of them are collected and critically analysed in [49].

Table 4 reports the techno-economic value ranges of PCM TES based on the cited reference. It is not a trivial task to estimate the costs related values for PCM TES, as it was done for SHTES since the literature is poor of examples referring to commercial PCM applications and the capital cost per power unit found varied in a wide range (650-1626 $/kW). For this reason, likewise SHTES, in the techno-economic analysis, a comprehensive cost per energy unit value is considered; this was evaluated starting from the comprehensive cost per energy unit value used for the sensible heat case (Table 2), considering that, as deduced from data reported in [26], the investment costs for a PCM TES is on average 2.5 higher than the ones related to SHTES.

Table 4

2.3.3 Compressed air energy storage

Compressed air energy storage works storing electrical energy using air as storage medium: first by compressing the air during charge, then expanding it through a turbine during discharge [50]. Figure 5 shows a functional representation of a conventional CAES. During charge, electricity from the grid is used to power a compression process. The compressed air is then stored at high pressure (4-8 MPa) into a pressurized storage vessel which, depending on the application, can be either underground or above ground. During discharge, compressed air is heated and then expanded into a turbine.

Figure 5

Well established mechanical components guarantee a long life to the plant (20-40 years) [25]. The rated power ranges from few hundreds kWs to hundreds of MWs for a single unit so that CAES offers a wide range of possible applications: energy management (time shifting, peak shaving, load levelling), renewable sources integration, seasonal energy storage and ancillary services [51]. The energy density depends on the pressure level and it can span from 30 to 60 Wh/kg [25]. CAES requires the use of large underground caverns or pressurized vessels as storage unit. Underground CAES brings geological constraints: in order to fit the safety and space requirements, the choice and preparation of the construction site is a major challenge; aboveground CAES is more expensive but simpler and more flexible to adopt since a pressured vessel does not pose any constraint from the geological point of view [25]. If natural gas is used to heat the air before expansion in a combustion chamber, the technology is defined as *diabatic* (i.e. non-adiabatic). Recent development improved CAES concept by recovering waste heat produced during the compression phase through thermal energy storage and reused to supply the heat required to the heat exchanger, avoiding combustion chamber, making the storage process almost completely adiabatic [52]. This is the principle behind Advanced Adiabatic CAES (AA-CAES), a locally emission free technology with high storage efficiency (above 70-90% [25]) that is attracting interest, and substantial investments, from both academia and industry. As per this paper, AA-CAES technology will be considered for both the qualitative and techno-economic analysis. Currently, there are two working CAES plants in the world: the first is located in Huntorf, Germany, built in 1978; while the second is located in McIntosh, Alabama, built in 1991; both are diabatic CAES systems designed as bulk energy storage [53]. In Germany, RWE Power is working on a project called ADELE, to build the first large scale adiabatic compressed-air energy storage for electricity supply [54]. Other pilot plants are expected from different companies around the world (General Compression, Lightsail Energy, SustainX, Ages), which are currently working at their own version of CAES [51]. R&D is focusing on new ways to enhance CAES performance with particular regard to the optimization of the heat exchange processes [20] [55] [56] and the improvement of compression efficiency through the concept of the almost isothermal compression [57]. Likewise Li-Ion EES, in this paper CAES system is considered as an electric storage that only serves the cooling system. In particular, it charges during off-peak hours and it discharges during peak-hours to drive the cooling chiller unit. Once defined the amount of cooling energy to be provided by the storage system, the storage energy capacity is calculated as:

$$\boldsymbol{SE_{capacity}}\,[\boldsymbol{kWh_e}] = \frac{\boldsymbol{CE_{demand}}\,[\boldsymbol{kWh_c}]}{\boldsymbol{COP}}$$ **equation 12**

The Daily electricity consumption is then calculated as:

$$\boldsymbol{El_{daily}}[\boldsymbol{kWh_e}] = \frac{\boldsymbol{SE_{capacity}}}{\boldsymbol{\eta_{sto}}}$$ **equation 13**

Table 5 reports the techno-economic value ranges of SHTES available in the market. It is worth noting that Table 5 reports the range of cost for the sizes of storage investigated in this paper: indeed, looking at the whole literature, the cost per power unit ranges between 400-1500 $/kW while the cost per energy unit ranges between 2-280 S/kWh.

Table 5

2.4.5 Liquid Air Energy Storage (LAES)

LAES uses liquid air, or liquid nitrogen, as storage medium. The operating principle of LAES is described in Figure 6: the electricity drives the compressor of an air liquefaction cycle (usually a Claude cycle) to produce liquid air, which is then stored in an insulated tank. At times of demand, liquid air is discharged from the tank, pumped to high pressure and heated up within a heat exchanger, which works as an evaporator and finally, the air is expanded in a power unit in order to generate electricity [58].

As power unit, LAES can adopt two typologies of technologies according to its power capacity. LAES systems from 1.5 MW up to hundreds of MW, uses a standard gas turbine; for small, decentralized, applications, or hybrid transports they can use a piston engine (e.g. Dearman engine) [59] or basic rotary technology (e.g. Epiqair engine) [60]. The Dearman engine is a modified version of standard internal combustion engines, and it uses a mixture of liquid air and water as working fluid in the cylinder [61]; Epiqair technology consists of rotary compressor and expanders which are specifically designed for air liquefaction.

Figure 6

LAES is a storage technology with high specific energy (214 Wh/kg) [51], suitable for mid to large scale applications (from hundreds of kWs, up to hundreds of MW). Well-established mechanical components guarantee a long life to the plant (20-40 years) [51]. One of the most interesting features of LAES technology is that it can produce both electricity and cooling energy at the same time. Indeed, during the discharging process, LAES produces two different outputs: electrical power from the generator (W_e) and cold power from the evaporator (Q_e). The high grade cold, which comes from liquid air re-gasification, can be harvested using outlet air coming from the turbine as energy vector. Depending on this aspect, two main operational modes can be distinguished, called in this work “full electric mode” and “cogeneration mode”. In “full electric mode”, the cold energy, collected from the power generation sub-system, is used to assist the liquefaction process, thus minimizing the compression work. In this case, the only useful output of the storage system is electrical power. Since the charging and discharging processes are usually decoupled, a high grade cold storage is necessary to store the cold energy which will then be used during the liquefaction process. In “Cogeneration mode” the storage system produces both cold (Q_{cold}) and electric power (W_e), usually with a two to one ratio: for every kW of electricity, it can also generate two kW_c of cold energy. The round trip efficiency of LAES depends on both the operating mode and the scale of the system. Large scale systems benefit from already commercialized components with high reliability and efficiency. A commercial scale LAES is able to produce at least 300 tons per day of liquid air and has a power output of at least 10 MWe [59]; as a rule of thumb, 10 tons of liquid air can produce 1 MWhe.

Table 6 shows the expected liquefaction and power conversion efficiencies: information is collected from Highview power's report [62].

Table 6

For LAES, the total efficiency is calculated as follows:

$$\boldsymbol{\eta_{total}} = \frac{\boldsymbol{W_e + W_{cold}}}{\boldsymbol{W_c}} \qquad \textit{Equation 14}$$

Where W_e and W_{cold} are the electrical and the cooling power produced, respectively; W_c is the power consumed by the liquefaction process. One main advantage of LAES systems is that they can recover low-grade waste heat (<100°C) by feeding the evaporator with waste heat, thus increasing the enthalpy content of the liquid air before entering the power unit. A linear correlation exists between the turbine inlet temperature and the generated power. From field experimentation, it has been estimated that a 1°C inlet air temperature increase results in 1 extra kW of electrical power produced [62]. In addition to this, LAES has no geographical constraints, neither contains toxic or strategic materials. All these features combined together, make this storage system suitable for a wide range of applications: energy management (load levelling, peak shaving, time shifting), backup power, seasonal energy storage and ancillary services [51]. A LAES pilot plant (300 kW, 2.5 MWh), designed and developed by Highview Power Storage, has been operating in the UK since 2010. In 2014, the same company was awarded by UK government to build a commercial scale demonstration plant (10 MW, 40 MWh) [63]. While large scale LAES benefits from well-established processes and components, at smaller scale the overall performances are lower due to a less efficient liquefaction process (refer to Table 6). Therefore, R&D is focusing on the challenges related to small scale LAES applications. Studies are being published relatively to the fine-tuning of the thermodynamic processes and the testing of various cycle configurations [65] [66]. Indeed, the more efficient the liquefaction process [67], the higher is the LAES round trip efficiency. As for the CAES, quasi-isothermal compression is one of the options which are currently being explored [57].

In this paper, the LAES is supposed to work only in cogeneration mode, with the electricity produced only serving the cooling system chiller. Given the cooling energy demand to be provided by the storage system, the storage energy capacity is calculated as:

$$\boldsymbol{SE_{capacity}}\,[\boldsymbol{kWh_e}] = \frac{\boldsymbol{CE_{demand}}}{\boldsymbol{(COP+2)}} \qquad \textit{Equation 15}$$

Equation 15 is obtained by considering that, starting from the electricity storage capacity, the cooling energy can be produced both by the chillers (as a function of the COP of the chiller) and by the cold energy recovered during the expansion of the air (with a 1:2 ratio as previously mentioned). The Daily electricity consumption is then calculated as:

$$\boldsymbol{El_{daily}}[\boldsymbol{kWh_e}] = \frac{\boldsymbol{SE_{capacity}}}{\boldsymbol{\eta_{sto}}} \qquad \textbf{equation 16}$$

Table 7 reports the techno-economic value ranges of LAES. As for the other technologies at demonstration level, the range of costs found in literature is wide because of sources refer to different scales and applications. However, as a general rule, the larger the scale of the application, the lower is the cost of power and energy unit. Therefore, in the techno-economic analysis the lowest values of the ranges provided in Table 7 are considered (i.e. 900 $/kW and 260 $/kWh).

Table 7

3. Results and comments

3.1 Techno-economic analysis

The techno-economic analysis was carried out to assess different storage technologies under different demand and tariff scenarios as those described in Section 2. Since not all the storage technologies are suitable for all sizes of demand, Table 8 reports the types of storage chosen for each demand scenario.

The results of the analysis are reported for each demand scenario under four tables:

- *Storage technical data:* for each type of energy storage are reported the efficiency (calculated as the average one of the storage available in the market), the energy capacity, the power requirement, the daily electricity consumption and the lifespan cycles. These values are calculated/selected according to the methodology presented in Section 2 and by assuming that the water cooled vapour compression system had an average *COP* of 5.
- *Storage economic data*: it includes the capital cost of the storage technologies calculated according to Equation 2. It is worth noting that, as already highlighted in Section 2, costs are presented as a range of values in order to take into account the uncertainties connected to the estimation of price for storage technologies not yet available in the market.
- *Economic results:* these tables report the annual savings and the payback period for each energy storage technology, considering the three different tariff scenarios described in Section 2.
- *Effectiveness indexes:* these tables report the effectiveness benchmarks described in Section 2.1 (levelized cost of energy and Savings per energy unit) for each storage technology, considering the three different tariff scenarios described in section 2.1.

Tables from 9 to 12 report the results for the demand scenario A (daily cooling energy demand of 1 MWh). The storage technologies considered are: SHTES, PCM TES and Li-Ion EES. The results show that the high efficiency of the Li-Ion EES corresponds with the highest savings per energy unit. However, Li-Ion EES is not economically viable: its payback period is always higher than the TES and the LCOE is always greater than zero; this is mainly due to the high capital costs.

Among the TES, PCM TES is more efficient than SHTES (higher savings per energy unit) and, most importantly, it has higher specific energy: the latter aspect becomes extremely important when space represents an important design constraint. However, due to the higher capital costs, the integration of a PCM TES is not as convenient as SHTES (higher LCOE). For most of the technologies assessed in this study, the payback period is significant; in particular, Li-Ion EES does not represent a viable business case: even for the most convenient tariff scenario, the results show its LCOE to be greater than zero. From an economic point of view, the only viable solutions are SHTES and PCM TES, which score negative LCOE in both tariff scenarios 1 and 2. As expected, tariff scenario 1 (TS1) is the most convenient for the applications studied in this paper since it makes it possible to better exploit price arbitrage opportunity; the smaller the difference between peak and off-peak tariffs the higher the LCOE and PBP are.

Table 9

Table 10

Table 11

Table 12

Tables 13 to 16 report the results obtained for the Demand scenario B (daily cooling energy demand of 10 MWh). The storage technologies considered are: SHTES, PCM TES, Li-Ion EES and LAES. Li-Ion EES is still too expensive to be considered viable, even if it is the most efficient technology (highest savings per energy unit). At this size, the only feasible investments are the SHTES and the PCM TES when applied to TS1. SHTES is still the best choice with the lowest CAPEX, LCOE and payback period. LAES is considered when operating in both cogeneration and full electrical mode.

Table 13

Table 14

Table 15

Table 16

Tables 17 to 20 report the results obtained for the Demand scenario C (daily cooling energy demand of 500 MWh). The storage technologies considered are: CAES and LAES. The SHTES was not included due to its low energy density as it would require an enormous volume to manage that amount of energy (around 110,000 m^3); in addition to this, in order to handle a daily cooling energy of 500 MWh_c, it would become much more complicated to design and manage the supporting equipment (heat exchangers, pumps, pipes etc.). PCM TES is currently focussed on proving its viability at a small scale and therefore the possibility to scale it up for grid applications is not considered viable. For such large scale applications, CAES high efficiency guarantees low daily electricity consumption (almost as low as Li-Ion EES). LAES is considered when operating in both cogeneration and full electrical mode. In cogeneration mode, despite the less energy capacity required, the daily electricity consumption is much higher due to lower energy storage efficiency. In full electrical mode, the daily electricity consumption is comparable with the other technologies. A low value of daily electricity consumption corresponds to less primary energy usage which corresponds with lower CO_2 emissions. Under the economic point of view, CAES is the best technology: higher savings, lowest payback periods and LCOE. CAES is proven to be a viable solution in both TS1 and TS2, thanks to the long expected life (up to 10,000 cycles). On the other hand, LAES either in cogeneration or full electrical mode is proven to be feasible only in TS1; indeed it scores positive LCOE for both TS2 and TS3 scenarios.

Table 17

Table 18

Table 19

Table 20

3.2 Sensitive analysis over the cooling system COP

In this section, the study presents a sensitive analysis to assess the influence of COP on the economic performance of each storage technology. While the results showed in table 9 to 20 are calculated considering a COP of 5, a second set of results has been obtained considering both a COP of 4 and 6. These values of COP were chosen to take into account a wider range of chiller efficiency in tropical climates countries: COP 4 aims at representing the average efficiency of conventional chiller plants; COP 5 represents the average efficiency of optimized chiller plants; COP 6 represents the average efficiency of the best available technology of variable speed chiller plants. The COP value is intended as the average annual chiller plant efficiency including also cooling tower fans, condenser and chilled water pumping [72, 73].

It is worth noting the main assumptions of the study: tropical and equatorial climate with low temperature difference between night and day; water cooled chillers; the average COP value is almost constant throughout the year (Figure 2) [9]. For the sake of brevity, the new results data tables are not reported. The most interesting results are shown in figures 7 to 10. The results showed in this section are all taken from the tariff scenario 1. The results confirm that the LCOE for Li-Ion EES is higher than the case without storage since the economic savings coming from the price arbitrage exploitation are not sufficient to offset the high investment cost. On the contrary, the LCOEs of the other types of storage are always lower than the case without storage. It is also worth noting how strongly the COP impacts the effectiveness of the systems which store directly the cooling energy (SHTES, PCM TES and $LAES_{cog}$); for these systems, the LCOE reduces much more than the electrical based energy storages. The lower the COP of the cooling system (i.e. the less efficient the chillers), the more effective the thermal storage solution becomes. Indeed, for large scale applications, $LAES_{cog}$ becomes an interesting solution, having a lower LCOE than the full electrical version. It is worth noting again that LCOE reported in Figure 7 is calculated as the difference with the traditional scenario without storage. For this reason, the LCOE with COP 4 is better than the LCOE with COP 5, while the one with COP 6 is even worse: indeed, the marginal benefit of thermal storages is higher/lower with respect to the less/more efficient solution because, the size and capital cost of the storage being the same, the savings achievable with price arbitrage exploitation are higher/lower. Savings per energy unit have been defined as the ratio between the yearly economic savings and the amount of cooling energy annually provided by the storage system. Figure 8 shows that the Savings per energy units are always higher in the case studies with COP 4 and lower for those having COP 6. This was expected since, for the different COP scenarios, the cooling demand remains the same, while the annual savings changes with the efficiency of the chillers system (the lower the COP, the higher the annual savings). It is worth noting that the LAES, while used in cogeneration mode, is the most positively affected by the lower COP scenario.

Figure 7

Figure 8

Figures 9 and 10 show the payback period of different storage solutions under different demand scenarios. For the systems storing electrical energy (Li-Ion EES, CAES, $LAES_{fullele}$) the PBP is almost unchanged with respect to the COP variation. This is due to the fact that the increase in terms of annual savings due to price arbitrage exploitation is offset by the higher capital cost of a bigger storage system.

On the other hand, the systems directly storing cooling energy (SHTES, PCM TES, $LAES_{cog}$) benefit from the lower COP. This is due to the fact that the thermal storages achieve higher annual savings, thanks to price arbitrage exploitation (Figure 8), while their volume, and consequently capital cost, remains the same.

At the same time, LAES in cogeneration mode obtains the lowest PBP among the others Demand scenario C solutions.

Figure 9

Figure 10

3.3 Qualitative analysis

In this section, a qualitative comparison among the different storage systems is performed using the comparison criteria described in Section 2.3. Tables from 21 to 25 summarize the findings of Section 2.3 highlighting, for each storage technology, the criterion, the description, the score and the reference of the information. The spider-web diagram in Figure 11 represents graphically the considerations reported in Tables 21 to 25, highlighting the main *pros* and *cons* of each technology.

Table 21

Table 22

Table 23

Table 24

Table 25

Li-Ion EES is a well-established technology. Its characteristics (high efficiency, high energy density and fast response time) are suitable for a wide range of applications. The main drawbacks are all related to the construction materials: cost (the highest among storage technologies), safety issues and sustainability aspects related to both manufacturing and disposal processes. Figure 11 shows that SHTES has several opposing characteristics than Li-ion EES. It is a mature technology, but scores poorly in terms of energy density (lowest among storage technologies presented), efficiency and flexibility: it is only suitable for small to mid-scale energy management applications. However, it is affordable, safe and reliable. It also scores the highest in terms of sustainability. PCM TES overcomes some of the issues of SHETS by being more efficient and having a higher energy density. However, it ends up being more expensive while safety and sustainability worsen depending on the material used as storage medium. The two air based storage technologies have similar working principles. They are both characterized by high complexity (highest among storage technologies presented) and sustainability scores. However, both advanced adiabatic CAES and LAES has yet to be demonstrated at large scale. It is worth mentioning that LAES has higher energy density and no geographical constraints, which translates into higher flexibility.

Figure 11

4. Conclusions

This study aimed to investigate five energy storage technologies for cooling energy application in hot climates and to provide a comparison amongst them. The analysis was carried out for tropical and equatorial climates taking as reference the climate of Singapore. The technologies taken into account were: Li-Ion Electrical Energy Storage (Li-Ion EES), chilled water Sensible Heat Thermal Energy Storage (SHTES), Phase Change Material Thermal Energy Storage (PCM TES), Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES). A comparison among the five energy storage systems is presented based on a hybrid quantitative-qualitative approach. The quantitative comparison was carried out for different sizes of daily cooling energy demand (1 MWh_c, 10 MWh_c and 500 MWh_c) and three different tariff scenarios characterized by different ratios between peak and off-peak electricity tariff. A techno-economic analysis was performed to show the suitability of the five cold energy storage systems at different scales. Three different cooling system's COP scenarios were considered. The qualitative analysis was based on five comparison criteria (Complexity, Technology Readiness Level, Sustainability, Flexibility and Safety). Both the quantitative and qualitative analysis showed that there are no overall winners among the storage technologies. Hence, it is important to deeply understand the *pros* and *cons* of every technology in order to properly choose the cold energy storage systems given the "boundary conditions" of the final user such as, among the others, the magnitude of the cooling load profile, the tariff scenario and space availability. SHTES seems to be the best solution for decentralized, small and mid-scale applications but its low energy density at large sizes translates into massive storage tank and consequently in high capital cost and in large volumes. When space requirements are an important design constraint, PCM TES can be preferred, even though it has longer payback period: 1 MWh_c can be stored in less than 20 m^3 versus the 220 m^3 required by SHTES. For large size centralized applications, CAES and LAES benefit from the economy of scale and become favourite, thanks to higher efficiency, energy density (with respect to SHTES) and flexibility. For CAES, the main challenge will be to demonstrate the performances and viability of the advanced adiabatic technology for both small and large-scale applications: in particular, the R&D efforts are focusing in developing reliable and cheap storage tanks in order to make CAES almost independent from the geological conditions. Also for LAES, the next step will be to demonstrate the expected performances for large-scale, centralized, applications; in particular, LAES, when used in full electrical mode, appears to be an interesting solution for large scale applications. At the present time, R&D is focusing on the development of new methods to improve the efficiency of small-scale liquefaction processes for decentralized demand management applications. Li-Ion EES characteristics are excellent under many terms: efficiency, flexibility and energy density. Their modularity makes them extremely versatile as they can virtually be integrated at every level. However, they are still too expensive to be a viable option for demand management applications, regardless of the scale. As highlighted by the sensitivity analysis, the COP of the cooling system directly influences the economic results in terms of cost of energy, savings per energy unit and pay back periods. The lower the COP, the more viable the thermal storage systems which are able to store cooling energy directly become. Techno-economic analysis highlighted the fundamental role of the tariff scenario. For cooling load shifting applications, the higher the difference between peak and off-peak electricity tariff, the shorter is the payback of the cold energy storage. Thus, future penetration of energy storage systems is strictly related with the evolution of both the national energy tariff and incentive system: increasing the spread between peak and off peak energy tariff can encourage price arbitrage strategies, boost economic savings and encouraging storage systems integration.

APPENDIX

Data acquisition and monitoring of water cooled compression chiller at Nanyang Technological University

In Figure 2 of the manuscript, the hourly COP of an actual water cooled chiller plant installed at Nanyang Technological University campus in Singapore was reported as an example. The graph presented the COP as a function of the ambient temperature for the month of May 2016; from the graph it is possible to pinpoint three values (out of 720, that is around 0.4%) that can be considered outliers, exceeding COP=8. The average COP of the water cooled compression chiller is 6.09: this value is in line with the Green Mark GoldPLUS or Platinum rating set by Building Construction Authority of Singapore [72]; indeed, according to the Bca Building Energy Benchmarking Report 2014 [73]: *"The new chiller plant efficiency for most of the 54 (retrofitted) buildings was in the range of 0.6 – 0.7 kW/RT. Such performance standard is comparable to a new building with a Green Mark GoldPLUS or Platinum rating."*

The data of the chiller plant are acquired and stored by an energy management system (EMS). Table A1 reports the measurement instruments used for cooling energy data acquisition together with their accuracy. Table A2 reports the measurement accuracy for the electric power meter Accuenergy ACUVIM II-D-50.

Table A1

Table A2

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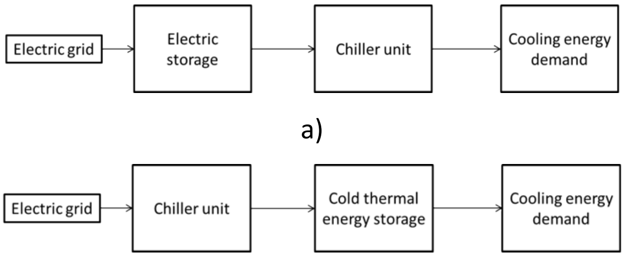
Figures and captions



a)

b)

Figure 1: Setup of the cold energy storage considered in this paper

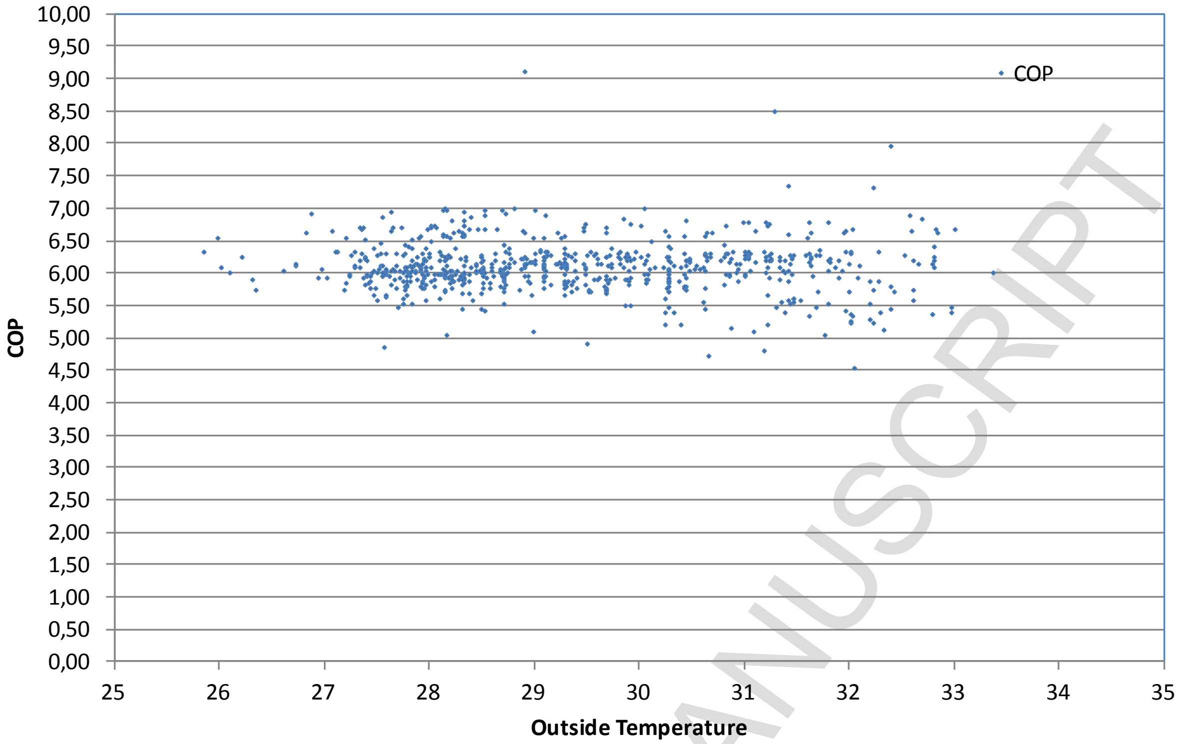


Figure 2 – COP vs. external temperature of a water chilled in NTU Campus in Singapore

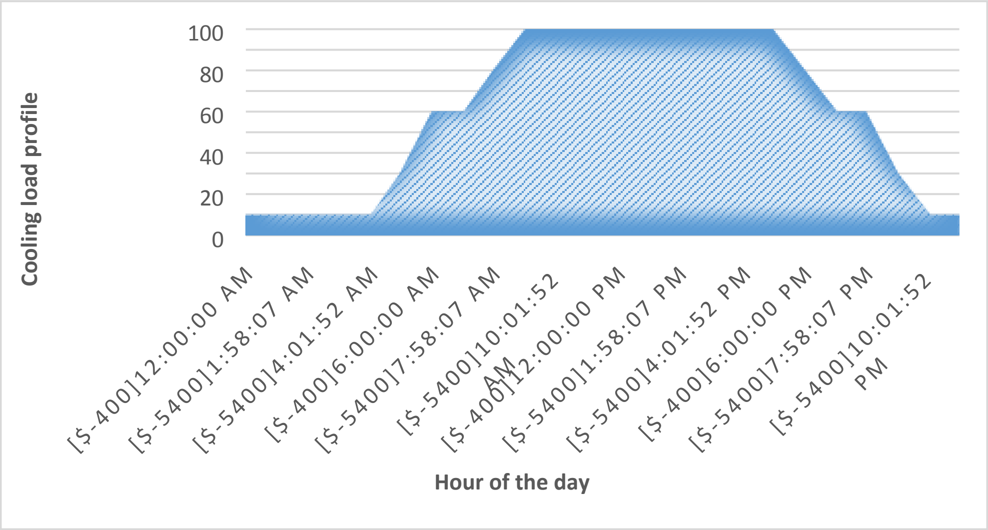


Figure 3: Qualitative cooling load profile

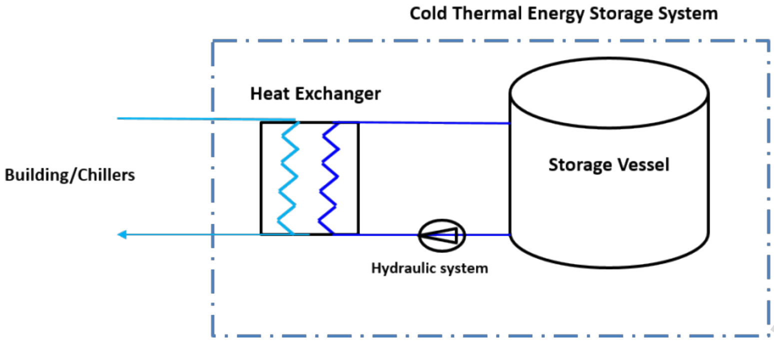


Figure 4 Functional scheme of a TES system

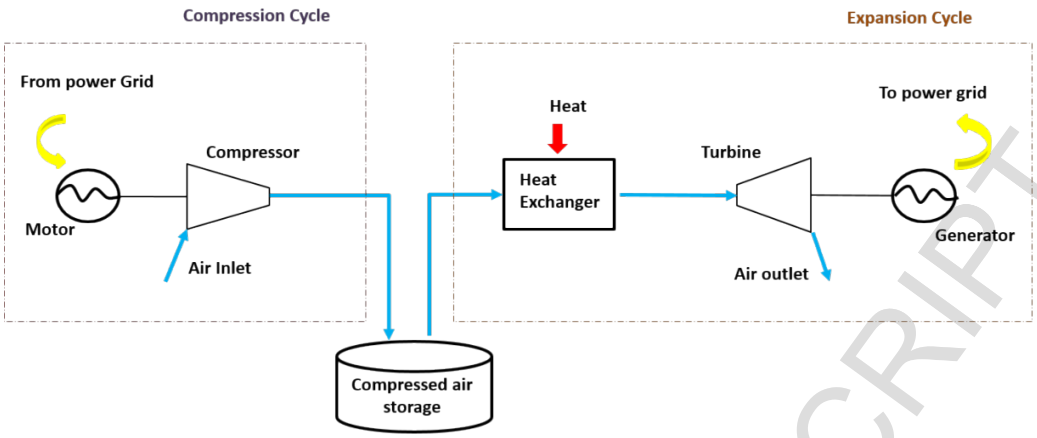


Figure 5: Schematic representation of a CAES system

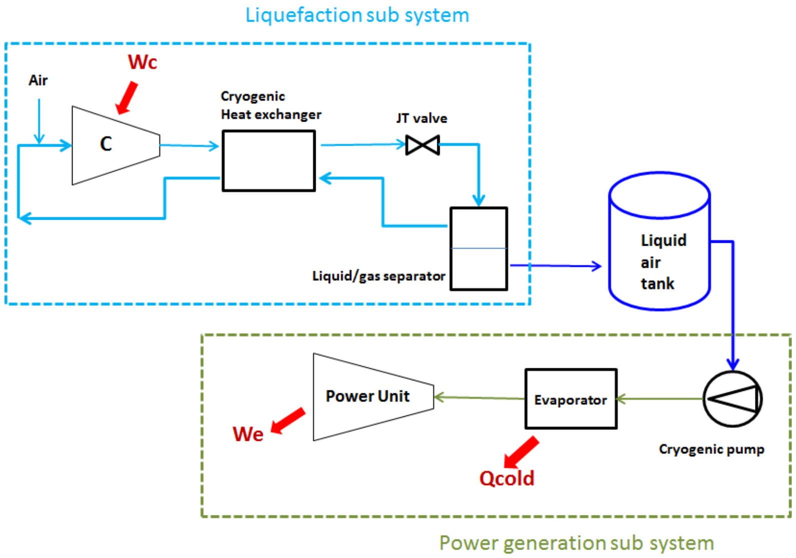


Figure 6: Schematic representation of a LAES system

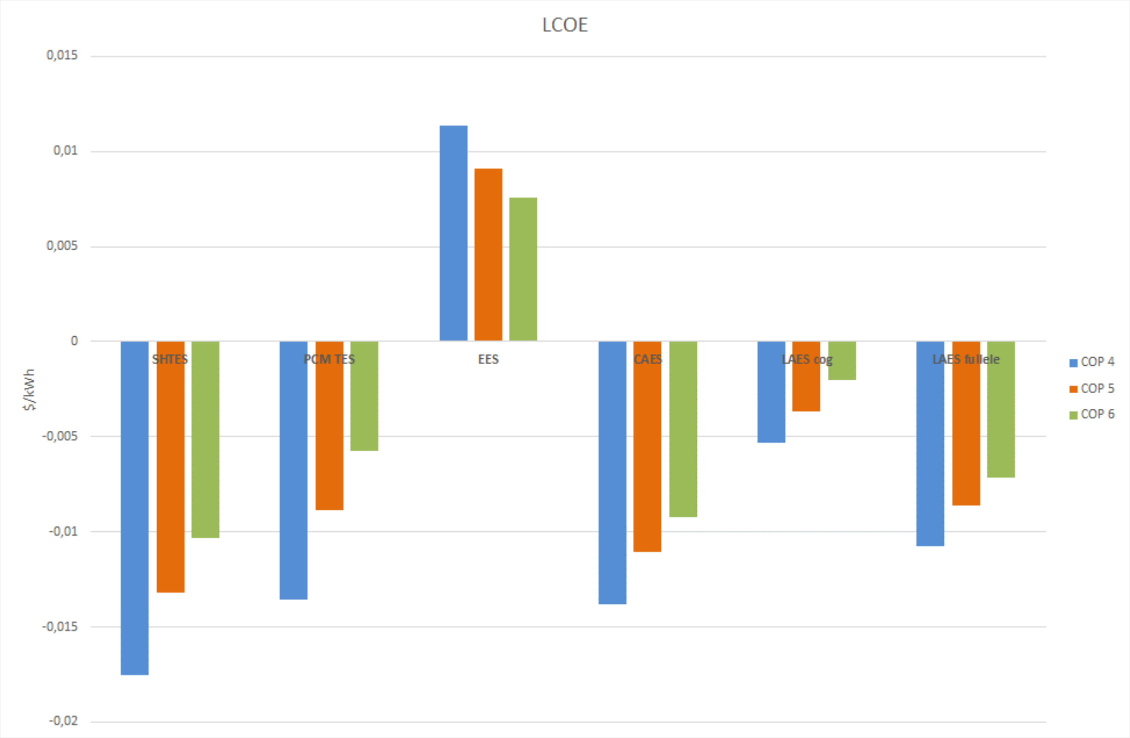


Figure 7: Histogram showing the results of the sensitivity analysis, in terms of LCOE values, for the different storage technologies

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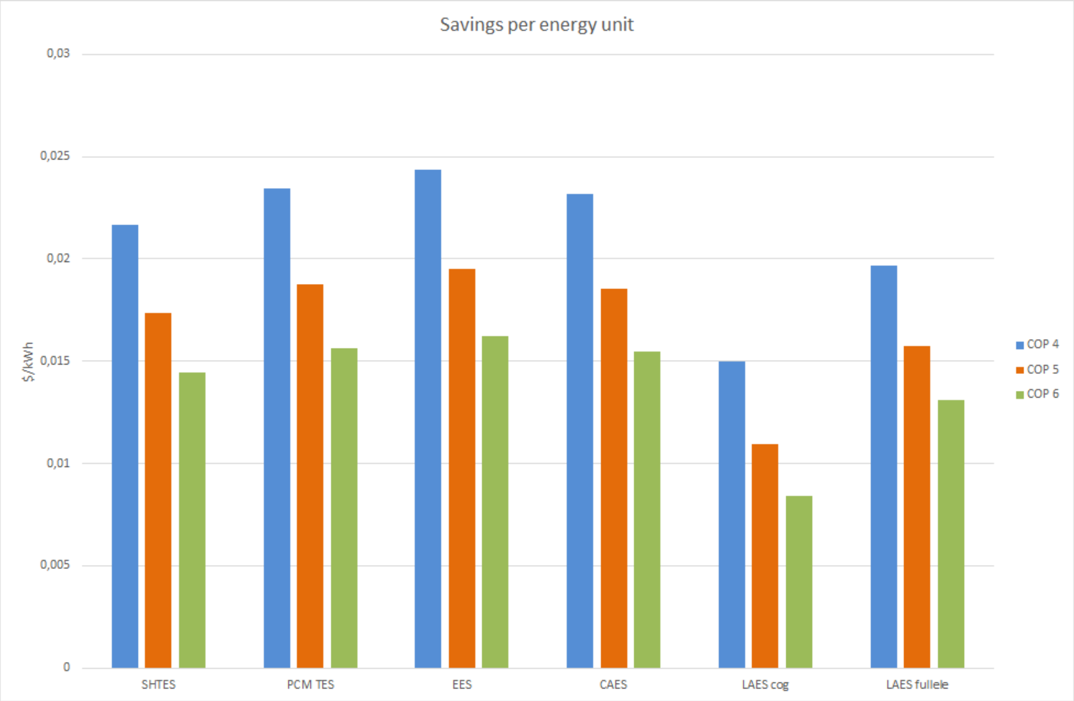

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929 Figure 8: Histogram showing the results of the sensitivity analysis, in terms of Savings per energy unit values, for the
930 different storage technologies

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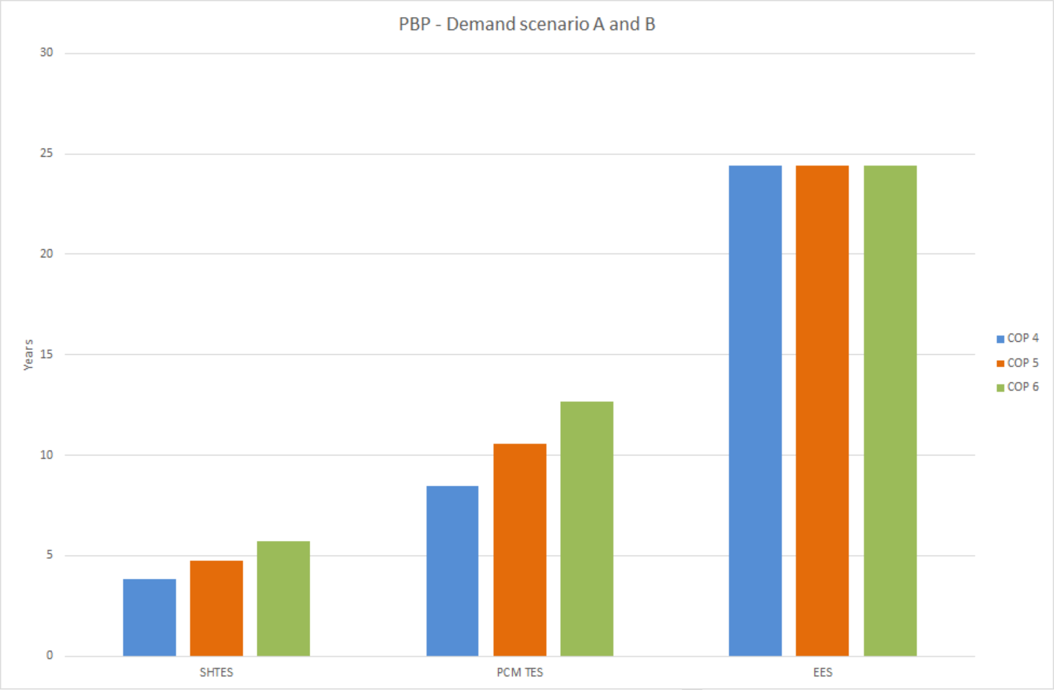

Figure 9: Histogram showing the results of the sensitivity analysis, in terms of PBP values, for the storage solutions available for Demand scenarios A and B

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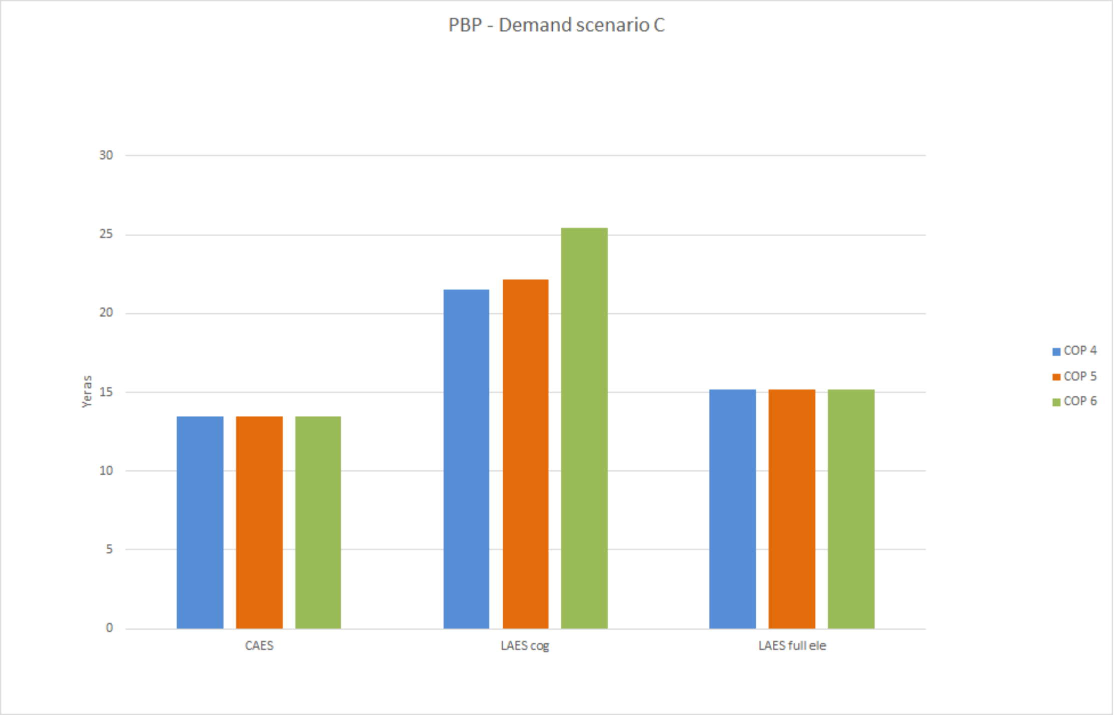

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939 Figure 10: Histogram showing the results of the sensitivity analysis, in terms of PBP values, for the storage solutions
940 available for Demand scenario C

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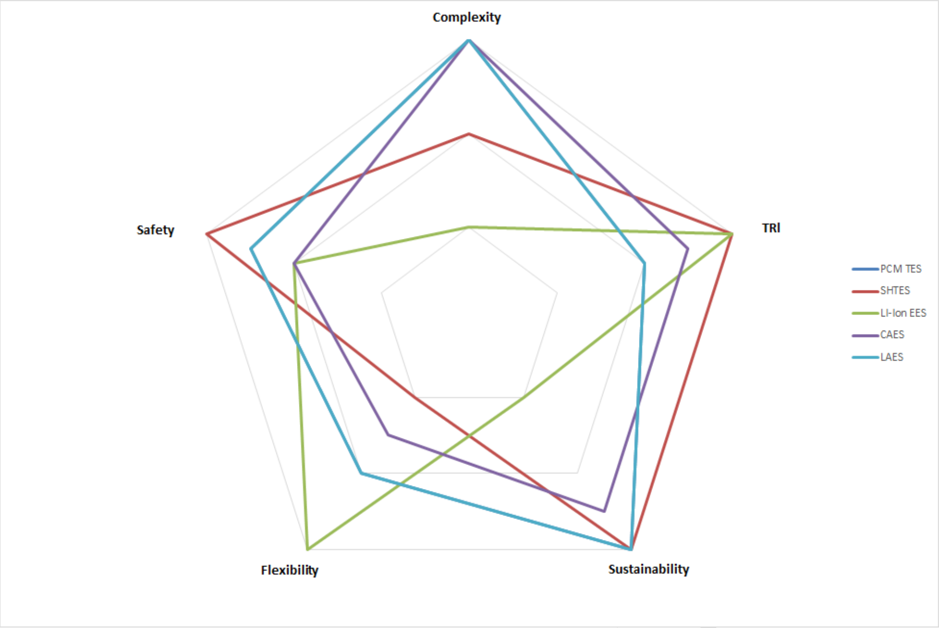

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944 Figure 11: Spider-web diagram for the qualitative analysis

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Tables

Table 1 Technical and economic characteristics of Li-Ion EES. Ranges are established collecting data related to different technologies and scales [25]

Cost per power unit, C_{pu} ($/kW)	**Cost per energy unit, C_{eu} ($/kWh)**	**Specific Energy (Wh/kg)**	**Rated Power (MW)**	**Lifetime (years)**	**Round trip efficiency**	**Discharge time)**	**Storage duration**
2109-2746	459 - 560	150 - 350	kW – Tens of MW	5-15	0.85 – 0.95	Min – hours	Min - days

Table 2 Technical and economic characteristics of SHTES storages. Ranges are established collecting data related to different technologies and scales [26] [27]

Cost per power unit, C_{pu} ($/kW)	**Cost per energy unit, C_{eu} ($/kWh)**	**Specific Energy (Wh/kg)**	**Rated Power (MW)**	**Lifetime (years)**	**Round trip efficiency**	**Discharge time**	**Storage duration**
-	31	10-60	0.001-10	10-30	0.6-0.9	hours	Hours-month

Table 3 List of phase change materials with melting temperatures reported at around 6-8 ^{o}C from commercial companies and literature

PCM	Phase Change temperature (^{o}C)	Density (kg/m3)	Specific heat capacity (kJ/kg K)	Latent heat capacity (kJ/kg)	Volumetric Heat capacity (MJ/m3)	Source
PlusICE S8 (Salt hydrate)	8	1,475	1.9	150	221	[40]
PlusICE A8 (Organic)	8	773	2.16	150	116	[40]
Rubitherm RT8* (Paraffin)	8	770 (liquid) 880 (solid)	*	140	108	[41]
$Na_2SO_4.10H_2O$ (Salt hydrate)	8	1,470	-	179, 122 (After 100 cycles)	190	[37]
LiClO3:3H2O (Salt hydrate)	8	1,720	-	253	435	[42]
$C_{14}H_{30}$ (Paraffin)	6	760	-	230	175	[36]
Polyglycol E400 (organic)	4-8	1,125 @ 20C	0.51 cal/g/C	99.6 (36 cal/g/C)	111	[31]
Pentadecane + docosane	7.6-8.99	-	-	214.83	-	[43]

*Heat storage capacity is given as 180 kJ/kg with a combination of latent and sensible heat in the temperature range of 0 to 15^{o}C.

Table 4: Technical and economic characteristics of PCM TES. Ranges are established collecting data related to different technologies and scales [26]

Cost per power unit, C_{pu} ($/kW)	Cost per energy unit, C_{eu} ($/kWh)	Specific Energy (Wh/kg)	Rated Power (MW)	Lifetime (years)	Round trip efficiency	Discharge time	Storage duration
	77.5	59 – 93	0.001 - 1	10 – 30	0.75 – 0.9	Hours	Hours - Days

Table 5: Technical and economic characteristics of CAES systems. Ranges are established collecting data related to different technologies and scales **[25]**

Cost per power unit, C_{pu} ($/kW)	**Cost per energy unit, C_{eu} ($/kWh)**	**Specific Energy (Wh/kg)**	**Rated Power (MW)**	**Lifetime (years)**	**Round trip efficiency**	**Discharge time**	**Storage Duration**
1286-1388	210-278	30.60	Hundreds of kW (aboveground) – Hundreds of MW	20-40	0.7-0.8	hours	Hours - months

Table 6: Data coming from Highview power studies and pilot plant tests [63] [64]

LAES Scale	Working mode	Liquefaction efficiency (kWhe/kg)	Power conversion (kWhe/kg)	Electrical efficiency	Thermal efficiency	Total efficiency
Commercial scale	Full electrical mode	0.2	0.12	60%	0	60%
Commercial scale	Cogeneration mode	0.4	0.12	30%	60%	90%
Small scale	Full electrical mode	0.5	0.05	10% *	0	10%
Small scale	Cogeneration mode	0.675	0.05	7.4% **	14.8%	22.2%

*These data referred to the first prototypes tested. Improving the liquefaction plant efficiency, the expected efficiency in full electric mode should be around 15%

** These data referred to the first prototypes tested. Improving the liquefaction plant efficiency, the expected electrical and thermal efficiencies should be around 10% and 20% for a total efficiency of about 30%.

Table 7: Technical and economic characteristics of LAES systems. Ranges are established collecting data related to different technologies and scales [51] [59] [62] [64]

Cost per power unit, C_{pu} (\$/kW)	**Cost per energy unit, C_{eu} (\$/kWh)**	**Specific Energy (Wh/kg)**	**Rated Power (MW)**	**Lifetime (years)**	**Round trip efficiency**	**Discharge time**	**Storage duration**
900-2000	260 - 530	214	0.3 – 300	20-40	0.6 – 0.9	Hours	Hours - months

974 Table 8 Storage typologies considered in each scenario

	Scenario A	Scenario B	Scenario C
Li-Ion EES	X	X	-
SHTES	X	X	-
PCM TES	X	X	-
CAES	-	-	X
LAES	-	X	X

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Table 9: Demand Scenario A - Storage technical data

	Energy storage Efficiency	**Storage energy capacity (kWh)**	**Power requirements (kW)**	**Daily electricity consumption (kWh)**	**Lifespan in cycles**
SHTES	0.7	1000 kWh_c	36	286	6000
PCM TES	0.82	1000 kWh_c	30	244	6000
Li-Ion EES	0.9	200 kWh_e	28	222	5000

Table 10: Demand Scenario A - Storage economic data

	Cost per energy unit ($/kWh) (-20%) - literature value – (+20%)	Cost per power unit ($/kW)	CAPEX (1000*$) (-20%) - literature value – (+20%)
SHTES	24.8 – 31 - 37.2	0	24.80 - 31 - 37.2
PCM TES	62 –77.5 - 93	0	59.52 – 74.4 - 89.28
Li-Ion EES	437 – 546 - 655.2	2000 – 2500 - 3000	142.92 – 178.64 - 214.37

983 Table 11: Demand Scenario A - Economic results

	TS1 Savings (1000*$)	TS1 PBP	TS2 Savings (1000*$)	TS2 PBP	TS3 Savings (1000*$)	TS3 PBP
SHTES	5.72	4.7 – 7.1	2314	10.7 – 16	Neg	Neg
PCM TES	5.87	10.6 – 15.8	3.16	18.8 – 28.2	0.691	86 – 129
Li-Ion EES	5.85	24.4 – 36.4	3.6	38.7 - 59	1.35	105 - 158

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Table 12: Demand Scenario A - Effectiveness indexes

	TS1 LCOE ($/kWh)	TS1 Savings per energy unit ($/kWh)	TS2 LCOE ($/kWh)	TS2 Savings per energy unit ($/kWh)	TS3 LCOE ($/KwH)	TS3 Savings per energy unit ($/kWh)
SHTES	-0.013|-0.011	0.017	-0.003 | -0.001	0.008	0.006 | 0.008	Neg
PCM TES	-0.009 | -0.004	0.019	-0.001 | 0.004	0.011	0.007 | 0.012	0.002
Li-Ion EES	0.009 | 0.023	0.02	0.014 | 0.031	0.012	0.023 | 0.038	0.004

989 Table 13: Demand Scenario B - Storage technical data

	Energy storage Efficiency	**Storage energy capacity (kWh)**	**Power requirements (kW)**	**Daily electricity consumption (kWh)**	**Lifetime in cycles**
SHTES	0.7	10000	357	2857	6000
PCM TES	0.82	10000	305	2439	6000
Li-Ion EES	0.9	2000	278	2222	5000
$LAES_{cog}$	0.17	1429	1051	8406	10000
$LAES_{fullele}$	0.25	2000	1000	8000	10000

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Table 14: Demand Scenario B - Storage economic data

	Cost per energy unit ($/kWh)	**Cost per power unit ($/kW)**	**CAPEX (1000*$)**
	(-20%) - literature value – (+20%)	**(-20%) - literature value – (+20%)**	**(-20%) - literature value – (+20%)**
SHTES	24.8 – 31 - 37.2	0	248 – 310 - 372
PCM TES	62 – 77.5 - 93	0	595.2 – 743.6 - 892
Li-Ion EES	437 – 546 - 655.2	2000 – 2500 - 3000	1429.2 – 1786.4 - 2143.7
LAES$_{cog}$	208 – 260 - 312	720 – 900 - 1080	1053.8 – 1317.2 - 1580.6
LAES$_{fullele}$	208 – 260 - 312	720 – 900 - 1080	1136 – 1420 - 1704

Table 15: Demand Scenario B - Economic results

	S1 Savings (1000*$)	S1 PBP	S2 Savings (1000*$)	S2 PBP	S3 Savings (1000*$)	S3 PBP
SHTES	52.07	4.7 – 7.1	23.14	10.7 – 16.1	Neg	Neg
PCM TES	56.3	10.6 – 15.8	31.6	18.8 -28.2	6.9	86 - 129
Li-Ion EES	58.5	24.4 – 36.6	36	39.7 – 59.5	13.5	106 -159
$LAES_{cog}$	NEG	NEG	NEG	NEG	NEG	NEG
$LAES_{fullele}$	0	NEG	NEG	NEG	NEG	NEG

Table 16: Demand Scenario B - Effectiveness indexes

	TS1 LCOE ($/kWh)	TS1 Savings per energy unit ($/kWh)	TS2 LCOE ($/kWh)	TS2 Savings per energy unit ($/kWh)	TS3 LCOE ($)	TS3 Savings per energy unit ($/kWh)
SHTES	-0.013 | -0.011	0.017	-0.004 | -0.002	0.008	0.006 | 0008	-0.0019
PCM TES	-0.009 | -0.004	0.019	-0.001 | 0.004	0.011	0.008 | 0.012	0.0023
Li-Ion EES	0.009 | 0.23	0.020	0.017 | 0.031	0.012	0.024 | 0.038	0.0045
LAES_{cog}	0.012 | 0.017	-0.001	0.038 | 0.044	-0.03	0.069 | 0.074	-0.058
$\text{LAES}_{fullele}$	0.011 | 0.017	0	0.04 | 0.046	-0.027	0.065 | 0.071	-0.054

Table 17: Demand Scenario C - Storage technical data

Demand Scenario C	**Energy storage Efficiency**	**Storage energy capacity (kWh)**	**Power requirements (kW)**	**Daily electricity consumption (kWh)**	**Lifespan in cycles**
CAES	0.8	100000	15625	125000	10000
LAES$_{cog}$	0.3	71428	29762	238093	10000
LAES$_{fullele}$	0.6	100000	20833	166667	10000

Table 18: Demand Scenario C - Storage economic data

	Cost per energy unit ($/kWh) (-20%) - literature value – (+20%)	**Cost per power unit ($/kW)** (-20%) - literature value – (+20%)	**CAPEX (1000*$)** (-20%) - literature value – (+20%)
CAES	210 – 263 - 316	1052 – 1315 - 1578	37477.5 – 46846.8 -56216.2
$LAES_{cog}$	208 – 260 - 312	720 – 900 - 1080	36285.4 – 45356.8 - 54428.2
$LAES_{fullele}$	208 – 260 - 312	720 – 900 - 1080	35800 – 44750 - 53700

Table 19: Demand Scenario C - Economic Results

	S1 Savings (1000*$)	**S1 PBP**	**S2 Savings (1000*$)**	**S2 PBP**	**S3 Savings (1000*$)**	**S3 PBP**
CAES	2784.4	13.4 – 20.2	1518.7	24.7 - 37	253.1	148 - 222
LAES$_{cog}$	1639.3	22.1– 33.2	Neg	Neg	Neg	Neg
LAES$_{fullele}$	2362.5	15.1- 22.7	675	53 – 79.5	Neg	Neg

Table 20: Demand Scenario C - Effectiveness indexes

	TS1 LCOE ($/kWh)	TS1 Savings per energy unit ($/kWh)	TS2 LCOE ($/kWh)	TS2 Savings per energy unit ($/kWh)	TS3 LCOE ($/kWh)	TS3 Savings per energy unit ($/kWh)
CAES	-0.011 | -0.007	0.019	-0.003 | 0.001	0.002	0.006 | 0.009	24.7 - 37
LAES$_{cog}$	-0.0037|0	0.011	0.012 | 0.016	-0.021	0.028 | 0.032	Neg
LAES$_{fullele}$	-0.0086 | -0.005	0.016	0.003 | 0.006	-0.007	0.014 | 0.018	57.3-86

Table 21 Comparison criteria for Li-Ion EES [11] [16] [19] [20] [22]

Criterion	**Description**	**SCORE**
Complexity	No geographical restrictions; almost plug-and play integration; “requires low maintenance (no scheduled cycling, no memory issues)”	1
Technology readiness level	Lithium-Ion batteries are technically developed and commercially available, however some critical issues still have to be overcome, Lack of standardization procedures and quality control protocols	3
Environmental footprint	The most critical aspects are the manufacturing process, which is really energy intensive, and the disposal of the storage materials.	1
Flexibility	Li-Ion technology are suitable for a wide range of applications, going from few kW-hours batteries up to MW systems	3
Safety	Five hazard categories: voltage, arc-flash/blast potential, fire potential, vented gas combustibility potential and vented gas toxicity	2

Table 22: Comparison criteria for SHTES [20] [26] [30]

Criterion	**Description**	SCORE
Complexity	The charging/discharging mechanism are well known, durable, commercialized components (compact heat exchangers, circulating pumps, metal tanks) which make the whole system reliable and easy to integrate with existing HVAC plants	2
Technology readiness level	Commercially available from many years for both domestic and industrial applications.	3
Environmental footprint	Using no toxic material for construction or as storage medium, the environmental impact of TES is mostly depending on its efficiency and the local energy mix.	3
Flexibility	SHTES are suitable just for demand management applications and renewable integration. Due to the low energy density, large scale large scale viability due to space constraints	1
Safety	Safe technology during operations: it does not involve risks derived from the use of toxic materials or pressurized equipment	3

Table 23: Comparison criteria for PCM TES [31] [36][37] [44] [68] [69] [70]

Criterion	**Description**	**SCORE**
Complexity	PCM TES system may utilize existing chillers and the charging/discharging mechanism is similar to a chilled water storage system.	3
Technology readiness level	Demonstrated on small to mid-level scales by Cristopia but not yet widely accepted. R&D is still essential to further reduce cost and increase efficiency.	1
Environmental footprint	PCM TES systems have been proven to reduce CO_2 emission	2
Flexibility	High flexibility as PCM has been demonstrated in passive (integrated into building materials), active (solar/HVAC systems) or a combination of passive and active PCM systems. Heat and cold energy storages possible.	2
Safety	Relatively safe as materials with low toxicity have been selected. However, if PCM TES is used integrated in buildings, leakage remains a concern and therefore R&D continues in this area.	2

Table 24: Comparison criteria for CAES [25] [51][52] [53] [54] [71]

Criterion	**Description**	**SCORE**
Complexity	Several mechanical components that have to be managed and maintained optimally to achieve high performances. The introduction of TES, in AA-CAES, furtherly increases the management challenges.	3
Technology readiness level	Uses well established mechanical components; there are currently two working CAES plants in the world. A growing number of demonstration projects and pilot plants are expected in the near future.	2
Environmental footprint	Diabatic CAES uses natural gas to preheat the air during operations. On the other hand, AA-CAES is a, locally, emission free technology with high storage efficiency. No toxic or hazardous materials are used for construction or as storage medium	2.5
Flexibility	CAES offers a wide range of possible application: energy arbitrage, renewable sources integration, peak shaving, seasonal energy storage or spinning reserve	1.5
Safety	No toxic or hazardous substances are used as construction materials or storage medium. Underground CAES presents a number of hazardous scenarios that can occur due to the high pressure levels involved.	2

Table 25: Comparison criteria for LAES [48] [55] [57] [58] [59]

Criterion	Description	Score
Complexity	Several mechanical components that has to be managed and maintained optimally to achieve high performance.	3
Technology readiness level	Uses well established mechanical components. A LAES pilot plant (300 kW, 2.5 MWh), designed and managed by Highview Power Storage, has been operating in the UK since 2010. In 2014, the same company was awarded a grant by UK government to build a commercial scale demonstration plant	2
Environmental footprint	No toxic or hazardous materials are used for construction or as storage medium. Locally emission free technology with extremely high total efficiency (when working in co-generation mode) Possibility to exploit low grade waste heat (< 100°C) and high grade waste cold sources (<-150°C)	3
Flexibility	LAES systems are suitable for a wide range of applications: energy management; backup power; time shifting and peak shaving; seasonal energy storage; provide response, black start and ancillary services to network operators.	2
Safety	LAES has no geographical constraint and it neither contains toxic, hazardous nor strategic materials. No chemical reaction involved. Liquid air tank must be carefully designed and maintained.	2.5

Table A1. Characteristiscs and accuracy for the measurement instruments used for monitoring chiller plant in NTU

Instrument	Characteristics	Measurement	Accuracy
Agilent 34970A	Data acquisition system with modules	Data logging	0.004% basic 1-year dcV accuracy; 0.06% basic 1-year acV accuracy; 0.01% basic 1-year resistance accuracy.
Siemens SITRANS FST020	ultrasonic flow meter	Mass flow rate	Flow: 0.5 - 1.0% for velocities ≥ 0.3 m/s (1 ft/s); 4...20mA ± 1.0% - 2.0% of span for assigned parameters. Pulse: relay output ±0.5% - 1.0% of flow Batch repeatability: ± 0.15% Zero Drift: 0.1% of rate: 0.0003 m/s (0.001 ft/s) Data refresh rate: 5 Hz
Thermistor NTC 10 K ohms	Immersion Temperature sensor	Temperature	

Table A2. Characteristiscs and accuracy of the electric power meter Accuenergy ACUVIM II-D-50 installed to measure the electri power of the chiller plant in NTU

Parameters	Accuracy	Resolution	Range
Voltage	0.2%	0.1V	10V~1000kV
Current	0.2% 0.1mA	5mA~50000A	
Power	0.2%	1W	-9999MW~9999MW
Reactive Power	0.2%	1var	-9999Mvar~9999Mvar
Apparent Power	0.2%	1VA	0~9999MVA
Power Demand	0.2%	1W	-9999MW~9999MW
Reactive Power Demand	0.2%	1var	-9999Mvar~9999Mvar
Apparent Power Demand	0.2%	1VA	0~9999MVA
Power Factor	0.2%	0.001	-1.000~1.000
Frequency	0.2%	0.01Hz	45.00~65.00Hz (50 or 60Hz type) 300.00Hz~500.00Hz (400Hz type)
Energy Primary	0.2%	0.1kWh	0-99999999.9kWh
Energy Secondary	0.2%	0.001kWh	0-999999.999kWh
Reactive Energy Primary	0.2%	0.1kvarh	0-99999999.9kvarh
Reactive Energy Secondary	0.2%	0.001kvarh	0-999999.999kvarh
Apparent Energy Primary	0.2%	0.1kVAh	0-99999999.9kVAh
Apparent Energy Secondary	0.2%	0.001kVAh	0-999999.999kVAh
Harmonics	1.0%	0.1%	
Phase Angle	2.0%	0.1°	0.0°~359.9°
Unbalance Factor	2.0%	0.1%	0.0%~100.0%
Running Time		0.01h	0~9999999.99h