Thermal Energy Storage for Grid Applications

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Contributor: Gianfranco Chicco , Diana ENESCU , , George Seritan

Thermal energy systems (TES) contribute to the on-going process that leads to higher integration among different energy systems, with the aim of reaching a cleaner, more flexible and sustainable use of the energy resources. Energy storage is also a key component of decarbonisation scenarios, such as the ones indicated in the European Roadmap to 2050, whose main targets include high energy efficiency, diversification of the production resources, and increase in the percentage of renewable energy sources (RES). TES-based solutions in systems connected to the electrical grid facilitate the energy system integration to get additional flexibility for energy management, enable better use of variable renewable energy sources (RES), and contribute to the modernisation of the energy system infrastructures.

thermal energy storage | electrical networks | variable renewable energy sources

1. Exploitation of TES with Variable Renewable Energy Sources

1.1. The Variable Nature of Energy Generation from RES

Renewable Energy Sources (RES), like geothermal energy, marine energy, solar energy, and wind energy, are naturally variable and provide clean and sustainable electricity. Due to the climatic changes, the operation of RES with storage has been studied very intensively. Special attention is focused on the variable renewable energy sources (VRES). A VRES is a non-dispatchable RES (that is, it cannot be controlled in order to follow the variable demand for electricity). Due to its fluctuating nature, a VRES cannot behave as a controllable RES such as hydro, biomass, or to some extent as a geothermal power source. Generation systems with VRES such as solar energy (solar photovoltaic, solar heating, and concentrated solar power CSP) and wind energy (onshore and offshore) have variable power generation due to their intermittent nature [1]. The power output of these VRES is uncertain and depends on weather conditions, compared to conventional dispatchable power plants that obtain their output with respect to market conditions and energy balances. For photovoltaic and CSP systems, the VRES-based power generation is variable depending not only on the presence of clouds but also of temporary shading effects (that should be avoided as much as possible by design). Furthermore, malfunctioning of the modules may require the storage system to work outside its normal operation ranges, to compensate for the lost energy generation.

Furthermore, the VRES location depends on the RES availability and does not generally match with the location of the load centres [2]. Moreover, a VRES requires energy storage to fit seasonal and everyday changes and to assure the continuous operation in various systems [3]. The VRES is used almost continuously to mitigate the fluctuations in output from the VRES. A thermo-electric energy storage (TEES), whose scheme is sketched in **Figure 1** [4], can be used to take excess electricity during off-peak demand periods, convert it into heat, and store heat to be used in a secondary thermodynamic cycle with a steam turbine to generate electricity that is injected in the grid in periods with peak electric load.

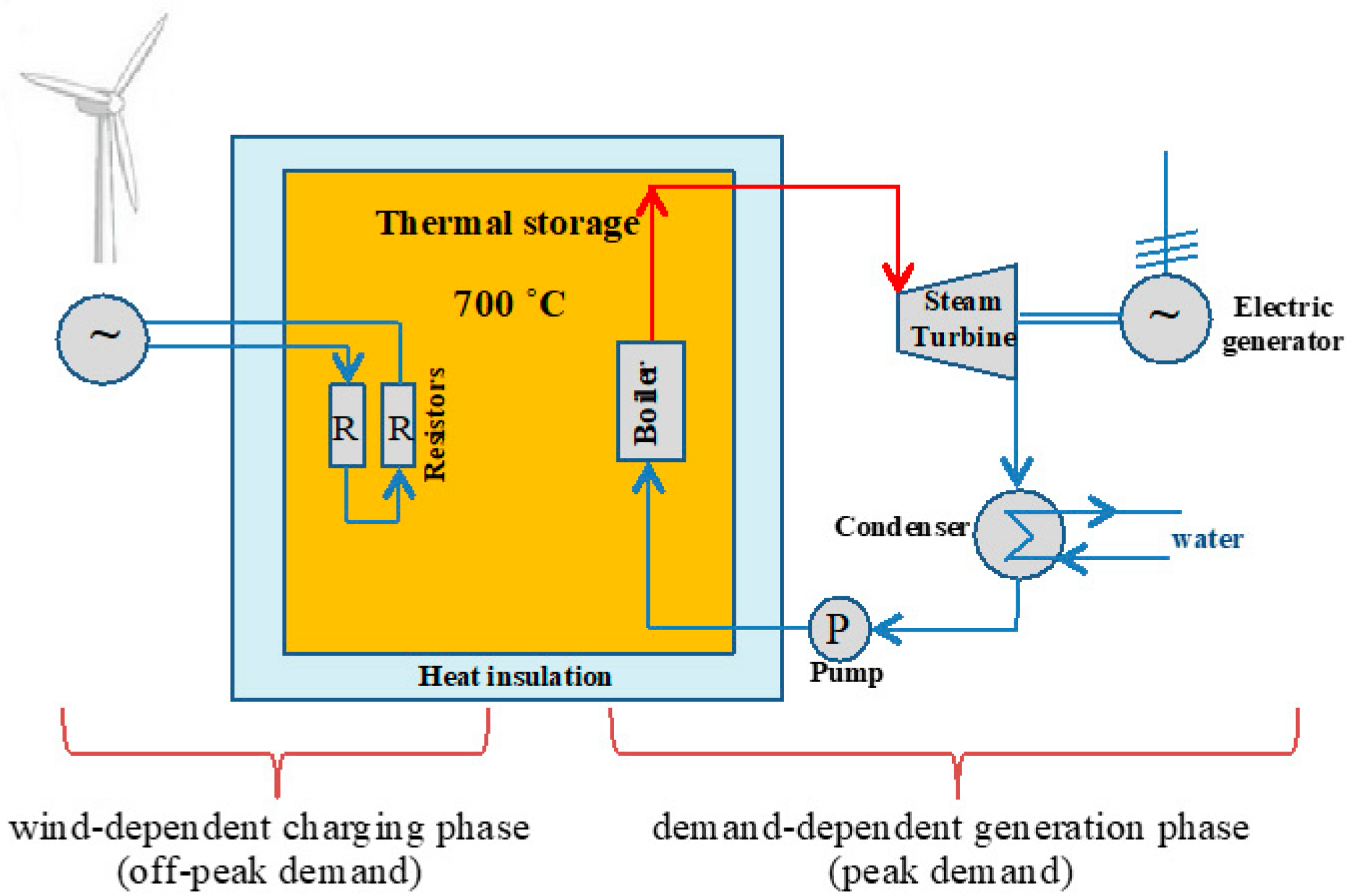

Figure 1. Thermo-electric energy storage (TEES) scheme.

The TES coupled with VRES can be either a heat thermal energy storage (HTES), or a cool thermal energy storage (CTES) [5]. In both cases, the impact of exploiting the TES is higher when the storage system is integrated with a district heating system or a district cooling system, respectively.

1.2. Concentrating Solar Power

A CSP system exploits the solar thermal energy to drive a heat engine (e.g., a steam turbine, **Figure 2** [6]). In this way, it is easy to couple CSP with TES, by using heat exchangers to transfer thermal energy between the heat transfer fluid used in the CSP and the storage system [7]. The fluid used in the storage system is typically a molten salt. The heat generated by the CSP that is not sent to the heat engine is then stored to be used at a later time. This fact is crucial to provide benefits by shifting the power delivery to the grid from time slots with low energy price to time slots with higher energy price. Furthermore, the presence of the TES may be an advantage to oversize the

CSP system with respect to the capacity of the connecting line, storing heat each time the CSP production exceeds the capacity of the line, and releasing the stored heat to the heat engine when the CSP production becomes lower than the connecting line capacity.

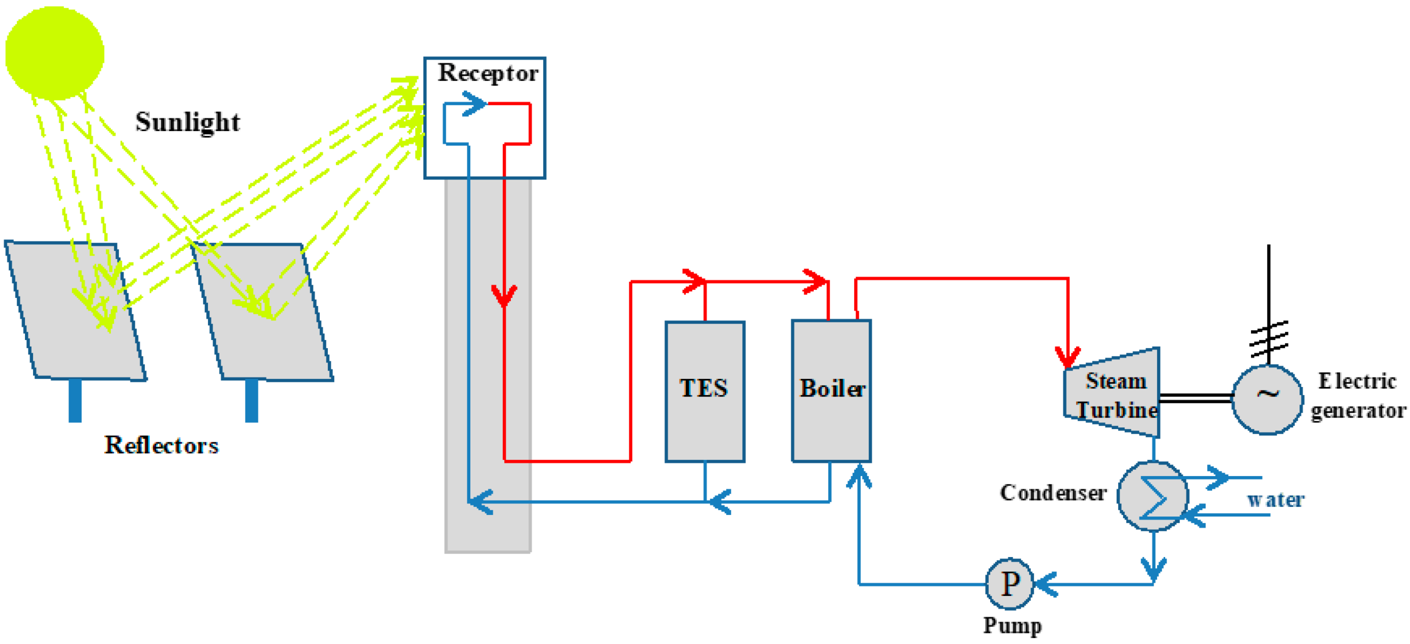

Figure 2. Concentrated solar power (CSP)-TES scheme.

Various references indicate that the presence of a TES system enhances the value of the CSP system [6]. The application shown in [8] refers to a CSP coupled with TES in a system connected to the electricity transmission network. The presence of the storage system allows the reduction of the overloads in the components, thus reducing the need for further investments. Therefore, the added value given by the TES leads to significant cost savings with respect to the use of the CSP alone. The value of TES is determined in optimal situations of charge and discharge of the storage, by minimising the production costs taking into account reserve capacity requirements, balancing needs, availability, and plant performance. The study carried out in [7] refers to a CSP system composed of parabolic troughs, power towers, or linear Fresnel reflectors. When the TES size increases, the CSP-TES system becomes more flexible in shifting the power injected in the grid (and sold to the market) to periods with higher electricity price.

Furthermore, increasing the TES size, it is possible to store and then use more energy, reducing the unused excess energy generation. The results provided show the breakeven cost (that is, the maximum capital cost that may be covered by the expected revenues) for using a CSP-TES system in different locations, considering the energy market, also with the addition of the ancillary services market. The trade-off between costs and revenues for a CSP plant with TES is also addressed in [9] by considering the uncertainty of renewable energy generation by using a scenario-based analysis.

The CSP-TES solution is addressed in [10] with the addition of an electric heater that converts electricity from other sources (e.g., the electrical grid, or the electrical output of other RES systems) into heat, to increase the operational flexibility. The application studied includes a CSP-TES and a wind energy system, and takes into account the RES uncertainty in a stochastic unit commitment and economic dispatch model with energy and reserves, by using scenario analysis.

1.3. Wind Energy Systems

Heat storage can be seen as a viable and helpful solution in systems with high wind energy generation when wind curtailment could be necessary and occurs during the heating period [11]. In this case, the problem has been analysed in the multi-objective framework, in which the conflicting objective functions to be minimised are the fuel cost of the conventional generation and the wind curtailed, and the size of the heat storage system is the decision variable.

On the other side, TES can be used to store the excess electricity provided from wind systems, upon proper energy conversion. In this way, it could be possible to avoid the construction of a new thermal power plant, as discussed in [12] with reference to wind power and to the possibility of storing heat (e.g., for space heating) or cooling energy (through electric chillers).

Some references address the possibility of generating thermal energy directly at the top of the wind tower, where a heat generator is located, following the principle of the TEES. In this structure, there is no electrical line inside the wind tower. The heat produced by the heat generator is transferred to the TES system located at the base by using a heat transfer fluid (HTF), then a secondary circuit that includes a steam turbine (connected to a synchronous generator for electricity generation and grid connection), a condenser and a circulating pump is supplied through a heat exchanger. In the solution presented in [13] (**Figure 3**), called the wind powered thermal energy system (WTES), the TES acts as a thermal energy buffer, and the electricity produced by the synchronous generator depends on the demand. This solution is deemed to be more cost-effective than the use of a wind system with battery storage. A further advantage is the possibility to share some parts of the plant with CSP-based or biomass-based plants that use TES. The same concepts are used in [14] for a WTES application with direct conversion of rotational energy into heat, also including on-site shares of electricity and heat generation.

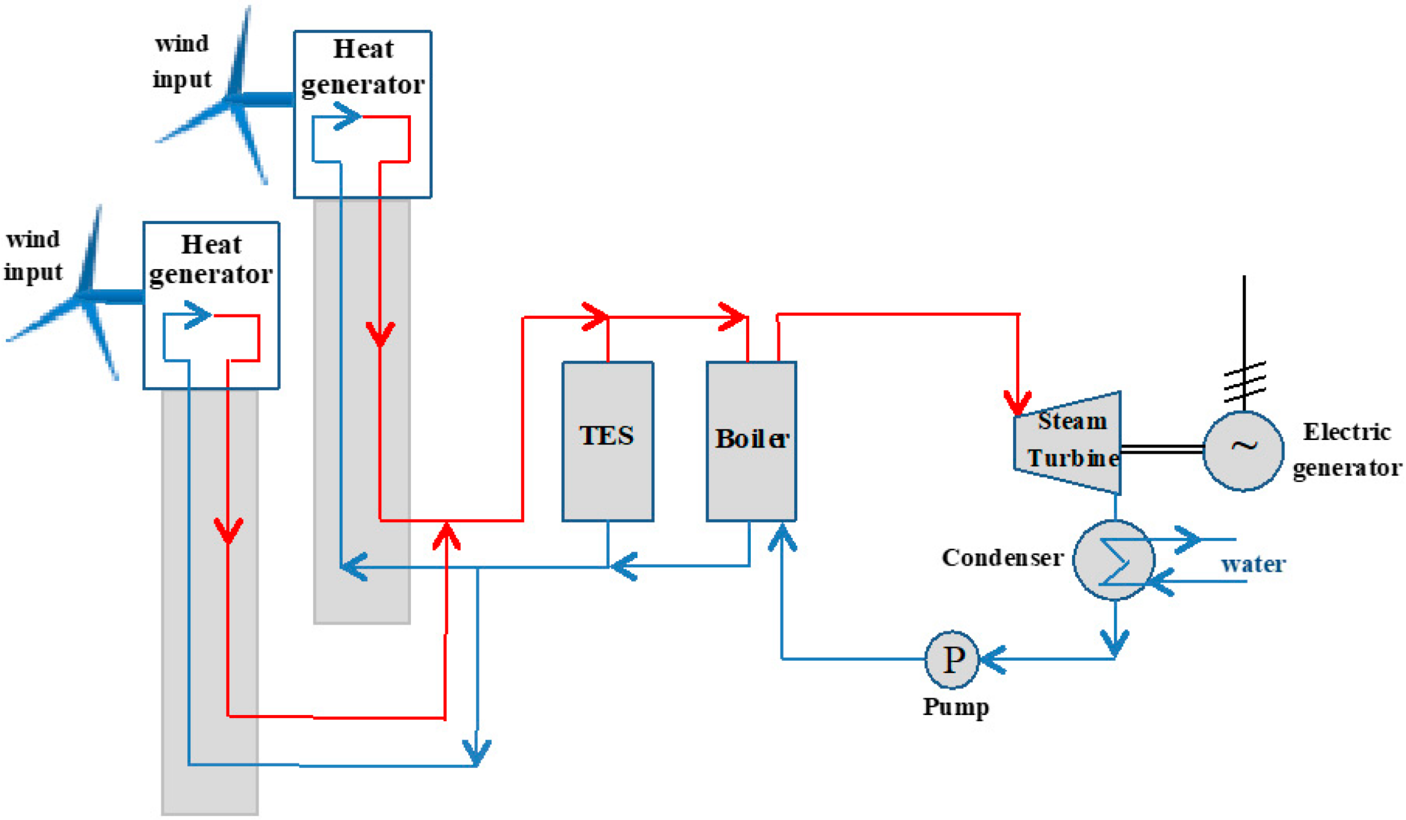

Figure 3. Wind powered thermal energy system (WTES) scheme.

From another point of view, passive heat storage has been considered, consisting of storing heat in the building structure when a given indoor air temperature variation is allowed. This solution is more convenient than the use of heat accumulation tanks for promoting better integration of wind power in combination with the installation of heat pumps [15]. Likewise, the thermal storage provided by buildings where heat pumps are installed is assessed in [16] in systems with high wind power penetration. In the application shown in [17], a positive aspect is the correlation that exists between wind energy and the request of energy for space heating during the seasons. In these conditions, it is sufficient to use heat storage from water tanks to compensate for the wind energy deviations with respect to the space heating needs. The feasibility and effectiveness of using heat storage with electric boilers to reduce wind energy curtailment, at wind penetration levels consistent with the break-even points for wind power system investments, is shown in [18].

Benefits from the combined exploitation of different VRES systems may generally arise when there is a negative correlation between the availability of the different VRES. In this way, the capacity factor (namely, the ratio between the average generation and the maximum generation, where the maximum generation is expressed by a power capacity, and the average power is assessed for the given time interval) of the combined plant can be increased, making the investment more effective. The addition of TES may further improve the situation. In the example shown in [19], wind and CSP are co-located, and further benefits arise from using low-cost and high-efficiency TES in the CSP.

2. TES in Microgrids and Multi-Energy Networks

2.1. Microgrid Applications

TES systems may become of practical interest for smaller energy systems, such as for microgrid applications with distributed energy resources (DER), as well as in isolated systems.

Mathematical models of optimal power flow and unit commitment have been formulated to describe the energy management strategies in a microgrid with high RES penetration. In these models, TES systems have been modelled in specific ways, taking into account their characteristics and constraints. The operation of a microgrid that contains a multi-energy system with electric and thermal loads, RES generation, combined cooling heat and power plants and thermal storage units, and transacts electric energy with the main grid (also including demand response services) is optimised in [20]. The contribution of ETS systems including heat losses for the microgrid energy management has been modelled in [21], together with other DER, taking into account the network constraints and the control of the reactive power support. In [22] an ice-thermal storage system is used in building energy models to assist voltage control and reduce the frequency fluctuations in weak electrical networks.

2.2. Multi-Energy Networks and Flexibility Aspects

Multi-energy systems (MES) [23], as an evolution of distributed multi-generation systems [24], add further dimensions and opportunities for energy management in local energy networks, also given by the interaction of different energy carriers. In particular, an MES enables the deployment of multiple network services [25], in which the combination of RES, CHP, boilers, batteries, and TES opens wide prospects to energy shifting [26] and multi-energy arbitrage [27]. An MES also includes the integration among different energy networks into energy hubs [28], considering district heating and cooling (DHC) systems. The TES provides many advantages with respect to other storage systems when coupled with DHC systems. An extended discussion of these advantages and the possible drawbacks is provided in [29]. For example, the reduction of the fluctuations from RES, and the thermal peak shaving or valley filling, could have an impact on the electrical network, as well as the exploitation of power-to-heat (P2H) solutions in which electric boilers are used instead of heat pumps. Energy cost optimisation with integrated electricity, heat, and gas networks and different types of storage (also including ramp constraints) have been formulated and solved in [30]. The provision of ancillary services by heat pumps coupled with TES in a hybrid RES system has been addressed in [31].

In an MES, a key aspect is the enhancement of flexibility to improve the system operation and the opportunities to provide energy services. Among the many definitions of flexibility, for electrical systems flexibility has been indicated as “the general characteristic of the ability of the aggregated set of generators to respond to the variation and uncertainty in net load” [32], or “the capability to balance rapid changes in renewable generation and forecast errors within a power system” [33]. In this context, a TES system can be integrated either at the generation side or at the net load side. The flexibility that can be provided by residential TES for load shifting, energy arbitrage and contingency reserves is discussed in [34]. Multi-energy storage is included among the various flexibility options modelled in [25]. Both electrical boilers and heat storage tanks are considered in [35] to improve flexibility. The heat storage tanks are effective to save energy in the whole energy system. In [36] TES is used in conjunction with dwelling materials in an optimisation process to provide demand response by also considering thermal comfort.

The flexibility of using electricity for heating purposes, denoted as P2H, in combination with heat storage, is becoming more and more interesting [37][38]. The potential of P2H could be significantly enhanced by the use of TES, depending on the TES size, as shown in [39] for a district heating application in which electric boilers are used for P2H.

3. Emerging Trends

The key aspect focused on the current trends is the flexibility of the multi-energy system operation. In this context, multiple resources are available for providing demand response capabilities, with which a reduction or increase of the electricity taken from the grid (upon request by a specific programme) is possible by also considering energy shifting among different energy carriers. TES is one of the components of the smart heating and cooling strategies that can make the flexibility options available in the short term at relatively low cost [40].

The incorporation of demand response aspects with the use of ETS in order to provide further peak shaving and enhance the RES capacity has been indicated in [41] as smart electric thermal storage (SETS). SETS is a form of decentralised P2H [38] and has been studied in a theoretical and experimental way in [42], with detailed analysis of the heat transfer aspects. Residential TES is an example of a demand-side resource that can be exploited for energy arbitrage, reduction of the variability of the net load and provision of reserves [34].

In the United States, the Advanced Research Projects Agency-Energy (ARPA-E) operates a programme called “Duration Addition to electricitY Storage (DAYS)” to develop storage systems with durations of between 10 to 100 hours [43]. Around one-half of the projects funded use some forms of TES. Furthermore, ARPA-E runs the programme “High Energy Advanced Thermal Storage” (HEATS), to develop revolutionary and cost-effective TES in three specific areas of high-temperature solar TES, conversion of sunlight into heat to create synthetic fuel, and use of TES for enabling thermal management of internal combustion engine vehicles and rise the driving range of electric vehicles. The potential of adopting TES solutions also passes from the development of materials with enhanced characteristics, among which some solutions under study include nanostructured heat storage materials, metal hydride thermal storage, supercritical fluid-based thermal energy storage system, thermal batteries, and new thermoelectric materials with increased efficiency of direct heat-to-electricity conversion. A detailed appraisal of key aspects for obtaining high-efficiency TES is provided in [44]. These aspects include the high energy density of the storage material, low internal losses and possibly high-temperature operation; the high heat transfer between the HTF and the storage material, also due to the performance of the heat exchanger; the reversibility of charging and discharging cycles, with mechanical and chemical stability of the storage material during cycling, and the facility of TES integration and control inside the overall energy system.

One of the main drivers for future developments is the assessment of the flexibility that may come from the integration of TES into the multi-energy systems targeted to smart cities and energy communities [30]. The attention given to TES application in local communities has been limited [45][46] but is now increasing [25]. Community energy storage has been addressed in [47] indicating that at present only traditional thermal storage with water tanks is in general economically viable. In the future, more integration among different energy carriers is envisioned. Additional flexibility for the multi-energy system may come from combining TES with P2G and battery storage, for enhancing the storage capability for both electricity and heat and provide better energy services to the grid. In this respect, P2G could be suitable for relatively long-term storage [48], while battery storage could cover the short-term operation, and TES could be a complementary option to enhance the effectiveness of mid-term operational strategies.

Moreover, mobile TES systems have been studied and tested [49]. These systems can be transported on trucks, to make the heat source available at remote locations from the thermal energy network. In particular, latent heat or chemical TES are suitable for mobile TES because of their relatively small volume with respect to sensible heat TES [29].

At a larger scale, TES is considered attractive to improve the efficiency of CAES technology, leading to the construction of Advanced Adiabatic CAES solutions (AACAES) [50]. In these systems, TES is used to store the heat resulting from the compression process. The stored heat is then used to preheat the air in the expansion phase. Beyond its increased efficiency, the AACAES technology is promising because of its negligible environmental impact and its relatively reduced costs and is in operation in a pilot site [51]. Experimental tests with combined sensible/latent heat TES have also been carried out, and their results have shown promising prospects for further analyses [52]. Among the possible solutions for large-scale TES, the pumped heat energy storage, or pumped thermal electricity storage [53] is a further attractive solution because it is not limited by geographical constraints (as it happens for PHS or CAES) or a low life-time.

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