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Analysis of Thermal Energy Storage to a Combined Heat and Power Plant

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Abstract: Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. TES systems are used particularly in buildings and in industrial processes. This paper is focused on TES technologies that provide a way of valorizing solar heat and reducing the energy demand of buildings. The principles of several energy storage methods and calculation of storage capacities are described. Sensible heat storage technologies, including water tank, underground and packed-bed storage methods, are briefly reviewed. Additionally, latent-heat storage systems associated with phase-change materials for use in solar heating/cooling of buildings, solar water heating, heat-pump systems, and concentrating solar power plants as well as thermo-chemical storage are discussed. Finally, cool thermal energy storage is also briefly reviewed and outstanding information on the performance and costs of TES systems are included.

I. INTRODUCTION

Recent projections predict that the primary energy consumption will rise by 48% in 2040 . On the other hand, the depletion of fossil resources in addition to their negative impact on the environment has accelerated the shift toward sustainable energy sources. Renewable energies such as solar radiation, ocean waves, wind, and biogas have been laying a major role in reforming the natural balance and providing the needs of the growing population demand However, due to the climatic vagaries, the means of storing these types of renewable energy has become urgent This has lead to a need to develop efficient and sustainable methods of storing energy. Energy storage has become an important part of renewable energy technology systems. Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications [4] and power generation. TES systems are used particularly in buildings and in industrial processes. Advantages of using TES in an energy system include an increase in overall efficiency and better reliability, and it can lead to better economics, reductions in investment and running costs, and less pollution of the environment, i.e., fewer carbon dioxide (CO2) emissions . Solar thermal systems, unlike photovoltaic systems with striving efficiencies, are industrially mature and utilize a major part of the Sun's thermal energy during the day. Yet, it does not have enough (thermal) backup to continue operating during the low or no solar radiation hours. TES is becoming particularly important for electricity storage in combination with concentrating solar power (CSP) plants where solar heat can be stored for electricity production when sunlight is not available. New materials are selected, characterized, and enhanced in their thermo-physical properties to serve the purpose ofa 24 h operation in an efficient TES system. In Europe, it has been estimated that around 1.4 million GWh/year can be saved and 400 million tons of CO2 emissions avoided, in buildings and in industrial sectors by more extensive use of heat and cold storage Storage density, in terms of the amountof energy per unit of volume or mass, is important for optimizing solar ratio (how much solar radiation is useful for the heating/cooling purposes), efficiency of appliances (solar thermal collectors and absorption chillers), and energyconsumption for space heating/coolingroom consumption. Therefore, the possibility of using phase-change materials (PCMs) in solar system applications is worth investigating. PCMs might be able to increase the energy density of small-sized water storage tanks, reducing solar storage volume for a given solar fraction or increasing thesolar fraction for a given available volume

A. Objective of this Study

TES systems have greatly developed over the last 40-50 years as industrialized nations have become increasingly electrified. As Dincer has brought to light, ―in many countries energy is produced and transferred in the form of heat. Thus, the potential for thermal energy storage warrants investigation in great detail‖ [8]. The results from the prior literature have provided sound validation for the following research into the modeling of a seasonal TES system for the UMass CHP plant. Additionally, it was observed that there is limited research using actual CHP plant data to model a seasonal TES system of this scale. Thus, what makes this study unique is that actual operating datafor a year was used from the UMass CHP plant to design and model a TES system.

In summary, the objectives of this research are as follows:

1) Utilize current CHP operating data to asses a proposed operation with TES
2) Design & model the performance of a TES system in TRNSYS
3) Asses the economic and environmental benefits of TES to CHP
4) Investigate system cost and payback

II. LITERATURE REVIEW

A. *Background*

Hourly data from 2020 was used to observe the current operation of the campus CHP plant in order to help model the proposed operation of the plant with TES. When the spring semester ends in early May, the thermal load of the campus is reduced and it increases again as the fall semester begins in September. The average hourly steam produced by the HRSG for May through September is approximately 60,000 pph. Thus, there is an opportunity to increase the steam production of the HRSG to 100,000 pph during this period to accommodate the application of a TES system.

Table 2.3 below shows the cost and fuel usage (both in MMBtu & MWh) for the three fuels used at the plant from July 2020 to June 2021

Month	**Natural Gas Cost (RS)**	**Natural Gas Usage**		**LNG Cost($)**	**LNG Usage**		**ULSD Cost($)**	**ULSD Usage**	
		MMBtu	**MWh**		**MMBtu**	**MWh**		**MMBtu**	**MWh**
July	RS93,793,273.2	133,400	39,126	0	0	0	0	0	0
August	RS81,877,825.7	120,888	35,456	0	0	0	0	0	0
September	RS84,901,957.8	125,353	36,766	0	0	0	RS3,376,565.5	1,754	514
October	RS91,407,825.3	136,895	40,151	0	0	0	RS7,247,142.1	3,764	1,104
November	RS1,470,589	153,027	44,882	RS34,344,052.6	18,760	5,502	RS15,029,714.7	7,807	2,290
December	RS101,952,305.4	144,701	42,440	RS75,974,603.1	47,309	13,876	RS41,149,510.6	21,375	6,269
January	RS84671424.2	119,549	35,063	RS79,794,179.3	41,546	12,185	RS154,231,179.3	80,113	23,497
February	RS96,296,272.6	135,934	39,869	RS79,513,898.2	46,705	13,698	RS76,728,259.3	39,856	11,690
March	RS95,855,472.9	135,934	39,869	RS71,065,814.6	49,884	14,631	RS31,620,026.9	16,425	4,817
April	RS108,755,110.2	150,884	44,254	RS23,473,376.3	6,701	1,965	RS6,898,614.8	3,583	1,051
May	RS88,003,696	122,219	35,846	0	0	0	0	0	0
June	RS81,006,249.5	112,501	32,996	0	0	0	RS1,812,135.6	941	276
Total	**RS1009992002**	**1,591,285**	**466,719**	**RS 364165924.1**	**210,905**	**61,858**	**RS 338093148.8**	**175,618**	**51,508**

The most recent cost and usage data was used rather than the data from 2020, as it betterrepresents the marginal cost of fuel at its current rates. Energy storage is critical for success in developing a sustainable energy grid because it facilitates higher renewable energy penetration by mitigating the gap between energy generation and demand. This review analyzes recent case studies—numerical and field experiments—seen by borehole thermal energy storage (BTES) in space heating and domestic hot water capacities, coupled with solar thermal energy.

System design, model development, and working principle(s) are the primary focus of this analysis. A synopsis of the current efforts to effectively model BTES is presented as well. The literature review reveals that: energy storage is most effective when diurnal and seasonal storage are used in conjunction; no established link exists between BTES computational fluid dynamics (CFD) models integrated with whole building energy analysis tools, rather than parameter-fit component models; BTES has less geographical limitations than Aquifer Thermal Energy Storage (ATES)and lower installation cost scale than hot water tanks and BTES is more often used for heating than for cooling applications.

III. EXPERIMENTAL DETAILS

A multitude of simulations were performed in order to determine an optimal system configuration. The proposed systems were designed to maintain a charging loop temperature below <90^{o}C, as operational temperatures above this limit can cause damage to the plastic U-tubes [21].

The number of boreholes varied from 11,250 to 12,250, in increments of 250. In order to maintain a loop temperature below the upper bound of 90^{o}C, the rated charging flow for each system size was adjusted. Furthermore, the rated load was tuned for each system size to ensure a balanced system after steady state operation is reached; energy into BTES after losses equals energy to load. Numerous simulations at each increment of system size were performed to obtain a balanced system at the required temperature. Each simulation was run for a five year span at one hour timesteps in order to attain steady state performance.

Depending on the number of boreholes each five year simulation runs for approximately 10-30 minutes Before deciding on this range of borehole sizing (11,250-12,250), many other system sizes were tested from 6,000 to 20,000 boreholes. It was found that for systems smaller than this range, the charging loop temperature rapidly exceeded 90^{o}C during the charging period. One way to mitigate the rapid temperature rise was to increases the load and charge loop flow rate.

However, this resulted in significant depletion of the storage system to the point that the minimum ground temperature was lower than the initial ground temperature before charging. Thus, the ground was unable to heat up over the five year simulations. Additionally, the pumping power required for the smaller systems greatly impacted the overall performance of the system. Thus, it was concluded that the chosen range demonstrated the highest performance with the most benefit to the campus building load. This is because low temperature radiators require a minimum of approximately 40^{o}C to be effective [31]. Conversely, for system sizes larger than this range, it was found that the minimum ground temperature fell below 40^{o}C, as theincreased storage volume requires more thermal input to heat up to the necessary levels. Thus, the chosen range of 11,250-12,250 boreholes was selected, as ground temperatureswithin this range never fell below 40^{o}C.

A. TRNSYS Simulation Results for Selected Range

Once a general range for the system size was determined, each 250 borehole increment required 5-10 simulations to produce a balanced system. Figure 3.1 is an example of a five year simulation in the TRNSYS plotter. The inlet, outlet and ground temperatures are plotted on the left axis, and the energy to the BTES system and energyto the load are plotted on the right axis

B. Results for TRNSYS Multiple Simulations

The following comparative results are from the 5th year of operation for each of the five system sizes simulated. The following information is shown: the annual ground temperature, energy input into the BTES system, the energy remaining after losses, the charge pump power consumption and the BTES system efficiency. It can be seen that as the number of boreholes increases, the ground temperature decreases. With 11,250 boreholes, the maximum and minimum storage temperatures reached are 72^{o}C and 42^{o}C, respectively. Conversely, with 12,250 boreholes the maximum and minimum storage temperatures reached are 68^{o}C and 40^{o}C, respectively.

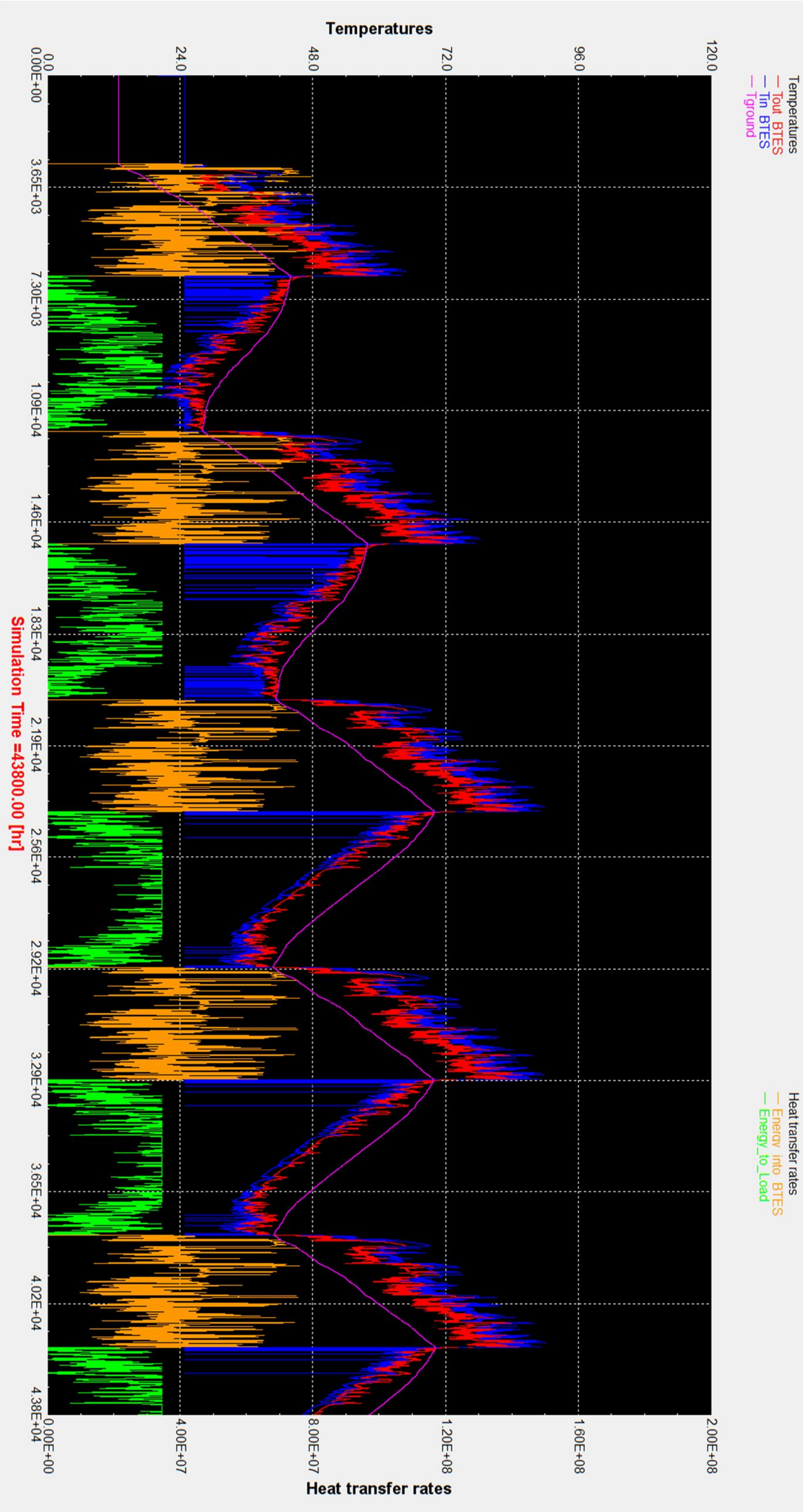

Figure 3.1 TRNSYS Plotter for 5 Year Simulation at 11,750 Boreholes

A higher ground temperature is preferable as it reduces the need for auxiliary heating at the low temperature campus load.

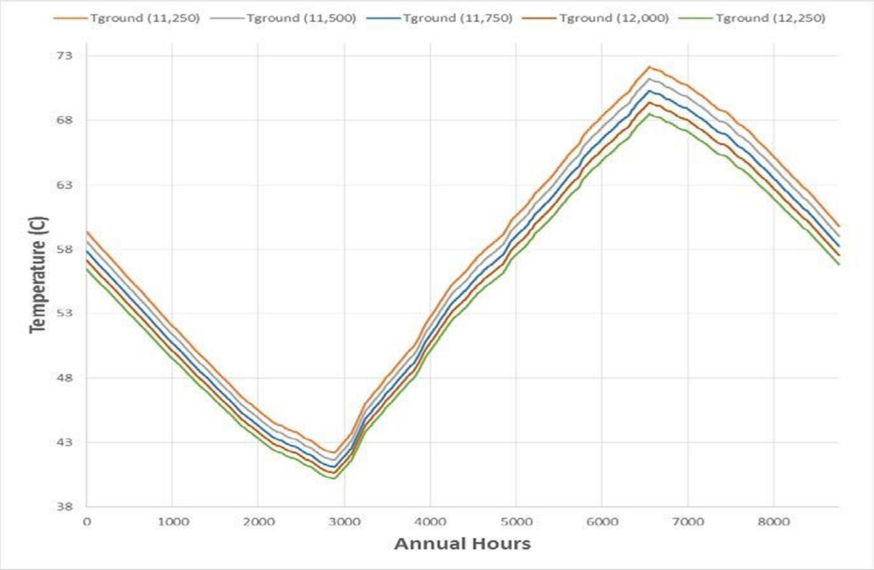

Figure 3.2 Comparisons of Ground Temperatures

Figure 3.3 shows the diminishing returns, in terms of heat input, to the BTES for increments less than 11,750 boreholes. This is due to the significantly higher flow rate needed to maintain a loop temperature below 90°C. From 12,000 to 11,750 boreholes thepercent energy into the BTES is reduced by 0.53%. However, from 11,750 to 11,500 boreholes the percent decrease is 0.79% and from 11,500 to 11,250 the percent decrease is 0.94%. Figure 3.4 shows the BTES energy stored after losses. The results again show the trend of diminishing performance for increments less than 11,750 boreholes. From 12,000 to 11,750 boreholes the percent of BTES energy remaining is reduced by 0.58%, from 11,750 to 11,500 boreholes the percent decrease is 0.90% and from 11,500 to 11,250 the percent decrease is 1%.

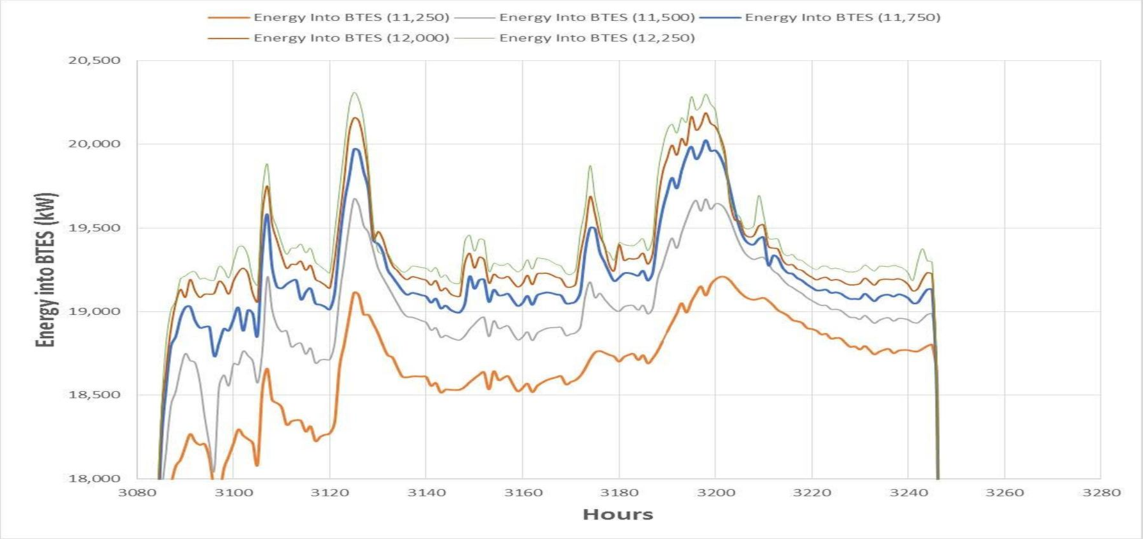

Figure 3.3 Comparison of Energy into the BTES (200 hour period)

Figure 3.5 shows the pump power over a 200 hour span during the charging period. A 200 hour time span was chosen as it better illustrates the additional pumping power required as the system size is reduced. Figure 3.6 shows the total pumping power for the 5th year of operation. It can be clearly seen that there is a significant increase in pumping power as the number of boreholes is reduced. From 12,000 to 11,750 boreholes the pumping power increases by 50%, from 11,750 to 11,500 boreholes the pumping power increases by 100% and from 11,500 to 11,250 the percent increases by 83%. The increase in pumping power is due to the need to keep the loop temperature below 90°C.

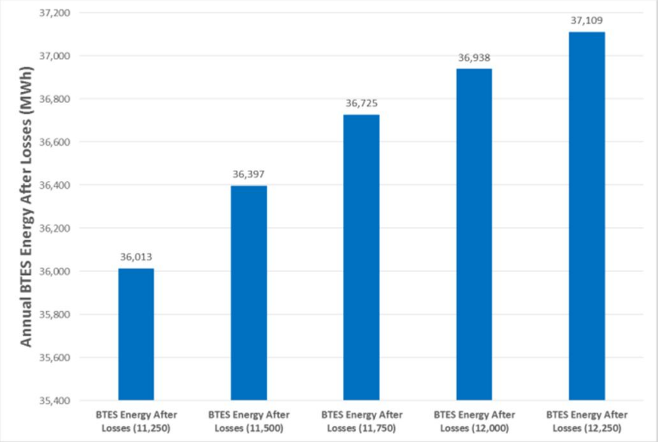

Figure 3.4 Comparison of BTES Energy Remaining After Losses

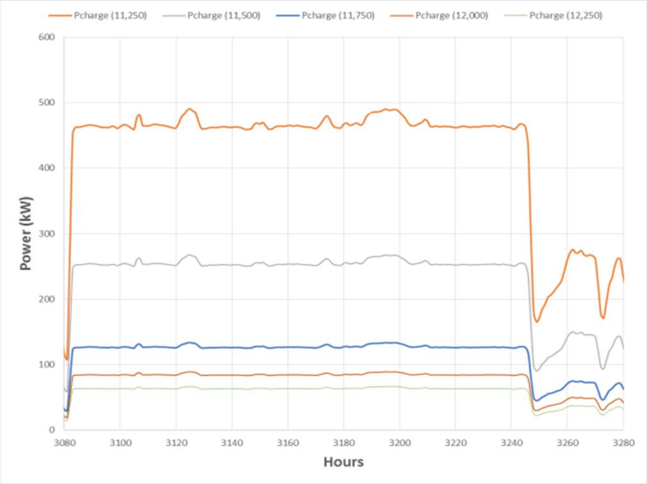

Figure 3.5 Comparison of Charging Pump Power Consumption (200 hour period)

IV. RESULTS AND DISCUSSION

The prior assessments have proven that the application of BTES is both thermodynamically and economically feasible. However, it is also important to look at the cost, simple payback and NPV of this system in order to better gauge its financial viability to the campus. The simple payback and NPV are only given for the ULSD case,as the economic and environmental benefits of offsetting ULSD were greater than that of LNG. Based on a prior detailed cost assessment conducted at UMass on the installation of a seasonal BTES system, industry quotes and the scale of this system, it is estimated that the system will cost approximately Rs18.5/m^3 [32]. The distribution of system costs isseparated into three parts: the BTES system, the distribution system and the mechanicalsystem. A summary of system costs and paybacks is shown in table 4.7.

Table 4.7 ACS, Estimated System Cost and Simple Payback

Fuel to Be Offset	ACS (RS)	BTES System Cost (RS)	Distribution System Cost (RS)	Mechanical System Cost (RS)	Total System Cost (RS)	Simple Payback
ULSD	178,970,449.5	705,195,010	693,588,124.11	614,075,702.12	2012858892.41	11

The simple payback for offsetting ULSD was found to be approximately 11 years. It is important to also considerthe NPV of the investment as the simple payback does not account for inflation. Thus, the present value of a future annual cost savings (cash flow) is neglected. This makes it difficult to compare the viability of this project to that of other cash flow producing projects. The NPV was calculated utilizing the initial investment cost of RS 2012854478.04. The discount rate used is 3.1% and is based onthe DOE nominal rate [33]. The time horizon considered is 45 years, as the life expectancy of the U-tube heat exchangers is approximately 45years [21].

V. CONCLUSIONS AND FUTURE WORK

TES is applicable to domestic systems, district heating, and industrial needs. The most popular and commercial heatstorage medium is water, which has a number of residential and industrial applications. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications. However, TES systems based on SHS offer a storage capacity that is limited by the specific heat of the storage medium.Furthermore, SHS systems require proper design to discharge thermal energy at constant temperatures. PCMs can offer a higher storage capacity that is associated with the latent heat of the phase change. PCMs also enable a target- oriented discharging temperature that is set by the constant temperature of the phase change. Melting temperature, latent heat of fusion, and PCM thermo-physical issues are three basic factors influencing the selection of PCMs in any application. A high heat of fusion and a precise melting/solidification temperature (without subcooling) are two primary requirements in the selection approach. Numerous mechanical and nano-level enhancements have been achieved to Sustainability 2019, 10, 191 28 of 32 increase the heat transfer rate, which is promising. Micro- encapsulation increases the heat transfer surface area and is also a solution for phase segregation in salt hydrates. Most of the literature is focused on routine and commercialized PCM materials such as paraffin. We recommend focusing on special PCMs with a wide temperature range such as salt hydrates and synthesizing specialized PCMs suitable for specific building applications. TCS can offer even higher storage capacities. Thermo-chemical reactionssuch as adsorption can be used to accumulate and discharge heat and cold on demand and to control humidity in a variety of applications using different chemical reactants. In CTES, materials with subzero temperatures are identified, but their thermal reliability, phase-segregation and subcooling issues have not been deeply studied. Studies on industrial (large scale) level thermal cold storage PCMs are hardly tested. At present, TES systems based on sensible heat are commercially available, while TCS- and PCM-based storage systems are mostly under development and demonstration. Support for the R&D of new storage materials, as well as policy measures and investment incentives for TES integration in buildings, for industrial applications, and for variable renewable power generation, is essential if its deployment is to be fostered. In future greenhouses, TES solutions can combine heating–cooling–dehumidification functions and provide poly-generation possibilitis.

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