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

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Abstract: ***The present study deals with the economic and environmental benefits that can be attained through the coupling of borehole thermal energy storage (BTES) and combined heat and power (CHP). Energy prices are significantly higher during the winter months due to the limited supply of natural gas. This dearth not onlyincreases operating costs but also emissions, due to the need to burn ultra-low sulfur diesel (ULSD). The scope of this paper is to present a TRNSYS model of a BTES system that is designed using actual operational data from the campus CHP plant.***

I. INTRODUCTION

The main objective of this research is to show the economic and environmental benefits that can be attained through the coupling of borehole thermal energy storage (BTES) and combined heat and power (CHP). Energy prices are significantly higher during the winter months due to the limited supply of natural gas. This dearth not only increases operating costs but also emissions, due to the need to burn ultra-low sulfur diesel (ULSD). The application of a TES system to a CHP plant allows the plant to deviate from the required thermal load in order to operate in a more economically and environmentally optimal manner. TES systems are charged by a heat input when there is excess or inexpensive energy, this heat is then stored and discharged when it is needed. The scope of this paper is to present a TRNSYS model of a BTES system that is designed using actual operational data from the campus CHP plant.

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

The TRNSYS model predicts that a BTES efficiency of 88% is reached after 4 years of operation. It is concluded that the application of BTES to CHP enables greater flexibility in the operation of the CHP plant. Such flexibility can allow the system to produce more energy in low demand periods. This operational attribute leads to significantly reduced operating costs and emissions as it enables the replacement of ULSD or liquefied natural gas(LNG) with natural gas.

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.

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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

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°C and 42°C,respectively. Conversely, with 12,250boreholes the maximum and minimum storage temperatures reached are 68°C and 40°C, respectively. A higher ground temperature is preferable as it reduces the need for auxiliary heating at the low temperature campus load.

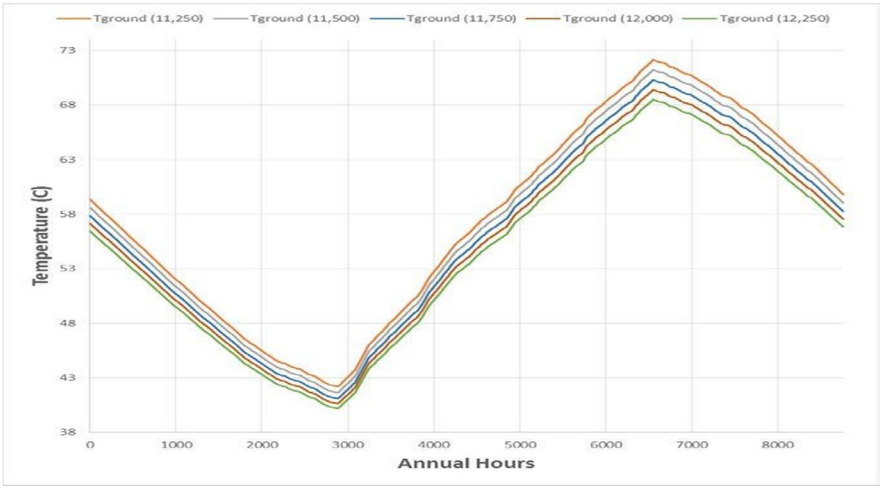


Figure 3.2 Comparisons of Ground Temperatures

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%.

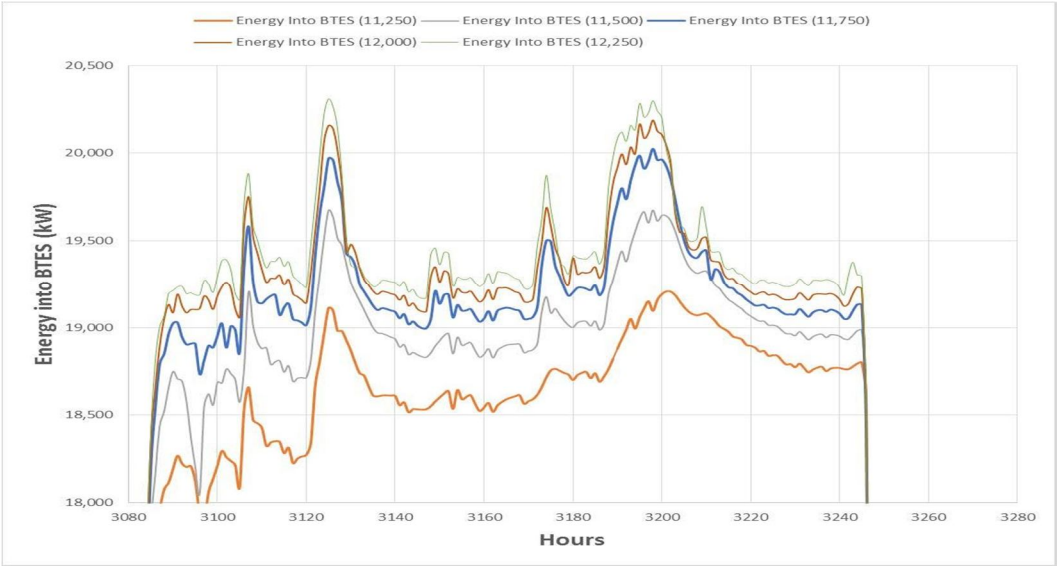


Figure 3.3 Comparison of Energy into the BTES (200 hour period)

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Figure 3.4 shows the BTES energy stored after losses. The results again show thetrend 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%.

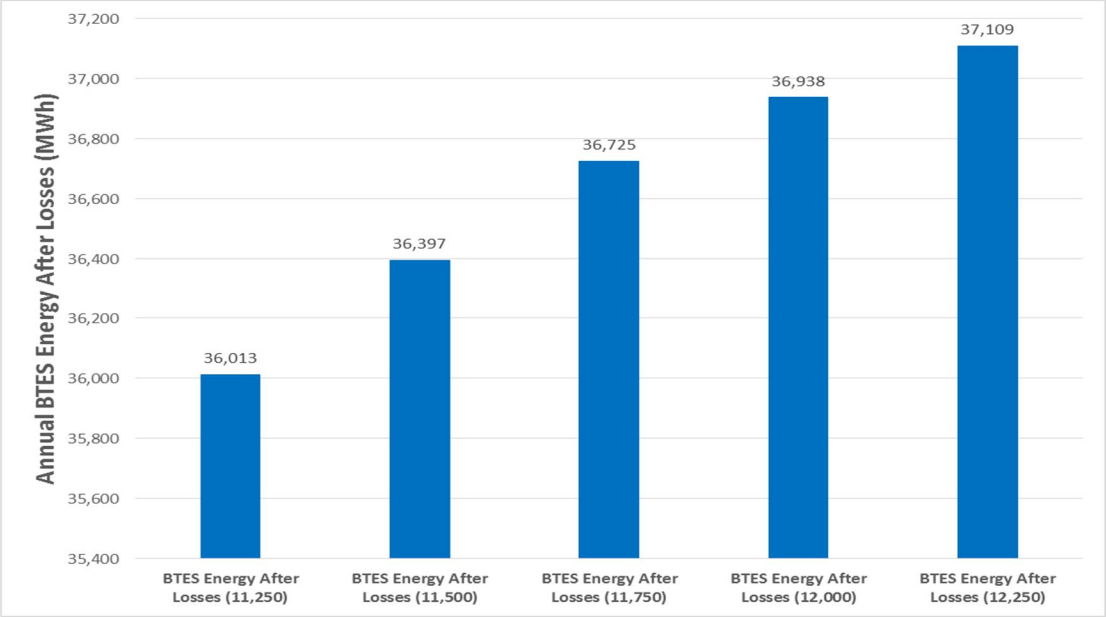


Figure 3.4 Comparison of BTES Energy Remaining After Losses

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^{o}C.



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

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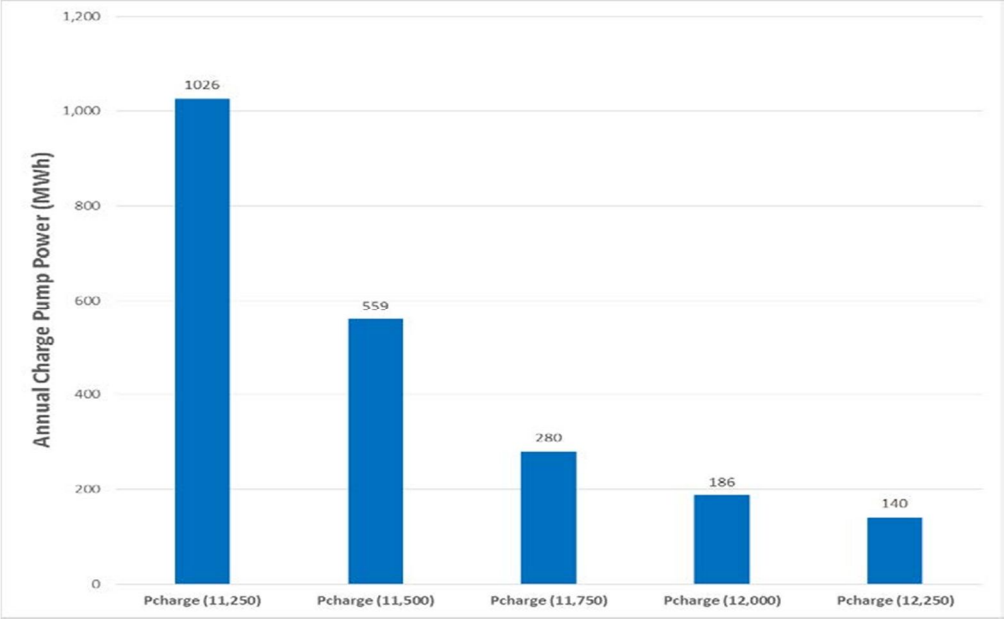


Figure 3.6 Comparison of Charging Pump Power Consumption Totals

Figure 3.7 shows the BTES efficiency for each increment of boreholes. Table 3.1illustrates the change in efficiency for the BTES system. (Note, the definition for the BTES efficiency is provided in the following chapter.) The results conclude the highest BTES efficiency is reached at 11,750 boreholes, with a 0.01% decrease in efficiency observed for each additional increment. Furthermore, there is a 0.13% decrease in BTESefficiency as the number of boreholes is reduced.

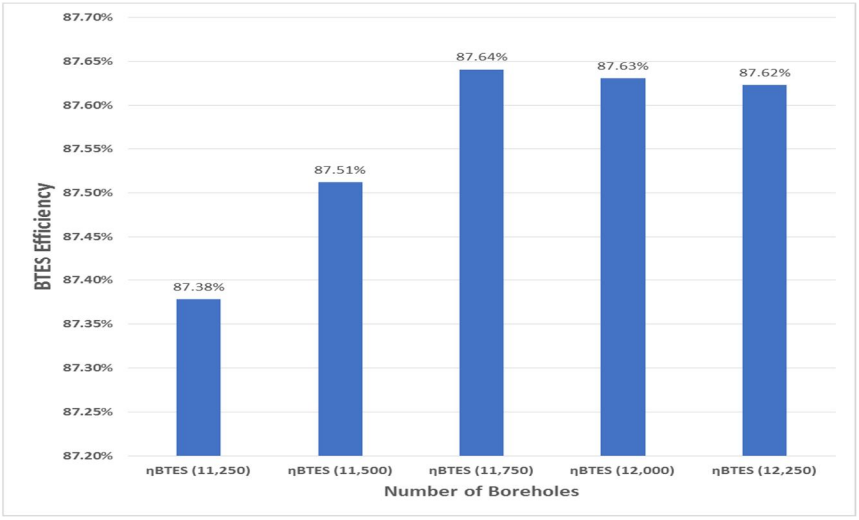


Figure 3.7 Comparison of BTES Efficiency

The results from this analysis conclude that as the size of the storage system decreases, the pumping power required increases and the energy input decreases, and as aresult the system performance drops. In order to maximize the offset to the campus building load and to reduce capital costs, it is important to choose a system with the lowest number of boreholes while maintaining high performance. For these reasons, a system comprised of 11,550 boreholes was chosen as it provides a lower capital cost, without compromising system performance. Although the larger systems use marginally less pumping power and deliver slightly more energy to the load, the additional capital cost incurred for the larger systems doesn't justify the small increase in performance.
Moreover, though smaller systems are feasible, the precipitous drop in performance for systems under 11,550 boreholes doesn't substantiate the capital cost savings.

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IV. RESULTS AND DISCUSSION

The UMass CHP plant has a SCADA system, which is capable of storing and transmitting instantaneous data about the plant's operation from 675 points in the system. This data includes, steam flows, fuel flows, temperature, pressure, power produced, and other critical data. 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 BTES. 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 BTES system. By setting the steam flow to 100,000 pph, it was determined that an additional 141,086,294 lbs of steam will be produced. This requires an additional 232,932 MMBtus (68,318 MWh) of natural gas. Using the temperature and pressure at the exit of the HRSG, it was determined that the average enthalpy is 1369 Btu/lb. This corresponds to an overall energetic steam input to the system of 193,139 MMBtus (56,647 MWh). A BTES systemcomprised of 11,750 boreholes was designed and simulated in TRNSYS, utilizing the proposed operational data of the CHP plant. The results from this assessment are presented in this chapter. A summary of the current and proposed operation (with TES charging) is given intables 4.1 & 4.2. Table 4.1 assumes that the thermal energy storageis used solely to offset ULSD. Table 4.2 assumes that the thermal energy stored is used tooffset.

Table 4.2 Current & Proposed CHP Plant Operation (LNG Reduction)

Summary of Results (LNG Offset)								
	Power Produced (MWh)	Steam Produced (lbs)	Natural Gas Fuel Input		LNG Fuel Input		ULSD Fuel Input	
			MMBtu	MWh	MMBtu	MWh	MMBtu	MWh
Current Operation	89,367	1,026,504,140	1,193,600	350,079	158,197	46,399	328,651	96,392
Proposed Operation	97,880	1,167,590,434	1,426,531	418,398	6,525	1,914	328,651	96,392
Increase (+) Decrease (-)	8,513	141,086,294	232,932	68,318	-151,672	-44,485	0	0

A. BTES & System Efficiency

The overall BTES efficiency is defined as the energy recovered divided by theenergy input and is as follows [8]:

$$\eta = \frac{\text{Energy Recovered}}{\text{Energy Input}} = \frac{\text{Energy to Load}}{\text{Energy into BTES}} \quad (16)$$

Additionally, it is vital to determine the effect that the TES system has on the overall efficiency of the CHP plant. Past research on the UMass CHP plant has concluded that the overall plant efficiency is 73%. Where the overall CHP plant efficiency (η_{CHP}) is defined as follows [27]:

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B. System Performance

The TRNSYS simulation was performed for a five year period in one hour time steps. The BTES utilizes 11,750 single U-tube heat exchangers at a depth of 30m for an approximate storage volume of 1,477,000 m^3. The simulation was run for five years in order to observe how the performance changed over time and to allow the system to reach steady state operation. It is expected that 80% of the steady state efficiency values will be obtained after approximately three years of operation [21]. At the fifth year of operation the maximum ground temperature and charging fluid inlet and outlet temperatures were found to remain constant at 70°C, 90°C and 86°C, respectively. See figure 4.1 below.

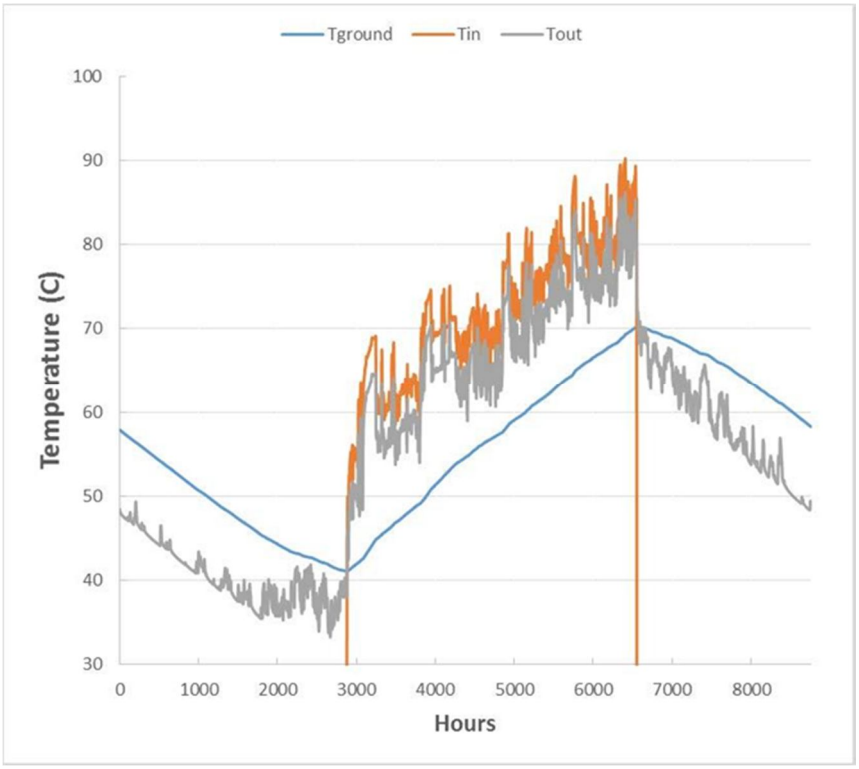


Figure 4.1 Year 5 Ground, Inlet & Outlet Temperatures

The following figures show the performance of the system over a year. Figure 4.2 showsthe energy injection during the charging period and energy extraction during the discharging period. Figure 4.3 shows the charge and discharge pump power, as well as the ground and ambient temperatures for the 5th year of operation.

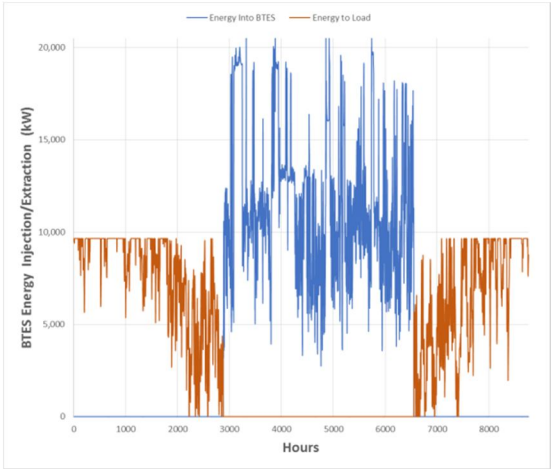


Figure 4.2 Year 5 BTES Energy Injection/Extraction

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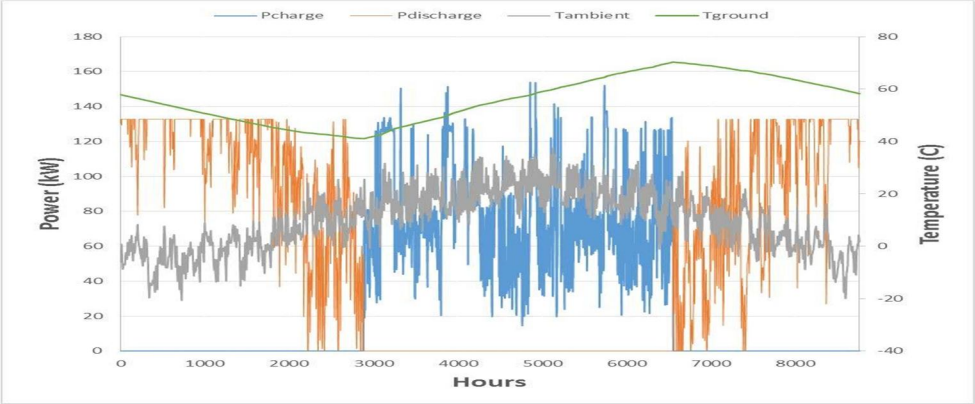


Figure 4.3 Charge and Discharge Pump Power, Ambient and Ground Temperatures

The summary of the system performance as presented in Table 4.3 is separated into four categories: a summary of the BTES system, the distribution system (charge anddischarge pumps), the steam turbines and a system energy balance. It is shown that after the third year the system begins to approach its steady state average ground temperature of approximately 56°C and after the fourth year of operation the BTES system efficiencyremains constant at 88%. The model predicts that as the temperature of the soil increases,the BTES efficiency increases from 15% to 88%.

Table 4.3 System Performance Summary

	Heat Flow Summary					
	Year of Operation	1	2	3	4	5
	BTES System					
	Energy into BTES (MWh)	44,034	42,896	41,916	41,937	41,919
	BTES Losses (MWh)	3,784	5,666	6,838	5,688	5,194
	Total	40,250	37,230	35,078	36,248	36,725
	H_{btes}	15%	44%	64%	88%	88%
	$T_{average}$ (°C)	27	43	55	56	56
	T_{Max} (°C)	44	58	70	70	70
	T_{min}(°C)	13	28	41	41	41
	Distribution Pumps					
	P_{Charge} (MWh)	280	280	280	280	280
	$P_{Discharge}$ (MWh)	91	261	371	506	506
	Total	371	540	651	785	785
	Steam Turbine Analysis					
	P_{HPST} (MWh)	2,721	2,721	2,721	2,721	2,721
	P_{LPST} (MWh)	5,792	5,792	5,792	5,792	5,792
	Total	8,513	8,513	8,513	8,513	8,513
	System Energy Balance					
In	Steam Energy Into System (MWh)	56,647	56,647	56,647	56,647	56,647
Out	Steam Turbine Power(MWh)	-8,513	-8,513	-8,513	-8,513	-8,513
	BTES Losses (MWh)	-3,784	-5,666	-6,838	-5,688	-5,194
	Energy to Load (MWh)	-6,608	-18,942	-26,955	-36,738	-36,738
	Condensate Return Energy (MWh)	-4,220	-5,283	-6,207	-6,184	-6,202
	Energy Balance (MWh)	33,522	18,243	8,134	-476	0

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As the steam flow during the charging period is increased to accommodate the charging of the BTES, additional electricity is produced by the HPST and LPST. These turbines were modeled in TRNSYS using flow following turbine (Type592) and the generators were modeled using a Type599. Where the maximum power produced from the HPST and LPST is limited to 2 MW and 4 MW, respectively. The additional steam flow in the summer months enables these turbines to produce on addition 8,513 MWh combined. This increased generation of onsite power by the CHP plant directly corresponds to a reduction in power purchased from the grid. This offset results in an annual reduction of CO_2, NO_x and SO_2 emissions by 3,900,057 kg, 2,201 kg and 4,826, respectively. Note, more information on emission factors is provided in appendix D.

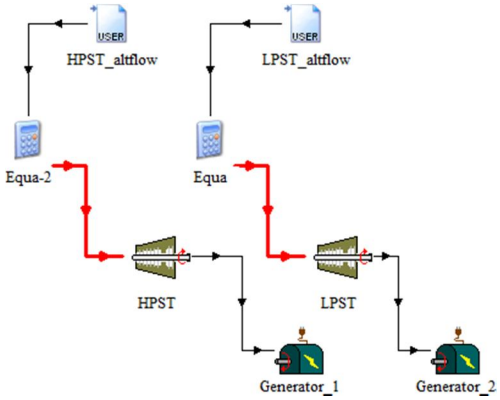


Figure 4.4. HPST & LPST TRNSYS Model

C. Economics & Emissions Results (ULSD)

A summary of the system economics and change in emissions for a five year span is presented. The energy to the load represents the energy discharged from the storage system that is used to offset campus heating. The boiler energy offset represents the equivalent boiler fuel input needed to generate the energy to the load

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 possibilities.

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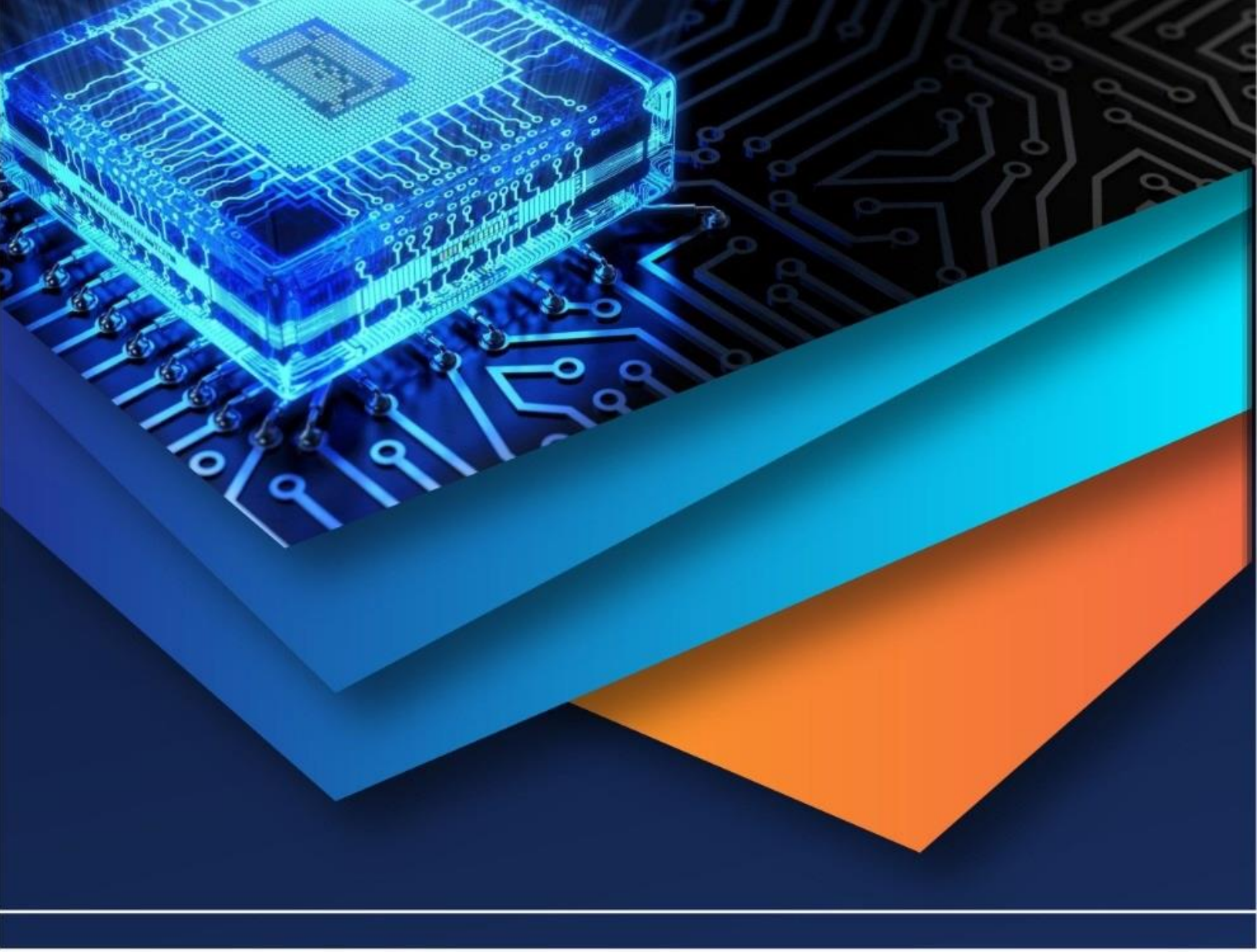
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