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

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ABSTRACT

The main objective of this paper 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). The subject of this investigation is the university Dr. Rammanohar Lohia Avadh University, Ayodhya District Heating System. 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. 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.

Keywords: thermal energy; environmentally; economic; natural gas; emissions;

1. INTRODUCTION

As the global demand for energy continues to rise, it is becoming increasingly important to find efficient ways to utilize energy and to lessen the use of fossil fuels. It is projected that the world's total energy consumption will increase by 71% from 2003 to 2030, with an increase in natural gas and oil consumption of 91.6% and 47.5%, respectively [1]. This trend presents serious environmental challenges to humanity, as current greenhouse gas emissions within the atmosphere have reached troubling concentrations [2]. Thus, if measures are not taken to lessen the production of greenhouse gas emissions the effects of climate change will be further exacerbated. Through the production of electricity, and in many other industrial processes, there is a great deal of waste heat generated. Utilizing this waste heat through the application of combined heat and power (CHP) can greatly increase the efficiency of a system when compared to centralized electricity production and independent heat generation [3,4]. The efficiency of a power producing system can be increased from 35-55% to more than 90% by simply utilizing waste heat [5,6]. Cogeneration plants produce electricity and thermal energy simultaneously by utilizing the hot effluent exhaust from a combustion gas turbine (CGT) to produce steam or hot water. This thermal energy can be then transferred with a district energy (DE) system to buildings close to the CHP plant. District heating systems using CHP are particularly popular in Europe, for example, 75% of the district heating energy in Denmark is generated by cogeneration [7] and in Sweden it is about 30% [6]. Although the coupling of CHP and DE increases the overall system efficiency, when compared to centralized power production, there are still economic and environmental shortcomings due to the operational limitations of CHP systems and the seasonal variation in fossil fuel availability. Electricity production is limited by the thermal load and peak periods in the demand for energy often do not align with supply. These limitations lead to inflated energy rates and short supplies in the periods of highest demand. One promising method to mitigate this discrepancy between the supply and demand for energy and to increase the electrical generation capacity of the CHP system is through the application of thermal energy storage (TES).

2. Thermal Energy Storage & Combined Heat and Power

TES can enable thermal systems to operate at an overall higher effectiveness, whether it is thermodynamic or economic effectiveness. These systems are often utilized when the demand for energy is not coincident with the most economically advantageous supply for energy. Dincer has identified some of the benefits that can be achieved through the use of TES with CHP plants [8]. Typically, CHP plants are controlled to match the requirements of the system's thermal load. TES can allow CHP plants to diverge operation from the required demand (thermal load) in order to operate in more favorable ways. This deviation can occur daily, seasonally or both and is aimed at shifting the purchase of energy to low-cost periods. Additionally, higher efficiencies are realized for CHP systems when they operate at full load with constant demand [9]. This is rarely attainable in CHP systems, since thermal loads are seldom constant. However, a full and constant thermal load can be attained through the use of a properly sized TES system. The uncoupling of electricity production and heat generation can lead to considerable savings as it allows more electricity to be produced during peak hours as well as the potential to offset peak heating loads. In summary, the application of an optimal TES system can allow the CHP plant to extend its operating hours leading to increased energy savings and reduced emissions [10].

3. Thermal Energy Storage

Thermal energy storage systems of all types operate on the same basic principle. Energy is delivered to a storage device for use at a more advantageous time. The main distinction between systems is the time-scale of storage, working temperature and the storage medium used. These design parameters are dependent on the requirements of the thermal system that the storage system is integrated to. Solar thermal power plants typically require TES systems that are designed for daily cycling and high working temperatures. Diurnal TES systems allow solar power plants to produce power continuously, thus countering the intermittency of the solar resource. However, district heating systems require TES systems with immense storage capacities that cycle daily and/or seasonally. The complete cycle of a storage system consists of 3 stages: charging, storing and discharging.

4. Sensible Heat Storage

In general, TES systems can be classified into three categories; sensible, latent and chemical thermal energy storage [11]. Sensible heat is the energy that is absorbed or released as the temperature in a substance is changed (with no change in phase experience in the material) [12]. The temperature of a storage medium increases proportionally to the energy input to the system. The quantity of energy accumulated in a storage medium is dependent on the specific heat, the mass of the storage medium and the temperature change [13]. Typical sensible storage materials are liquid (water, oil) and solid (rocks, concrete, metal). The most common sensible energy storage systems in operation are tank, pit, borehole and aquifer thermal energy storage.

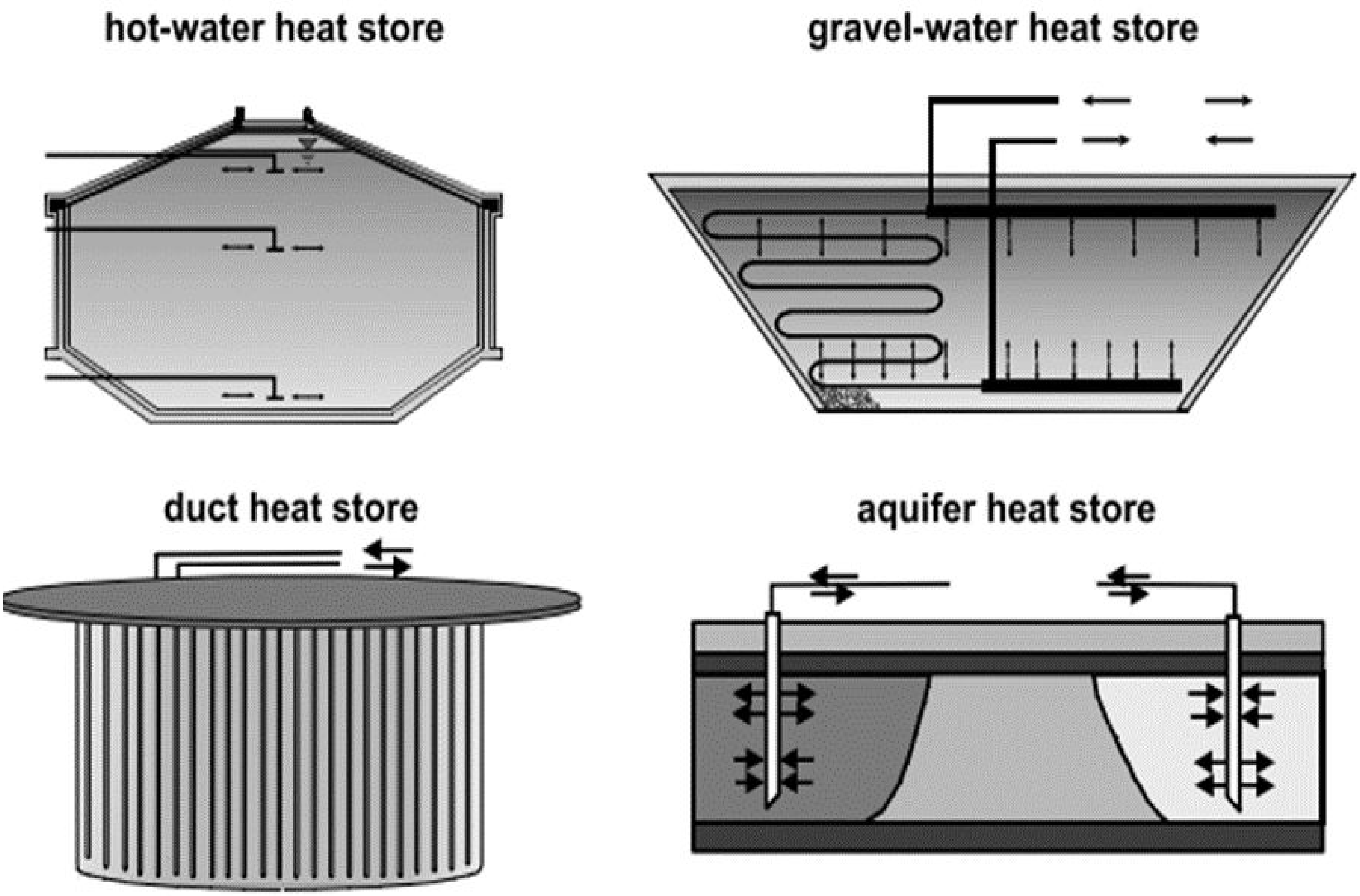

Figure 1. Types of sensible seasonal thermal energy systems

4.1 Tank Thermal Energy Storage

Tank thermal energy storage (TTES) systems are generally made of reinforced concrete, with the interior layer lined with stainless steel to create a watertight seal. The storage medium is typically water because of its high specific heat capacity. These tanks are insulated and buried underground and working temperatures are in the range of 30-90oC [15]. Bauer investigated the performance of German central heating plants with seasonal energy storage [16]. One of the studied systems was a tank thermal energy storage (TTES) system in Friedrichshafen, Germany. The tank was made of reinforced concrete with a storage volume of 12,000m3 (with a height of 20m and diameter of 32m). The efficiency of this TTES system was found to be 60%. Solar collectors with a solar fraction of approximately 33% and two condensing gas boilers provide the energy input to the TTES system.

Figure 2 Construction of a tank thermal energy storage system [17]

4.2 Pit Thermal Energy Storage

A pit thermal energy storage (PTES) system consists of an excavated pit that is lined with plastic. These systems are generally insulated on the top only, as the losses from the sides/bottom to the soil are relatively low (temperature dependent). Due to the low cost of construction when compared to tank storage, PTES storage capacities can be immense. Dannemand studied a district heating system in the town of Marstal, Denmark (one of the largest of its kind) that had been coupled with solar thermal collectors, a biomass boiler, heat pumps and seasonal pit thermal energy system [15]. This system has a storage volume of 80,000m3 [18] and operates at temperatures in the range of 30-90oC, with a efficiency of approximately 55% [15].

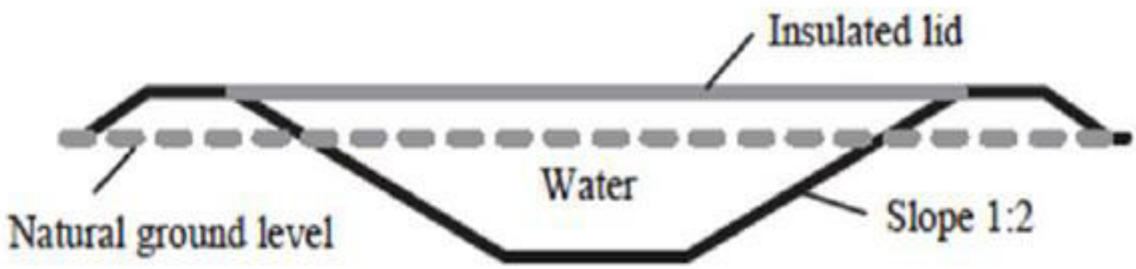

Figure 3 Cross section of the PTES [15]

4.3 Borehole Thermal Energy Storage

Borehole thermal energy storage (BTES) systems are made up of a sizeable number of boreholes, where each borehole is typically filled with thermally conductive bentonite grout and a heat exchange pipe (typically PEX tubing). The ground (soil) is used as the storage device, where heat is transferred to the ground by circulating water or propylene glycol through the piping. Typical borehole depths are 20-200 meters, with operational temperatures in the range of 20-90oC and an efficiency of approximately 40-90% [19–21]. Because the specific heat capacity of soil is low, large storage volumes are needed. It is important to minimize the surface area as it is directly proportional to thermal losses. Moreover, since the volume of the system is proportional to the energy storage capacity it is desired to maximize the volume while minimizing the surface area within the constraints of the geographic and geotechnical features of the site in order to find an optimal volume to area ratio [21]. One of the largest systems in Neckarsulm, Germany has a storage volume of 63,360m3, with 538 boreholes [16]. Sibbitt investigated the performance of a solar seasonal energy storage system in Alberta, Canada. This system utilized seasonal borehole thermal energy storage to provide space heating for 52 homes through a district-heating network. The system was designed to provide 90% of the spacing heating requirements. In this study, Sibbitt compared the actual performance and operation over 5 years against a TRNSYS model of the system. The outcome of this study found that the system was able to reach its design target of 90% (space heating load) over the 5 years of operation. Additionally, TRNSYS accurately predicted the performance of the BTES system. The actual efficiency of the BTES system after 5 years of operation was realized at 36% [19].

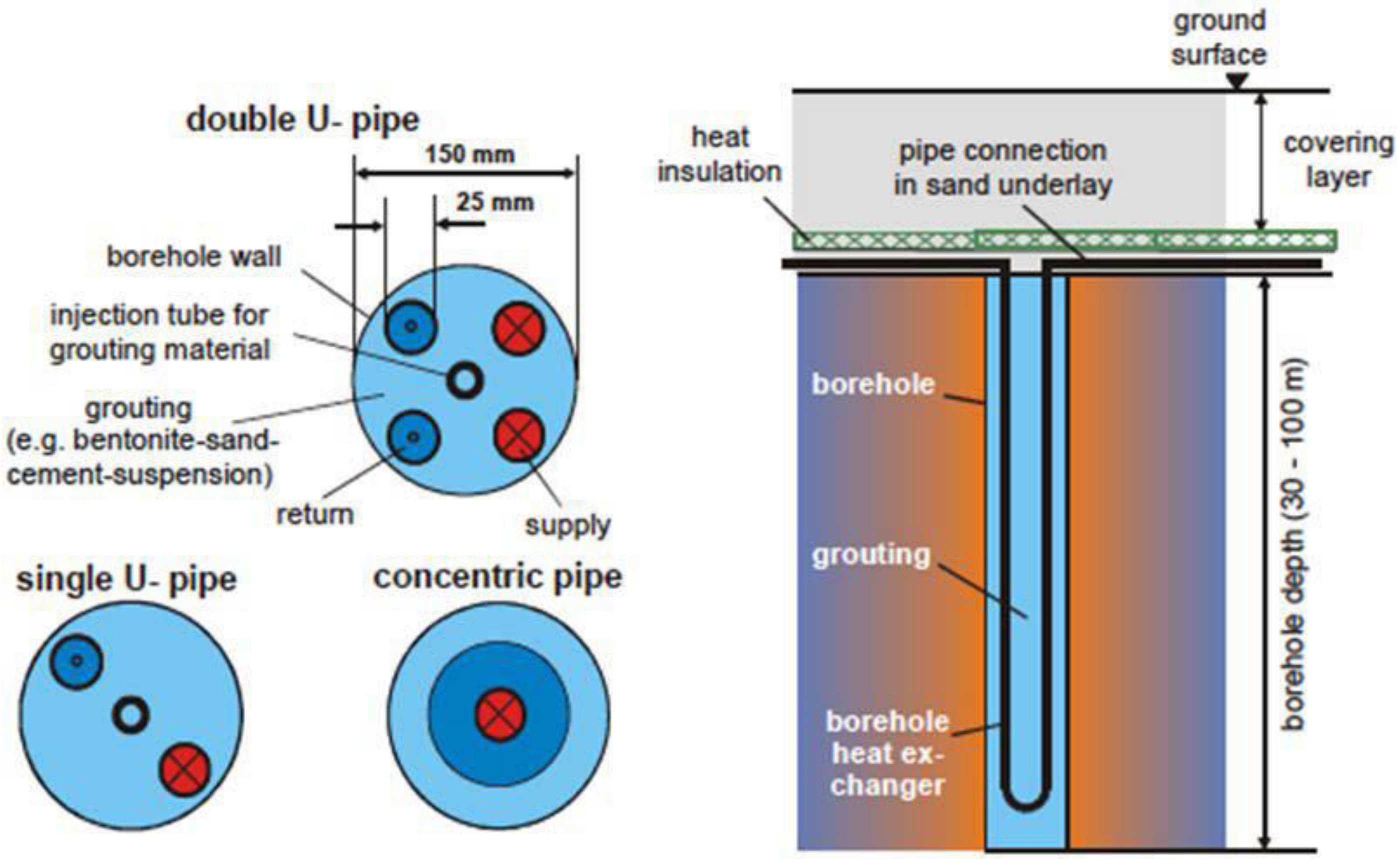

Figure 4 Types of borehole heat exchangers [14]

4.4 Aquifer Thermal Energy Storage

Aquifer thermal energy storage (ATES) systems store heat in ground water aquifers. Information about the aquifer must be known before this application of TES is to be considered, as water is typically drawn from one well and discharged into another. Thus, a drawdown test must be performed to ensure the well is able to replenish itself at the same rate or faster than it is extracted. The typical operating temperature for this system is in the range of 5-90oC, with efficiencies up to approximately 87% [3,15,16,22]. These systems are often coupled with heat pumps and used for summertime cooling [15]. However, in Rostock, DE there is an ATES system that is used for space heating, cooling and preheating hot water. This system is charged with solar thermal collectors and utilizes a heat pump [16].

Figure 5 ATES system [16]

5. Phase Change Material Thermal Energy Storage

The German Aerospace Center (DLR) built a promising phase change material (PCM) latent storage prototype using sodium nitraite (NaNO3) as the storage medium. This system is the world's largest high temperature PCM storage module, at 700kWh, with 14 tons of NaNO3 and a melting temperature of 306oC [24]. The storage efficiency for this type of system can be upwards of 91% [25]. This system is pictured in figure 6 below.

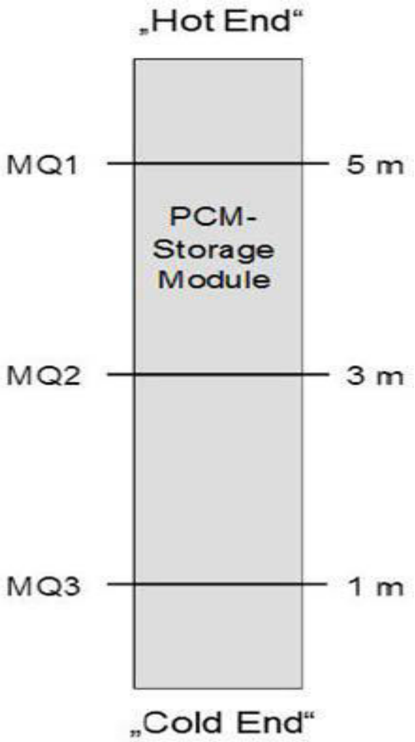

Figure 6: 700kWh PCM storage module [24]

Laing studied the use of nitrate salts for high temperature latent thermal energy storage applications. With 4,000 hrs of testing and 172 cycles (with no degradation) the designed heat transfer rate was achieved. The most economically promising option was a sandwich concept utilizing fins of graphite or aluminum. A latent heat capacity of 93kWh/m3 at an estimated cost of $9.5/kWh and a melting temperature of 305oC was achieved using NaNO3 (sodium nitrate). Laing later demonstrated and tested a 700kWh (14 tons of NaNO3) phase change material (PCM) module that was able of achieving high discharge/charge rates of 350 kW [25]. Newmarker evaluated the performance of a 100kWh prototype heat exchanger for PCM thermal energy storage. Using commercially available heat exchanger materials, Newmarker developed a unique PCM storage module. This prototype used an agitation mechanism to improve heat transfer during the discharge process. TRNSYS was used to model the performance of this system, with a calculated round trip efficiency upwards of 93%. The purpose of this project was to design and validate a PCM storage system at a prototype level. In order to demonstrate at an industrial scale (800MWh), a PCM storage module with an efficiency of over 93%. The prototype system did not perform as well as the model predicted nor did the final cost align with the goals set by the DOE. With 56% of the costs attributed to the phase change material and 27% of the cost for the heat exchanger surface. Though the tested performance and estimated cost did not meet DOE goals in the early stages of its development, with a multiyear RD&D plan it is believed that costs and performance goals can be met [26].

6. Objective of Research

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 data for 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:

- Utilize current CHP operating data to asses a proposed operation with TES
- Design & model the performance of a TES system in TRNSYS
- Asses the economic and environmental benefits of TES to CHP

- Investigate system cost and payback

7. Combustion Gas Turbine (CGT) Hourly Profile

In 2011 the CGT was in operation for 7,787 hours and the average power generated was 8,795 kW. Figure 2.2 shows the power production by the CGT during this period.

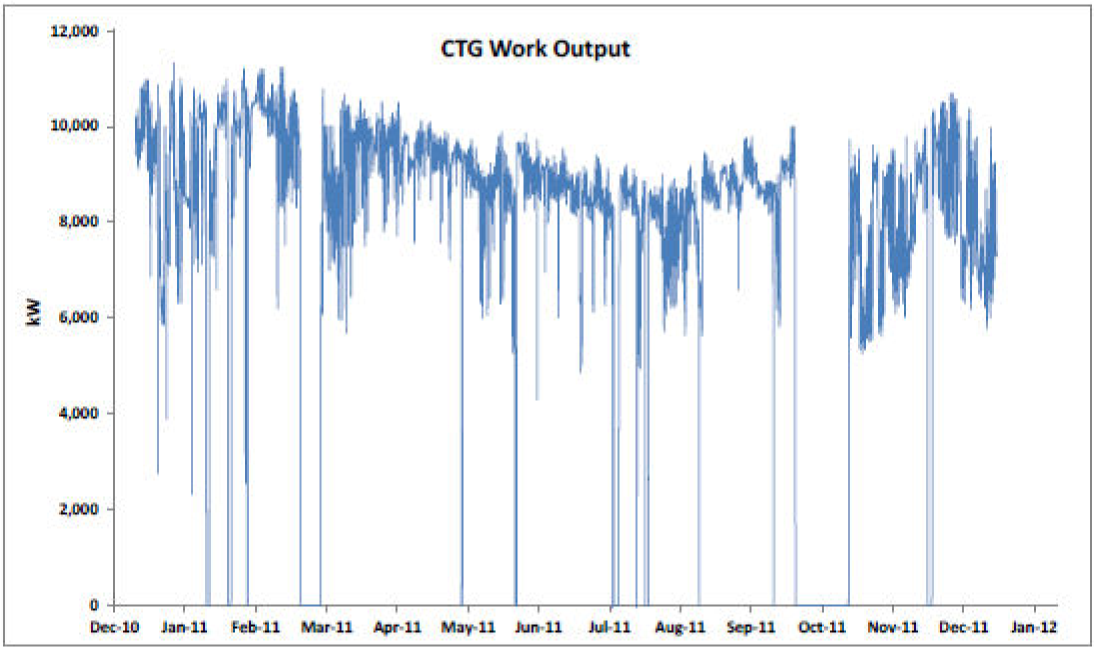

Figure 7 Hourly power produced by the CTG

8. Heat Recovery Steam Generator (HRSG) Hourly Profile

The HRSG was in operation for 6,469 hours with supplementary firing and 1,318 hours by purely utilizing exhaust gases from the CGT. On average the product mass flow to the HRSG from the CGT is approximately 43.11 kg/s. Figure 8 shows the steam production by the HRSG during this period.

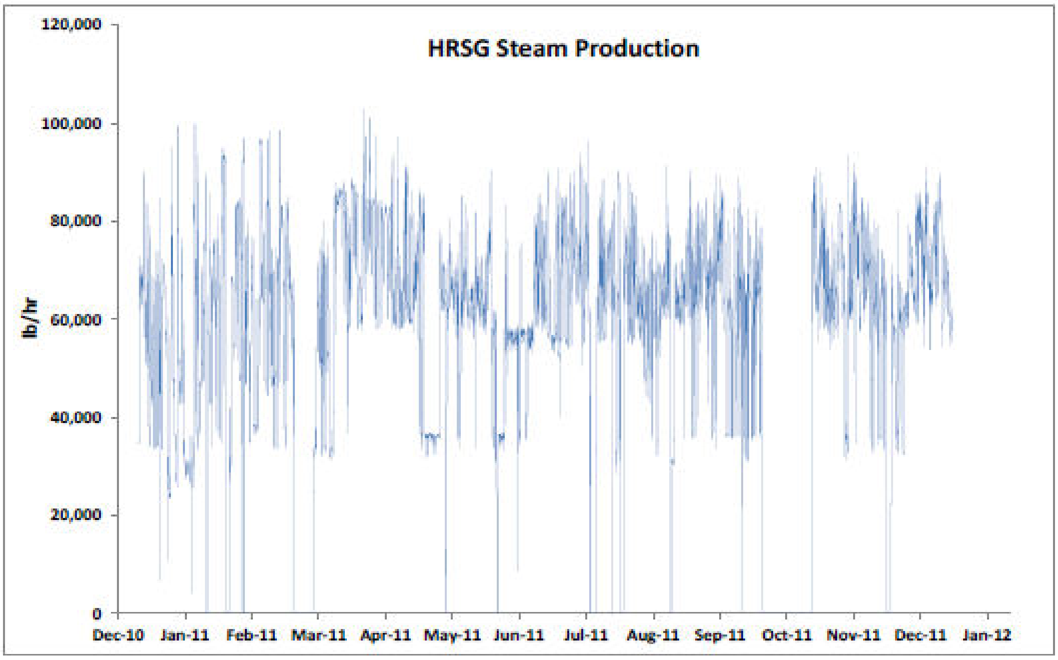

Figure 8 Hourly steam produced by the HRSG

9. TRNSYS Multiple Simulations

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 <90oC, 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 90oC, 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 time steps in order to attain steady state performance. Depending on the number of boreholes each five year simulation runs for approximately 10-30 minutes.

10. Selection of TRNSYS Simulation Range

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 90oC 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 40oC to be effective [31]. Conversely, for system sizes larger than this range, it was found that the minimum ground temperature fell below 40oC, as the increased 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 temperatures within this range never fell below 40oC.

11. 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 72oC and 42oC, respectively. Conversely, with 12,250 boreholes the maximum and minimum storage temperatures reached are 68oC and 40oC, respectively. A higher ground temperature is preferable as it reduces the need for auxiliary heating at the low temperature campus load.

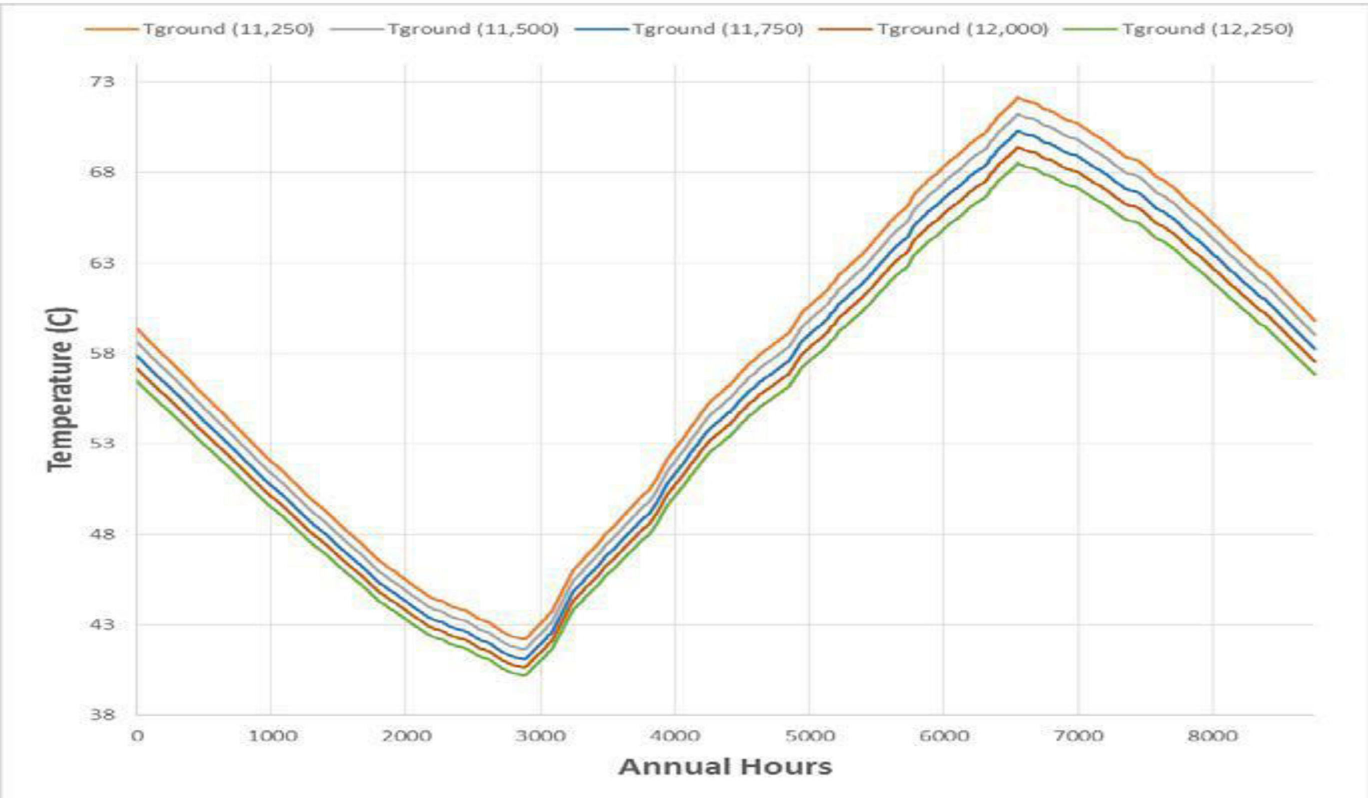

Figure 9 Comparisons of Ground Temperatures

12. CONCLUSION

The scope of this research was to assess the benefits of a seasonal BTES system for a CHP plant. Benefits were realized by mitigating the high cost of fuel in the winter months by charging the TES system when fossil fuel costs are low. Using data from the campus CHP plant and district heating system, a BTES system model was designed using TRNSYS. This simulation was performed over a five year period in order to observe the system performance at steady state operation. The simulation showed that the BTES system could achieve an efficiency of 88% with an offset to campus heating energy of approximately 36,700 MWh. Furthermore, an additional 8,513 MWh of electricity could be produced due to the increased thermal load in the summer months. A summary of two cases was presented, where offsetting ULSD was compared to offsetting LNG. It was determined that offsetting ULSD is preferable as it allows for higher cost savings and emissions reductions. The results for offsetting ULSD indicate that the proposed BTES system achieved an annual cost savings of $2,430,343 for an 8% reduction in total campus utilities. In additional to the economic benefits, a reduction of 836,700 kg of CO2 and 4,790 kg of SO2 was also realized through this application of TES. Conversely, offsetting LNG with the thermal energy stored enabled an annual cost savings of $2,059,187 for a 6.8% reduction in total campus utilities. In all, the application of TES to CHP proves to be economically and environmentally promising as it enables greater flexibility in CHP operation. This added flexibility allows for strategic operation of the plant, where additional thermal energy can be produced at economically advantageous times in order to hedge against seasonal variations in fossil fuel rates.

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