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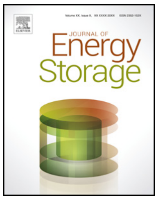

Modeling of combined heat and power plant performance with seasonal thermal energy storage

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ABSTRACT

The objective of this paper is to show the economic and environmental benefits that can be attained through the coupling of seasonal thermal energy storage (TES) and combined heat and power (CHP). Operational data from the UMass CHP district heating system was utilized to validate these benefits. 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 borehole thermal energy storage (BTES) system that is designed using operational data from the campus CHP plant. The TRNSYS model predicts that a BTES efficiency of 90% 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.

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, as current greenhouse gas emissions within the atmosphere have reached troubling concentrations [2]. 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 can greatly increase the efficiency of a system when compared to centralized electricity production and independent heat generation [3,4]. The overall energy efficiency of a power producing system can be increased from 35 to 55% to more than 80% 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]. The coupling of CHP and DE increases the overall system efficiency, when compared to centralized power production. However, there are still economic and environmental shortcomings due to the operational limitations of CHP systems and the seasonal variation in fossil fuel availability. That is to say, electricity production is limited by the thermal load and peak periods in the demand for energy often do not align with supply. These constraints lead to inflated energy rates and short supplies during periods of high demand. One promising method to mitigate this discrepancy between the supply and demand for energy and to

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Nomenclature

AC	Air compressor
ACI_{NG}	Annual NG cost increase
ACR_{Elec}	Annual electric cost reduction
ACR_{LNG}	Annual LNG cost reduction
ACR_{ULSD}	Annual ULSD cost reduction
ACS	Annual cost savings
APR	Annual pollutant reduction
BTES	Borehole thermal energy storage
CC	Combustion chamber
CGT	Combustion gas turbine
CHP	Combined heat & power
CO_2	Carbon dioxide
CST	Condensate storage tank
DA	Deaerator
DE	District energy
GT	Gas turbine
HHV	Higher heating value
HPB	High pressure boiler
HPST	High pressure steam turbine
HRSG	Heat recovery steam generator
LNG	Liquefied natural gas
LPB	Low pressure boiler
LPST	Low pressure steam turbine
NG	Natural gas
NO_X	Nitrogen oxides
P_{Charge}	BTES charge pump energy usage
$P_{Discharge}$	BTES discharge pump energy usage
PEX	Cross-linked polyethylene tubing
P_{HPST}	Additional power produced by the HPST due to TES
P_{LPST}	Additional power produced by the LPST due to TES
P_{total}	Total energy produced by the plant
$Q_{Boiler,Gas}$	Boiler fuel input, gas
$Q_{Boiler,Oil}$	Boiler fuel input, oil
$Q_{BTES\ Losses}$	Thermal energy storage system losses
$Q_{Cond.\ Return}$	Condensate return energy
$Q_{Excess,HRSG}$	Excess energy produced due to the increased capacity of the heat recovery steam generator during charging period
$Q_{fuel,in}$	Fuel input to the CHP plant
$Q_{in,BTES}$	Energy delivered to the thermal energy storage system
Q_{Load}	Energy delivered to the load
SCR	Selective catalytic reduction
SO_2	Sulfur dioxide
$T_{avgerage}$	Average BTES ground temperature
TES	Thermal energy storage
T_{max}	Maximum BTES ground temperature
T_{min}	Minimum BTES ground temperature
ULSD	Ultra low sulfur diesel
UMass	University of Massachusetts

Greek symbols

ΔP	Additional power produced by the HPST & LPST
$\Delta Q_{fuel,in}$	Additional fuel input to the CHP plant for TES charging
ΔQ_s	Total thermal energy gain of steam delivered to the campus
$\eta_{Boiler,Gas}$	Average boiler efficiency when using gas; 82.6%
$\eta_{Boiler,Oil}$	Average boiler efficiency when using oil; 83.4%
η_{BTES}	Borehole thermal energy storage efficiency
η_{CHP}	Combined heat and power plant efficiency

increase the electrical generation capacity of the CHP system is through the application of thermal energy storage.

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 and Rosen have 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 diurnally, seasonally or both and is aimed at shifting the purchase of energy to low-cost periods. Higher efficiencies are realized for CHP systems when they operate at full load with constant demand [9]; this is rarely attainable, 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 thermal demand 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. The application of an optimal TES system can allow the CHP plant to extend its operating hours and generation capacity, leading to increased energy savings and reduced emissions [10].

The results from the aforementioned literature have provided validation for the following research into the modeling of a seasonal TES system for a CHP plant. It is worth noting that there is limited research using actual CHP plant data to model a seasonal TES system of this scale. What makes this study unique is that a seasonal TES system was used to optimize CHP system economic performance and reduce total annual emissions.

2. TES-CHP case study

2.1. Assessment of current CHP system operation

The University of Massachusetts's CHP plant has been in operation since 2009 and currently produces approximately 75% of the campus's electric power and 100% of its steam load, representing over 200 campus buildings. Electrical power is produced by a 10 MW combustion gas turbine (CGT), a 2 MW high-pressure steam turbine (HPST) and a 4 MW low-pressure steam turbine (LPST). Steam is produced by a heat recovery steam generator (HRSG), capable of producing 5 kg/s (40,000 pph) (unfired) using exhaust heat from the CGT and up to 12.6 kg/s (100,000 pph) by firing its duct burners. Additionally, steam is produced by a high-pressure boiler (HPB) and two low-pressure boilers (LPB), each capable of producing 15.7 kg/s (125,000 pph). The boilers are used in the fall, winter and spring months to help provide additional steam capacity to meet the campus load. The CGT, HRSG, HPB and LPBs can all operate on natural gas or ULSD. Natural gas is utilized throughout the year, although limited supplies in the heating season necessitate supplementing the fuel requirements of the plant with ULSD and LNG.

The seasonal shortage of natural gas in the winter months is primarily due to the limited capacity of natural gas pipelines in the Northeast. The percentage of natural gas fired generation has increased from 15% in 2000 to approximately 50% in 2013, as older coal, oil and nuclear plants are retired or are set to be retired. Additionally, the region's considerable dependence on natural gas for heating further constricts the already short supply of natural gas. Efforts for expansion have been largely impeded due to environmental concerns and aspirations to advance sustainable energy generation [11].

The UMass CHP plant has a SCADA system, which is capable of storing and transmitting instantaneous data about the plant's