ASTFE
American Society
of Thermal and Fluids Engineers

7th Thermal and Fluids Engineering Conference (TFEC)
May, 16-18, 2022
Partially Online Virtual and in Las Vegas, NV Conference

TFEC-2022-41027

EFFECT OF UNDELIVERED ENERGY AND DYNAMIC DEMAND ON OVERALL DISTRICT ENERGY SYSTEM EFFICIENCY

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ABSTRACT

With the discussion of alternative energies on the rise due to climate change – existing energy utilities may be hesitant to change, due to the immense cost to and lack of experience in this new realm to retrofit. Yet, these existing industries can participate in the conversation by increasing their efficiencies and reallocating their resources to reduce the consumption of fossil fuels to their furthest potential. It has been increasingly recognized that the recovery of wasted energy is the creation of new energy. Therefore, regardless it is traditional energy source or alternative energies, the need to achieve their highest level of efficiencies is fundamentally critical to make the energy industry "greener." This study examines a case study through field data on how the undelivered energy in a moderate- to high-pressure steam and chilled water generation plant can be recovered using data-driven analysis, thus improving the overall efficiency of a district energy system. The research ultimately aims to develop an intelligent feedback control system that potentially transfers the benefit of energy efficiency measures to the stakeholders of the system, including energy producers, end users and infrastructure investors.

KEY WORDS: Energy Efficiency, CHP

1. INTRODUCTION

A District Energy (DE) boiler/chiller plant typically contains a significant amount of equipment options in order to better optimize efficiencies at different conditions. Fig. 1 show an example boiler/chiller plant equipment diagram. Recent studies include increasing adoption of renewable energy production in the portfolios of DE systems [1]. Still, dominant energy sources for DE systems are still natural gas for steam production. The steam generated in the boiler can be routed to many different loads: a) provide steam to the main supply send-outs, b) drive a centrifugal chiller via a steam turbine, and c) a steam turbine generator.

This study focuses on community-based DE systems, as these are typical for municipal systems or even campuses of buildings with multiple billed tenants. In these community-based systems, each customer typically has control over the amount of steam (or hot water) and chilled water (CHW) which is consumed at the site. Condensate meters and flowmeters record the amount of energy used, and the customer is billed accordingly. The large array of equipment and stakeholders in these community-based DE systems create an extremely difficult optimization problem for energy efficiency or resilience. The

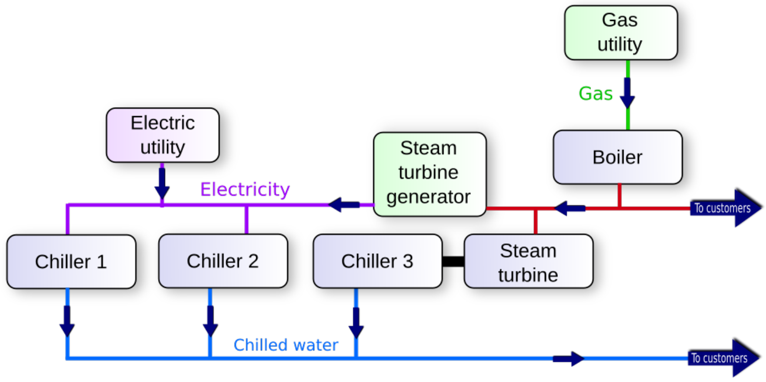

Fig. 1 Example DE plant equipment system

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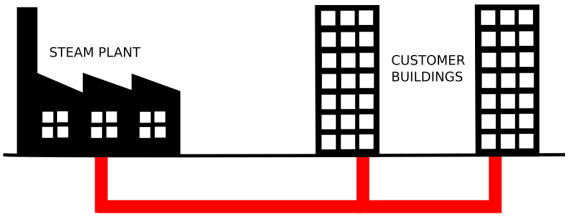
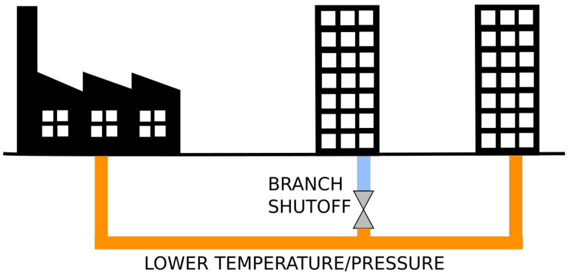
*Corresponding Author: y.tao19@csuohio.edu combination of the potential for rapidly changing demand and conditions, with a lack of real-time communication between the utility and customer ultimately limits the capabilities of the system.



NORMAL HEAT DEMAND



REDUCED ANTICIPATED HEAT DEMAND

Fig. 2 DE setback options

The above-identified problem offers an opportunity of energy saving if the areas of improvement for the overall system energy efficiency can be identified in conjunction with the normal billing cycles. Energy usage of a DE system can generally be split into "delivered" and "undelivered" energy. Steam or CHW which is successfully sent to a customer and subsequently utilized is considered delivered. Any remaining energy lost by the system due to a variety of reasons such as equipment inefficiencies, leaks, or heat loss during transmission, can be considered undelivered. The cost of this undelivered loss is borne by the utility, and wasted greenhouse gases (GHG) are generated.

While the ultimate goal is to provide the system optimization and control technology for improving the overall system efficiency and reducing various losses including both the delivered and undelivered energy losses, this study lays down an analytical framework that enables both physics-based and data-driven modelling techniques and can be applied to the practical sensing and control system for improving the DE system operation.

2. ANALYSIS AND PRELIMINARY RESULTS

In this study, the system analysis is limited to a simplified system model consisting of following three elements:

1. DE Plant with back-pressure turbines for electricity or chilled water.
2. Distribution lines (steam or chilled water lines) to one of the N customers in parallel (customer A)
3. One of the M number of customer A's buildings in parallel.

2.1 System Performance. A sample DE plant (based on a real case) illustrated in Fig. 1 consists both boilers for steam generation and chillers for chilled water generation. The location of the system is in midwestern region of United States with 5,618 annual heating degree days (HDD) and 1,284 cooling degree days (CDD). The energy source is natural gas for boilers and electricity for the chillers. To improve the system efficiency, the plant can adopt combined heat and power (CHP) system technology so that part of steam can be used to generate electricity through a turbine, and generate chilled water through a steam-drive chiller. The CHP will result in an increase in overall energy generation system efficiency. Table 1 shows the specification of sample energy profile, and the data is extracted from a case study.

Table 1 Sample Energy System Specification

Category	Steam	Chilled Water	Turbine
Capacity	350,000 lbs/hr (106.67 MW)	12,000 Tons	1 MW

Energy generation. Table 2 lists an annual energy profile of the sample DE system. The boilers generates steam that carries 77% of total energy production. Chilled water production occupies about 22% of energy including 3% steam energy used in an additional steam-turbine driven chiller. About 4 MWh (1%) of annual energy is produced by a steam turbine for the plant electricity use.

Overall system efficiency. If we only consider the energy production of steam, cooling and

Table 2 Analysis of the Sample DE System Performance

Energy Category	*Energy Production*		*Energy Source*		*Generation System Efficiency*	*Post-Generation Energy Losses*	*Total DE System Efficiency*
	Annual MWH	%	Annual MWH	%		Annual MWH	
Steam Sendout	246.6	77%					
Electric Chiller Ton-hrs*	59.7	19%					
Chiller Steam Use	9.2	3%					
Turbines Output	4.0	1%					
Electricity			12.4	3%			
Natural Gas			358.3	97%			
Distribution Losses (12% of steam sendout assumed)						8.52	
Customer building system losses (5% of sold steam assumed)						358.33	
Subtotal	319.5	100%	370.8	100%	86%		78%

**MWH in chiller ton-hrs include the cooling energy produced by electricity-driven refrigeration equipment. Chill-water loss is neglected.*

electricity, the overall system efficiency is estimated as 86% with the example data, using the following definition:

$$\eta_p = \frac{Q_{st,s} + Q_{st,CW} + Q_{CW} + E_{e,t}}{E_{NG} + E_e} \qquad (1)$$

We also estimate that 12% of the energy may be lost due to the piping of distribution system from the energy plant to the customer building [2], and additional 5% loss from the building systems of the end users (customers). Therefore, the modified overall system efficiency may be estimated as follows,

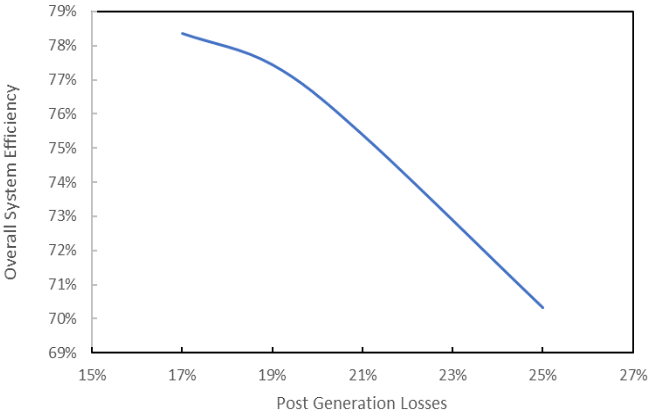


Fig. 3 Overall DE system efficiency as a function of assumed post-generation steam loss (include percentage of steam sendout as the distribution loss and percentage of steam sold as the customer building system loss. Chill-water distribution loss is neglected.)

$$\eta_{sys} = \frac{(1 - f_d - f_b)(Q_{st,so} + Q_{steam,\,CW}) + Q_{CW} + E_{e,t}}{E_{NG} + E_e} \qquad (2)$$

where,

$$f_d = \frac{m_{st}\, h_{st} - m_{so}\, h_{so} - \Sigma\, [mg\,(\Delta\, p/\rho + \Delta\, V^2/2)]}{m_{st}\, h_{st}} \qquad (3)$$

$$f_d = \frac{m_{so} - m_b}{m_{so}} \qquad (4)$$

In this case, the modified efficiency now becomes 78% (Table 2). Fig. 3 shows that if the post-generation losses increases from 17% to 25% as [2] discussed, the overall system energy efficiency could be further reduced from 78% to 70%, a significant 8% reduction. Further study will be conducted to quantify this effect more accurately.

Building energy demand. One of the uncertainties in seeking the potential improvement opportunities is the dynamic load profile that reflects the customer energy demands.

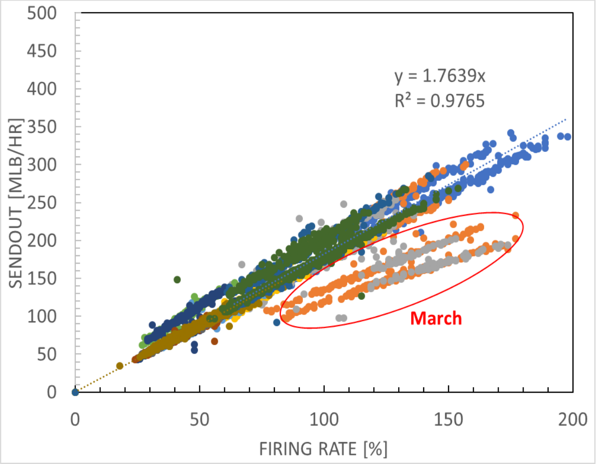
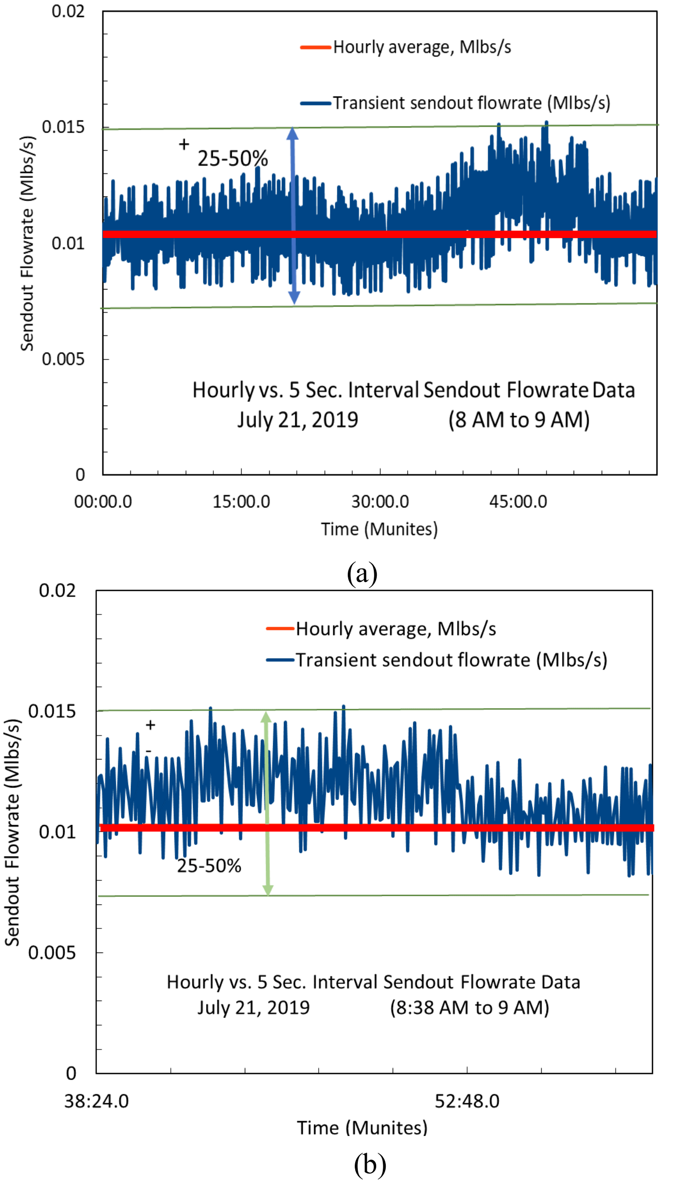


Fig. 5 Correlation between the sendout and firing rate

Fig 4. shows a one-hour variation of steam sendout rate taken for every 5 seconds for a hot day in July, 2019. As it can be seen that the transient steam sendout rates can have a deviation from the hourly averaged rate up to 25% to 50%. An analysis of annual data of steam sendout rate plotted against the boiler firing rate (Fig. 5) indicates that there are significant set of data in March with the high firing rates actually correspond to low steam sendout rates. This may indicate potential opportunities to diagnose the source of energy waste and improve the overall system efficiency. The observation can be made for the monthly sold steam data as compared with the steam sendout data in Fig. 6. There are significant energy losses (almost four times) in the month of July when the demand is low. Further studies are on the way to develop sensing methodology to capture the detailed information accurately.



(a)

(b)

Fig. 4 Sample transient boiler sendout rate (every five second): (a) from 8-9 am; (b) 8:38- 9 am

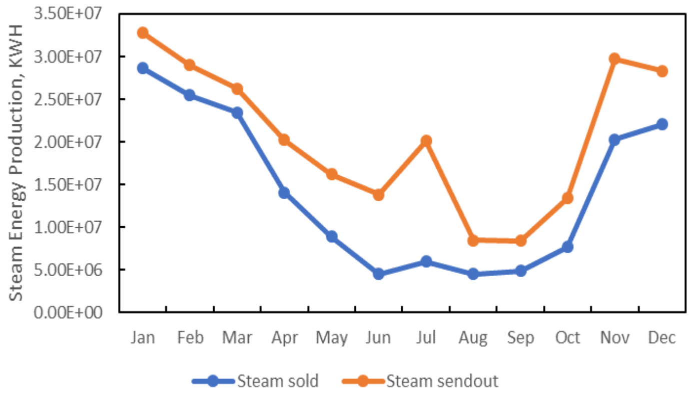


Fig. 6 Example district energy system performance: Monthly steam sendout vs steam sold

System Energy Loss. One of the challenges is the identification of wasted energy, which can come from several sources, including distribution loss from both long-distance piping energy loss and the aging piping leak. From Fig. 6, the ratio of monthly steam sold to steam sendout is plotted in Fig. 7. It can be seen that for during the summer the ratio can be as low as about 0.3. This means that only 30% of the steam supplied are actually used by the customers, which is much lower than the predicted system efficiency based on the thermodynamics. Therefore, there are opportunities in the system operation and control to reduce the waste of steam thermal energy during the low-demand season in the absence of noticeable leak loss. Further analysis is needed to deploy sensing strategy to capture the details of the loss.

3. SUMMARY AND FUTURE WORK

The above discussions provide preliminary analysis of energy efficiency improvement potential at a system-level, district energy system. Modeling work, based on the thermal energy balance, and field data acquisition are in progress to develop a sensor and data acquisition system that can provide a cost-effective feedback for an intelligent control system. Future work includes building HVAC and total energy load analysis, integrated energy production, distribution and end-user system modeling.

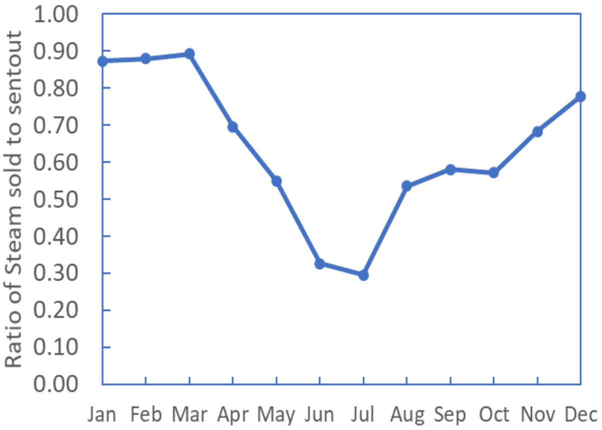


Fig. 7 Ratio of monthly steam sold to steam sendout

ACKNOWLEDGMENT

The research project team wishes to acknowledge the US Department of Energy, Office of Energy Efficiency and Renewable Energy, for the support to the study through the award No. DE-EE0009143. The support from Cleveland State University Foundation and assistance from Christopher Dodge for data processing are also deeply appreciated.

NOMENCLATURE

E	energy	(kJ)
f	loss coefficient	(-)
h	enthalpy	(kJ/kg)
m	mass flow rate	(kg/s)
p	pressure	(Pa)
Q	heat	(kJ)
η	efficiency	(-)

Subscript

b	building
CW	chilled water
d	distribution system
e	electricity
l	loss
p	plant
s	sendout
so	sold
st	steam
sys	system
NG	natural gas

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