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Customer-side electricity load management for sustainable manufacturing systems utilizing combined heat and power generation system

Zeyi Sun, Lin Li*, Andres Bego, Fadwa Dababneh

Department of Mechanical and Industrial Engineering University of Illinois at Chicago, 842 W. Taylor Street, Chicago, IL 60607, USA

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ABSTRACT

Customer-side electricity load management can effectively improve the reliability of electricity grid and reduce the cost of electricity for customers. Combined heat and power (CHP) generation systems have been considered a promising method to implement electricity load management and have been widely applied in commercial and residential building sectors. Recently, the benefit of CHP application in electricity load management in industrial sector has also been gradually recognized. On-site generated electricity by a CHP system can be utilized to support the operation of industrial equipment and thus the cost of electricity purchased from the grid can be reduced. In this paper, we focus on the utilization of CHP in electricity load management for industrial manufacturing systems to examine the benefits regarding cost savings for the manufacturers. The optimal schedule for both the manufacturing and the CHP systems under a Time-of-Use (TOU) electricity tariff can be identified by minimizing the electricity billing cost and CHP operation cost under the constraint of production throughput. Mixed-Integer Nonlinear Programming (MINLP) formulation is developed to model this scheduling problem mathematically. Particle Swarm Optimization (PSO) is used to find a near optimal solution for the problem with a reasonable computational cost. A numerical case study is used to illustrate the effectiveness of the proposed method.

1. Introduction

The electricity demand in the U.S. is expected to keep growing in the next several decades (EIA, 2006). The total demand of the country is estimated to increase by 45% by 2030 (EIA, 2006). To satisfy this increasing demand, additional capacity for electricity generation, transmission, and distribution needs to be created, which involves about $300 billion in investments (Edison Electric Institute, 2006).

In addition to capacity creation, a method that better utilizes the existing infrastructure of electricity grid has also been considered. It involves endeavors from both electricity suppliers and customers. For suppliers, the topic mainly focuses on optimal electricity tariff design (Yousefi et al., 2011; Faria and Vale, 2011), future demand forecast (De Felice et al., 2013; Tanrisever et al., 2013), and options of renewable energy (Serrano Gonzalez et al., 2013; Byon and Ding, 2010). For customers, electricity load management has drawn wide attention from both academia and industry. It encourages electricity customers to actively alter their regular consumption patterns to respond to the variable electricity price at different periods. The benefits of effective electricity load management are two-folded. On one hand, it can help customers curtail their electricity cost by strategically adjusting their consumption modes. On the other hand, it can relieve the unbalanced situation between electricity demand and supply to improve grid reliability and thus the investment for the construction of new peaking power plants, that are especially run for the extremely peak periods that only occur a few hundred hours per year (Ahn et al., 2011), can be reduced.

Combined heat and power (CHP) generation has been considered a promising on-site generation method that can facilitate customer-side electricity load management. The on-site electricity generated by the CHP system can be utilized to support electrical appliances to cut down the electricity purchased from the grid and thus the electricity billing cost for the customers can be reduced. With CHP, electricity and heat can be produced simultaneously from a single fuel source such as natural gas, biomass, biogas, coal, waste heat, or oil (EPA, 2013a). Compared to traditionally purchased electricity and on-site generated heat, high efficiency and less Greenhouse Gas (GHG) emission are two main benefits that can be offered by CHP (EPA, 2013b, 2014). It can capture and utilize

* Corresponding author. Tel.: +1 312 996 3045; fax: +1 312 413 0447.
E-mail addresses: zsun25@uic.edu (Z. Sun), linli@uic.edu (L. Li), abego2@uic.edu (A. Bego), fdabab2@uic.edu (F. Dababneh).

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the heat that would otherwise be wasted from the production of electricity and thus less fuel is needed than equivalent separated heat and power systems to produce the same amount of energy (EPA, 2013b). Figs. 1 and 2 illustrate the improvement of energy efficiency (EPA, 2014) and the reduction of CO_2 emissions (EPA, 2013b) compared with separated heat and power generation systems, respectively.

Much research focusing on the utilization of CHP systems to implement effective electricity load management in commercial and residential building sectors has been reported. For example, Zogg et al. (2005) introduced the applications of CHP and its electricity load reduction and energy saving potential in commercial buildings. Houwing et al. (2011) proposed an electricity load management method using micro-CHP system with a Model Predictive Control strategy integrated with price-based electricity tariff for residential buildings. Smith et al. (2012) investigated the benefits regarding electricity load reduction, cost saving, and GHG emission reduction by the CHP in eight different commercial building types located in Chicago considering hourly based electricity and thermal loads management. Sossan et al. (2014) developed a Model Predictive Control strategy to integrate CHP in the context of electricity load management for smart buildings.

In the industrial sector, a few studies on CHP utilization towards sustainability have also been implemented. For example, Blok and Turkenburg (1994) investigated the CO_2 emission reduction by means of industrial CHP in Netherlands. Danon et al. (2012)

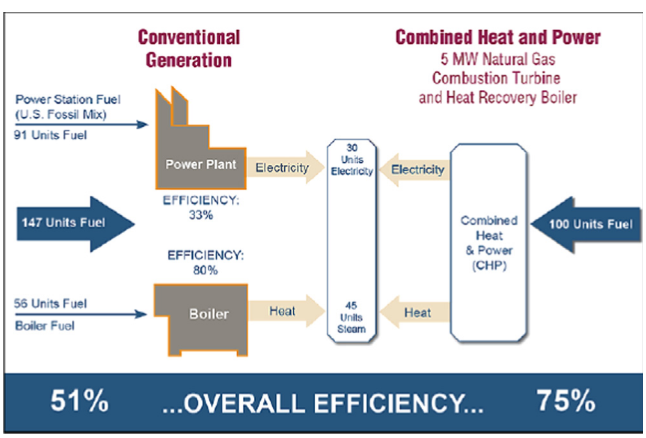

Fig. 1. Energy efficiency comparison between CHP system and separated heat and power generation systems.
(source: http://www.epa.gov/chp/documents/catalog_chptech_full.pdf)

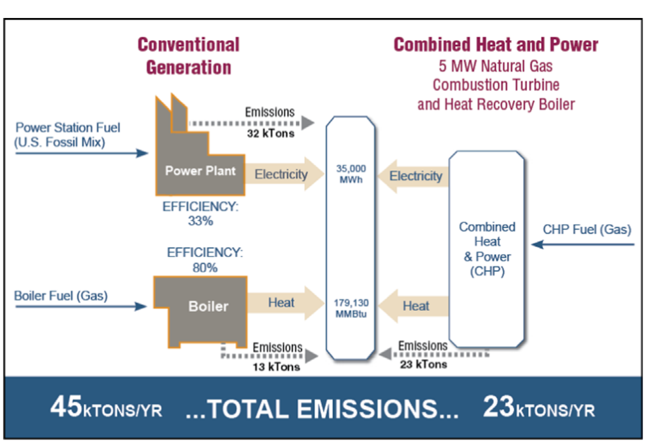

Fig. 2. CO_2 emission comparison between CHP system and separated heat and power generation systems.
(source: http://www.epa.gov/chp/basic/environmental.html)

studied the possibilities of the implementation of CHP in the wood industry in Serbia. Anderson and Toffolo (2013) investigated the energy efficiency improvement for sawmill industrial sites integrated with CHP system.

It can be seen that the research on CHP applications for industrial systems mainly focuses on the benefit investigation from the perspective of GHG emission reduction and energy efficiency improvement. However, the detailed methods of CHP application in electricity load management for industrial systems has received less attention compared with much existing literature using scheduling methods to implement electricity load management for industrial users (Sun et al., 2014; Wang and Li, 2013; Wang and Li, 2014). Very few studies consider the utilization of CHP to facilitate load management to reduce the cost for manufacturers. In this paper, we focus on the application of CHP in electricity load management for typical manufacturing systems with multiple stations and buffers. The potential benefits regarding cost savings for manufacturers are examined. The objective is to identify a schedule for both the manufacturing system and the CHP system under a Time-of-Use (TOU) electricity tariff by minimizing the electricity billing cost and CHP operation cost under the constraint of production throughput. A Mixed-Integer Nonlinear Programming (MINLP) formulation is developed to model this scheduling problem mathematically. Particle Swarm Optimization (PSO) is used to find a near optimal solution for the problem with a reasonable computational cost. A numerical case study is used to illustrate the effectiveness of the proposed method.

The rest of the paper is organized as follows. The proposed method is introduced in detail in Section 2 where problem definition, mathematical model, and solution approach are included. The numerical case study is given in Section 3. The conclusions are drawn and the future works are discussed in Section 4.

2. Proposed method

2.1. Problem definition

The objective of this research is to identify the optimal strategy of electricity load management for manufacturing systems utilizing on-site CHP. The optimal operation schedule for both manufacturing and CHP systems that can minimize the overall cost including electricity billing cost and CHP operation cost is identified under the constraint of production target, manufacturing system characteristics (i.e., buffer capacity and material flow balance), and CHP characteristics (i.e., minimum ON/OFF time and output power capacity).

2.2. Mathematical model

We will introduce the notations used in our model in this section.

Notations

ONP	the set of intervals that belong to peak periods
OFP	the set of intervals that belong to off peak periods
Ψ	the set of intervals where the decision is to turn off the CHP from ON state
Ω	the set of intervals where the decision is to start the CHP from OFF state
A	the production target (units) of the planning horizon
AB_i	the operation status of auxiliary boiler
B_{in}	the buffer contents in buffer n at the beginning of interval i
C_{CHP}	CHP operation related cost
C_E	electricity billing related cost