Energy System Flexibility in Healthcare Facilities: Ensuring Reliable Power for Intensive Care and Ancillary Services

Dr. Kenji Tanaka[1]*, Dr. Yuki Sato[1]
[1]Department of Biomedical Systems Engineering, University of Tokyo Hospital, Tokyo, Japan

ABSTRACT

CHP plants have the ability to provide ancillary services and therefore contribute to the improvement of flexibility and reliability of the power system. This work presents a model-based approach for estimating overall revenue for participating in both energy and frequency regulation markets. The integration of the thermal energy storage can further increase the capability of CHPs in providing flexibility services. A security constrained economic dispatch with the income from frequency regulation market is proposed to determine optimal operating strategies of a CHP plant with thermal energy storage (TES). The total profit of participating in both energy and regulation markets is maximized in consideration of power and heat revenues, fuel cost, energy storage, frequency regulation capability and revenue. The benefit from providing CHP flexibility is demonstrated through simulation for a medium-sized CHP plant with TES of a Swedish energy company, highlighting its ability to merge frequency regulation capability with cost reducing objectives of traditional CHP plant supplying heat and electric energy.

Keywords: CHP plant flexibility, energy dispatch, frequency regulation, profit maximization, heat and electric power integration.

NONMENCLATURE

Abbreviations	
CHP	combine heat and power
DA	day-ahead
FG	flue gas
FRR	frequency regulation reserves
REG	regulation
TES	thermal energy storage
Parameters	
c_e	Fuel cost
h_d	heat demand
r_{DA}	price on day-ahead energy market
$r_{FR,up}$	regulation price for upward regulation
$r_{FR,dn}$	regulation price for downward regulation
Variables	
h	Enthalpy [kJ/kg]
h_{CHP}	heat generation by CHP(steam condenser)
h_{FG}	heat produced by flue gas condenser
h_{total}	total heat generation
h_{SOC}	thermal energy storage state of charge
h_{TDH}	heat to cover the demand
h_{TTESDH}	heat from TES to cover the demand
h_{TTS}	heat to TES
LHV	Low Heating value [kJ/(kgK)]
$\dot{m}$	mass flow rate [kg/s]
p_{CHP}	electricity generation from CHP
p_{DA}	electricity sold on day-ahead market
$p_{FR,up}$	regulation electricity for upward regulation
$p_{FR,dn}$	regulation electricity for downward regulation
P	Power [kW]
$\dot{Q}$	Heat Flow Rate [kW]
r_{ph}	heat production profit
η	Efficiency[%]
Subscripts	
a	air
b	boiler
ch	charge
dch	discharge
el	electricity
f	fuel
fg	flue gas
s	steam
sh	steam for heat generation
sp	steam for power generation
t	turbine
w	water

1. INTRODUCTION

The operation of integrated energy system requires the procurement and scheduling of resources over several different time scales [1-2]. Energy dispatch in day-ahead energy market secures the availability of adequate generation capacity to meet the daily load demand, while short-term power balancing services ensure the reliability of power system through continuously adjusting the power supply to compensate for the deviations between supply and demand. Traditional CHP plants have played relatively inflexible role in the electric energy market, requiring additional non-spinning or spinning reserves to achieve the power balancing operations. However, fast response of CHP plant may be able to provide ancillary services, e.g. frequency regulation reserves (FRR), to make more profit. More flexibility from CHP plant is needed for the benefits of both CHP plant and the power system including increased system reliability, reduced cost of system operation, improved market efficiency, efficient CHP plant management, and increased total CHP revenues.

Recent work towards optimal operation of CHP plant provides an important source of relevant literature. CHP modeling with integrated heat and power generation has been developed [2-3], as well as the combined model of CHP and TES for enhanced reliability and flexibility [4]. However, CHP plants are not actively involved in providing flexibility in the energy market. The primary responsibility of CHP plant is to provide reliable supply to the district heating demand by adjusting the operation modes of condensers, turbine, and the energy storage devices. The electricity production is less crucial and the market incentives are not attractive due to the low electricity prices compared to the market price of heat. Moreover, additional intricacy may be created by coupled heat-power generation. In response to frequency regulation signals, the capacity limits and efficiency of CHP equipments may be affected.

Previous work has demonstrated that significant revenue increase in both heat and electricity markets can be achieved through optimal operational control of CHP [5-9]. CHP heat-power simulation programs have been coupled with energy dispatch routines in electricity market to determine the heat and power setpoints considering varying energy trading prices in different energy and ancillary service markets. In general, formulations seek to determine a preferred operational point (i.e. baseline heat and power generation) for the whole planned period that guarantees the supply of district heating network and maximize the profits by selling energy to electricity market. In general, previous work has presented various operational control methods for CHP plant to maximize the benefits while providing reliable supply for heat demand. CHP plants are usually not active in providing flexibility, especially those equipped with back pressure steam turbines, which operation is determined by the heat demand. However such CHP still have a big potential to provide flexibility. The development of an optimal multi-market scheduling methodology for this type of CHP plant presents an electricity market oriented operation in which making more profit from electricity market becomes the main purpose. The objective of this paper is to assess the potential benefit for providing flexibility.

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For a typical CHP plant with thermal energy storage to participate in ancillary service markets it is necessary to estimate the regulation capacity and quality of service that is able to be provided. It is also necessary to develop optimal operation strategies that maximize the revenues from both energy and regulation markets with fuel cost reducing objectives. In order to estimate the regulation capacity of CHP and the benefit for multi-market optimization, this work presents: 1) a heat-power model based approach for estimating the hourly regulation capability of a CHP plants that supplies both electric and heat power networks, and 2) a security constrained economic dispatch based CHP multi-market optimization for maximizing both heat and electric power revenues in energy and regulation markets.

2. MODELING OF CHP PLANT FOR ENERGY AND REGULATION MARKETS

A multi-market optimization is developed by integrating CHP plant model to maximize the total benefit from energy and ancillary services markets. In the day-ahead energy market, a baseline operating point is given by the energy dispatch. The frequency regulation capacity is determined by the potential variation around the baseline operation point. An operational model of CHP is firstly built based on the generic installation of CHP plant in a Swedish energy company. The CHP control diagram for multi-market optimization is given in Fig. 1 and additional characteristics of CHP operation with TES are summarized in Table 1.

2.1 Description of Studied CHP Plant and Electricity Market

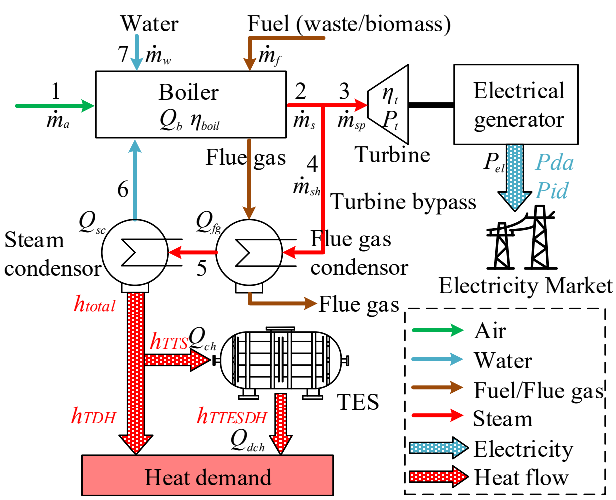

Fig. 1 Studied CHP plant in multi-market optimization.

To participate in frequency regulation markets it is necessary to satisfy the specification of manual FRR (mFRR) and submit the regulation capacity during each bid period (often hourly). Potential regulation capacity varies throughout the day as a function, for example, of heat generation and how much TES is operating in response to the heat demand changes. The regulation-up and down capacities together with energy dispatch in day-ahead market are refined within the operating range of electric power generator at any moment.

A CHP plant with TES was developed for supplying the heat demand and selling electricity. The energy flow in the gas turbine cycle with boiler, steam turbine, electrical generator and other devices are presented in Fig. 1. The energy conversion and power losses are taken into account in the heat-power energy flow written by the following equations:

$$P_t = \dot{m}_{sp} h_3 \quad (1)$$

$$P_{el} = \eta_{mec} \eta_{el} P_t \quad (2)$$

$$\dot{Q}_{fg} = \frac{\dot{m}_{sh}(h_5 - h_4)}{\eta_{fg}} \quad (3)$$

$$\dot{Q}_{sc} = \frac{\dot{m}_{sh}(h_5 - h_6)}{\eta_{sc}} \quad (4)$$

The energy balance and the charging discharging process of the TES can be expressed by:

$$\dot{Q}_{TES} = \dot{Q}_{ch} - \dot{Q}_{dch} - \dot{Q}_{loss} \quad (5)$$

$$\dot{Q}_{ch} = \dot{Q}_{CHP} \eta_{ch} \quad (6)$$

$$\dot{Q}_{dch} = \frac{\dot{Q}_{user}}{\eta_{dch}} \quad (7)$$

2.2 CHP Capability in Energy and Regulation Markets

The continuous regulating capacity of CHP for participating in day-ahead and regulation markets must be quantified with respect to a particular operating point of heat production that is determined by heat demand. Two polygon-shaped operational limits on power-heat generation are developed according to the real operation data of studied CHP plant as below:

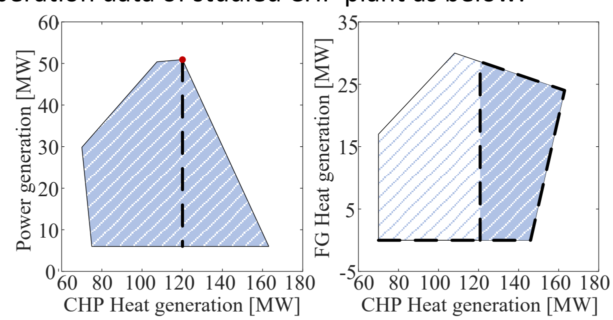

Fig. 2 Operational limits on power-heat production of CHP

$$-p_{CHP}(t) + 0.55 \cdot h_{CHP}(t) - 8.68 > 0 \quad (8)$$

$$p_{CHP}(t) - 0.041 \cdot h_{CHP}(t) - 46 < 0 \quad (9)$$

$$p_{CHP}(t) + 1.046 \cdot h_{CHP}(t) - 176.58 < 0 \quad (10)$$

$$p_{CHP}(t) + 4.8 \cdot h_{CHP}(t) - 366 > 0 \quad (11)$$

The heat produced by the interaction of flue gas and steam condenser are within the given range:

$$h_{FG}(t) - 0.342 \cdot h_{CHP}(t) + 6.947 < 0 \quad (12)$$

$$h_{FG}(t) + 0.109 \cdot h_{CHP}(t) - 41.78 < 0 \quad (13)$$

$$h_{FG}(t) - 1.412 \cdot h_{CHP}(t) + 206.1 > 0 \quad (14)$$

3. MULTI-MARKET OPTIMIZATION

A security constrained economic dispatch is integrated with frequency regulation services for optimizing the CHP plant operation in the presence of day-ahead energy prices, frequency regulation profit, and the fuel cost for heat and power generation. The overall objective function can be described as:

$$\max \sum_{t \in T} [p_{DA}(t) \cdot r_{DA} + p_{FR,up}(t) \cdot r_{FR,up} - p_{FR,dn}(t) \cdot r_{FR,dn}] + r_{ph} - FC\{p_{CHP}(t), h_{CHP}(t)\} \quad (15)$$

where $p_{FR,up}$ and $p_{FR,dn}$ are the regulation electricity for upward and downward regulation. The fuel cost of CHP plant for both heat and power generation can be expressed as:

$$FC\{p_{CHP}(t), h_{CHP}(t)\} = \sum_{t \in T}[h_{CHP}(t) + p_{CHP}(t)]c_e \quad (16)$$

where c_e is the unified energy cost for heat and power production.

The constraints mainly include the heat balance in CHP and TES, equipment capacities, and operating limits of heat-power generation as described by Eq. (8)-(14).

Table 1 Parameter settings

Parameter	Value	Unit
c_e	5	Euros/MWh
η_{ch} / η_{dch}	99%	
Δp_{CHP}	(-25,25)	MW
Δh_{total}	(-50,50)	MW
$p_{DA} / p_{FR,up} / p_{FR,dn}$	(0,51)	MW
h_{CHP}	(70,163)	MW
h_{FG}	(0,30)	MW

4. RESULTS

The parameter settings of the key devices in the studied CHP plant are summarized in Table. 1. The optimization for day-ahead market only (DA only) was firstly conducted, and then the case of multi-market optimization (DA+Reg) was performed using the regulation power as the modulation variable. According to the historical data of electricity market Nordpool [10], regulation up and down prices rarely appear in the same day. In this section, a regulation-up day is taken as an example. As shown in the first subplot of Fig. 3, regulation up and down prices together with day-ahead price taken from Nordpool website are used in the simulation.

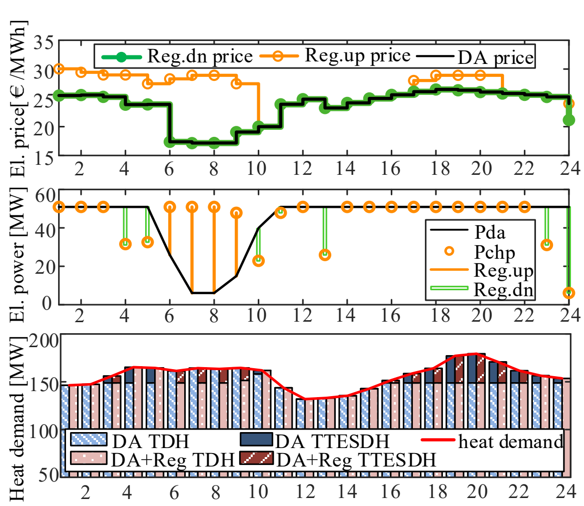

Fig. 3 Optimization with Reg.up and high heat demand

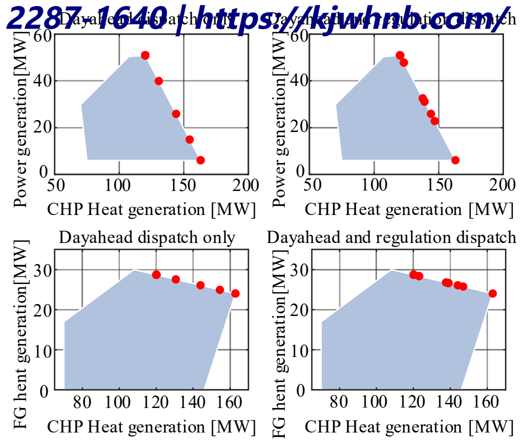

Fig. 4 Comparison of CHP operation points

Table 2 Profit breakdown [thousands EURO]

	DA	DA+Reg
Heat	215.73	215.73
Power	20.67	21.53
Total	236.40	237.26

The results for the regulation-up day with high heat demand are shown in Fig. 3. The top panel shows the highest price difference between regulation-up and day-ahead occurs from 6AM to 10AM and the only regulation-down hour appears at the last hour of the day. The three prices in the electricity market are the main incentives for regulating powers provided by CHP. In the DA+Reg case, the heat-power generation is optimized to be able to participate in regulation up during the hours of high price difference and reach lowest generation point at the hour of regulation-down price. The regulation powers of the day and the actual production of CHP are shown in the second panel of Fig. 3. The heat productions from CHP steam condenser and flue gas condenser together with the charging/discharging of TES are adjusted to firstly meet the varying heat demand over the day, as shown in the third panel of Fig. 3. TES is charged to store energy and release the energy when the regulation price is much above the day-ahead price to make sure the electricity generation at the highest possible level. The operating points of CHP tend to stick near the upper bound of heat-power generation, as shown in polygon-shaped area in Fig. 4. The regulation power at the hours of high price difference may not all be at maximum capacity due to the heat-power operating limits of CHP and the regulation capability for each individual hour is determined by the optimizer. Since the DA+Reg solution indicates greater regulating potential, the revenue generated is increased nearly by € 1000 for the day. The total revenue and profit breakdown of heat and power sections are summarized in Table 2.

It is further noted that the majority revenue comes from heat section as the market price of heat is much higher than electricity. The increasing electricity price in the future may help secure a higher profit and greater priority given to electricity production in the combined heat and power optimization of CHP.

5. CONCLUSION

This paper presented a new methodology for estimating the potential economic benefit to participate in both energy and ancillary services markets. The security constrained economic dispatch of CHP plants, considering both cost and revenues of power regulation and heat supply, can appropriately determine the revenue-generating opportunities when CHP plant performs mFRR along with the traditional operation for heat and power generation.

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