

Optimal Dispatch Strategy of Cogeneration with Thermal Energy Storage for Building Energy Management System

Kebsiri Manusilp¹ and David Banjerdpongchai², Members

ABSTRACT

This paper presents optimal dispatch strategy of cogeneration with thermal energy storage (TES) for building energy management system (BEMS). In previous research related to cogeneration as a supply system, it is observed that there is some excessive heat from cogeneration operation released to the atmosphere. In order to improve energy efficiency, we therefore incorporate TES to utilize the excessive heat from cogeneration into two objective functions, i.e., total operating cost (TOC) and total carbon dioxide emission (TCOE). In particular, we aim to minimize TOC which is referred to economic optimal operation and to minimize TCOE which is referred to environmental optimal operation. Both optimal operations are subjected to energy dispatch strategy which TES constraint is taken into account. We demonstrate the dispatch strategy with a load profile of a large shopping mall as a test system and compare the results to that of previous dispatch of cogeneration without TES. The proposed strategy of cogeneration with TES can reduce TOC of the test system up to 4.15% and 1.85% for economic and environmental optimal operations, respectively. Furthermore, TCOE can be reduced up to 5.25% and 6.25% for economic and environmental optimal operations, respectively.

Keywords: Combined Heat and Power Generation (CHP), Thermal Energy Storage, Building Energy Management System (BEMS), Energy Efficiency

1. INTRODUCTION

Energy consumption in buildings is essential for energy efficiency plan because energy consumption has been rising while energy supply is limited. Therefore, building energy management system (BEMS) has become an interesting topic which aims to obtain high efficiency of energy usage. Building's load can be normally classified in three types: electrical,

cooling, and heating loads which can receive energy from power grids. The power grid generally provides high carbon dioxide emission and cost of importing power from power grid also depends on on/off peak hours. There are many researches [1-2] seeking for technology to reduce importing power from grid and reduce operating cost and CO₂ emission from electrical generation to the building. One of important technologies normally applied with BEMS is cogeneration or combined heat and power (CHP).

CHP [3-4] is simultaneous production of heat and power which uses only a single source. Heat energy can obtain from fuel combustion in the process. Several survey articles indicate that CHP technology can provide more reliable and higher energy efficiency compared to conventional generation. Moreover, Thailand Power Development Plan (PDP2015) [5] also promotes CHP as an energy source due to its efficiency. Since the buildings such as commercial buildings or shopping malls contain coincidence of onsite cooling, heating, and electrical loads, CHP is suitable for the building supply. In research report [6], implementation of integrated model of cogeneration, solar, and conventional energy source is applied to energy demand in commercial building. The problem aims to minimize cost of life-cycle and earn profit from exporting onsite-generated electrical energy to grid based on national policy.

Cogeneration system is focused on the economic operation under emission constraints which tries to achieve minimum cost and minimum pollutant emission of cogeneration [7]. Linear model is designed to respond the electrical, thermal, and cooling loads in the small industrial building. In [8], the economic operation aims to reduce investment, save more energy and time, and gain more benefit and comfort.

In [9], the modified model of cogeneration is integrated with BEMS to minimize operating cost and CO₂ emission. The research [9] has proposed design of cogeneration which is applied to a large shopping mall. Their framework provides optimal operation which aims to minimize total operating cost (TOC) and total CO₂ emission (TCOE). The major components of BEMS [9] consists of CHP, absorption chiller, and auxiliary boiler as energy supply. CHP is main component which supplies both electrical energy and heat energy to demand in building's load. It is observed that CHP releases some waste heat, i.e., exces-

Manuscript received on August 15, 2016 ; revised on November 10, 2016.

Final manuscript received on February 7, 2017.

^{1,2} The authors are with the Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, 254 Phayathai Road, Pathumwan, Bangkok, 10330 Thailand, E-mail: kmanusilp@gmail.com and b david@chula.ac.th

² Corresponding author.

sive thermal energy over the load demand. In this paper, we incorporate Thermal Energy Storage (TES) [10] to utilize excessive thermal energy from CHP system. TES is employed to store excessive thermal energy from CHP and cooperate to supply thermal energy to absorption chiller. We will give a guideline how to choose capacity of TES. Furthermore, we demonstrate that TES can significantly improve operation of auxiliary boiler which, in return, reduce TOC and TCOE. Then, we analyze energy flow of both economic and environmental optimal operation.

This paper is organized as follows. Section 2 describes the main components of BEMS. Section 3 presents problem formulation including objective functions and dispatch strategies. Effects of TES to TOC and TCOE are given in section 4. Section 5 presents numerical results of optimal dispatch strategies. Section 6 analyzes optimal energy flow. Conclusions are given in section 7.

2. SYSTEM DESCRIPTION

The proposed BEMS is composed of CHP, auxiliary boiler, absorption chiller, and thermal energy storage as internal energy supply of the building. Power grid is external energy supply which serves as power exchange unit with BEMS. CHP is the main energy supply which responds to load demand in the building. Following the research [9], we classify building load into two types for consideration: electrical load and cooling load. In Figure 1, CHP simultaneously produces electrical energy (EE) and thermal energy or heat energy (HE) which supply to the building load. CHP mainly supplies EE to respond the electrical load. Moreover, power grid is connected to BEMS serving as a backup supply. In case of power shortage, power grid takes responsibility to supply EE to electrical load. On the other hand, BEMS can export EE to power grid when EE production from CHP exceeds the building demand. Absorption chiller is a component which converts HE to be cooling energy before supplies to cooling load. Absorption chiller receives HE from CHP, auxiliary boiler and TES to respond cooling load demand in the building. Furthermore, excessive HE from CHP production which is over the load demand will be charged to TES.

3. PROBLEM FORMULATION

Optimal dispatch operation for the proposed BEMS can be defined by two objective functions, namely, economic optimal operation and environmental optimal operation. Both objective functions are subjected to electrical energy dispatch and cooling energy dispatch. TES utilization is taken into account of cooling energy dispatch. We simplify model of each component to be linear and neglect internal losses.

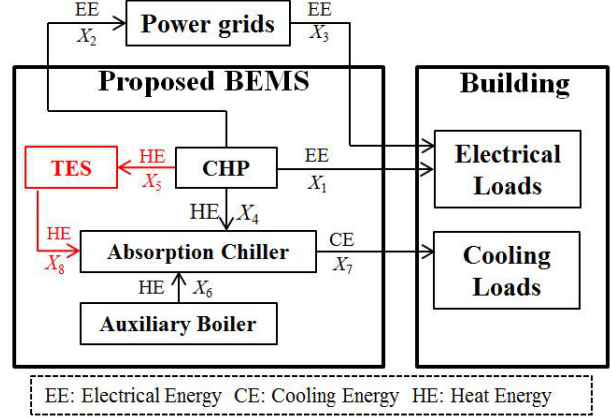


Fig.1: Diagram of proposed BEMS.

3.1 Objective Functions

The economic optimal operation aims to minimize total operating costs of BEMS. The objective function, total operating cost (TOC), is equal to the sum of energy cost (EC) and demand charge cost (DCC). EC consists of the sum of energy cost of CHP, selling and purchasing of power trading with power grids, and auxiliary boiler. DCC is calculated from maximum imported power from power grids. The economic objective function is stated as follows.

$$\text{TOC} = \text{EC} + \text{DCC} \quad (1)$$

$$\text{EC} = \sum_{k=1}^{nxd} c_{\text{CHP}}(x_{1,k} + x_{2,k}) - q_k x_{2,k} + p_k x_{3,k} + c_{\text{AB}} x_{6,k} \quad (2)$$

$$\text{DCC} = \frac{d_{\text{PG}}}{\Delta t} \max_{h=1, \dots, nxd} x_{3,k} \quad (3)$$

where $x_{i,k}$ is energy flow following Fig.1 in time interval of k . c_{CHP} and c_{AB} are operating cost of the CHP and the auxiliary boiler which depend on fuel price, q_k is electrical energy base price, p_k is electrical energy charge price during on-peak or off-peak time, d_{PG} is demand charge depending on maximum imported power from power grids, n is the number of time interval in one day, d is the number of days, and Δt is time duration of each time interval. Unit of cost is baht.

The environmental optimal operation addresses issues of greenhouse gas effect. The objective function aims to minimize carbon dioxide emission which considers in terms of total carbon dioxide emission (TCOE). TCOE is equal to the sum of carbon dioxide emission from CHP, power grids, and auxiliary boiler. The environmental optimal operation is stated as follows.

$$\text{TCOE} = \sum_{k=1}^{nxd} (\text{EF}_{\text{CHP}, \text{CO}_2}(x_{1,k} + x_{2,k}) + \text{GEF} x_{3,k} + \frac{\text{EF}_{\text{AB}, \text{CO}_2}}{\eta_{\text{AB}}} x_{6,k}) \quad (4)$$

where EF_{CHP,CO_2} and EF_{AB,CO_2} are CO_2 emission of the CHP operation and the auxiliary boiler which depend on fuel price, GEF is grid emission factor, and η_{AB} is efficiency of boiler. Unit of TCOE is $tonCO_2$.

3.2 Thermal Energy Storage Model

Thermal Energy Storage (TES) is component which stores excessive heat from CHP. Status of TES is represented by state of charge (SOC) which depends on charging and discharging of thermal energy with TES. Thermal energy charges and discharges of TES are under limitation of charge and discharge rate. Moreover, we need to take into account of the maximum and minimum states of charge of TES. Constraints of TES are given as follows.

$$\varepsilon x_{5,k} \leq R_1 \quad (5)$$

$$\frac{1}{\delta} x_{9,k} \leq R_2 \quad (6)$$

$$x_{9,k} = \text{init}(1 - \mu)^k + \sum_{j=1}^k (\varepsilon x_{5,j} - \frac{1}{\delta} x_{8,j}) (1 - \mu)^{k-j+1} \quad (7)$$

$$S_{\min} \leq x_{9,k} \leq S_{\max} \quad (8)$$

where ε and δ are TES charge and discharge efficiency, R_1 and R_2 are charge and discharge rate. The variable $x_{9,k}$ represents state of charge at time k . μ is loss coefficient of TES and init is initial heat stored in TES. Finally, $S_{\min}$ and $S_{\max}$ are minimum and maximum states of TES.

3.3 Dispatch Strategies

Dispatch strategies of optimal operation aim to efficiently supply energy to meet demand in the building. The EE dispatch concerns management of EE supplies to the load. CHP and power grid together cooperate to supply EE to meet electrical load (U_k). CHP will operate for EE production under limitation of its production, $P_{CHP,\min}$ and $P_{CHP,\max}$, when there is EE load. The production of CHP is usually operated with a proportion of EE and HE equal to power-to-heat ratio (P2H) of their CHP. Ramp rate (R_{CHP}), calculated from the difference between EE production at current and previous state, should be considered. EE dispatch is given as follows.

if $U_k = 0$, then

$$x_{1,k} = x_{2,k} = x_{4,k} = x_{5,k} = 0$$

else

$$P_{CHP,\min} \Delta t \leq x_{1,k} + x_{2,k} \leq P_{CHP,\max} \Delta t$$

$$\frac{x_{1,k} + x_{2,k}}{x_{4,k} + x_{5,k}} = P2H$$

$$|(x_{1,k} + x_{2,k}) - (x_{1,k-1} + x_{2,k-1})| \leq R_{CHP} \Delta t$$

end

$$x_{1,k} + x_{3,k} = U_k$$

For CE dispatch, energy supplies consist of CHP, auxiliary boiler, TES, and absorption chiller. CE dispatch manages cooling energy from these operations supply to meet cooling load (C_k) in the building which can divided in four conditions. Firstly, in case of no cooling load there is no HE supply to chiller and chiller does not operate. The excessive heat from CHP will be charged to TES under charging rate. Secondly, in case there is C_k less than minimum operation of chiller and CHP can supply enough HE to chiller, CHP and TES cooperate to supply HE to chiller. The chiller operates at its minimum cooling production ($CP_{AC,\min}$) to convert HE to CE supply to C_k in the building. Auxiliary boiler is not necessary to use, the boiler shuts down. Thirdly, in case C_k is over the minimum operation of chiller, CHP and TES cooperate to supply HE to chiller. Auxiliary boiler still shuts down when CHP can supply enough HE to chiller. Lastly, auxiliary boiler will operate in case CHP cannot supply enough HE. CHP, TES, and boiler cooperate to supply HE to chiller. Chiller will operate at the C_k level but not over the maximum of cooling production of chiller ($CP_{AC,\max}$). CE dispatch is given as follows.

if $C_k = 0$, then

$$x_{4,k} = x_{6,k} = x_{7,k} = x_{8,k} = 0$$

$$x_{9,k} = (x_{9,k} + x_{5,k})(1 - \mu)$$

$$\varepsilon * x_{5,k} \leq R_1 \Delta t$$

elseif $C_k \leq CP_{AC,\min} \Delta t$, then

$$(x_{4,k} + x_{8,k}) COP_{AC} = x_{7,k}$$

$$\frac{1}{\delta} x_{8,k} \leq R_2 \Delta t$$

$$x_{9,k} = (x_{9,k-1} - x_{8,k})(1 - \mu)$$

$$x_{5,k} = x_{6,k} = 0$$

$$x_{7,k} = CP_{AC,\min} \Delta t$$

elseif $C_k \leq \frac{P_{CHP,\max} \Delta t}{P2H} COP_{AC}$, then

$$(x_{4,k} + x_{8,k}) COP_{AC} = x_{7,k}$$

$$\frac{1}{\delta} x_{8,k} \leq R_2 \Delta t$$

$$x_{9,k} = (x_{9,k-1} - x_{8,k})(1 - \mu)$$

$$x_{5,k} = x_{6,k} = 0$$

$$x_{7,k} = \min(C_k, \frac{P_{CHP,\max} \Delta t}{P2H} COP_{AC})$$

else

$$(x_{4,k} + x_{6,k} + x_{8,k}) COP_{AC} = x_{7,k}$$

$$\frac{1}{\delta} x_{8,k} \leq R_2 \Delta t$$

$$x_{9,k} = (x_{9,k-1} - x_{8,k})(1 - \mu)$$

$$HP_{AB,\min} \Delta t \leq x_{6,k} \leq HP_{AB,\max} \Delta t$$

$$x_{5,k} = 0$$

$$x_{7,k} = \min(C_k, CP_{AC,\max} (\frac{P_{CHP,\max} \Delta t}{P2H} + HP_{AB,\max} \Delta t) COP_{AC})$$

end

The optimal dispatch can be formulated as optimization problem with economic and environmental optimal operation subject to operation constraints. The problems are linear program (LP) which can be efficiently solved by LP solvers.

3.4 System Parameters

The proposed BEMS requires appropriate operations to establish as a system. There are some research articles reporting CHP operations. For CHP operation, BEMS employs gas turbine as the CHP system with size and capacity based on peak electrical demand. Moreover, gas turbine can obtain high temperature steam [12]. There is report of varying CHP size from 22-25 MW and observe TOC and TCOE [9]. In this paper, we choose CHP of 24 MW which is appropriate for the load demand of test system. To select the absorption chiller, we consider heat energy input of absorption chiller and heat energy output of CHP system. The double-effect absorption chiller is selected and the coefficient of performance (COP) is 1.1 following regulation on energy usage for building recommendation [9]. We choose industrial boiler as an auxiliary boiler. Based on surveys, industrial boiler utilizes natural gas and gives approximately 75% of thermal efficiency at full load and there are various capacities [9, 13]. CO₂ emission factor from natural gas combustion (EF_{AB,CO_2}) is 0.1810 tCO₂/MWh [14].

For electricity price, there are two types of electricity price in Thailand, i.e., time-of-day (TOD) and time-of-use (TOU) but we consider TOU in this study. TOU rates depend on time of use during the day; on-peak time is on Monday to Friday 09.00-22.00 and the rest is off-peak time. Moreover, TOU tariffs consist of energy charge, demand charge, service charge, power factor charge, fuel adjustment (Ft), and VAT. In this study, we consider only energy charge and demand charge and the rest are neglected. BEMS operation pays for energy charge as 4.1283 and 2.6107 baht/kWh for on-peak and off-peak time, respectively. The demand charge for large general service with 69-kV is 74.14 baht/kW [15]. Besides, electricity price for selling EE from CHP production is referred in [16]. For grid emission factor (GEF) of Thailand, CO₂ emission is estimated when BEMS uses electricity from grid [17]. Parameters of TES and other parameters are summarized in Table. 1.

4. EFFECTS OF THERMAL ENERGY STORAGE

As TES is introduced to utilize excessive thermal energy from CHP, how to select a suitable capacity of TES will be considered in this section. We will compare TOC and TCOE for several TES capacities and for the case without TES. TES is varied in range from 41 to 60 MW. The comparison is based on economic and environmental optimal operation.

4.1 Economic Optimal Operation

This subsection shows TOC and TCOE under economic optimal operation. Figure 2 presents TOC comparing between BEMS with TES and BEMS

Table 1: System parameters.

Description	Notation	Value
CHP system		
Rated power (MW)	-	24
Electrical energy efficiency (%)	$\eta_{CHP,EE}$	33.90
Power to heat ratio	P _{2H}	0.9244
Maximum power production (MW)	P _{CHP,max}	24
Minimum power production (MW)	P _{CHP,min}	4.8
Electrical energy ramp rate (MW)	R _{CHP}	24
CO ₂ emission factor (tCO ₂ /MWh)	EF _{CHP,CO₂}	0.5349
Auxiliary boiler		
Rated heat power (MW)	-	13.1882
Efficiency (%)	η_{AB}	75
Maximum heat production (MW)	HP _{AB,max}	13.1882
Minimum heat production (MW)	HP _{AB,min}	2.6376
CO ₂ emission factor from natural gas combustio	EF _{AB,CO₂}	0.1810
Absorption chiller		
Rated cooling power	-	42.2
Coefficient of performance	COP _{AC}	1.1
Maximum cooling production (MW)	CP _{AC,max}	42.2
Minimum cooling production (MW)	CP _{AC,min}	8.44
Thermal energy storage		
Rated heat power (MW)	-	50
Heat charge rate (MW)	R ₁	15
Heat discharge rate (MW)	R ₂	15
Charging efficiency	ε	0.95
Discharging efficiency	δ	0.95
TES loss coefficient	μ	0.001
Initial heat energy in TES (MW)	init	5
Maximum heat storage (MW)	S _{max}	50
Minimum heat storage (MW)	S _{min}	5
Others		
Electrical energy load in time interval k (MWh)	U _k	-
Cooling energy load in time interval k (MWh)	C _k	-
Time duration of each interval (hour)	Δt	1
Number of time interval per day	n	24
Number of days in month	D	7
Average Price of Natural Gas of December 2015 (bath/MMBtu)	APNG	179.54

without TES. It clearly shows that TOC continually decrease when TES capacity increases. It is observed that TOCs can be reduced by BEMS with TES at least 1.45% and at most 5.25%.

As Eq. (1), TOC comes from the sum of energy cost of components in BEMS and demand charge cost of imported EE from power grids. It is shown that BEMS with TES can linearly reduce energy cost or EC when capacities of TES increase as in Figure 3 (top). TOC can be reduced at least 4% and at most 6.22% when compared to that of BEMS without TES. Besides, BEMS with TES makes demand charge cost increase when compared to that BEMS without TES as shown in Figure 3 (bottom). Demand charge cost linearly decreases in range 41 to 46 MW of TES ca-

capacities and starts saturating at 47 MW of TES capacity. The reason is that CHP tries to produce EE to meet building load while HE produced from CHP cannot exceed TES capacity. Therefore, CHP cannot produce enough EE to meet the building load so EE is imported from power grids due to inexpensive cost of imported EE. As a result, BEMS with TES has higher demand charge cost.

To further investigate the effects of TES, EC is broken down by components as shown in Figure 4. Operating cost of CHP linearly increases as TES capacity ranges from 41 to 51 MW and starts saturating at 52 MW. Furthermore, the last point which makes cost of CHP operation less than the case without TES is at TES capacity 50 MW as shown in Figure 4 (top). Figure 4 (middle) shows that the main reduction of energy cost comes from auxiliary boiler which can reduce at least 29.97% and at most 44.48% when compared to the case of without TES. Figure 4 (bottom) shows the cost of importing EE from power grids linearly decreases as TES capacity ranges from 41-51 MW and starts saturating at 52 MW but the cost is a bit higher than that BEMS without TES.

TCOE consists of emission from operating components as shown in Eq. (4). In Figure 5, BEMS with TES linearly reduces TCOE as TES capacity increases. In particular, BEMS with TES can decrease TCOE at least 4.24% and at most 6.19%.

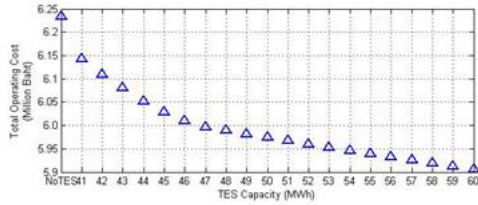


Fig.2: Total operating cost when varying TES capacity for economic optimal operation.

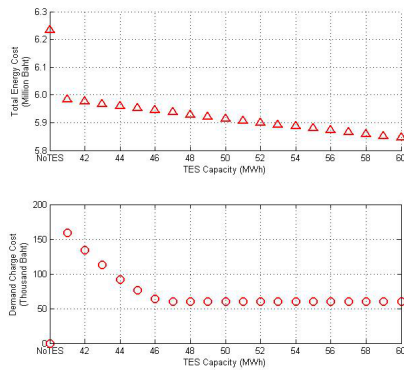


Fig.3: Total energy cost and demand charge cost when varying TES capacity for economic optimal operation.

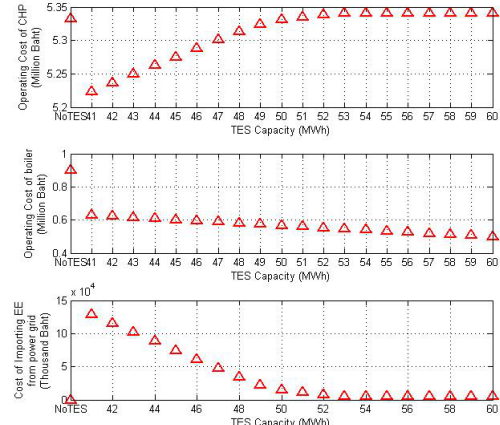


Fig.4: Operating cost of each component when varying TES capacity for economic optimal operation.

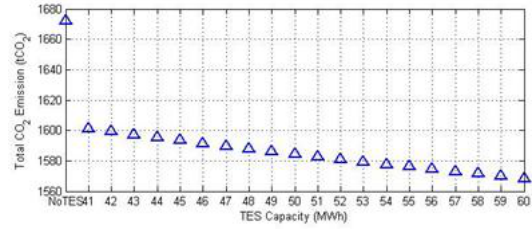


Fig.5: Total CO₂ emission when varying TES capacity for economic optimal operation.

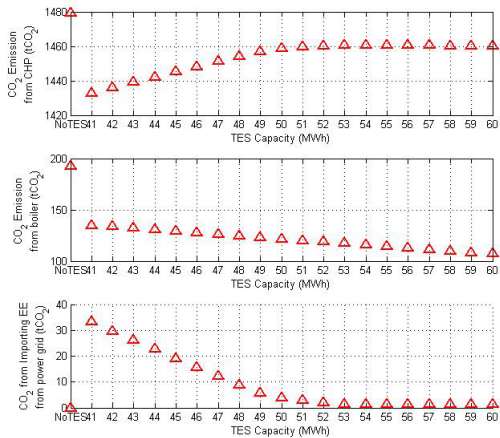


Fig.6: CO₂ emission of each component when varying TES capacity for economic optimal operation.

When breaking down TCOE by components, we find that the trend looks similar to TOC. Main CO₂ emission comes from auxiliary boiler operation as shown in Figure 6 (middle). CO₂ emission of CHP operation linearly increases as TES capacity ranges from 41-50 MW and starts saturating at 51 MW. Although BEMS with TES makes CO₂ emission of CHP increase, all CO₂ emission still less than that of BEMS without TES as shown in Figure 6 (top). CO₂ emission of importing EE from grids inversely varies with emission from CHP and starts saturating at 54 MW but emission is a bit higher than that BEMS without TES.

4.2 Environmental Optimal Operation

In this subsection, we show the effects of TES on TOC and TCOE under environmental optimal operation. Figure 7 shows that BEMS with TES makes TOCs continually decrease when TES capacity increases. It is observed that TES of 41-43 MW makes TOC higher than that of BEMS without TES. BEMS with TES can reduce TOC at least 0.45% and at most 3.57%. Besides, Figure 8 shows EC and DCC as Eq. (1). BEMS with TES provides EC lower than that BEMS without TES. EC linearly reduces when TES capacity increases as shown in Figure 8 (top). Demand charge cost when applied TES is still higher than the case without TES. TOC continuously decreases when TES capacity increases and starts saturating at 53 MW of TES capacity as shown in bottom subplot Figure 8.

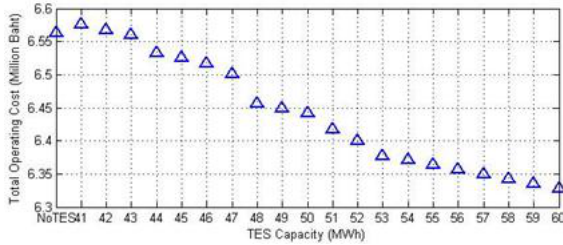


Fig.7: Total operating cost when varying TES capacity for environmental optimal operation.

When breaking down EC by components, the main reduction of energy cost comes from auxiliary boiler operation. BEMS with TES can linearly reduce energy cost of auxiliary boiler operation at least 15.70% and at most 27.80% as shown in Figure 9 (middle). In Figure 9 (top), operating cost of CHP linearly increases when TES capacity increases and starts saturating at 53 MW. It's observed that TES of 50 MW gives the cost of CHP operation less than that of BEMS without TES. Cost of importing EE from grids linearly decreases as TES capacity ranges from 41-50 MW and starts saturating at 53 MW. In Figure 9 (bottom), we observe the cost of importing EE from power grids with TES greater than 53 MW is slightly higher than the case without TES.

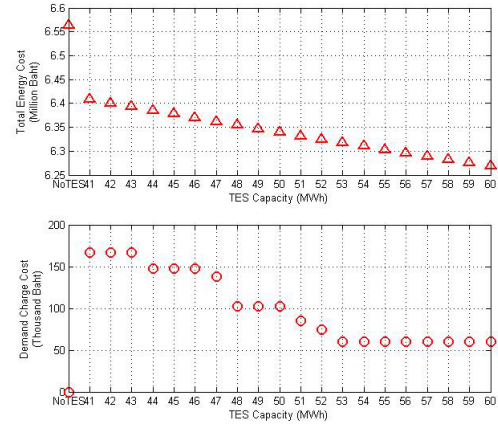


Fig.8: Total energy cost and demand charge cost when varying TES capacity for environmental optimal operation.

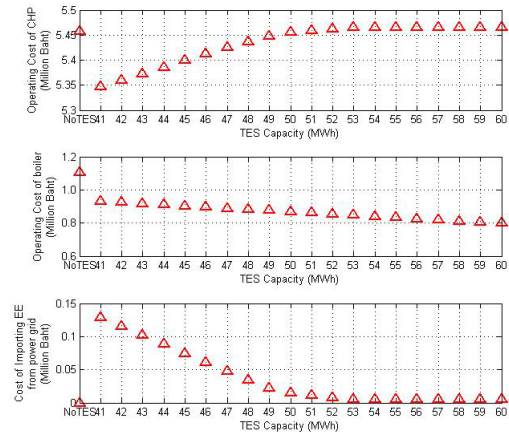


Fig.9: Operating cost of each component when varying TES capacity for environmental optimal operation.

Figure 10 shows TCOE linearly decreases when capacity of TES increases. BEMS with TES can reduce TCOE at least 5.25% and at most 7.25% when compared to that of BEMS without TES. As expressed in Eq. (4), TCOE is combination of emission from CHP, auxiliary boiler, and importing EE from grids. The main reduction of CO₂ emission comes from the auxiliary boiler operation as shown in Figure 11 (middle). CO₂ emission from boiler reduces at least 15.61% and at most 27.85% compared to the case without TES. In Figure 11 (top), when operating BEMS with TES, CHP system gives lower CO₂ emission compared to the case without TES. CO₂ emissions from CHP start saturating at TES of 53 MW. CO₂ emissions of importing EE from grid linearly decreases when TES capacity increases and saturates at 53 MW as shown in Figure 11 (bottom). However, importing EE from

power grids when operating with TES greater than 53 MW gives slightly higher CO₂ emission when compared to the case without TES.

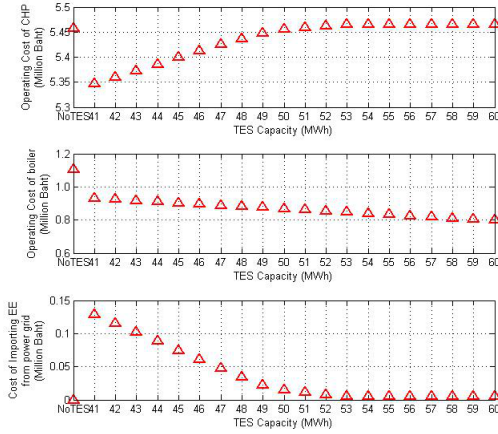


Fig.10: Total CO₂ emission when varying TES capacity for environmental optimal operation.

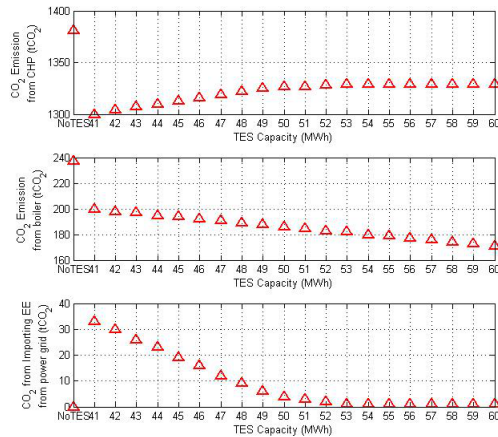


Fig.11: CO₂ emission of each component when varying TES capacity for environmental optimal operation.

It is observed that in both economic and environmental optimal operations, BEMS with TES can reduce more TOC and TCOE when TES capacity increases. It is essential to have some criteria for the selection of TES. When we break down EC, it is obvious that at 50 MW is the minimum capacity which can maintain cost of CHP operation lower than the cost of CHP without TES. Therefore, TES of 50 MW is chosen for BEMS.

5. NUMERICAL RESULTS

In this section, we compare TOC and TCOE between BEMS with TES and BEMS without TES. We

consider electrical and cooling load profiles of a large shopping mall for 7 days. The average of natural gas price on December 2015 [11] at 179.54 baht/MMBtu is used for calculation. TES with 50 MW is applied to support CHP operation. Table 2 summarizes comparison results.

In Table 2, BEMS with TES can reduce TOC 258,504 and 121,188 baht for economic and environmental optimal operations, respectively. Moreover, when applying TES, TCOE is reduced by 88 and 101 tonCO₂ for economic and environmental optimal operation, respectively. To further investigate the benefits of TES, we note that the main reduction of both TOC and TCOE comes from auxiliary boiler operation as shown in Table 3 and Table 4. For economic operation, BEMS with TES can reduce operating cost of auxiliary boiler up to 332,475 baht and reduce CO₂ emission up to 71 tonCO₂. In part of environmental optimal operation, operating cost of auxiliary boiler is reduced up to 237,042 baht when operating TES. Moreover, CO₂ emission from boiler decreases up to 51 tonCO₂. It is obvious that TES plays a cooperative role to supply heat to cooling load of building. However, there exists some cost and CO₂ emission for importing EE from power grids when applying TES. In both economic and environmental optimal operation, we find that operating cost and CO₂ emission increases because the charge of importing EE from power grids during off-peak period is cheaper than running operation of CHP.

6. ANALYSIS OF OPTIMAL ENERGY FLOW

In this section, we demonstrate daily electrical and cooling energy flow of BEMS with TES and compare to the case without TES [9]. The analysis is divided into economic and environmental optimal operations.

Table 2: Comparison of total operating cost and CO₂ emission.

Objective function	BEMS without TES	BEMS with TES	% change
Economic Optimal Operation			
Total Operating Cost (TOC,baht)	6,233,275	5,974,771	-4.15
Total CO ₂ Emission (TCOE,tCO ₂)	1,672	1,584	-5.25
Environmental Optimal Operation			
Total Operating Cost (TOC,baht)	6,563,078	6,441,890	-1.85
Total CO ₂ Emission (TCOE,tCO ₂)	1,618	1,517	-6.25

6.1 Economic Optimal Operation

In Figure 12, the main EE supply to electrical load comes from CHP production. Moreover, the BEMS without TES [9] tries to utilize power grid to sup-

Table 3: Operating cost classified by component.

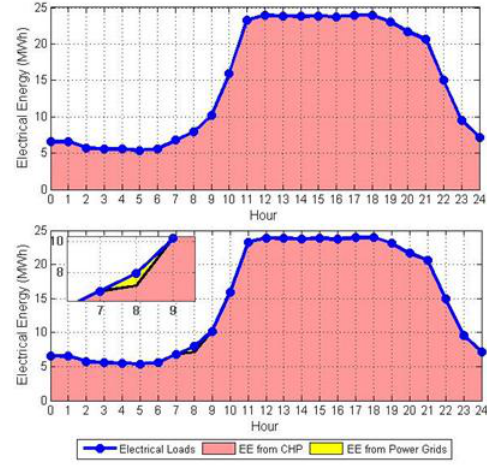
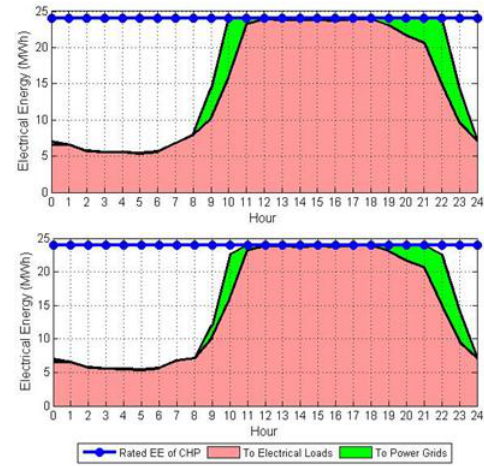
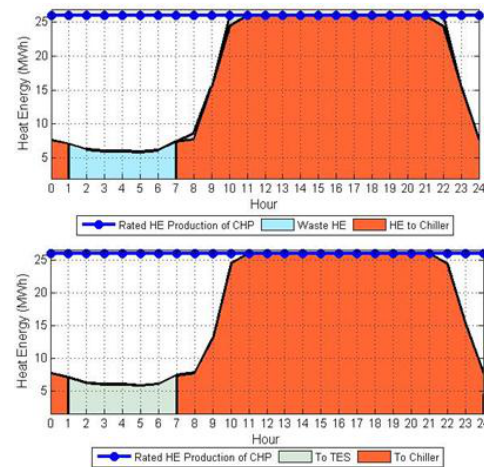
Component	BEMS without TES	BEMS with TES	% change
Economic Optimal Operation			
CHP	5,332,627	5,331,534	-0.02
Auxiliary Boiler	900,648	568,173	-36.92
Power Grids	0	15,134	N/A
Environmental Optimal Operation			
CHP	5,457,205	5,455,525	-0.03
Auxiliary Boiler	1,105,874	868,832	-21.43
Power Grids	0	15,131	N/A

Table 4: CO₂ emission classified by component.

Component	BEMS without TES	BEMS with TES	% change
Economic Optimal Operation			
CHP	1,479	1,459	-1.38
Auxiliary Boiler	193	122	-36.92
Power Grids	0	4	N/A
Environmental Optimal Operation			
CHP	1,381	1,327	-3.92
Auxiliary Boiler	237	186	-21.43
Power Grids	0	4	N/A

ply EE to electrical load during off-peak hour as yellow area in bottom figure. The reason is that operating cost of EE production of CHP is higher than charge of imported EE from power grids during off-peak period. The power grid takes responsibility with CHP to reduce TOC as least as possible. EE and HE production of CHP are shown in Figure 13 and 14. BEMS with TES operates quite similar to BEMS without TES. The main EE production of CHP supply to electrical load is shown as pink region in Figure 13. They try to earn profit from selling excessive EE to power grids as green area. In Figure 14, CHP also supplies main heat energy production to chiller. The excessive heat at off-peak hours is released to the atmosphere as shown in Figure 14 (top). On the other hand, BEMS with TES utilizes excessive heat energy, shown as white region in Figure 14 (bottom) by charging to TES.

Cooling energy flow are shows in Figure 15. Absorption chiller receives heat energy from supply sources, and converts to cooling energy to supply to the cooling load. CHP is the main supply source of HE to chiller in both BEMS without TES [5] and BEMS with TES. In BEMS without TES, auxiliary boiler cooperates with CHP to supply HE to chiller during on-peak hours as shown in Figure 15 (top). In contrary, BEMS with TES incorporates with auxiliary boiler and CHP to supply HE to chiller at on-peak hours as shown in Figure 15 (bottom). It is obvious that TES comes to reduce the operation of auxiliary boiler at on-peak hours which makes the main reduction of operating cost and CO₂ emission.

**Fig.12:** Electrical energy flow to electrical load of BEMS without TES (top) and BEMS with TES (bottom) for economic optimal operation.**Fig.13:** Electrical energy production of CHP of BEMS without TES (top) and BEMS with TES (bottom) for economic optimal operation.**Fig.14:** Heat energy production of CHP of BEMS without TES (top) and BEMS with TES (bottom) for economic optimal operation.

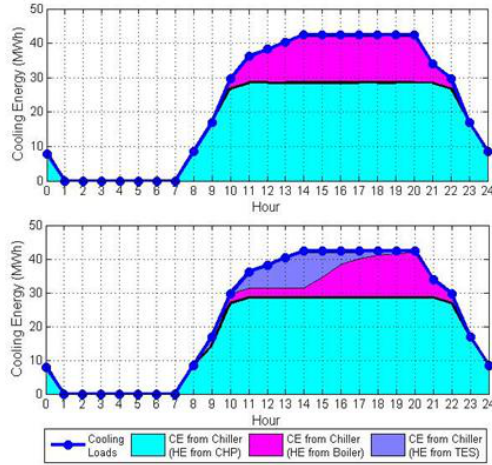


Fig.15: Cooling energy flow to cooling load of BEMS without TES (top) and BEMS with TES (bottom) for economic optimal operation.

6.2 Environmental Optimal Operation

Environmental optimal operation aims to minimize TCOE. As Figure 16, CHP is the main EE supply source to electrical load. Figure 16 (bottom) shows that BEMS with TES imports EE from power grids as yellow area to supply to electrical load. Power grids take responsibility with CHP to supply EE because importing EE from grid gives CO₂ emission lower than running CHP operation during off-peak hours. In Figure 17, EE production of CHP mainly supplies to electrical load in both BEMS without TES and BEMS with TES. In Figure 17 (top), BEMS tries to earn profit of selling excessive EE of CHP production at on-peak hours. In contrary, BEMS with TES has zero exporting EE to power grid. The reason is that TES cooperates with CHP and boiler to support HE, whereas EE (proportional to HE under P2H ratio) is not produced more than electrical demand. To minimize CO₂ emission as least as possible, CHP does not produce EE to earn profit from selling EE to power grids.

Heat energy production of CHP is referred in Figure 18. It is quite similar to that of economic optimal operation. CHP supplies the main HE production to absorption chiller and excessive heat during off-peak hour is released to the atmosphere as shown in Figure 18 (top). BEMS with TES utilizes excessive HE from CHP operation by charging to TES. Figure 19 shows that the main heat energy supplied to chiller comes from CHP operation in both BEMS without TES and BEMS with TES. TES cooperates with CHP and auxiliary boiler at on-peak hours to obtain minimum CO₂ emission. It is obvious that TES can reduce operation of auxiliary boiler at on-peak hours as shown in Figure 19 (bottom).

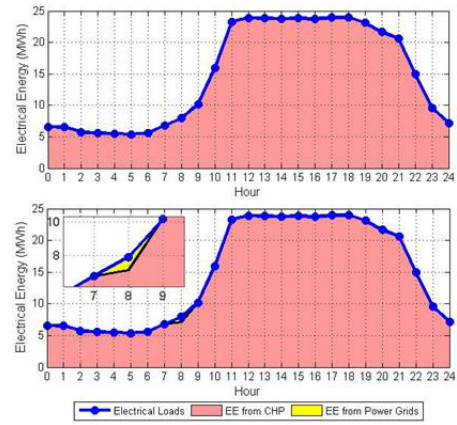


Fig.16: Electrical energy flows to electrical load of BEMS without TES (top) and BEMS with TES (bottom) for environmental optimal operation.

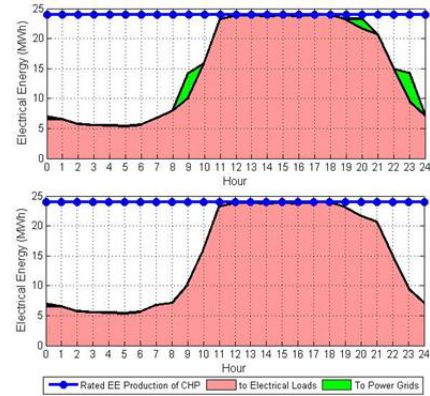


Fig.17: Electrical energy production of CHP of BEMS without TES (top) and BEMS with TES (bottom) for environmental optimal operation.

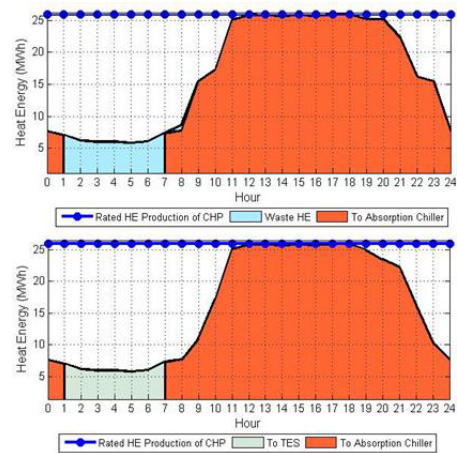


Fig.18: Heat energy production of CHP of BEMS without TES (top) and BEMS with TES (bottom) for environmental optimal operation.

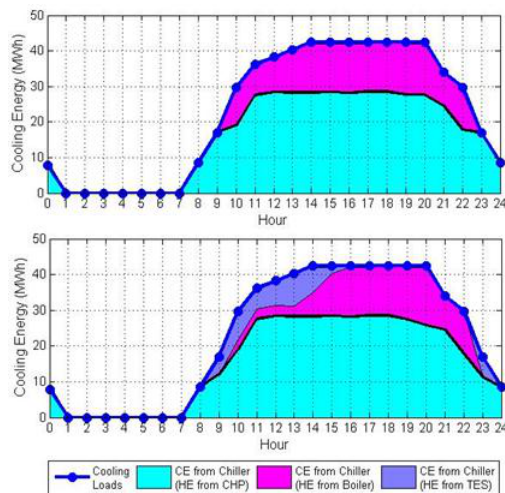


Fig.19: Cooling energy flow to cooling load of BEMS without TES (top) and BEMS with TES (bottom) for environmental optimal operation.

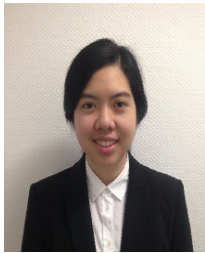
7. CONCLUSIONS

In this paper, thermal energy storage in conjunction of cogeneration utilizes excessive heat to improve energy efficiency of BEMS. TES constraints are taken into account in the energy dispatch strategy. It is observed that TES can cooperate with CHP and auxiliary boiler at on-peak hours. Moreover, BEMS with TES can significantly reduce TOC and TCOE when compared to the case of BEMS without TES. The main energy improvement comes from the reduction of heat energy production from auxiliary boiler.

References

- [1] Z. Jiang and H. Rahimi-Eichi, "Design, modeling and simulation of a green building energy system," *IEEE Power & Energy Society General Meeting*, Calgary, AB, pp. 1-7, 2009.
- [2] D. Estates, "Building energy management systems," *Her Majesty's Stationery Office, Ministry of Defense*, United Kingdom, Jan. 2001.
- [3] S. Yokoyama, "A Guide for Biomass Production and Utilization," *The Asian Biomass Handbook*, pp. 94-97, 2008.
- [4] U.S. Environmental Protection Agency and Combined Heat and Power Partnership (Dec. 2008). Catalog of CHP Technologies [Online]. Available from: www.epa.gov/chp/documents/catalog_chptech_full.pdf.
- [5] Energy, Ministry. Energy Policy and Planning Office, "Thailand Power Development Plan 2015-2036 (PDP2015)," *Energy Policy and Planning Office. Ministry of Energy. Thailand.* [Online]. June 2015. Available from: www.egat.co.th/en/images/
- [6] C.-C. Tseng, W.-H. Lin, S.-Y. Wu, S.-H. Chen, and S.-Y. Lin, "The transition mechanisms of type-II GaSb/GaAs quantum-dot infrared light-emitting diodes," *J. Cryst. Growth*, Vol. 323, pp. 466-469, 2011.
- [7] M. T. Tsay, W. M. Lin, J. L. Lee, "Interactive best-compromise approach for operation dispatch of cogeneration systems," *IEEE Proceedings: Generation, Transmission and Distribution*, vol. 148, no. 4, July 2001.
- [8] R. Hashemi, "A Developed Offline Model for Optimal Operation of Combined Heating and Cooling and Power Systems," *IEEE Transactions on Energy Conversion*, vol. 24, no. 1, pp. 222-229, Mar. 2009.
- [9] T. Petkajee and D. Banjerdpongchai, "Design of Cogeneration and Analysis of Economic and Environmental Optimal Operations for Building Energy Management System", *ECTI Transactions on Electrical Engineering, Electronics, and Communications (EEC)*, vol. 11, no. 2, pp. 79-94, Aug. 2013.
- [10] K. Manusilp and D. Banjerdpongchai, "Optimal dispatch of cogeneration with thermal energy storage for Building Energy Management System," *2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Chiang Mai, pp. 1-6, June 2016.
- [11] "Fuel Prices in December 2015", *Department of Mineral Fuels, Ministry of Energy, Thailand*, Dec. 2015.
- [12] United States Environmental Protection Agency (US EPA) and Combined Heat and Power Partnership. "Catalog of CHP Technologies. US EPA. United States of America," [Online]. December 2008. Available from: http://www.epa.gov/chp/documents/catalog_chptech_full.pdf
- [13] L. V. Wortswinkel and W. Nijs, "Industrial Combustion Boilers," *International Energy Agency Energy Technology Systems Analysis Program (IEAETSAP)* [Online]. May 2010. Available from: <http://www.ieaetsap.org/web/e-techds/pdf/i01-ind.boilers-gs-ad-gct1.pdf>.
- [14] United States Environmental Protection Agency (US EPA). Office of Atmospheric Programs. Climate Protection Partnerships Division and Climate Change Division. "Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type: Industrial Boiler Efficiency," *Climate Protection Partnerships Division and Climate Change Division. Office of Atmospheric Programs. US EPA. United States of America.* [Online]. Available from: <http://www.epa.gov/climateleadership/documents/resresour/industrial.boiler.protocol.pdf>

- [15] Metropolitan Electricity Authority (MEA). "Electricity Tariffs for Large General Service MEA. Thailand," [Online]. Nov. 2015. Available from: http://www.mea.or.th/upload/download/file_55c49b349ab063d4bcd0d5033e699707.pdf
- [16] Electricity Generating Authority of Thailand (EGAT). "Electricity Wholesale Prices for Metropolitan Electricity Authority (MEA) and Provincial Electricity Authority (PEA)". EGAT. Thailand. [Online]. www.egat.co.th
- [17] Thailand Greenhouse Gas Management Organization (TGO) (Public Organization). "Summary Report: The Study of Emission Factor for an Electricity System in Thailand 2010," TGO (Public Organization). Thailand. [Online]. Available from: conference.tgo.or.th/download/tgo_or_th/publication/GEF/2010/GEFReport_ENrevise4.pdf



Kebsiri Manusilp received the B.Eng. degree in Electrical Engineering from Khon Kaen University in 2012. Currently, she is studying a master's degree in Electrical Engineering at Control System Research Laboratory (CSRL), Department of Electrical Engineering, Chulalongkorn University. Her research interest is energy management system.



David Banjerdpongchai received the B.Eng. degree from Chulalongkorn University, and the M.S. and Ph.D. degrees from Stanford University, all in Electrical Engineering. Currently, he is a professor at Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University. He is a member of ECTI Association and had served as a founding chair of Systems and Control from 2012-2015. He is a senior member

of IEEE and has served as a founding chair of IEEE Control Systems Society Thailand Chapter since 2015. His research interests are energy management systems, analysis and synthesis of robust control systems, and convex optimization in robust control problems.