Design of Cogeneration and Analysis of Economic and Environmental Optimal Operations for Building Energy Management System

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ABSTRACT

This paper proposes a design of cogeneration or combined heat and power (CHP) system and analysis of economic and environmental optimal operations for a building energy management system (BEMS). The proposed BEMS consists of a CHP system, an auxiliary boiler, an absorption chiller, and power grids. The design problem concerns with multi-objective cost functions: total operating costs (TOC) and total carbon dioxide emissions (TCOE) which can be formulated as a linear program. The optimal operation analysis is employed to determine a suitable capacity of the CHP system for the proposed BEMS. Then, we analyze the optimal energy flow for each component and the relationship between TOC and TCOE. The numerical results show that the proposed BEMS can reduce both TOC and TCOE up to 30% and 14%, compared to the original electricity usage. Furthermore, the simulation is extended to determine risk in a long-term operation by investigating the impact of fuel prices to TOC and TCOE.

Keywords: CHP, BEMS, Economic and Environmental Optimal Operation, CO_2 Emissions, Linear Programs.

1. INTRODUCTION

Combined heat and power (CHP) generation or cogeneration becomes popular around the world due to its efficient energy utilization and support from the government. Several surveys on its commercial technology [1-4] indicate that CHP has been developed so that it would fit on-site loads. There are many researches on optimal operation of CHP systems. For example, an economic optimal operation model of CHP systems has been developed to earn the maximum profit from the viewpoint of energy producers to small industrial loads [5]. Afterwards, this model has been modified in order to suit the economic situation in Thailand and applied to a large shopping mall to determine economic cost benefit [6]. Some research is focused on the impact of power generation on the environment. Economic and environmental dispatch algorithms in electrical power systems have been compiled to draw attention from the utility to reduce emissions from fossil-fueled generation [7]. An optimal operation of CHP systems based on operational cost, fuel consumption and CO_2 emission has been applied to five cities with different climate conditions to examine which of these operations is suitable for the city [8]. A multi-objective function based on economic and environmental operations of CHP systems for factory energy management system using steam turbine technology has been developed [9]. They apply evolutionary programming and least squares method to find the optimal compromise between two operating criteria.

The objectives of this paper are twofold. The first objective is to develop a multi-objective approach to economic and environmental optimal operations of the CHP system with an application to building energy management system for a large shopping mall in Thailand. The CHP operation model is taken from the economic and environmental optimal operations of the CHP system for BEMS [10], but its economic model is further modified by additionally considering demand charge costs. The second objective is to determine a suitable capacity of the CHP system, including the type and size of major components for BEMS. Moreover, we investigate the factors which affect the optimal operation of each component and examine how fuel prices make an impact on a long-term operation.

The paper is organized as follows. Section 2 describes the main component of BEMS. Section 3 formulates economic and environmental optimal operations and describes dispatch strategies. A case study of BEMS and design results are given in Section 4 and Section 5, respectively. Section 6 and 7 give analysis of the optimal operations and the impact of fuel prices, respectively. Section 8 presents conclusions.

2. BUILDING ENERGY MANAGEMENT SYSTEM

BEMS is a computer-controlled system that manages electrical and cooling energy supply and con-

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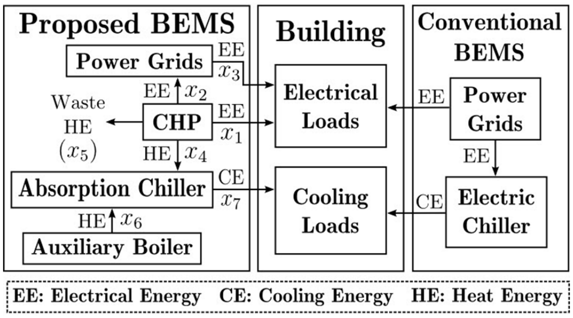

Fig.1: *Diagram of proposed and conventional BEMS.*

sumption in the building for comfort and efficiency. In this work, the proposed BEMS, Figure 1, controls and optimizes the operation of CHP generation, auxiliary boiler, absorption chiller and power grids. The CHP system is given priority to generating electricity for electrical loads (x_1), and simultaneously-produced heat (x_4) will be supplied to the absorption chiller which converts it to cooling energy (x_7). However, if recovered heat is greater than cooling energy demand, its surplus will be released as waste heat (x_5). Besides the operation of the CHP system, power grids play a role in purchasing electrical energy from the customer in case of excessive electricity production from cogeneration (x_2) and in selling energy to the customer in case of power shortages (x_8). Lastly, the auxiliary boiler will cooperate with the CHP system to compensate for heat shortages (x_6).

Compared to the proposed BEMS, the conventional BEMS utilizes electrical energy from power grids and cooling energy from electric chillers. Nevertheless, electric chillers require electrical energy as input energy, so cooling loads are converted to be part of electrical loads. As a consequence, the conventional BEMS purchases electrical energy only from power grids to meet all energy demand.

3. PROBLEM FORMULATION

There are two steps to formulate optimal operation problems for BEMS. The first step is to determine objective functions to achieve economic and environmental optimal operations, including their relationship. Next, we consider dispatch strategies for each component, based on the assumptions that the operation of each component is linear and internal losses are negligible.

3.1 Objective Functions

We formulate objective functions for economic and environmental optimal operations of BEMS as well as the objective functions to find their relationship.

The economic optimal operation is aimed to minimize total operating costs of BEMS. The objective function is defined as the total operating costs, (Baht), which consists of energy costs (EC) and demand charge costs (DCC). EC is the sum of the operating costs of the CHP system, the auxiliary boiler, and the income and expense from electrical energy trading with power grids throughout the operation. DCC is calculated from maximum power imported from power grids during the operation. Therefore, the economic objective function can be written as follows:

$$TOC = EC + DCC \tag{1}$$

$$\begin{aligned} EC = \sum_{k=1}^{n\times d} [&c_{CHP}(x_{1,k} + x_{2,k}) \\ &- q_k x_{2,k} + p_k x_{3,k} + c_{AB} x_{6,k}] \end{aligned} \tag{2}$$

$$DCC = \frac{d_{PG}}{\Delta t} \max_{h=1,\ldots,n\times d} x_{8,k} \tag{3}$$

where $x_{i,k}$ is energy flow in the time interval of k. Also, c_{OHP} and c_{AB} are operating costs of the CHP system and the auxiliary boiler, q_k, p_k, and d_{PG} are electrical energy selling price, electrical energy charge and demand charge from power grids. Lastly, n, d, and Δt are the number of time intervals in a day, the number of days, and time duration of each time interval.

Next, the environmental optimal operation enables BEMS to reduce a greenhouse gas, especially carbon dioxide (CO_2). Hence, the environmental optimal operation is focused on minimizing total CO_2 emissions of BEMS, (tonnes of CO_2, tCO_2), which is comprised of CO_2 emissions from the CHP system, the auxiliary boiler, and power grids as follows:

$$\begin{aligned} TCOE = \sum_{k=1}^{n\times d} \Big[&EF_{CHP,CO_2}(x_{1,k} + x_{2,k}) \\ &+ GEF x_{8,k} + \frac{EF_{AB,CO_2}}{\eta_{AB}} x_{6,k}\Big] \end{aligned} \tag{4}$$

where EF_{CHP,CO_2} and EF_{AB,CO_2} are CO_2 emission factors of the CHP system and auxiliary boiler, and GEF is grid emission factor, and η_{AB} is boiler's efficiency.

To find the relationship between two operations, we employ a multi-objective approach with three steps. First, we normalize each objective function with its minimum value, i.e., TOC_{min} and $TCOE_{min}$. Then, we use a weighting factor, α, to define the weighted objective function as follows:

$$min \;\; (1-\alpha)\frac{TOC}{TOC_{min}} + \alpha\frac{TCOE}{TCOE_{min}} \tag{5}$$

Subsequently, we vary the weighting factor from 0 to 1 and minimize the linear combination in (5) to obtain multi-objective optimal operation.

3.2 Dispatch Strategies

The core of the optimal operation is to design dispatch strategies or constraints because they reflect how well BEMS can supply energy to meet the demand. In this work, BEMS will operate under different objective functions but subject to the same constraints. The constraints are mainly grouped into electrical energy (EE) and cooling energy (CE) dispatch strategies.

The EE dispatch strategy involves the operation of the CHP system and power grids. The operation of the CHP system depends on electrical loads or EE demand (U_k), that is, it shuts down when there is no EE demand. In such case, only power grids take responsibility for supplying EE to electrical loads. On the contrary, when cooperating with power grids, the CHP system produces EE within its limitations, $P_{CHP,min}$ and $P_{CHP,max}$, and heat energy (HE) proportional to its power-to-heat ratio (P2H). Moreover, the difference in the EE generation between the current and the previous hour is taken into account of the energy ramp rate (R_{CHP}) constraint of the CHP system. The EE dispatch strategy is summarized by the following constraints.

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

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

The CE dispatch strategy is related to the operation of the CHP system, the auxiliary boiler, and the absorption chiller. The CHP system and the boiler produce HE which is converted to CE by the chiller; also, their operation relies on CE demand (C_k).Firstly, the boiler and the chiller shut down when there is no CE demand. In this case, HE produced from CHP is released as waste HE. Secondly, if there is CE demand but less than the minimum cooling production level ($CP_{AC,min}$) of the chiller, the chiller operates at that level so that the temperature in the building is still cool. Regarding HE supply, BEMS utilizes HE which is simultaneously produced with EE generation by the CHP system before HE from the boiler. Thirdly, BEMS still does not use the boiler if the CHP system can provide HE enough for the chiller to satisfy CE demand. Finally, when the boiler starts co-operating with the CHP system, it produces heat to compensate for the shortage but operates in its limitations, $HP_{AB,min}$ and $HP_{AB,max}$.The chiller operates following CE demand but not more than its maximum cooling production level ($CP_{AC,max}$) or maximum heat from the CHP system and the boiler. In sum, the CE dispatch strategy can be explained with the following constraints.

If $C_k = 0$, then

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

else if $C_k < CP_{AC,min}\Delta t$, then

$$x_{4,k}COP_{AC} = X_{7,k}$$

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

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

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

$$x_{4,k}COP_{AC} = x_{7,k}$$

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

$$x_{7,k} = C_k$$

else

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

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

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

end.

The proposed economic and environmental optimal operations are formulated as a linear program (LP) which can be efficiency solved by LP solvers, such as MATLAB optimization toolbox.

4. BEMS CASE STUDY

In a case study, we consider electrical and cooling load profiles of a large shopping mall in Thailand as loads for BEMS. Figure 2 and Figure 3 show the hourly electrical and cooling load profiles which are modified from 15-minute real electrical load profiles metered from 2 to 29 June 2012 to suit the purposes of the study. Obviously, the daily pattern of the load profiles looks similar but has different peak which is in the range of 22-24.5 MW for electrical loads and 38.69-43.26 MW or 11,100-12,300 tonnes of refrigeration (TR) for cooling loads. However, the selected shopping mall, in fact, uses the electric chiller with the capacity of 12,000 TR, so it sometimes cannot provide CE to meet peak demand. Moreover, the electrical power system of the building is connected to 69 kV distribution grids of Metropolitan Electricity Authority (MEA) as the primary energy supply source. Hence, TOC and TCOE of the conventional BEMS come from electricity tariffs and equivalent CO_2 emissions from power grids. On the contrary, the energy sources of the proposed BEMS are concentrated on natural gas as the primary and electricity from power grids as the secondary one.

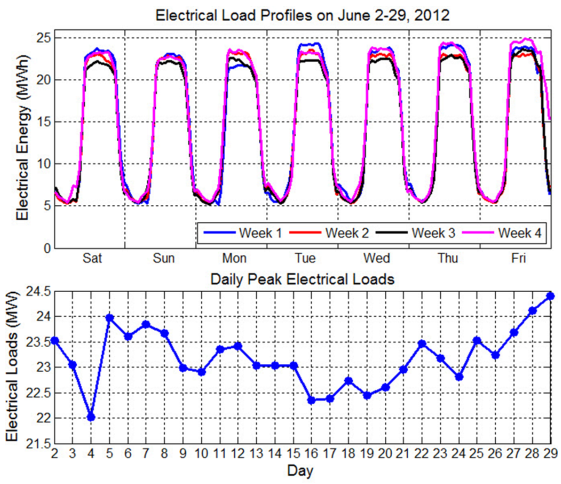

Fig.2: *Electrical load profiles and peak power.*

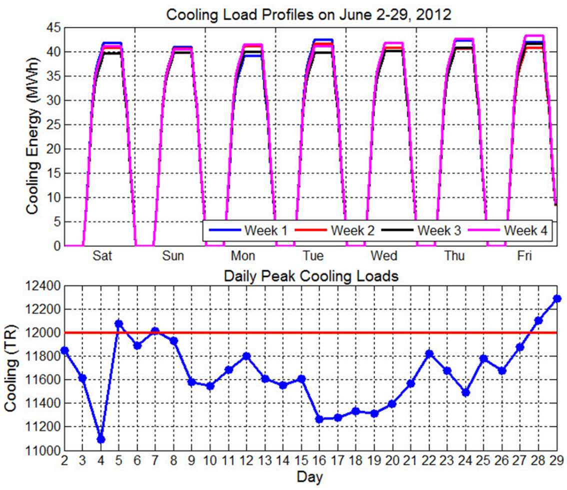

Fig.3: *Cooling load profiles and peak power.*

Natural gas tariff (NGT), Baht/MMBtu, for business operators [16], according to National Energy Policy Commission, is calculated as follows:

$$NGT = APNG + min(0.0933 \times APNG, 11.4759) + 13.1766 \tag{6}$$

where APNG is a monthly average price of natural gas or a pool price of natural gas (Baht/MMBtu). This term can be checked from the Department of Mineral Fuels, Minister of Energy [18]. The second term in (6) is the remuneration for the gas supply and distribution service which depends on consumer's type [16]. The last term in (6) is the total charge of gas transportation provided by a natural gas supply company [17].

Electricity prices in Thailand are classified into time-of-day (TOD) and time-of-use (TOU) rates, but this study focuses on the latter for both electricity purchase and selling prices. TOU rates offer two electricity prices based on the time of day: on-peak time which is 9.00-22.00 on Monday-Friday and off-peak time which is the other. Monthly TOU tariffs, in general, consist of energy charge, demand charge, service charge, power factor charge, fuel adjustment charge (Ft), and VAT; however, this work only concentrates on the first two and omits the rest because they are fixed and very small charges. Therefore, the building operator pays 3.5982 and 2.1572 Baht/kWh for energy charge and 74.14 Baht/kW for demand charge with the schedule of large general service of MEA [20]. On the other hand, electricity selling prices for power producers using CHP systems [19] are the wholesale prices at which Electricity Generating Authority of Thailand (EGAT) sells electricity to MEA at connected voltage levels. Hence, BEMS earns 3.2504 and 2.0198 Baht/kWh for selling EE back to MEA distribution grids [21]. Finally, the grid emission factor (GEF) of Thailand is exploited to estimate equivalent CO_2 emissions when BEMS utilizes electricity from power grids. Table 1 summarizes all parameters about power grids for the study.

Table 1: *Parameters of power grids.*

Description		
Electrical energy charges for on-peak and off-peak time (Baht/kWh)	p_k	3.5982
		2.1572
Electrical energy selling prices for on-peak and off-peak time (Baht/kWh)	q_k	3.2504
		2.0198
Demand charge (Baht/kW)	d_{PG}	74.14
Grid emission factor (tCO_2/MWh)	GEF	0.5994

To design the proposed BEMS, we use the following guideline for equipment selection. First, we consider the type and capacity of CHP systems that suit electrical loads. Then, we choose the type and size of absorption chillers match the characteristics of heat production of CHP systems and cooling loads. Next, the capacity of auxiliary boilers is calculated from the heat shortage. Lastly, the well-designed combination will be simulated to find the best proposed BEMS.

CHP systems suitable for building [3], typically, have the capacity of 10-250 MW based on prime mover technologies, such as simple-cycle gas turbines, combined-cycle gas turbines, and steam turbines. In this work, we consider gas turbines as the CHP system of BEMS because their size is appropriate for the peak electricity demand. Also, gas turbines produce high temperature steam; for example, a 25 MW gas turbine can generate 150 pounds per square inch gauge (psig) saturated steam whose temperature is $185.55°C$ [2]. Due to the peak electricity demand, the CHP system data ranging from 22 to 25 MW, as shown in Table 2, are estimated based upon available technical data [2-4] and used as the candidates in the simulation. The minimum and maximum power production of the CHP systems, $P_{CHP,min}$ and $P_{CHP,max}$ are set to 20% and 100% of the rated power, and electrical energy ramp rate (R_{CHP}) is set

Table 2: *CHP data.*

CHP Systems							
Rated Power (MW)	Electrical Efficiency (%)	Power to Heat Ratio	Max Power Production (MW)	Min Power Production (MW)	Elec Energy Ramp Rate (MW)	CO_2 Emission Factor (tCO_2/MWh)	O&M Costs (Baht/MWh)
-	$\eta_{CHP,EE}$	P2H	$P_{CHP,max}$	$P_{CHP,min}$	R_{CHP}	EF_{CHP,CO_2}	OM_{CHP}
22	33.11	0.8933	22	4.4	22	0.5497	0.1598
23	33.51	0.9088	23	4.6	23	0.5423	0.1555
24	33.90	0.9244	24	4.8	24	0.5349	0.1513
25	34.30	0.9400	25	5.0	25	0.5275	0.1470

Table 3: *Combinations for proposed BEMS.*

CHP System (MW)	Absorption Chiller (TR)	Auxiliary Boiler (MMBtu/hr)
22	12,000	50
23	12,000	45
24	12,000	45
25	12,000	45

to 100% of the rated power thanks to the fast start capability of gas turbines, i.e., operating at full load within a few minutes. Furthermore, the operating costs of the CHP system (C_{CHP}) can be computed from the following equation:

$$c_{CHP}(Baht/MWh) = \frac{NGT \times 3.412}{\eta_{CHP,EE}} + OM_{CHP} \quad (7)$$

where OM_{CHP} is operation and maintenance costs of the CHP system.

Absorption chillers are commercially categorized into two types: single-effect absorption chillers (SEAC) and double-effect absorption chillers (DEAC) [11-12]. SEAC are available in sizes ranging of 100-1,500 TR and suitable for 14.5-29 psig steam input. DEAC are in the same range but require 130.5-145 psig steam input. Besides, coefficient of performance (COP_{AC}) of absorption chillers are in the range of 0.6-0.7 and 0.9-1.2, but the energy usage regulation in new buildings [15] recommends at least 0.65 and 1.1 for the single-effect and double-effect types, respectively. Therefore, in this work, we choose DEAC with the COP_{AC} of 1.1 because the steam output of the CHP system matches the steam input of absorption chiller. However, the total capacity of the chiller is fixed at 12,000 TR or 42.2 MW which is the same size of the present chiller at the shopping mall. Auxiliary boilers suitable for the proposed BEMS are industrial combustion boilers due to the variety of the capacity, MMBtu/hr. Industrial boilers firing natural gas, generally, has approximately 75% of thermal efficiency [13] and CO_2 emissions per HE output (EF_{AB,CO_2}) 0.181 tCO_2/MWh [14]. The capacity of boilers, in the study, is chosen from the heat shortage depending on

Table 4: *Parameters of equipment and other notations.*

Absorption Chiller		
Rated cooling power (MW)	-	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
Auxiliary Boiler		
Rated heat power (MW)	-	-
Efficiency (%)	η_{AB}	75
Maximum heat production (MW)	$HP_{AB,max}$	-
Minimum heat production (MW)	$HP_{AB,min}$	-
CO_2 emission factor from natural gas combustion (tCO_2/MWh)	EF_{AB,CO_2}	0.1810
Operation and Maintenance Costs (Baht/MWh)	OM_{AB}	0.1980
Other notations		
Electrical energy demand in each time interval (MWh)	U_k	-
Cooling energy demand in each time interval (MWh)	C_k	-
Counter indices of time intervals for variables	k	-
Time duration of each time interval (hr)	Δt	1
Number of time intervals in a day	n	24
Number of days in a month (days)	d	28
Average Price of Natural Gas as of June 2012 (Baht/MMBtu)	APNG	211.75

the CHP candidates. Moreover, the minimum and maximum heat production of the boiler, $HP_{AB,min}$ and $HP_{AB,min}$, are set to 20% and 100% of the rated heat power, and the operating costs of the boiler can be calculated as follows:

$$c_{AB}(Baht/MWh) = \frac{NGT \times 3.412}{\eta_{AB}} + OM_{AB} \quad (8)$$

where OM_{AB} is operation and maintenance costs of the boiler which are referred to Hashemi's survey [5]. Table 3 and 4 give the combinations and parameters related to the absorption chiller, the auxiliary boiler and others to be used in the study.

5. DESIGN RESULTS

In this section, we investigate which combination of the equipment is the best for the proposed BEMS. We compare TOC and TCOE of all combinations of the proposed BEMS with those of the conventional one. For the conventional BEMS, the shopping mall pays TOC of 39,924,388 Baht and produces TCOE of 7,503 tCO_2. To analyze TOC further, EC and DCC are 37,543,604 and 2,380,784 Baht or account for 94.04% and 5.96%, respectively. We use aforementioned information to design the capacity of each component in BEMS. For example, a 22-MW CHP system can produce heat 24.63 MW, but the 12,000-TR DEAC requires heat input 38.37 MW; as a result, the heat shortage 13.74 MW or 46.88 MMBtu/hr is compensated from the auxiliary boiler with the size of 50 MMBtu/hr. Each choice of the proposed BEMS is simulated under economic and environmental optimal operations with APNG of June 2012 [18], i.e., 211.75 Baht/MMBtu. Table 5 summarizes TOCs and TCOEs of the combinations of the proposed BEMS under the economic and environmental optimal operations. The results indicate that all candidates can reduce TOCs and TCOEs. TOCs decrease by 24.0%-30.2% for the economic optimal operation and 22.0%-26.6% for the environmental operation. Clearly, the larger the capacity of CHP systems is, the lower TOC is. It can be explained that when the size of CHP increases, the proposed BEMS earns more income from selling EE and the operating costs of the CHP system decrease according to its operation and maintenance costs. If we consider the constitution of TOCs as shown in Table 6, ECs and DCCs represent 99.4%-100% and 0%-0.6% of TOCs for both optimal operations. This result shows that the proportion of EC increases and the proportion of DCC decreases, compared to those of the conventional BEMS. It reflects that the proposed BEMS utilizes electricity from power grids as little as possible to obtain the minimum DCC. However, when compared to EC of the conventional BEMS, ECs of the proposed BEMS decrease by 19.7%-25.8% and 17.6%-21.9% for the economic and environmental optimal operations, respectively. DCCs, which look quite similar for both optimal operations, are reduced more than 92.5% and up to 100% when the capacity of CHP is larger than peak electricity demand. To investigate the contribution of EC to the decrease in TOC, Table 7 reveals ECs of each component of the proposed BEMS, including income from selling EE to power grids. It is obvious that when the capacity of the CHP system increases, the CHP system produces more EE. As a result, total EC goes up. Nevertheless, the proposed BEMS can earn additional income due to the increase in EE export, so net EC of the CHP system does not increase much. The increase in EE generation of the CHP system leads to the decrease in HE production of the auxiliary boiler and EE utilization from power grids. Therefore, ECs of the boiler and power grids decline. The decrease of EC results in the decrease in TOC.

TCOEs decrease by 10.4%-11.6% for the economic optimal operation and 13.0%-14.0% for the environmental operation. The decreasing trend does not depend on the size of the CHP system, i.e., TCOE does

Table 5: *System design results.*

CHP (MW)	Economic Optimal Operation		Environmental Optimal Operation	
	TOC (Baht)	TCOE (tCO_2)	TOC (Baht)	TCOE (tCO_2)
22	30,329,548	6,669	31,123,557	6,526
23	29,483,497	6,635	30,450,384	6,458
24	28,686,091	6,671	29,892,437	6,455
25	27,877,388	6,624	29,309,652	6,484

Table 6: *Energy and demand charge costs.*

CHP (MW)	Economic Optimal Operation		Environmental Optimal Operation	
	EC (Baht)	DCC (Baht)	EC (Baht)	DCC (Baht)
22	30,152,250	177,298	30,946,259	177,298
23	29,380,339	103,158	30,347,226	103,158
24	28,649,881	36,210	29,863,4197	29,018
25	27,877,388	0	29,309,652	0

Table 7: *Energy costs according to equipment.*

CHP (MW)	Equipment		Economic Optimal Operation EC (Baht)	Environmental Optimal Operation EC (Baht)
22	CHP	Total EC	25,940,626	25,701,669
		Income	(1,705,461)	(503,515)
		Net EC	24,235,165	25,198,154
	Boiler		4,501,483	5,017,948
	Power Grids		1,415,602	730,155
23	CHP	Total EC	26,795,345	26,030,038
		Income	(2,281,377)	(706,605)
		Net EC	24,513,968	25,323,433
	Boiler		4,194,461	4,866,588
	Power Grids		671,910	157,205
24	CHP	Total EC	27,787,078	26,247,007
		Income	(3,242,411)	(1,168,194)
		Net EC	24,544,667	25,078,813
	Boiler		3,883,994	4,779,854
	Power Grids		221,220	4,752
25	CHP	Total EC	28,650,953	26,543,829
		Income	(4,337,845)	(1,880,039)
		Net EC	24,313,108	24,663,790
	Boiler		3,564,280	4,645,862
	Power Grids		0	0

Table 8: *CO_2 Emissions according to equipment.*

CHP (MW)	Economic Optimal Operation			Environmental Optimal Operation		
	CHP (tCO_2)	Boiler (tCO_2)	Grids (tCO_2)	CHP (tCO_2)	Boiler (tCO_2)	Grids (tCO_2)
22	5,493	853	323	5,443	951	132
23	5,670	795	170	5,509	922	27
24	5,874	736	61	5,548	906	1
25	6,049	675	0	5,603	881	0

not decrease continuously like TOC even if the CO_2 emission factor of the CHP system goes down according to the capacity. Table 8 shows CO_2 emissions of each component. It demonstrates that there are two trends in CO_2 emissions: an upward trend of the CHP system and a downward trend of the boiler and grids. The CHP system working under both optimal operations is likely to increase CO_2 emissions due to the increase in selling EE to power grids and in producing more HE to the absorption chiller. On the contrary, the auxiliary boiler and power grids have a tendency to supply less HE and EE when the capacity of the CHP system increases. These two trends cause changes in TCOE in two directions. TCOE starts with decrease because the downward trend is more outstanding; then they change to increase due to the upward trend. As a result, the proposed BEMS has the minimum TCOE when the capacity of the CHP system is 23 and 24 MW for the economic and environmental optimal operations, respectively. Finally, to find the best combination of the proposed BEMS, we need to consider the criteria for the selection. From Table 5, it is observed that all candidates working under both optimal operations can reduce TOC more and more when the capacity of the CHP increases. Therefore, TOC is not suitable to be used as a decision criterion. On the other hand, Table 5 demonstrates that there are two minimum TCOEs depending on the operation. This result shows that TCOE is appropriate to be used as a decision criterion. In this study, we choose minimum TCOE of the environmental optimal operation as the decision criterion because this operation is designed to obtain the minimum TCOE. As a result, we select the 24-MW CHP, 12000-TR double-effect absorption chiller, and 45-MMBtu/hr auxiliary boiler as the best combination for the proposed BEMS.

6. ANALYSIS OF OPTIMAL OPERATIONS

After obtaining the best combination of BEMS, we analyze the operating behavior of each component under the economic and environmental optimal operations. In particular, we will investigate how each component of the proposed BEMS works under the economic and environmental optimal operations and whether the proposed BEMS can supply EE and CE to meet the demand.

In the analysis, the optimal energy flows on 5 June 2012, a workday, are chosen as examples because we can examine the effect of TOU rates on the optimal operations; moreover, the peak cooling demand of this day is more than the rated cooling power of the absorption chiller, so we will see that how the chiller operates in this situation. Lastly, the relationship between the economic and environmental optimal operation is established via the multi-objective approach.

6.1 Deciding Factors in Optimal Operations

Before analyzing the optimal operations of the proposed BEMS, we investigate deciding factors in the economic and environmental optimal operations of each component.

In view of the economic optimal operation, the proposed BEMS orders the equipment to supply EE or CE based on deciding factors: EE production cost of the CHP system, electricity prices of power grids, and CE production costs of the absorption chiller. The EE production cost and electricity prices are related to the operation of the CHP system and power grids. The EE production cost of the 24-MW CHP system based on APNG as of June 2012 is 2.5308 Baht/kWh which is greater than the EE charge and selling price during off-peak time. Hence, in this period of time, the proposed BEMS should not sell EE and may utilize EE from power grids but not much due to the existence of the demand charge. During on-peak time, the EE production cost is lower than the EE charge and selling price, so the CHP system should operate at the maximum EE production level to supply EE to electrical loads and earn income from excessive EE generation. The CE production costs of the absorption chiller rely on 3 ways of HE supply: HE coincident with EE generation of the CHP system to electrical loads and power grids, HE produced by the CHP system to cooling loads, and HE produced by the auxiliary boiler. Generally, the proposed BEMS utilizes HE from the CHP system first if it results from generating EE to electrical loads or earning income from power grids during the on-peak time. In this case, the absorption chiller has no CE production cost because the proposed BEMS obtains free HE which is coincident with EE genera-

Table 9: *Comparison of EE and CE production costs and electricity prices.*

EE Production Cost and Electricity Prices	
EE production cost of CHP (Baht/kWh)	2.5308
Electrical energy charges for on-peak and off-peak time (Baht/kWh)	3.5982 2.1572
Electrical energy selling prices for on-peak and off-peak time (Baht/kWh)	3.2504 2.0198
Demand charge (Baht/kW)	74.14
Cooling Costs	
CE production cost of absorption chiller using HE from CHP (Baht/kWh$_{CE}$)	2.1268
CE production cost of absorption chiller using HE from auxiliary boiler (Baht/kWh$_{CE}$)	1.5437

Table 10: *Comparison of CO_2 emission factors.*

CO_2Emission Factors	
CO_2 emission factor of CHP (tCO_2/MWh)	0.5349
Grid emission factor (tCO_2/MWh)	0.5994
Equivalent CO_2 emission factor of absorption chiller using HE from CHP (tCO_2/MWh$_{CE}$)	0.4495
Equivalent CO_2 emission factor of absorption chiller using HE from auxiliary boiler (tCO_2/MWh$_{CE}$)	0.2195

tion of the CHP system. However, if free HE is not enough for the absorption chiller to satisfy CE demand, the proposed BEMS orders the CHP system to produce HE more if it does not operate at the maximum EE production level yet; otherwise, the proposed BEMS commands the auxiliary boiler to start operating. In last two cases, the absorption chiller has the CE production costs which can be calculated from the amount of HE required to generate one megawatt-hour of CE (MWh$_{CE}$). Therefore, the absorption chiller has the CE production costs of 2.1268 and 1.5437 Baht/MWh$_{CE}$ when using HE from the CHP system and auxiliary boiler, respectively. Table 9 summarizes the comparison of EE and CE production costs and electricity prices based on APNG as of June 2012. In view of the environmental optimal operation, the proposed BEMS commands the equipment to supply EE and CE based on deciding factors: CO_2 emissions factor of the CHP system, grid emission factor, and equivalent CO_2 emissions factors of the absorption chiller. The CO_2 emission factor of the 24-MW CHP system and grid emission factor, which are directly linked to EE supply, are 0.5349 and 0.5994 tCO_2/MWh; therefore, the proposed BEMS should use the CHP system as the main EE supply source to obtain the minimum TCOE. Like the CE production costs, equivalent CO_2 emissions of the absorption chiller are considered according to HE supply sources. The absorption chiller supply CE with CO_2 emissions if it does not use free HE which is coincident

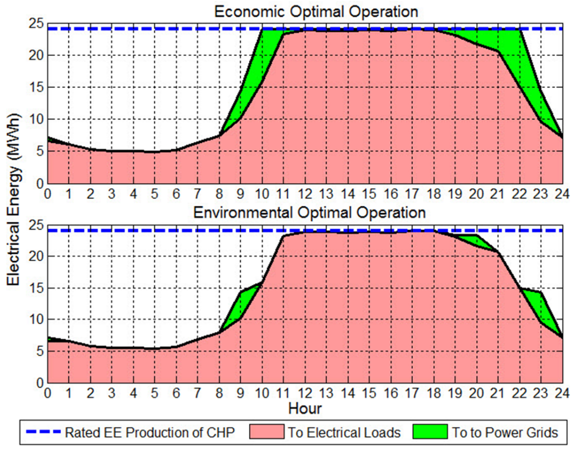

Fig.4: *EE production of CHP.*

with EE generation of the CHP system to electrical loads and power grids. The equivalent CO_2 emission factors of the absorption chiller can be computed from CO_2 emissions released to produce a megawatt-hour of CE, i.e., 0.4495 and 0.2195 tCO_2/MWh$_{CE}$ for the chiller using HE from the CHP system and auxiliary boiler, respectively. Table 10 summarizes the comparison of CO_2 emissions factors.

6.2 Analysis of the CHP system

Figure 4 and 5 show EE and HE production of the CHP system on 5 June 2012. Obviously, the CHP system mainly generates EE to electrical loads rather than sells it while coincident HE is supplied to the absorption chiller except when there is no cooling demand, i.e., this HE is released as waste HE.

In view of the economic operation, the CHP system depends on EE and CE production costs, including electricity prices of power grids. During the on-peak time or 9.00-22.00, the EE production cost of the CHP system is lower than both the EE charge and selling price, so the CHP system generates EE at the maximum level in order to supply electrical loads with lower costs and export the surplus EE to power grids to reduce operating costs as much as possible. Most of the coincident HE is supplied to the absorption chiller as HE without costs, and a little of it is released as waste HE. During the off-peak time, the CHP system produces EE only to electrical loads and does not export EE to power grids because the EE production cost is higher than the EE prices.

In view of the environmental operation, the CHP system operates following either electrical or cooling loads in each hour but does not try to export EE because it causes additional CO_2 emissions unnecessarily. Almost all of the operation time, the CHP system produces EE following EE demand except when HE demand for the absorption chiller is more than the existing HE which is coincident with EE generation of the CHP system to electrical loads.

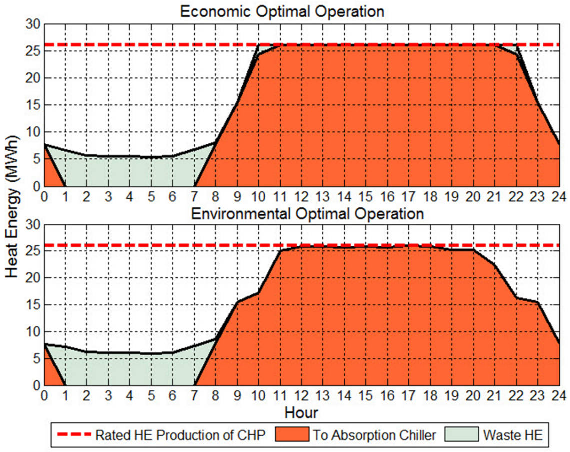

Fig.5: *HE production of CHP.*

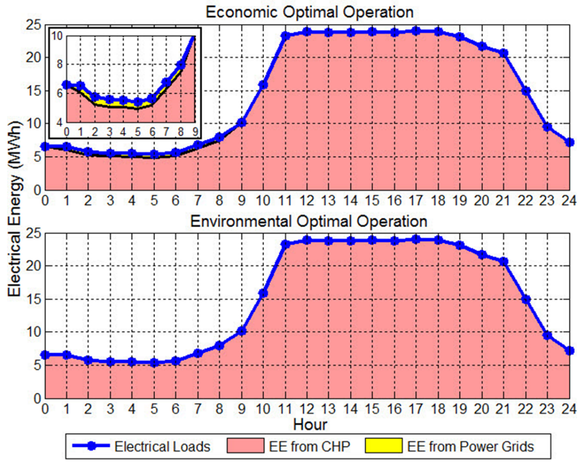

Fig.6: *EE flow to electrical loads.*

In the case of operation following cooling loads, the proposed BEMS has two choices in dealing with the heat shortage. First, it orders CHP system to produce heat more. Second, it commands auxiliary boiler to start generating heat. The proposed BEMS decides which one offers the minimum CO_2 emissions. The proposed BEMS will choose the first if the heat shortage is little. In other words, it is worth having the CHP system produces heat a little bit more instead of running the auxiliary boiler at the minimum heat production level which may causes more CO_2 emissions. When the CHP system produces heat more, it operates following cooling loads and the surplus EE will be sold to power grids.

6.3 Analysis of the optimal EE flows to electrical loads

Figure 6 demonstrates that the proposed BEMS supplies EE to meet EE demand. Noticeably, EE flows of both optimal operations look quite similar, i.e., almost all of EE is supplied from the CHP system, but the reason why each optimal operation dispatches such EE flows is different.

On the subject of the economic optimal operation, the proposed BEMS uses the CHP system as the primary EE supply source for electrical loads with the following reason. During the on-peak time, the CHP system is the main supply source because the EE production cost is lower than the EE charge. However, during the off-peak time, the cost is higher than the charge, so power grids participate in supplying EE to electrical loads to reduce operating costs as little as possible. In this case, the proposed BEMS needs to compromise three factors, namely, the EE production cost, EE charge, and demand charge. As a consequence, the proposed BEMS still exploits the CHP system as the main EE supply source but permits power grids to provide a little bit of EE to electrical loads to obtain the minimum operating costs in this period of time.

With regard to the environmental optimal operation, the proposed BEMS considers CO_2 emission factors before deciding which power source between the CHP system or power grids is in charge of supplying EE to electrical loads. Due to the fact that the CO_2 emission factor of the CHP system is lower than grid emission factor, the CHP system is the main EE supply source, and power grids will not take part in supplying EE as long as the CHP system can provide EE to meet the demand.

6.4 Analysis of the optimal CE flows to cooling loads

Figure 7 displays CE flows to cooling loads. It reveals that the proposed BEMS can supply CE to meet CE demand almost all of the operation time except when peak cooling demand is greater than the rated cooling power of the absorption chiller. In that case, the chiller operates at the maximum CE production level and cannot provide CE to satisfy CE demand. The CE production of the chiller working under both optimal operations is the same, i.e., trying to supply CE to meet CE demand, but HE supply to the chiller is different.

As analyzed earlier for the economic optimal operation, the CHP system produces HE at the maximum level during the on-peak time due to EE export, and this HE production has no cost. Therefore, the proposed BEMS utilizes this existing HE before the HE produced from the auxiliary boiler which has the HE production cost.

As examined earlier for the environmental operation, the CHP system provides HE according to its operation modes: following electrical or cooling loads. Generally, the CHP system operates in the first mode which offers HE proportional to EE supplied to electrical loads, so we can consider that the absorption chiller produces CE without CO_2 emissions. However, if there is little heat shortage, the CHP system

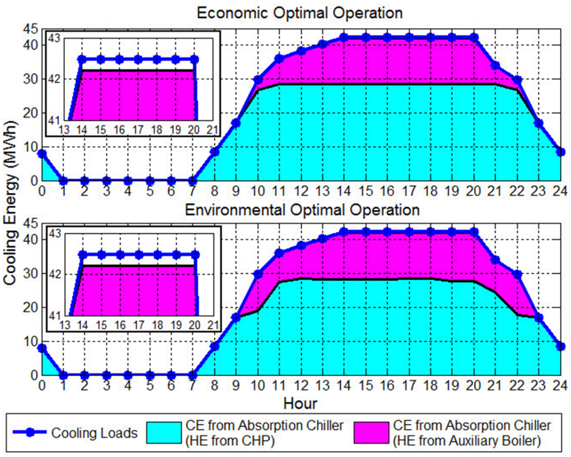

Fig.7: CE flow to cooling loads.

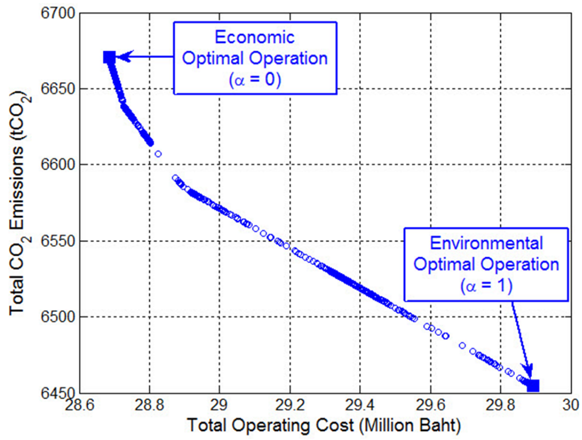

Fig.8: Relationship between economic and environmental optimal operations.

Fig.9: APNG during 2003-2012.

will operate in the second mode which causes extra CO_2 emissions a little bit more. If the shortage increases, the proposed BEMS will change the operation of the CHP system to the first mode and order the auxiliary boiler to start supplying HE instead due to its lower CO_2 emission factor. Therefore, the proposed BEMS supplies HE to the absorption chiller depending on which HE source offers the minimum CO_2 emissions at that hour.

6.5 Relationship between economic and environmental optimal operations

To find the relationship between the economic and environmental optimal operations, we apply a weighted sum approach to those two objective functions and then solve this optimization problem for each weighting factor varied from 0 to 1. When the weighting factor is 0, we obtain the economic optimal operation. On the other hand, the linear combination becomes the environmental optimal operation problem when the weighting factor increases to 1. Figure 8 shows the relationship between two optimal operations is a trade-off between TOC and TCOE. If the proposed BEMS operates with low TOC, it gives high TCOE. This curve is useful for operators in changing operating points of the proposed BEMS apart from the economic or environmental operating point. For example, if operators want to keep TOC less than 29 million Baht, the proposed BEMS will have TCOE in the range of 6,570-6,671 tCO_2 depending on their decision.

7. IMPACT OF APNG

This section investigates the risk in a long-term operation of the proposed BEMS. In particular, we focus on analyzing an impact of APNG onto TOC, TCOE, and optimal operations of equipment. APNG is the most important external factor because it is an unscontrollable factor for building owners but has a direct and major effect on the operating costs of equipment like the CHP system and auxiliary boiler in a long run. Figure 9 shows APNG in Thailand during 2003-2012 [18]. Obviously, APNG increases almost every year and more than twice in 10 years. Besides, the lifetime of equipment in the proposed BEMS, typically, is in the range of 20-30 years, so this is the reason we need to consider the impact of APNG in a long-term operation. In the simulation, we vary APNG from 50 to 550 Baht/MMBtu and then solve the economic and environmental optimal operation problems of the proposed BEMS, while EE charges, EE selling prices, and CO_2 emission factors are fixed.

7.1 Impact of APNG on TOC

Figure 10 indicates that TOCs of both optimal operations increase linearly as APNG goes up. TOC of the environmental optimal operation rises steadily, but TOC of the economic optimal operation go up dramatically until APNG reaches 160 Baht/MMBtu due to exporting EE to cut TOC as much as possible; then, it starts reducing EE export and grows with the

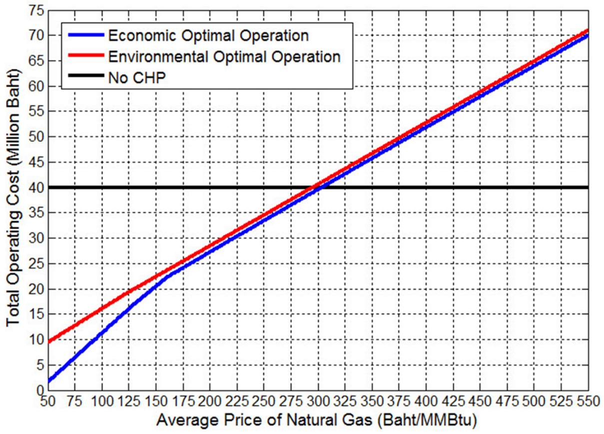

Fig.10: *TOC vs. APNG.*

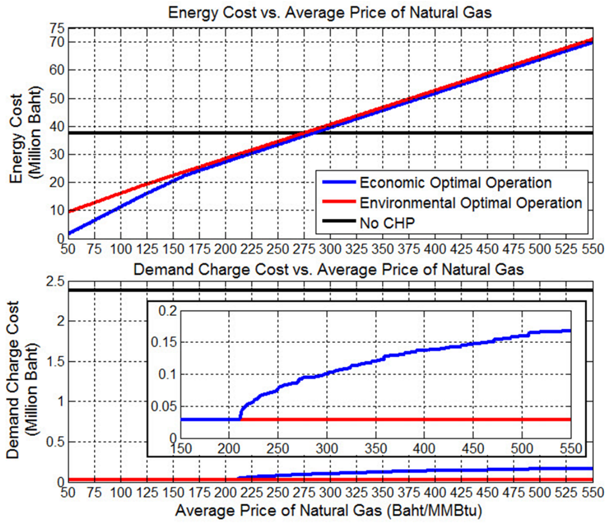

Fig.11: *EC and DCC vs. APNG.*

same rate of TOC of the environmental one. Moreover, TOCs of the proposed BEMS are more than TOC of the conventional one when APNGs reach 295 and 303 Baht/MMBtu, which means that it is not worth using the proposed BEMS. If we delve deeply into the constitution of TOC, Figure 11 shows ECs and DCCs versus APNG. ECs of both optimal operations go up linearly like TOC, but DCCs is different. DCC of the economic optimal operation is constant until APNG reaches 211 Baht/MMBtu; then, it begins to increase nonlinearly but is still much less than DCC of the conventional BEMS. On the other hand, DCC of the environmental optimal operation is constant; this means that the change in APNG does not cause any effect on DCC. The reason is that APNG does not cause change in CO_2 emission factors, and the grid emission factor is still higher than the CO_2 emission factor of the CHP system. As a result, the proposed BEMS needs to keep utilizing electricity from power grids as little as possible in order to obtain the minimum CO_2 emissions.

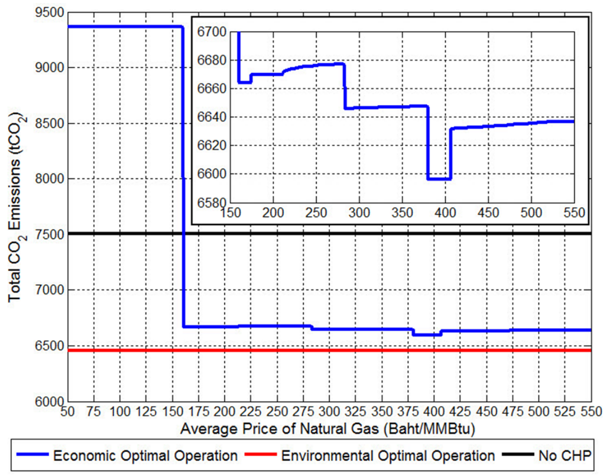

Fig.12: *TCOE vs. APNG.*

7.2 Impact of APNG on TCOE

Figure 12 shows TCOEs of both optimal operations. Obviously, TCOE of the environmental optimal operation is constant because CO_2 emission factors which are the important deciding factors in the operation do not depend on APNG. Therefore, the change in APNG does not cause any effect on TCOE; in other words, each component of the proposed BEMS still works at the same environmental optimal operating point. In contrast, TCOE of the economic optimal operation changes in six steps at APNGs of 161, 175, 211, 283, 380, and 407 Baht/MMBtu. To investigate the causes of the change, we consider the changes in the EE production cost of the CHP, the CE production costs of the absorption chiller, and the net energy production and the usage of each component. The changes of TCOE of the economic optimal operation will be analyzed in the next subsections.

7.3 Impact of APNG on EE and CE Costs

Figure 13 shows the EE production cost of the CHP system versus APNG. The EE production cost of the CHP system increases linearly. When we consider it together with the EE charges and EE selling prices which is fixed in the simulation, the result is that there are 4 intersection points at APNGs of 161, 175, 283, and 318 Baht/MMBtu. Hence, the CHP system and power grids could cooperate in 5 possible schemes for the EE dispatch under the economic optimal operation. These schemes depend on the range of APNG as follows.

Scheme 1: When APNG is less than 161 Baht/MMBtu, the EE production cost of the CHP system is lower than the off-peak EE selling price. The CHP system should operate at the maximum EE production level throughout the operation. In other words, the proposed BEMS should earn income from selling EE during off-peak and on-peak time to reduce operating costs as much as possible. Moreover, the proposed BEMS should not utilize EE from power grids to supply electrical loads as long as the CHP system can provide EE to meet EE demand.

Scheme 2: When APNG is in the range of 161-175 Baht/MMBtu, the EE production cost is higher than the off-peak EE selling price but still lower than the off-peak EE charge. During the off-peak time, the CHP system should stop selling EE to power grids and only generate EE electrical loads. During the on-peak time, the CHP system still operates at the maximum EE production level to earn income from selling EE. Furthermore, the proposed BEMS still does not need to utilize EE from power grids.

Scheme 3: When APNG is in the range of 175-283 Baht/MMBtu, the EE production cost is greater than the off-peak EE charge but less than the on-peak EE selling price. During the off-peak time, the CHP system should reduce EE production to electrical loads, and power grids should take part in supplying EE to meet the demand. In this case, the proposed BEMS need to compromise among the EE production cost, the off-peak EE charge, and the demand charge before deciding how much EE the CHP system and power grids should supply to meet EE demand with the minimum TOC. During the on-peak time, the CHP system still operates at the maximum EE production level and power grids participate in supplying EE in case of electricity shortage.

Scheme 4: When APNG is in the range of 283-318 Baht/MMBtu, the EE production cost is higher than the on-peak selling price but still lower than the on-peak EE charge. During the off-peak time, the CHP system and power grids should operate like their cooperation in the scheme 3. During the on-peak time, the CHP system should stop selling EE and only generate EE to electrical loads; moreover, power grids will supply EE when there is electricity shortage.

Scheme 5: When APNG is greater than 318 Baht/MMBtu, the EE production cost is higher than the on-peak EE charge. The proposed BEMS compromises the cooperation between the CHP system and power grids based on the EE production cost, the EE charges and the demand charge during the off-peak and on-peak time in order to obtain the minimum TOC.

Figure 14 shows the CE production costs of the absorption chiller using HE from the CHP system and auxiliary boiler versus APNG. These two CE production costs increase linearly, but the CE production cost of the chiller using HE from the CHP system rises more rapidly. Therefore, the proposed BEMS under the economic optimal operation should reduce HE supply from the CHP system and increase HE production of the auxiliary boiler when APNG increases.

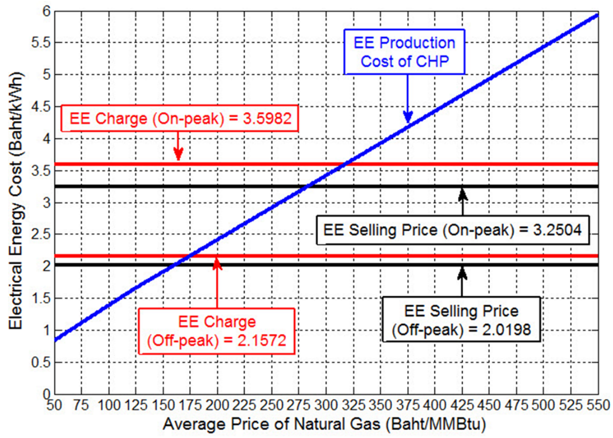

Fig.13: Electricity costs vs. APNG.

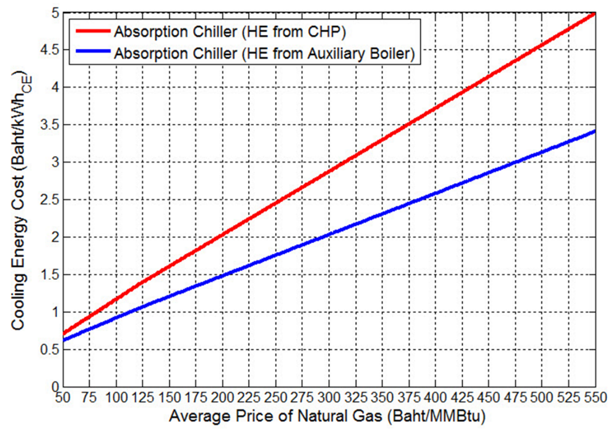

Fig.14: Cooling costs vs. APNG.

7.4 Impact of APNG on optimal operations

Figures 15-17 show the EE dispatch of the CHP system and power grids and Figure 18 displays the HE dispatch of the CHP system and the auxiliary boiler to the absorption chiller. As analyzed via TCOE earlier, the optimal operating point of each component in the proposed BEMS working under the environmental optimal operation does not change following APNG; therefore, we will not further discuss the EE and HE production of equipment under this operation. On the contrary, the EE and HE dispatch of the proposed BEMS working under the economic optimal operation causes 6-step changes in TCOE. Figure 15 reveals that total EE production of the CHP system based on loads as of June 2012 has 6-step changes like the changes of TCOE. In other words, each operating point of the CHP system causes a direct change of TCOE. Figure 16 demonstrates that total EE supply to electrical loads results in 3-step changes and the other 3-step changes result from total exported EE to power grids as shown in Figure 17. Figure 18 displays total HE supply to the absorption chiller which contributes to supporting the investigation. In summary, the changes of TCOE due to the economic optimal operation can be explained as follows.

Step 1:At APNG of 161 Baht/MMBtu, the EE production cost of the CHP system starts rising higher than the off-peak EE selling price, so the CHP system stop exporting EE to power grids during the off-peak time (see in Figure 17). As a result, TCOE falls sharply following the largest decrease in total EE production of the CHP system.

Step 2:At APNG of 175 Baht/MMBtu, the EE production cost of the CHP system begins to go higher than the off-peak EE charge, so the proposed BEMS decreases EE supply from the CHP system to electrical loads during the off-peak time but increases the utilization of EE from power grids instead (see in Figure 16). As a result, the CHP system reduces total EE production, but TCOE go up a little bit because the grid emission factor is greater than the CO_2 emission factor of the CHP system. In other words, EE from power grids causes CO_2 emissions more than that from EE from the CHP system.

Step 3:At APNG of 211 Baht/MMBtu, the demand charge starts having an influence on the economic optimal operation, i.e., the proposed BEMS needs to compromise among the EE production costs of the CHP system, the off-peak EE charge, and the demand charge in order to obtain the minimum TOC. The CHP system decreases EE supply to electrical loads continuously while power grids provide EE to them more and more (see in Figure 16). Therefore, total EE production of the CHP system decrease slowly, but TCOE increases gradually following maximum power from power grids.

Step 4:At APNG of 283 Baht/MMBtu, the EE production cost of the CHP system begins rising higher than the on-peak selling price, so the CHP system quits selling EE during the on-peak time (see in Figure 17). Consequently, TCOE drops following the total EE production of the CHP system.

Step 5:At APNG of 380 Baht/MMBtu, the cooling costs have an effect on the economic optimal operation, i.e., the proposed BEMS reduce HE supply from the CHP system in case of slight heat shortage. In other words, if APNG is less than 380 Baht/MMBtu, and it is worth commanding the CHP system to produce HE a little bit more, from existing HE proportion to EE generation to electrical loads, to supply the heat shortage. However, if APNG is greater than 380 Baht/MMBtu, it is worth using HE from the auxiliary boiler only to supply slight heat shortage. As a consequence, the CHP system reduces HE supply to the absorption chiller, but the auxiliary boiler takes charge of HE supply instead (see in Figure 18). Also, such an operation of the CHP system leads to the decrease in EE export during the on-peak time (see in Figure 17). Therefore, TCOE goes down because the CHP system reduces total EE production and the use of HE produced from the auxiliary boiler causes lower CO_2 emissions.

Step 6:At APNG of 407 Baht/MMBtu, the EE production cost of the CHP system is already greater than the on-peak EE charge, so the proposed BEMS needs to consider three factors, namely, the EE production cost, the on-peak EE charge, and the demand charge in order to acquire the minimum TOC. The CHP system decreases EE supply to electrical loads during the on-peak time while power grids increase EE supply instead (see in Figure 17). Also, this operation of the CHP system brings about the decrease in HE supply to the absorption chiller, so the auxiliary boiler has to produce additional HE to compensate the shortage (see in Figure 18). TCOE increases following the larger utilization of EE from power grids even though the total EE production of CHP decreases.

Finally, although the proposed BEMS can reduce both TOC and TCOE, it has a room for improvement, i.e., there is still waste HE from both optimal operations as shown in Figure 19. Almost all of waste HE occurs in the off-peak time when there is no CE demand. To improve energy efficiency in the proposed BEMS, we recommend adding heat storage to keep waste HE, especially in the off-peak time, and use it in the on-peak time to reduce TOC and TCOE. It is obvious that when APNG is in the range of 50-161 Baht/MMBtu, total waste HE is more than total HE production of the auxiliary boiler. Therefore, in this case, the proposed BEMS does not need HE from the auxiliary boiler; in other words, TOC and TCOE come only from the sum of operating costs and CO_2 emissions of the CHP system and power grids. However, if APNG is greater than 161 Baht/MMBtu, the utilization of waste HE contributes to reducing TOC and TCOE in part of operating costs and CO_2 emissions of the auxiliary boiler.To determine a suitable capacity of heat storage, we employ total waste HE shown in Figure 19. For example, if APNG is greater than 161 Baht/MMBtu, it is observed that total waste HE of both optimal operations is in the range of 1.03-1.35 GWh per month or 36.78-48.21 MWh per day. Therefore, we may choose the size of heat storage in the range of 37-49 MWh. To estimate on how much the full utilization of total waste HE contributes to cutting TOC and TCOE, we find that TOCs can be reduced by 5.5-8.4% and 6.8%-7.5% and TCOEs are decreased by 3.7-4.9% and 4.8% for the economic and environmental optimal operations, respectively.

8. CONCLUSIONS

In this paper, we demonstrate that the application of BEMS consisting of the CHP system, absorption chiller, and auxiliary boiler is suitable for a large shopping mall due to the pattern of electrical and cooling loads. We design a suitable combination of CHP systems and analyze economic and environmental optimal operations. The numerical results show

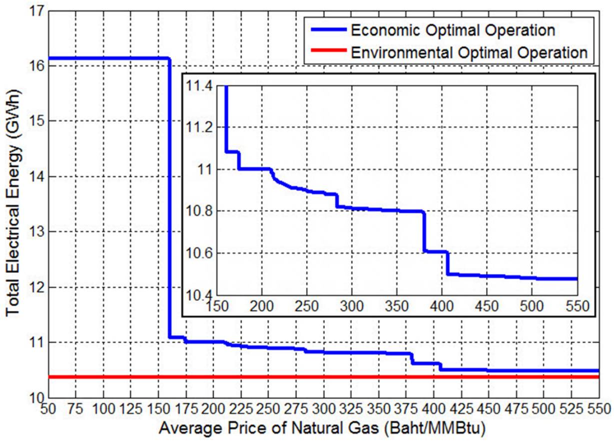

Fig.15: *Total EE production of CHP vs. APNG.*

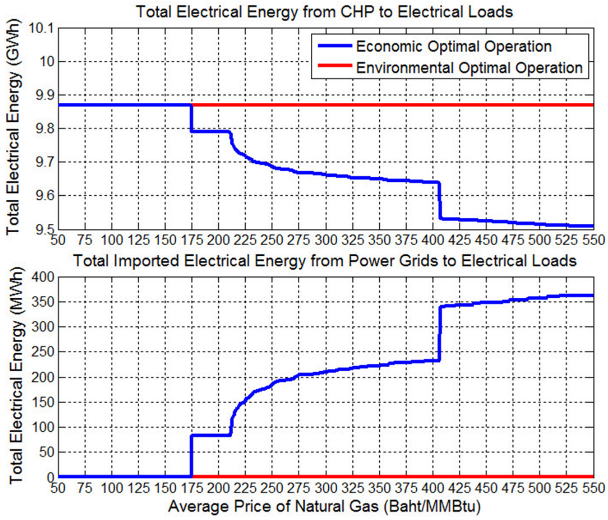

Fig.16: *Total EE supply to electrical loads vs. APNG.*

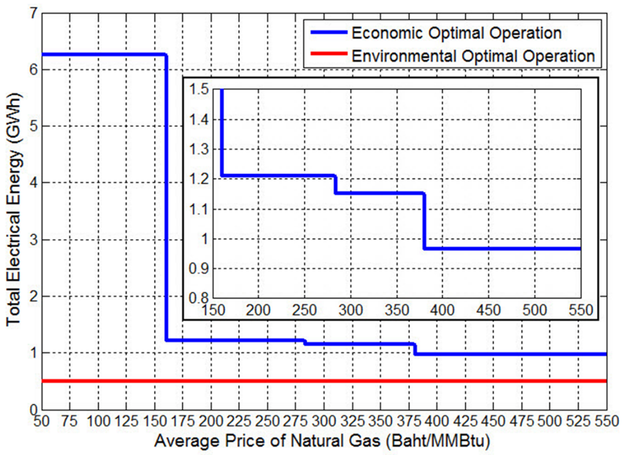

Fig.17: *Total EE exported to power grids vs. APNG.*

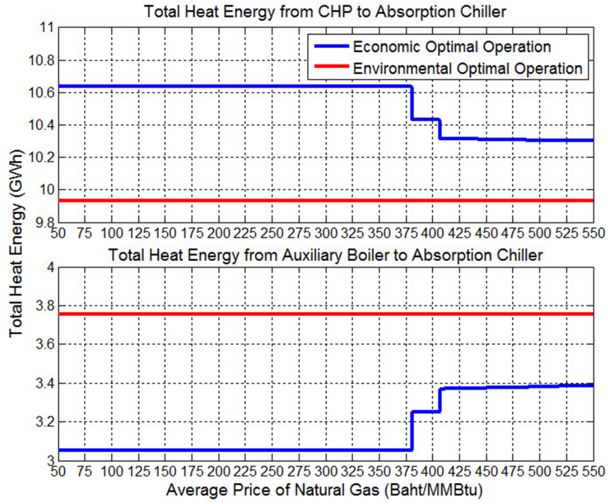

Fig.18: *Total HE supply to absorption chiller vs. APNG.*

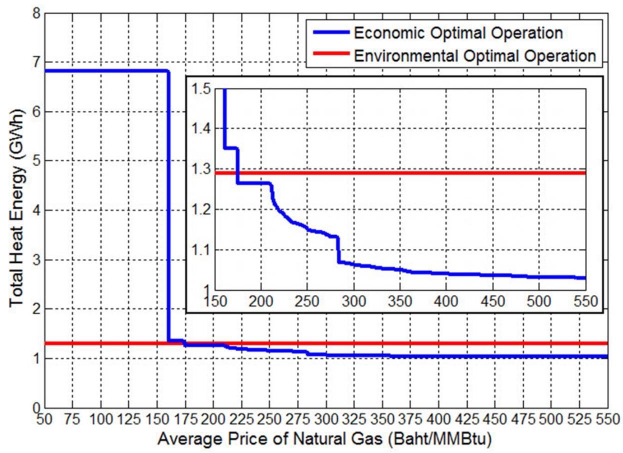

Fig.19: *Total waste HE vs. APNG.*

that the designed CHP system can reduce both TOC and TCOE up to 30% and 14%, compared to the original electricity usage. Furthermore, the fluctuation in APNG has impacts on a long-term operation.

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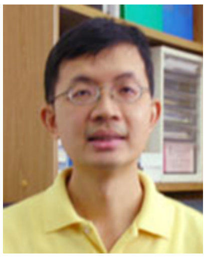

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