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AN ENVIRONMENTAL AND ECONOMIC OPTIMAL OPERATION OF COMBINED COOLING AND HEATING AND POWER GENERATION SYSTEM FOR BUILDING LOAD

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Electrical Engineering
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วิทยานิพนธ์ฉบับนี้นำเสนอการดำเนินการเหมาะที่สุดเชิงเศรษฐศาสตร์และสิ่งแวดล้อมของระบบการผลิตความร้อนและกำลังไฟฟ้าร่วมสำหรับระบบการจัดการพลังงานในอาคาร (building energy management system, BEMS) 2 ระบบ BEMS แรกประกอบด้วยระบบการผลิตความร้อนและกำลังไฟฟ้าร่วม, เครื่องทำน้ำเย็นแบบดูดซึม, หม้อต้มน้ำเสริม และกริดไฟฟ้า แต่ BEMS ที่สองแทนที่หม้อต้มน้ำเสริมด้วยเครื่องทำน้ำเย็นแบบไฟฟ้า ปัญหาการดำเนินการเหมาะที่สุดจะเกี่ยวข้องกับฟังก์ชันหลายวัตถุประสงค์ได้แก่ ต้นทุนการดำเนินการรวม (total operating costs, TOC) และการปล่อยก๊าซคาร์บอนไดออกไซด์รวม (total carbon dioxide emissions, TCOE) ส่วนยุทธวิธีการจ่ายพลังงานไฟฟ้าและความเย็นสำหรับแต่ละประเภทของ BEMS จะถูกนำมาใช้เป็นเงื่อนไขบังคับ ปัญหานี้สามารถกำหนดให้เป็นปัญหาการโปรแกรมเชิงเส้นซึ่งมีวิธีหาคำตอบอย่างมีประสิทธิภาพโดยเครื่องมือแก้ไขปัญหาการโปรแกรมเชิงเส้นต่างๆ อาทิเช่น กล่องเครื่องมือการหาค่าเหมาะที่สุดของ MATLAB วิทยานิพนธ์นี้ประยุกต์ใช้ BEMS กับโหลดการใช้ไฟฟ้าของห้างสรรพสินค้าขนาดใหญ่แห่งหนึ่งและการจำลองผลแบ่งออกเป็น 3 ส่วน ส่วนที่หนึ่งจะออกแบบขนาดของอุปกรณ์โดยตั้งอยู่บนพื้นฐานของรูปแบบโหลดไฟฟ้าและความเย็นของอาคารเพื่อหาขนาดเหมาะที่สุดสำหรับแต่ละ BEMS ผลลัพธ์เชิงตัวเลขแสดงให้เห็นว่า BEMS แรกสามารถลด TOC และ TCOE ได้สูงสุดถึง 30.2% และ 14.0% และ BEMS ที่สองสามารถลด TOC และ TCOE ได้สูงสุดถึง 37.5% และ 21.6% เมื่อเปรียบเทียบกับ TOC และ TCOE ของการใช้ไฟฟ้าแบบดั้งเดิม ส่วนที่สองจะวิเคราะห์การดำเนินการเหมาะที่สุดทั้งสองของ BEMS รวมไปถึงความสัมพันธ์ระหว่าง TOC กับ TCOE ผลลัพธ์การวิเคราะห์แสดงให้เห็นว่า ความสัมพันธ์ระหว่างทั้งสองการดำเนินการเหมาะที่สุดเป็นการแลกเปลี่ยนระหว่าง TOC กับ TCOE ส่วนสุดท้ายจะประเมินความเสี่ยงในการดำเนินการระยะยาวของ BEMS โดยใช้ผลกระทบของราคาเชื้อเพลิงต่างๆที่มีผลต่อ TOC, TCOE และการดำเนินการเหมาะที่สุด ผลลัพธ์การประเมินแสดงให้เห็นว่า ความผันผวนในราคาเชื้อเพลิงสามารถก่อให้เกิดความเสี่ยงในระยะยาว

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KEYWORDS : COMBINED HEAT AND POWER (CHP) / BUILDING ENERGY MANAGEMENT SYSTEM (BEMS) / ECONOMIC AND ENVIRONMENTAL OPTIMAL OPERATIONS / CO_2 EMISSIONS / LINEAR PROGRAMS

THANAKORN PETKAJEE : AN ENVIRONMENTAL AND ECONOMIC OPTIMAL OPERATION OF COMBINED COOLING AND HEATING AND POWER GENERATION SYSTEM FOR BUILDING LOAD. ADVISOR : PROF. DAVID BANJERDPONGCHAI, Ph.D., 95 pp.

This thesis proposes economic and environmental optimal operations of combined heat and power (CHP) systems for two building energy management systems (BEMS). The first BEMS consists of a CHP system, an absorption chiller, an auxiliary boiler, and power grids, but the second BEMS replaces an auxiliary boiler with an electric chiller. The optimal operation problem concerns with multi-objective functions: total operating costs (TOC) and total carbon dioxide emissions (TCOE), while electrical and cooling energy dispatch strategies for each BEMS are used as constraints. The problem can be formulated as a linear program (LP) which can be efficiently solved by LP solvers, such as MATLAB optimization toolbox. This thesis applies BEMS to load demand of a large shopping mall, and the simulation is divided into three parts. The first part designs the capacity of the equipment based on electrical and cooling load profiles of the building to find the most suitable combination for each BEMS. The numerical results demonstrate that the first BEMS can reduce TOC and TCOE by up to 30.2% and 14.0% and the second can decrease TOC and TCOE by up to 37.5% and 21.6%, compared TOC and TCOE of original electricity usage. The second part analyzes optimal operations of BEMS, including the relationship between TOC and TCOE. The analysis results indicate that the relationship between both optimal operations is a trade-off between TOC and TCOE. The final part investigates the risk in the long-term operation of BEMS via the impact of fuel prices on TOC, TCOE, and optimal operations. The assessment results reveal that the fluctuation in fuel prices can cause risks in the long run.

Department : Electrical Engineering Student's Signature

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CONTENTS

Page

ABSTRACT IN THAI iv

ABSTRACT IN ENGLISH v

ACKNOWLEDGEMENTS vi

CONTENTS vii

LIST OF TABLES x

LIST OF FIGURES xii

LIST OF ABBREVIATIONS xiv

CHAPTER I INTRODUCTION 1

- 1.1 Research Motivation 1
- 1.2 Literature Review 2
- 1.3 Thesis Objective 3
- 1.4 Scope of Thesis 3
- 1.5 Methodology 3
- 1.6 Contributions 3
- 1.7 Structure of Thesis 4

CHAPTER II BASIC KNOWLEDGE 5

- 2.1 Combined Heat and Power Technologies 5
- 2.2 Heating, Ventilation and Air-Conditioning 8
- 2.3 Industrial Boilers 9
- 2.4 Energy Usage in Buildings 10
- 2.5 Summary 11

CHAPTER III BEMS USING COMBINED HEAT AND POWER WITH BOILER **12**

- 3.1 System Description 12
- 3.2 Objective Functions 13
  - 3.2.1 Economic Optimal Operation 13
  - 3.2.2 Environmental Optimal Operation 14

Page

3.2.3 Multi-objective Approach 14

3.3 Dispatch Strategies 14

3.3.1 Electrical Energy Dispatch Strategy 14

3.3.2 Cooling Energy Dispatch Strategy 15

3.4 Case Study on a Large Shopping Mall 16

3.4.1 Load Profiles of a Large Shopping Mall 17

3.4.2 Natural Gas Prices 20

3.4.3 Electricity Prices 20

3.4.4 System Design 21

3.5 Simulation Results 24

3.5.1 System Design Results 25

3.5.2 Analysis of Optimal Operations 28

3.5.3 Impact of Natural Gas Prices 35

3.6 Summary 48

CHAPTER IV BEMS USING COMBINED HEAT AND POWER WITH ELETRIC CHILLER 49

4.1 System Description 49

4.2 Objective Functions 50

4.2.1 Economic Optimal Operation 50

4.2.2 Environmental Optimal Operation 51

4.2.3 Multi-objective Approach 51

4.3 Dispatch Strategies 52

4.3.1 Electrical Energy Dispatch Strategy 52

4.3.2 Cooling Energy Dispatch Strategy 52

4.4 Case Study on a Large Shopping Mall 54

4.5 Simulation Results 58

4.5.1 System Design Results 58

4.5.2 Analysis of Optimal Operations 62

4.5.3 Impact of Natural Gas Prices 72

Page

4.6 Summary 87

CHAPTER V CONCLUSIONS 88

5.1 Summary 88

5.2 Recommendations for Future Work 89

REFERENCES 91

BIOGRAPHY 95

LIST OF TABLES

Page

Table 2.1 Summary of typical cost and performance characteristics by CHP technology 7

Table 2.2 Summary of air-conditioning types including its applications 9

Table 2.3 Summary of key data and figures for industrial boilers 10

Table 2.4 Proportion of energy use according to building types 11

Table 2.5 Minimum efficiency requirements according to air-conditioning types 11

Table 3.1 Proportion of EE consumption in each hour of electric chillers 18

Table 3.2 Parameters of power grids 21

Table 3.3 CHP data for BEMS1 23

Table 3.4 Capacity combinations for BEMS1 23

Table 3.5 Parameters of equipment and other notations for BEMS1 24

Table 3.6 BEMS1 design results 25

Table 3.7 Energy and demand charge costs of BEMS1 26

Table 3.8 Energy costs according to equipment of BEMS1 27

Table 3.9 CO_2 emissions according to equipment of BEMS1 27

Table 3.10 Comparison of EE and CE production costs of BEMS1 and electricity prices 30

Table 3.11 Comparisons of CO_2 emission factors of BEMS1 30

Table 3.12 Summary of changes in TCOE and total energy production according to the equipment due to economic optimal operation of BEMS1 47

Table 4.1 CHP data for BEMS2 56

Table 4.2 Capacity combinations for BEMS2 57

Table 4.3 Parameters of equipment and other notations for BEMS2 57

Table 4.4 BEMS2 design results 58

Table 4.5 Energy and demand charge costs of BEMS2 59

Table 4.6 Energy costs according to equipment of BEMS2 60

Table 4.7 CO_2 emissions according to equipment of BEMS2 61

Table 4.8 Comparison of energy and demand charge costs, and CO_2 emissions of BEMS1 and BEMS2 in overall picture 62

Page

Table 4.9 Comparison of EE and CE production costs of BEMS2 and electricity prices 64

Table 4.10 Comparisons of CO_2 emission factors of BEMS2 65

Table 4.11 Summary of changes in TCOE and total energy production according to the equipment of BEMS2 86

LIST OF FIGURES

		Page
Figure 3.1	Diagram of proposed BEMS1 and conventional BEMS	12
Figure 3.2	Actual electrical load profiles and peak power	17
Figure 3.3	Modified electrical load profiles and peak power	19
Figure 3.4	Cooling load profiles and peak power	20
Figure 3.5	EE production of CHP system of BEMS1	31
Figure 3.6	HE production of CHP system of BEMS1	32
Figure 3.7	EE flow to electrical loads of BEMS1	33
Figure 3.8	CE flow to cooling loads of BEMS1	34
Figure 3.9	Relationship between economic and environmental optimal operations of BEMS1	37
Figure 3.10	APNG during 2003-2012	36
Figure 3.11	TOC of BEMS1 vs. APNG	37
Figure 3.12	EC and DCC of BEMS1 vs. APNG	37
Figure 3.13	TCOE of BEMS1 vs. APNG	38
Figure 3.14	EE production cost of CHP system of BEMS1 vs. APNG	40
Figure 3.15	CE production cost of absorption chiller of BEMS1 vs. APNG	41
Figure 3.16	Total EE production of CHP of BEMS1 vs. APNG	43
Figure 3.17	Total EE supplied to electrical loads of BEMS1 vs. APNG	44
Figure 3.18	Total EE exported to power grids of BEMS1 vs. APNG	44
Figure 3.19	Total HE supplied to absorption chiller of BEMS1 vs. APNG	45
Figure 3.20	Total waste HE from CHP of BEMS1 vs. APNG	45
Figure 4.1	Diagram of proposed BEMS2 and conventional BEMS	49
Figure 4.2	EE production of CHP system of BEMS2	66
Figure 4.3	HE production of CHP system of BEMS2	67
Figure 4.4	EE flow to electrical loads of BEMS2	68
Figure 4.5	EE flow to electrical loads and electric chiller of BEMS2	69
Figure 4.6	CE flow to cooling loads of BEMS2	71

Page

Figure 4.7 Relationship between economic and environmental optimal operations of BEMS2 72

Figure 4.8 TOC of BEMS2 vs. APNG 73

Figure 4.9 EC and DCC of BEMS2 vs. APNG 74

Figure 4.10 TCOE of BEMS2 vs. APNG 75

Figure 4.11 EE production cost of CHP system of BEMS2 vs. APNG 77

Figure 4.12 CE production costs of absorption and electric chillers of BEMS2 vs. APNG 77

Figure 4.13 Total EE production of CHP of BEMS2 vs. APNG 80

Figure 4.14 Total EE supplied to electrical loads and electric chiller of BEMS2 vs. APNG 81

Figure 4.15 Total EE exported to power grids of BEMS2 vs. APNG 81

Figure 4.16 Total CE production of absorption and electric chillers of BEMS2 vs. APNG 82

Figure 4.17 Total waste HE from CHP of BEMS2 vs. APNG 82

Figure 4.18 Comparison of EE production of CHP system of BEMS2 at APNGs on holiday 83

Figure 4.19 Comparison of EE production of CHP system of BEMS2 at APNGs on workday 84

LIST OF ABBREVIATIONS

APNG	Average Price of Natural Gas
BEMS	Building Energy Management System
CCHP	Combined Cooling, Heating and Power
CE	Cooling Energy
CHP	Combined Heat and Power
COP	Coefficient of Performance
DCC	Demand Charge Costs
EC	Energy Costs
EE	Electrical Energy
EGAT	Electricity Generating Authority of Thailand
HE	Heat Energy
HVAC	Heating, Ventilation, and Air-Conditioning
LP	Linear Program
MEA	Metropolitan Electricity Authority
PDP	Power Development Plan
TCOE	Total Carbon Dioxide (CO_2) Emissions
TOC	Total Operating Costs
TR	Tonnes of Refrigeration

CHAPTER I

INTRODUCTION

1.1 Research Motivation

Around the world, all countries are attaching significance to energy supply along with environmental impacts, especially the effect of electricity generation on global warming. In Thailand, electrical energy security and adequacy go according to Thailand Power Development Plan 2010-2030 (PDP2010) [1]. Also, PDP2010 responds to the policies of the Ministry of Energy on the issue of environmental concerns, particularly by promoting cogeneration as an efficient power generation. Therefore, cogeneration will play a major role in strengthening the power system and in reducing greenhouse gases for the next 20 years, undoubtedly.

Cogeneration (also known as combined heat and power, CHP) [2] is the simultaneous production of electrical and useful thermal energy from a single source, such as natural gas, oil, coal, liquefied gas, biomass or solar. Typically, CHP has an efficiency of over 80% which is higher than traditional electricity generation whose efficiency is about 30-35% because it can recover waste heat energy to useful heat energy. In the past, CHP is widely used in many industries to generate electricity to electrical loads and produce useful thermal energy, usually in the form of steam, to the industry process. However, many researchers, nowadays, attempt to apply CHP to the resident sector by converting heat energy to cooling energy, which leads to tri-generation or combined cooling and heating and power (CCHP). CHP is suitable for buildings, such as hotels, hospitals, offices, shopping malls, educational institutions, including single- and multi-family residential buildings due to the coincidence of cooling, heating, and electrical loads. CHP applications for on-site building loads contributes to reducing loss in electricity transmission; moreover, recovered heat energy can be utilized in many applications, such as domestic water heating, space heating, and space cooling, which results in the decrease in electricity demand. As a result, CHP does not only directly improve energy efficiency in buildings but also indirectly reduce emissions from power grids.

Building energy management system (BEMS) [3] is a computer-controlled system that manages cooling, heating, and electrical energy supply and demand in the building for comfort and efficiency. BEMS enables building operators to control and monitor building facilities; also, it reports and alarms equipment malfunctions. If buildings have their generation systems like CHP, BEMS optimizes the operation of generation system and balances energy production and consumption. Generally, optimal operations of BEMS using CHP as a main source are classified into economic optimal operation and environmental optimal operation. Economic optimal operations usually focus on minimum operating costs and are important for investors to recoup their investment as quickly as possible. Environmental optimal operations concentrate on minimum emissions and are significant for building owners because they need to care about the impact of electricity generation on communities.

This thesis is aimed to design economic and environmental optimal operation models of BEMS using CHP as a main source. Next, BEMS is applied to a selected large shopping mall as a case study. Then, we analyze optimal operations of BEMS, including their relationship, and assess the risk in the long-term operation of BEMS via the impact on fuel prices. Lastly, the author hopes that this thesis will sparks interest in CHP applications for buildings which contributes to supporting one of energy efficiency plans in Thailand PDP2010.

1.2 Literature Review

There are many researches on optimal operations 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 [4]. 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 [5]. 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 [6]. 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 [7]. 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 and solved by evolutionary programming and least squares method to find the optimal compromise between two operating criteria [8]. A multi-objective approach to economic and environmental optimal operations of CHP systems for BEMS [9] is developed based on the economic model [5] and the environmental model [7], and a linear combination technique [6] to find the relationship between two optimal operations; also, it is extended to determine the impact of fuel prices on total operating costs and total CO_2 emissions.

In this thesis, we design economic and environmental optimal operation model of BEMS using CHP systems based on a multi-objective approach model [8].

1.3 Thesis Objectives

1. To design economic and environmental optimal operations of BEMS using combined cooling, heating, and power generation in order to obtain minimum total operating costs and CO_2 emissions.
2. To analyze economic and environmental optimal operations of BEMS, including their relationship.
3. To assess the risk in the long-term operation of BEMS.

1.4 Scope of Thesis

1. Consider economic and environmental optimal operations of BEMS in steady state.
2. Consider cooling, heat, and electrical energy supply to building loads in the hourly pattern.
3. Ignore losses in cooling, heat, and electrical energy transfer from generation sources to building loads.
4. Design and simulate optimal operations of BEMS on MATLAB.

1.5 Methodology

1. Literature review on optimal operations of combined cooling, heating, and power generation.
2. Design economic and environmental optimal operation models of BEMS using combined cooling, heating, and power generation.
3. Apply BEMS to a selected large shopping mall in Thailand as a case study.
4. Analyze economic and environmental optimal operations of BEMS, including their relationship.
5. Investigate the risk in the long-term operation of BEMS via the impact of fuel prices.

1.6 Contributions

1. Economic and environmental optimal operation models of BEMS using combined cooling, heating, and power generation.
2. Approaches to BEMS design, analysis of optimal operations and their relationship, and the risk assessment in the long run.

1.7 Structure of Thesis

This thesis is organized as follows. Chapter 2 provides basic knowledge about CHP, absorption and electric chillers, boilers, including building loads. Chapter 3 formulates economic and environmental optimal operations of BEMS consisting of CHP, absorption chillers, boilers, and power grids with an application to a large shopping mall in Thailand followed by another BEMS replacing boilers with electric chillers in Chapter 4. Lastly, Chapter 5 presents conclusions.

CHAPTER II

BASIC KNOWLEDGE

This chapter provides basic knowledge about CHP technologies, heating, ventilation and air-conditioning (HVAC) systems, industrial boilers, and building loads, all of which will be used to formulate optimal operation problems in the next chapters.

2.1 Combined Heat and Power Technologies

Combined heat and power (CHP) technologies suitable for buildings [2, 10-12] can be commercially classified according to prime mover technologies: reciprocating engines, micro-turbines, fuel cells, gas turbines, and steam turbines. Due to the size of CHP systems, the first three types are appropriate for small and medium buildings like educational institutions, but the last two suit large buildings such as shopping malls. The characteristics of each type can be summarized as follows.

Reciprocating engines used in CHP-related projects are typically available in sizes ranging from 10 kW to 5 MW and divided into two types: spark ignition and compression ignition (CI). Spark ignition engines prefer natural gas in electricity generation applications while compression ignition engines operate on diesel fuel or heavy oil. The benefits of reciprocating engines are fast start-up, high power efficiency with part-load operational flexibility, and high reliability. The drawbacks are high maintenance costs, high air emissions, and high levels of low frequency noises. Reciprocating engines are well suitable for applications that require hot water or low-pressure steam.

Micro-turbines are small electricity generators that can operate on a wide variety of fuels, such as, natural gas, biogas, and oil. Micro-turbines use the fuel to create high-speed rotation that turns an electrical generator to produce electricity. In CHP operation, micro-turbines recover useful heat from the exhaust gas via a heat exchanger, and the useful heat suits many applications, especially water heating, spacing heating, space cooling. Micro-turbines have several advantages: low emissions, compact size and light weight, and low noise due to the small number of moving parts; however, the disadvantages are high costs and low power efficiency. Commercial models of micro-turbine are available in sizes from 30 kW to 250 kW

Fuel cells are an emerging technology that has the potential to generate power and heat cleanly and efficiently. Fuel cells use an electrochemical process or battery-like process to produce water and electricity from the chemical energy of hydrogen which can be obtained from natural gas, methanol, and other hydrocarbon fuels. In CHP applications, heat is recovered in the form of hot water or low-pressure steam (<

30 pounds per square inch gauge (psig). Currently, fuel cells are developed in five types, namely, phosphoric acid (PAFC), proton exchange membrane (PEMFC), molten carbonate (MCFC), solid oxide (SOFC), and alkaline (AFC); moreover, their commercial products are available in sizes of 5 kW – 2 MW. For the pros and cons, fuel cells have low emissions, low noise, and high efficiency over load range, but high costs, low durability and power density.

Gas turbines, typically, range in sizes from 500 kW to 250 kW and can operate on different fuels, such as natural gas, synthetic gas, landfill gas, and fuel oils. In CHP applications, gas turbines are coupled to heat recovery exchangers and can produce high-temperature steam as high as 1,200 psig and 900 degree Fahrenheit (°F). The benefits of gas turbines are high reliability, low emissions, and high grade heat, but the drawbacks are poor efficiency at low loading and high pressure gas requirement as input.

Steam turbines generate electricity from high-pressure steam produced in a boiler and transferred to power the turbine and generator. Due to the separation of functions, steam turbines can operates on a large number of fuels including natural gas, solid waste, coal, wood, wood waste, and agricultural by-products. Steam turbines are commercially available in capacities of 50 kW – 250 MW. The advantages of steam turbines are high overall efficiency, long working life, high reliability, and varying power to heat ratio; however, the disadvantages are low start-up and low power to heat ratio.

Table 2.1 summarizes typical costs and performance characteristics by CHP technologies. The table does not include CO_2 emissions because the amount of CO2 emitted in any of the CHP technologies depend on the type of fuels and the system efficiency.

Table 2.1: Summary of typical cost and performance characteristics by CHP technology [10].

Technology	**Reciprocating Engine**	**Micro-turbine**	**Fuel Cell**	**Gas Turbine**	**Steam Turbine**
Typical capacity (MW)	0.01-5	0.03-0.25	0.005-2	0.5-250	0.5-250
Electrical efficiency (%)	22-40%	18-27%	30-63%	22-36%	15-38%
Overall efficiency (%)	70-80%	65-75%	55-80%	70-75%	80%
Typical power to heat ratio	0.5-1	0.4-0.7	1-2	0.5-2	0.1-0.3
Part-load	ok	ok	poor	poor	ok
CHP installed costs ($/kW)	1,100-2,200	2,400-3,000	5,000-6,500	970-1,300 (5-40 MW)	430-1,100
Operation and maintenance (O&M) costs ($/kWh)	0.009-0.022	0.012-0.025	0.032-0.038	0.004-0.011	< 0.005
Availability (%)	92-97%	90-98%	> 95%	90-98%	near 100%
Power density (kW/m^2)	35-50	5-70	5-20	20-500	> 100
Start-up time	10 sec	60 sec	3 hrs - 2 days	10 min - 1 hr	1 hr – 1 day
Uses for thermal output	hot water LP steam	heat, hot water, LP-HP steam	hot water, LP-HP steam	heat, hot water, LP-HP steam	LP-HP steam
Fuels	natural gas, biogas, propane, landfill gas	natural gas, biogas, propane, oil	hydrogen, natural gas, propane, methanol	natural gas, biogas, propane, oil	all
Noise	high	moderate	low	moderate	high

Note: 1) LP and HP are low and high pressure. 2) For steam turbine, installation costs are not included boiler package.

2.2 Heating, Ventilation and Air-Conditioning

Heating, ventilation, and air-conditioning (HVAC) [13] is the technology that controls the temperature, humidity, and quality of air in buildings for comfort. Due to hot weather in Thailand, this research focuses only on air-conditioning systems which can be divided into decentralized and centralized systems [14]. Decentralized air-conditioning systems are suitable for small buildings, and have three types, namely, window air conditioners, split air conditioners, air-cooled packaged air conditioners, and water-cooled packaged air conditioners. Centralized air-conditioning systems are appropriate for medium and large buildings, and use chillers as the main equipment to produce cooling water. Chillers are mainly classified into absorption and electric chillers.

Absorption chillers produce cooling water from the heat input in the form of hot water or steam corresponding to the heat output of CHP systems. Absorption chillers are commercially categorized into single-effect and double-effect types [15-16]. Single-effect absorption chillers are available in sizes ranging of 3-2,000 tonnes of refrigeration (TR) and suitable for 14.5-29 psig steam as input. Double-effect absorption chillers are available in the same capacity range but require 130.5-145 psig steam as input. Besides, the coefficient of performance (COP) of absorption chillers is in the range of 0.6-0.7 and 0.9-1.2, for the single-effect and double-effect types, respectively.

Electric chillers use electricity to produce cooling water. There are two main types of electric chillers: air-cooled and water-cooled type [14]. Air-cooled chillers suit medium buildings and are available in sizes of 3-500 TR with COP over 2.2. Water-cooled chillers are appropriate for large buildings and range in capacities of 20-10,000 TR with COP over 4.69.

Table 2.2 summarizes air-conditioning types including its applications.

Table 2.2: Summary of air-conditioning types including its applications [14-16].

Type of Air Conditioning	**Typical Capacity (TR)**	**COP**	**Applications**
Window air conditioner	0.5-3	> 2.34	house, office, etc.
Split air conditioner	0.75-3	> 2.34	house, office, etc.
Air-cooled packaged air conditioner	3-30	> 2.34	condominium, office, etc.
Water-cooled packaged air conditioner	1-50	> 2.93	condominium, office, etc.
Air-cooled chiller	3-500	> 2.2	condominium, small community mall, computer center, medium hotel, medium hospital, etc.
Water-cooled chiller	20-10,000	> 3.91	large office, large hospital, large hotel, large computer center shopping complex, etc.
Single-effect absorption chiller	3-2,000	0.6-0.7	depend on CHP applications
Double-effect absorption chiller	3-2,000	0.9-1.2	depend on CHP applications

2.3 Industrial Boilers

Industrial boilers [17] are widely used to generate steam for industrial applications and power generation and can operate on a different variety of fuels including natural gas, oil, coal, biomass, and others. In CHP applications, industrial boilers can be used as an auxiliary boiler to produce additional steam to absorption chillers. Industrial boilers are commercially available in various capacities ranging from less than 10 MMBtu/hr for small scale up to over 250 MMBtu/hr for very large scale. However, the efficiency and CO_2 emissions depend on fuel types. Table 2.3 summarizes key data and figures for industrial boiler [17-18].

Table 2.3: Summary of key data and figures for industrial boilers [17-18].

Technical Performance			
Fuel input	Natural gas, oil, coal, biomass, and other fuels		
Output	Steam		
Typical capacity (MMBtu/hr)	Small < 10	Large 10-250	Very Large > 250
Actual efficiency (%) (or thermal efficiency)		At full load	At low load
	Natural gas	75%	70%
	Oil	80%	72%
	Coal	85%	75%
	Biomass	70%	60%
Technical lifetime (yrs)	25-40		
Availability (%)	86.6-94.2%		
CO_2 emissions per heat energy output		kgCO_2/MMBtu	tCO_2/MWh
	Natural gas	53.06	0.1810
	Distillation fuel oil	73.15	0.2496
	Residual fuel oil	78.80	0.2689
	Coal	93.98	0.3207

2.4 Energy Usage in Buildings

Energy usage in buildings [19], generally, consists of three main parts: HVAC, lighting, and others such as elevators, escalators, computers, and appliances. In Thailand, there is a survey on energy use proportion according to building types as shown in Table 2.4 which indicates that HVAC is the largest proportion of energy usage in buildings. To reduce energy usage in buildings, the Department of Alternative Energy Development and Efficiency made regulations on energy use for new buildings in 2010. One of the important issues is standards for air-conditioning systems, i.e, they set minimum efficiency requirements according to air-conditioning types as shown in Table 2.5. Moreover, in large air-conditioning, total COP of other parts in HVAC systems such as air handling units (AHU), cooling towers, and others is required at least 7.03.

Table 2.4: Proportion of energy use according to building types [19].

Building Type	HVAC (%)	Lighting (%)	Others (%)
Shopping mall	43%	25%	32%
Office	52%	20%	28%
Hospital	65%	17%	18%
Hotel	66%	20%	14%
Educational Institution	66%	15%	19%

Table 2.5: Minimum efficiency requirements according to air-conditioning types [19].

Air-conditioning Type	Capacity (TR)	Minimum COP
Window air conditioners Split air conditioners Air-cooled packaged air conditioner	All capacities	2.82
Water-cooled packaged air conditioner	All capacities	3.99
Air-cooled chiller	< 100	2.70
	> 100	2.93
Water-cooled chiller	< 150	3.91
	150-200	4.69
	200-250	5.25
	250-500	5.40
	> 500	5.67
Single-effect absorption chiller	All capacities	0.65
Double-effect absorption chiller	All capacities	1.10

2.5 Summary

This chapter presents background knowledge about CHP technologies suitable for buildings, HVAC especially air-conditioning, industrial boilers for CHP applications, and energy usage in buildings including the standard for air-conditioning. All of the information will be useful in the design or equipment selection of BEMS in the next chapters.

CHAPTER III

BEMS USING COMBINED HEAT AND POWER WITH BOILER

This chapter proposes an economic and an environmental optimal operation of BEMS consisting of the CHP system, the absorption chiller, the auxiliary boiler, and power grids. First, we formulate objective functions of BEMS and design dispatch strategies of equipment. Then, the proposed optimal operations of BEMS are applied to a large shopping mall as a case study to determine the most suitable capacity of each component. Lastly, we analyze optimal operations of BEMS via optimal energy flows, and investigate the risk in a long-term operation via the impact of fuel prices.

3.1 System Description

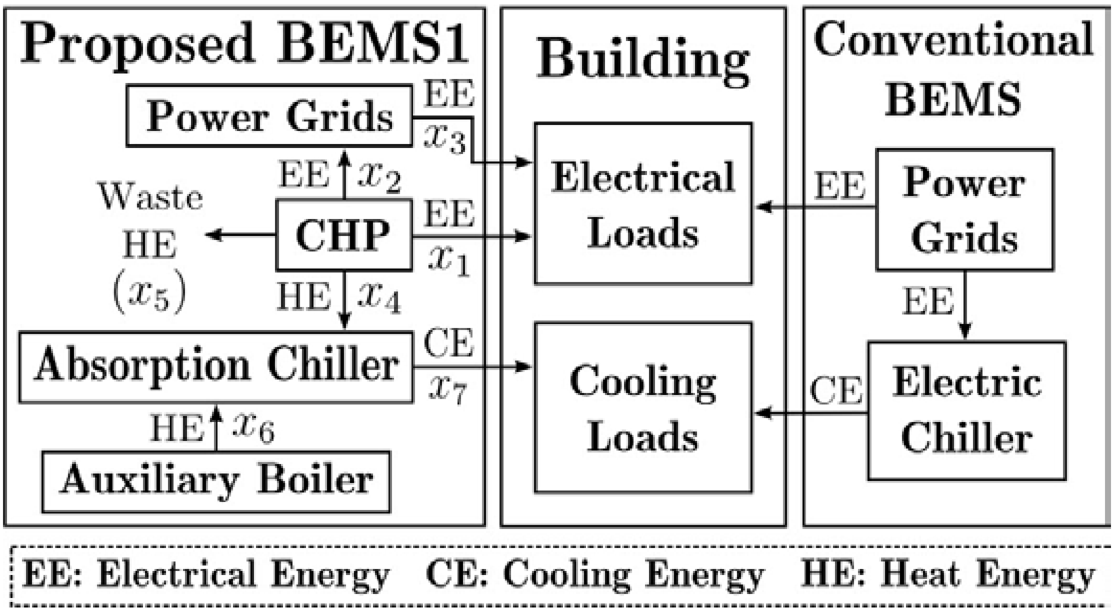

Figure 3.1: Diagram of proposed BEMS1 and conventional BEMS.

The proposed BEMS1, Figure 3.1, controls and optimizes the operation of the CHP generation system, the auxiliary boiler, the 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 heat required to meet cooling energy demand, its surplus is 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 electrical energy production from cogeneration (x_2) and in selling electricity to the customer in case of power shortages (x_3). Lastly, the auxiliary boiler will cooperate with the CHP system to compensate for heat shortages (x_6).

Compared to BEMS1, the conventional BEMS utilizes electrical energy from power grids and cooling energy from the electric chiller. Nevertheless, the electric chiller requires 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.

3.2 Objective Functions

This section formulates objective functions for economic and environmental optimal operations of BEMS1 as well as a multi-objective approach to find their relationship.

3.2.1 Economic Optimal Operation

The economic optimal operation is aimed to minimize total operating costs of BEMS1. The objective function is defined as the total operating costs, TOC (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:

$$\mathrm{TOC} = \mathrm{EC} + \mathrm{DCC} \tag{3.1}$$

$$\mathrm{EC} = \sum_{k=1}^{n\times d} \left[c_{\mathrm{CHP}}(x_{1,k} + x_{2,k}) - q_k x_{2,k} + p_k x_{3,k} + c_{\mathrm{AB}} x_{6,k} \right] \tag{3.2}$$

$$\mathrm{DCC} = \frac{d_{\mathrm{PG}}}{\Delta t} \max_{k=1,\ldots,n\times d} x_{3,k} \tag{3.3}$$

where $x_{i,k}$ is energy flow in the time interval of k. Also, c_{CHP} and c_{AB} are operating costs of the CHP system and the auxiliary boiler, and 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.

3.2.2 Environmental Optimal Operation

The environmental optimal operation enables BEMS1 to reduce a greenhouse gas, especially carbon dioxide (CO_2). Hence, the environmental optimal operation is focused on minimizing total CO_2 emissions, TCOE (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:

$$\mathrm{TCOE} = \sum_{k=1}^{n\times d}\left[\mathrm{EF}_{\mathrm{CHP,CO_2}}(x_{1,k} + x_{2,k}) + \mathrm{GEF}x_{3,k} + \frac{\mathrm{EF}_{\mathrm{AB,CO_2}}}{\eta_{\mathrm{AB}}}x_{6,k}\right] \tag{3.4}$$

where $\mathrm{EF}_{\mathrm{CHP,CO_2}}$ and $\mathrm{EF}_{\mathrm{AB,CO_2}}$ 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.

3.2.3 Multi-objective Approach

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

$$\mathbf{min} \quad (1-\alpha)\frac{\mathrm{TOC}}{\mathrm{TOC}_{\mathrm{min}}} + \alpha\frac{\mathrm{TCOE}}{\mathrm{TCOE}_{\mathrm{min}}}. \tag{3.5}$$

Subsequently, we vary the weighting factor from 0 to 1 and minimize the linear combination in (3.5) to obtain multi-objective optimal operation.

3.3 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, BEMS1 operates under the different objective functions but the same constraints. The constraints are mainly grouped into electrical energy (EE) and cooling energy (CE) dispatch strategies.

3.3.1 Electrical Energy Dispatch Strategy

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, $P_{\mathrm{CHP,min}}$ and $P_{\mathrm{CHP,max}}$, and heat energy (HE) proportional to its power-to-heat ratio

($\mathrm{P2H}$). 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

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

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

$$\left|(x_{1,k} + x_{2,k}) - (x_{1,k-1} + x_{2,k-1})\right| \le R_{\mathrm{CHP}}\Delta t$$

end.

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

3.3.2 Cooling Energy Dispatch Strategy

The CE dispatch strategy is related to the operation of the CHP system, the auxiliary boiler, and the absorption chiller, i.e., the CHP system and the boiler produce HE which is converted to CE by the chiller. The CE dispatch strategy can be divided into 4 conditions relying 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 ($\mathrm{CP}_{\mathrm{AC,min}}$) of the chiller, the chiller operates at the minimum level so that the temperature in the building is still cool. Regarding HE supply, BEMS1 utilizes HE which is simultaneously produced with EE generation by the CHP system before HE from the boiler. Thirdly, BEMS1 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, $\mathrm{HP}_{\mathrm{AB,min}}$ and $\mathrm{HP}_{\mathrm{AB,max}}$. The chiller operates following CE demand but not more than its maximum cooling production level ($\mathrm{CP}_{\mathrm{AC,max}}$) 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 $C_k < \mathrm{CP}_{\mathrm{AC,min}}\Delta t$, then

$$x_{4,k}\mathrm{COP}_{\mathrm{AC}} = x_{7,k}$$
$$x_{6,k} = 0$$
$$x_{7,k} = \mathrm{CP}_{\mathrm{AC,min}}\Delta t$$

else if $C_k \le \frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} \times \mathrm{COP}_{\mathrm{AC}}$, then

$$x_{4,k}\mathrm{COP}_{\mathrm{AC}} = x_{7,k}$$
$$x_{6,k} = 0$$
$$x_{7,k} = C_k$$

else

$$(x_{4,k} + x_{6,k})\mathrm{COP}_{\mathrm{AC}} = x_{7,k}$$
$$\mathrm{HP}_{\mathrm{AB,min}}\Delta t \le x_{6,k} \le \mathrm{HP}_{\mathrm{AB,max}}\Delta t$$
$$x_{7,k} = \min\left(C_k, \mathrm{CP}_{\mathrm{AC,max}}\Delta t, \left(\frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} + \mathrm{HP}_{\mathrm{AC,max}}\Delta t\right)\mathrm{COP}_{\mathrm{AC}}\right)$$

end.

3.4 Case Study on a Large Shopping Mall

In a case study, we apply BEMS1 to a large shopping mall in Bangkok, Thailand. The shopping mall, actually, utilizes electricity from 69-kV distribution grids of Metropolitan Electricity Authority (MEA) as the primary energy supply source of the conventional BEMS. In contrast, BEMS1 exploits natural gas as the primary and electricity from power grids as the secondary energy source. Therefore, this section considers sample load profiles of the large shopping mall, natural gas and electricity prices in Thailand, and the selection of the type and capacity of equipment in BEMS1.

3.4.1 Load Profiles of a Large Shopping Mall

Figure 3.2 shows 15-minute actual electrical load profiles of the large shopping mall which is metered from 2 to 29 June 2012. Obviously, the daily pattern of the load profiles looks similar in shapes but different in peaks ranging from 28.9 MW to 32 MW. However, from the structure of BEMS1, it requires separate electrical and cooling load profiles, and the study focuses only on hourly operation of BEMS1. Therefore, we will create hourly electrical and cooling load profiles based on the real electrical load profiles.

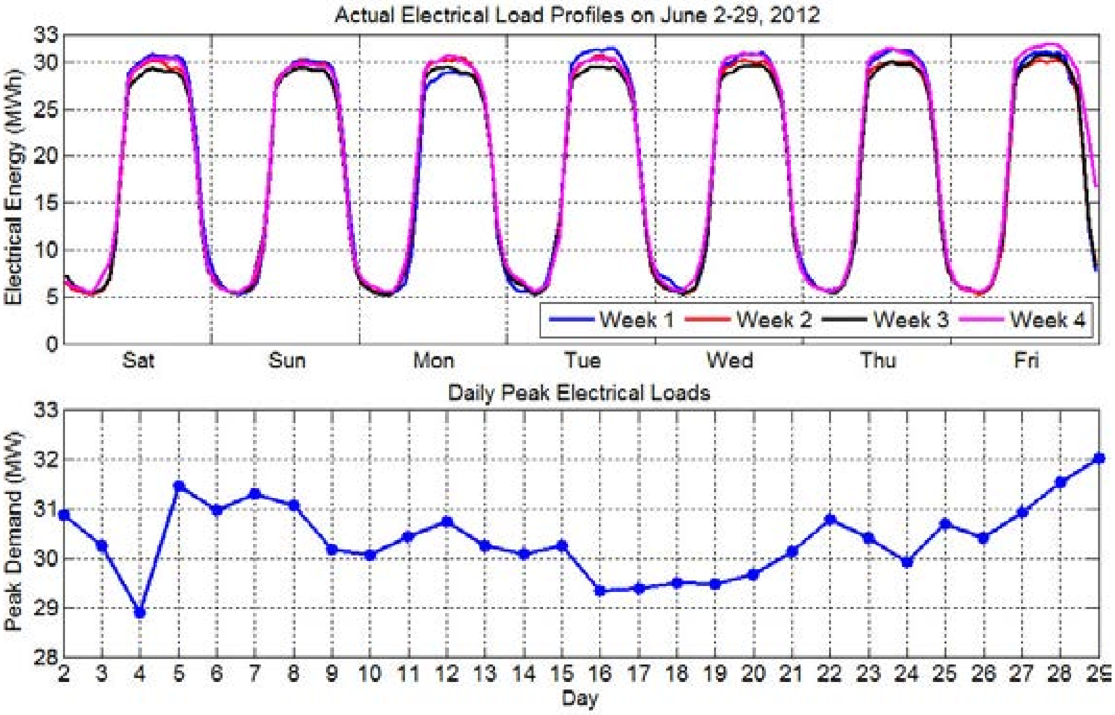

Figure 3.2: Actual electrical load profiles and peak power.

To construct hourly electrical and cooling load profiles, we firstly assume that the shopping mall uses water-cooled electric chillers in supplying cooling energy, and hourly cooling load profiles can be built from hourly EE consumed by electric chillers. We further assume that daily peaks of cooling load profiles vary according to the daily peaks of the actual electrical load profiles. Hourly electrical load profiles can be found from the difference between the actual hourly electrical load profiles and hourly EE consumption of electric chillers. Hence, the procedure for constructing hourly electrical and cooling load profiles is summarized as follows.

Step 1: Find the daily peaks of the actual electrical load profiles

Step 2: Calculate daily electrical peak power used by electric chillers from the following equation:

$$\hat{P}_j = \hat{U}_j \times \%\mathrm{HVAC} \times \frac{\mathrm{COP}_{\mathrm{EC}}}{\mathrm{COP}_{\mathrm{EC}} + \mathrm{TCOP}_{\mathrm{OP}}} \tag{3.6}$$

where $\hat{P}_j$ and $\hat{U}_j$ is daily electrical peak power of electric chillers and the actual electrical load profiles on day j, respectively. $\%\mathrm{HVAC}$ is the ratio of EE consumption of the HVAC system to total EE consumption, $\mathrm{COP}_{\mathrm{EC}}$ is coefficient of performance (COP) of electric chillers, and $\mathrm{TCOP}_{\mathrm{OP}}$ is total coefficient of performance of other parts in the HVAC system, such as air handling units (AHU), cooling towers, and so on. According to the survey in regulations on energy use for new building [19], the EE consumption of the HVAC system in shopping malls, $\%\mathrm{HVAC}$, accounts for 43% of total energy use. Also, the regulations recommend that $\mathrm{COP}_{\mathrm{EC}}$ and $\mathrm{TCOP}_{\mathrm{OP}}$ should be at least 5.67 and 7.03 for HVAC systems in large buildings.

Step 3: Construct the daily pattern of EE consumption profiles of electric chillers by assuming that EE consumption in each hour is a percentage of peak power demand. Moreover, we consider the opening hours of the shopping mall which is 10.00-22.00, and the number of customers which is generally large since afternoon as the contributing factors in the construction. Table 3.1 summarizes the proportion of EE consumption in each hour of electric chillers.

Table 3.1: Proportion of EE consumption in each hour of electric chillers.

Time	Percentage	Time	Percentage
0.00 – 7.00	0%	12.00 – 13.00	95%
7.00 – 8.00	20%	13.00 – 20.00	100%
8.00 – 9.00	40%	20.00 – 21.00	80%
9.00 – 10.00	70%	21.00 – 22.00	70%
10.00 – 11.00	85%	22.00 – 23.00	40%
11.00 – 12.00	90%	23.00 – 24.00	20%

Step 4: After obtaining hourly EE consumption profiles of electric chillers, we can find electrical load profiles from the difference between the actual electrical load profiles and EE consumption profiles of electric chillers. Cooling load profiles can be obtained from the definition of COP, i.e.,

$$\mathrm{CE\ Output} = \mathrm{COP}_{\mathrm{EC}} \times \mathrm{EE\ Input} \tag{3.7}$$

Figure 3.2 and Figure 3.3 show the hourly electrical and cooling load profiles which are the results from the procedure. The daily pattern of the electrical load profiles still looks similar in shapes but their peaks is reduced into the range of 22-24.5 MW. The peaks of cooling loads are in the range of 38.69-43.26 MW cooling or 11,100-12,300 tonnes of refrigeration (TR), which is corresponding to the fact that the selected large shopping mall uses electric chillers with total capacity of 12,000 TR. Therefore, this study will fix the capacity of the chiller in BEMS1 at 12,000 TR to make the same comparison, and we can take the advantage of such cooling load profiles to investigate how BEMS1 will operate when it cannot supply CE to meet the demand.

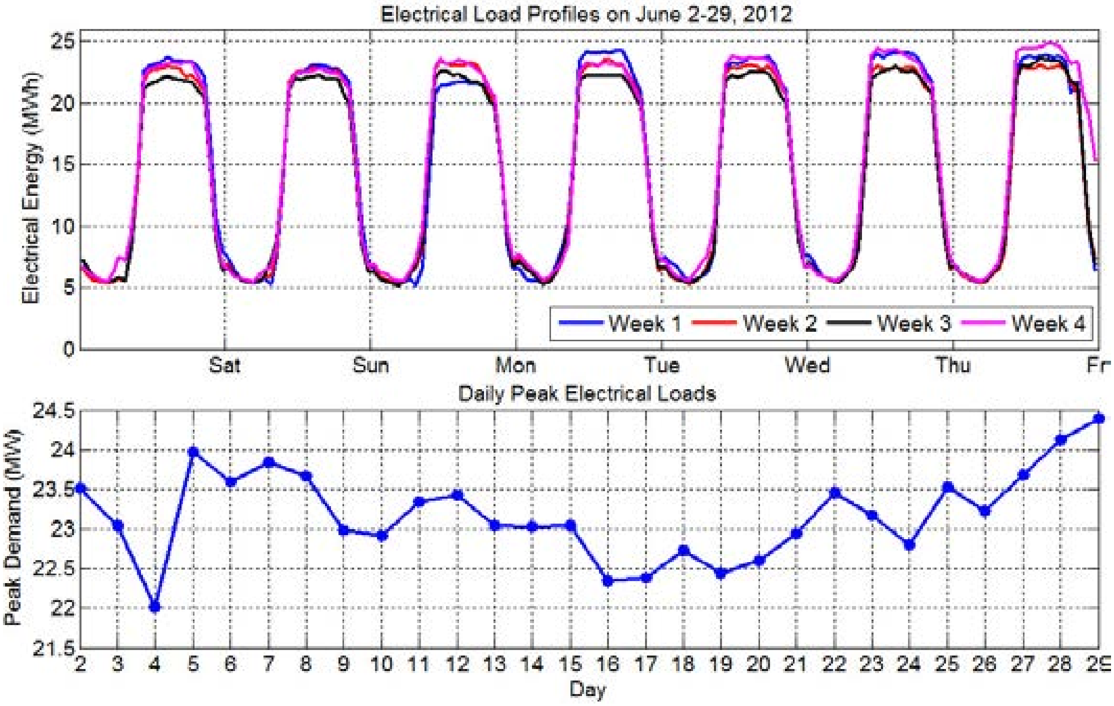

Figure 3.3: Modified electrical load profiles and peak power.

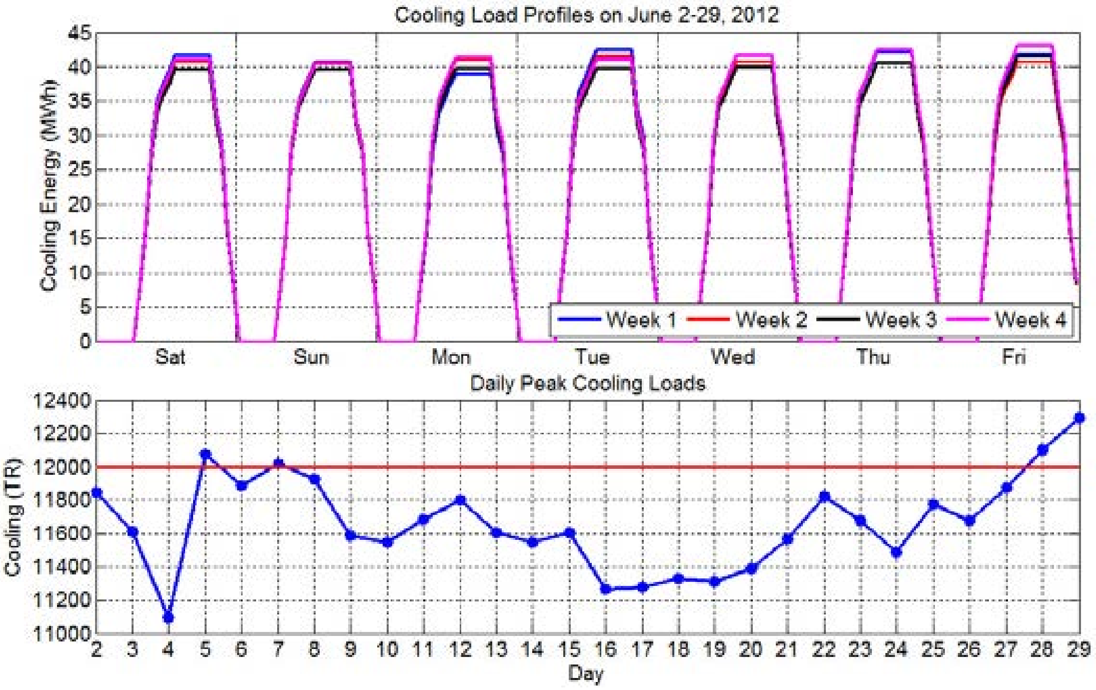

Figure 3.4: Cooling load profiles and peak power.

3.4.2 Natural Gas Prices

Natural gas tariff (NGT, baht/MMBtu) for business operators, according to National Energy Policy Commission [20], is calculated as follows:

$$\mathrm{NGT} = \mathrm{APNG} + \min(0.0933 \times \mathrm{APNG}, 11.4759) + 13.1766 \tag{3.8}$$

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 [22]. The second term in (3.8) is the remuneration for the gas supply and distribution service which depends on consumer's types [20]. The last term in (3.8) is the total charge of gas transportation provided by a natural gas supply company [21].

3.4.3 Electricity Prices

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 study only concentrates on the first two and omits the rest because they are fixed and very small charges. Therefore, BEMS1 pays 3.5982 and 2.1572 baht/kWh for energy charge and 74.14 baht/kW for demand charge as a 69-kV electricity user with the schedule of large general service of MEA [24]. On the other hand, electricity selling prices for power producers using CHP systems [23] are the wholesale prices at which Electricity Generating Authority of Thailand (EGAT) sells electricity to MEA at connected voltage levels. Hence, BEMS1 earns 3.2504 and 2.0198 baht/kWh for selling EE back to MEA distribution grids [25]. Finally, the grid emission factor (GEF) of Thailand [26] is exploited to estimate equivalent CO_2 emissions when BEMS1 uses electricity from power grids. Table 3.2 summarizes all parameters about power grids for the study.

Table 3.2: 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

3.3.4 System Design

To design BEMS1, we use the following guideline for equipment selection. First, we consider the type and capacity of the CHP system that suits electrical loads. Then, we choose the type and size of the absorption chiller matching the characteristics of heat production of the CHP system and cooling loads. Next, the capacity of the auxiliary boiler is calculated from the heat shortage. Lastly, the well-designed combination will be simulated to find the best BEMS1.

We consider gas turbines as the CHP system of BEMS1 because their sizes are 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 [10]. Due to the range of the peak electricity demand, the CHP system data ranging from 22 to 25 MW, as shown in Table 3.3, are estimated based upon available technical data [10-12] and used as the candidates in the simulation. The minimum and maximum power production of the CHP systems, $P_{\mathrm{CHP,min}}$ and $P_{\mathrm{CHP,max}}$, are set to 20% and 100% of the rated power, and electrical energy ramp rate (R_{CHP}) is set to 100% of the rated power thanks to the fast start capability of gas turbines, i.e., it can operate at full load in a few minutes. Furthermore, the operating costs of the CHP system (c_{CHP}) can be computed from the following equation:

$$c_{\mathrm{CHP}}(\mathrm{baht/MWh}) = \frac{\mathrm{NGT} \times 3.412}{\eta_{\mathrm{CHP,EE}}} + \mathrm{OM}_{\mathrm{CHP}} \tag{3.9}$$

where $\mathrm{OM}_{\mathrm{CHP}}$ is operation and maintenance costs of the CHP system.

The double-effect absorption chiller is appropriate for BEMS1 because the steam input, which is range of 130.5-145 psig, suits the steam output of the CHP system. Also, the coefficient of performance of the double-effect type ($\mathrm{COP}_{\mathrm{AC}}$) is set to 1.1 according to the recommendation in regulations on energy usage for new buildings [19]. However, total capacity of the absorption 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 BEMS1 are industrial boilers due to the variety of the capacity, MMBtu/hr. Industrial boilers firing natural gas, generally, has approximately 75% of thermal efficiency at full load [17] and CO_2 emissions per HE output ($\mathrm{EF}_{\mathrm{AB,CO_2}}$) 0.181 tCO_2/MWh [18]. The capacity of boilers, in the study, is chosen from the heat shortage depending on the CHP candidates. Moreover, the minimum and maximum heat production of the boiler, $\mathrm{HP}_{\mathrm{AB,min}}$ and $\mathrm{HP}_{\mathrm{AB,max}}$, are set to 20% and 100% of the rated heat power, and the operating costs of the boiler can be calculated as follows:

$$c_{\mathrm{AB}}(\mathrm{baht/MWh}) = \frac{\mathrm{NGT} \times 3.412}{\eta_{\mathrm{AB}}} + \mathrm{OM}_{\mathrm{AB}} \tag{3.10}$$

where $\mathrm{OM}_{\mathrm{AB}}$ is operation and maintenance costs of the boiler which are referred to Hashemi’s survey [4].

Finally, we use aforementioned information to design the capacity of each component in BEMS1. For instance, A 22-MW CHP system can produce heat 24.63 MW, but the 12,000-TR double-effect absorption chiller 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. Table 3.4 and 3.5 summarize all of the combinations and parameters related to the absorption chiller, the auxiliary boiler and others to be used in the study.

Table 3.3: CHP data for BEMS1.

Description		CHP Systems			
Rated Power (MW)	-	22	23	24	25
Electrical Efficiency (%)	$\eta_{\text{CHP,EE}}$	33.11	33.51	33.90	34.30
Power to Heat Ratio	P2H	0.8933	0.9088	0.9244	0.9400
Maximum Power Production (MW)	$P_{\text{CHP,max}}$	22	23	24	25
Minimum Power Production (MW)	$P_{\text{CHP,min}}$	4.4	4.6	4.8	5.0
Electrical Energy Ramp Rate (MW)	R_{CHP}	22	23	24	25
CO_2 Emission Factor (tCO_2/MWh)	$\text{EF}_{\text{CHP,CO}_2}$	0.5497	0.5423	0.5349	0.5275
Operation and Maintenance Costs (baht/MWh)	OM_{CHP}	0.1598	0.1555	0.1513	0.1470

Table 3.4: Capacity combinations for BEMS1.

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

Table 3.5: Parameters of equipment and other notations for BEMS1.

Absorption Chiller		
Rated cooling power (MW)	-	42.2
Coefficient of performance (-)	$\mathrm{COP}_{\mathrm{AC}}$	1.1
Maximum cooling production (MW)	$\mathrm{CP}_{\mathrm{AC,max}}$	42.2
Minimum cooling production (MW)	$\mathrm{CP}_{\mathrm{AC,min}}$	8.44
Auxiliary Boiler		
Rated heat power (MW)	-	-
Efficiency (%)	η_{AB}	75
Maximum heat production (MW)	$\mathrm{HP}_{\mathrm{AB,max}}$	-
Minimum heat production (MW)	$\mathrm{HP}_{\mathrm{AB,min}}$	-
CO_2 emission factor from natural gas combustion (tCO_2/MWh)	$\mathrm{EF}_{\mathrm{AB,CO_2}}$	0.1810
Operation and Maintenance Costs (baht/MWh)	$\mathrm{OM}_{\mathrm{AB}}$	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

3.5 Simulation Results

The proposed economic and environmental optimal operations of BEMS1 are formulated as a linear program (LP) which can be efficiency solved by LP solvers, such as MATLAB optimization toolbox. In the simulation, we investigate three main parts. The first focuses on the questions: can BEMS1 reduce TOC and TCOE and which combination is the best for the BEMS1. Next, after obtaining the best candidate for BEMS1, we analyze the optimal operations of each component working under the economic and environmental optimal operations, including the relationship between them. Lastly, we examine the risk in long-term operation via the question: how does

APNG, the most important external factor, have an impact on TOC, TCOE and optimal operations of BEMS1.

3.5.1 System Design Results

This subsection answers two questions: are TOC and TCOE reduced by the proposed optimal operations, and which combination of the equipment is the most appropriate for the BEMS1. We compare TOC and TCOE of BEMS1 with those of the conventional BEMS. Each candidate is simulated under the economic and environmental optimal operations based on APNG as of June 2012 [22], 211.75 baht/MMBtu.

Regarding the conventional BEMS, the selected shopping mall has TOC of 39,924,388 baht and TCOE of 7,503 tCO_2. However, if we delve deeply into TOC, EC and DCC are 37,543,604 and 2,380,784 baht or account for 94.04% and 5.96%, respectively. In contrast, Table 3.6 summarizes TOCs and TCOEs of all combinations of BEMS1 working under the economic and environmental optimal operations. It indicates that all candidates are able to cut TOCs and TCOEs.

Table 3.6: BEMS1 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	6,724	29,309,652	6,484

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, BEMS1 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 3.7, 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 BEMS1 attempts to draw maximum electricity power from power grids as little as possible to obtain minimum DCC. However, when compared to EC of the conventional BEMS, ECs of BEMS1 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 3.8 reveals ECs of each component of BEMS1, 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, BEMS1 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 not decrease continuously like TOC even if the CO_2 emission factor of the CHP system goes down according to the capacity. Table 3.9 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 decrease HE and EE supply 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, BEMS1 has the minimum TCOE when the capacity of the CHP system is 23 and 24 MW for the economic and environmental optimal operations, respectively.

Table 3.7: Energy and demand charge costs of BEMS1.

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	29,863,419	29,018
25	27,877,388	0	29,309,652	0

Table 3.8: Energy costs according to equipment of BEMS1.

CHP (MW)	**Equipment**		**Economic Optimal Operation**	**Environmental Optimal Operation**
			EC (Baht)	**EC (Baht)**
22	CHP	Total EC	25,940,626	25,701,669
		Income from EE export	(1,705,461)	(503,515)
		Net EC	24,235,165	25,198,154
	Auxiliary Boiler		4,501,483	5,017,949
	Power Grids		1,415,602	730,156
23	CHP	Total EC	26,795,345	26,030,038
		Income from EE export	(2,281,377)	(706,605)
		Net EC	24,513,968	25,323,433
	Auxiliary Boiler		4,194,461	4,866,588
	Power Grids		671,910	157,205
24	CHP	Total EC	27,787,078	26,247,007
		Income from EE export	(3,242,411)	(1,168,194)
		Net EC	24,544,667	25,078,813
	Auxiliary Boiler		3,883,994	4,779,854
	Power Grids		221,220	4,752
25	CHP	Total EC	28,650,953	26,543,829
		Income from EE export	(4,337,845)	(1,880,039)
		Net EC	24,313,108	24,663,790
	Auxiliary Boiler		3,564,280	4,645,862
	Power Grids		0	0

Table 3.9: CO_2 emissions according to equipment BEMS1.

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

Finally, to find the best combination of BEMS1, we need to consider the criteria for the selection. From Table 3.6, 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 3.6 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 the 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 BEMS1.

3.5.2 Analysis of Optimal Operations

After obtaining the best combination of BEMS1, we analyze the operating behavior of each component under the economic and environmental optimal operations. In particular, we will investigate how each component of BEMS1 works under the economic and environmental optimal operations and whether BEMS1 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.

Deciding Factors in Optimal Operations

Before analyzing the optimal operations of BEMS1, we investigate deciding factors in the economic and environmental optimal operations of each component.

In view of the economic optimal operation, BEMS1 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, BEMS1 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 generate EE at the maximum 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, BEMS1 utilizes HE from the CHP system first if it results from EE generation to electrical loads or earning income from power grids during on-peak time. In this case, the absorption chiller has no CE production cost because BEMS1 obtains free HE which is coincident with EE generation of the CHP system. However, if free HE is not enough for the absorption chiller to satisfy CE demand, BEMS1 orders the CHP system to produce HE more if it does not generate EE at the maximum level yet; otherwise, BEMS1 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 kilowatt-hour of CE (kWh_{CE}). Therefore, the absorption chiller has the CE production costs of 2.1268 and 1.5437 baht/kWh_{CE} when using HE from the CHP system and auxiliary boiler, respectively. Table 3.10 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, BEMS1 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, BEMS1 should use the CHP system as the main EE supply source to obtain 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 supplies CE with CO_2 emissions if it does not use free HE which is coincident 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 (MWh_{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 3.11 summarizes the comparison of CO_2 emissions factors.

Table 3.10: Comparison of EE and CE production costs of BEMS1 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
CE Production 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 3.11: Comparisons of CO_2 emission factors of BEMS1.

CO_2 Emission 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

Optimal Operations of CHP system

Figure 3.5 and 3.6 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 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 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. In the case of operation following cooling loads, BEMS1 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. BEMS1 decides which one offers the minimum CO_2 emissions. BEMS1 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.

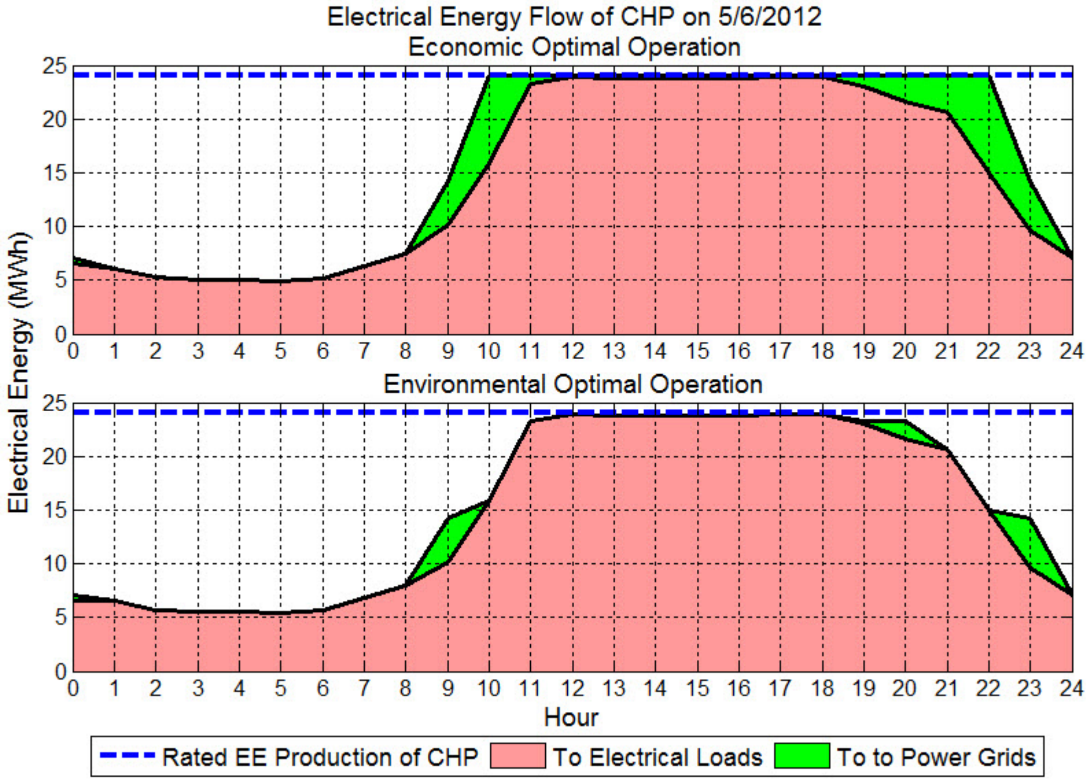

Figure 3.5: EE production of CHP system of BEMS1.

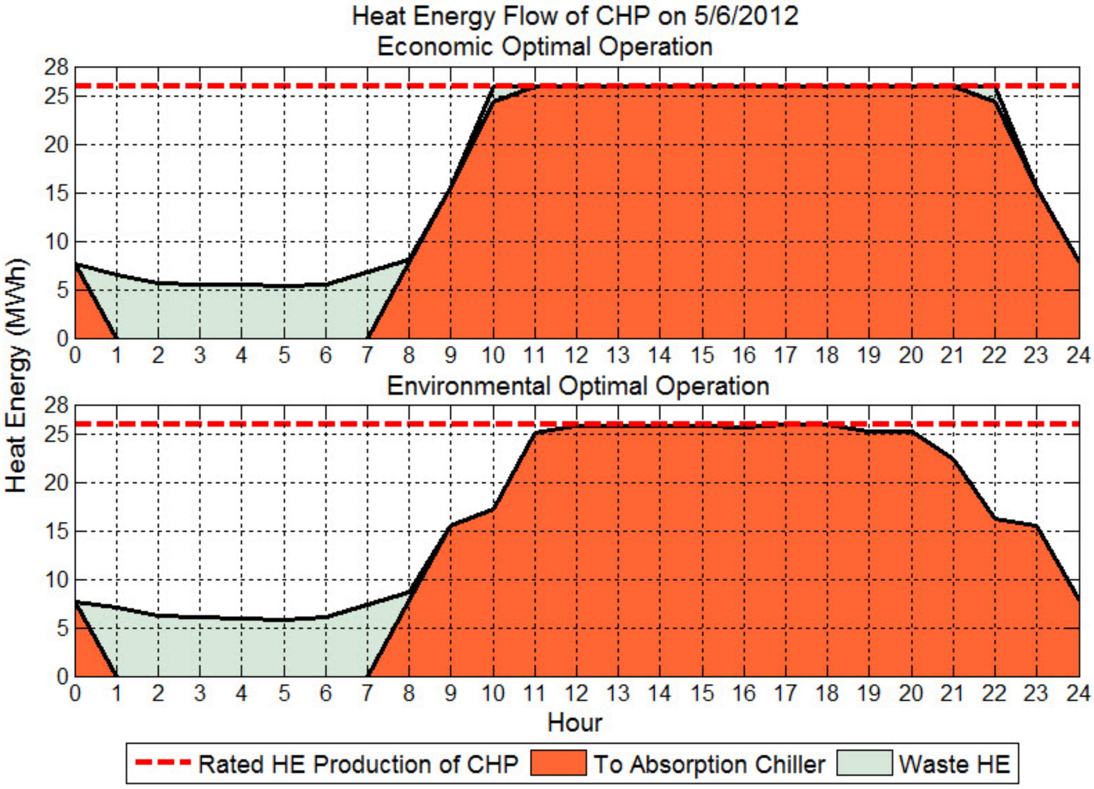

Figure 3.6: HE production of CHP system of BEMS1.

Optimal Electrical Energy Flows

Figure 3.7 demonstrates that BEMS1 is able to supply 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, BEMS1 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, BEMS1 needs to compromise three factors among the EE production cost, EE charge, and demand charge. As a consequence, BEMS1 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, BEMS1 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.

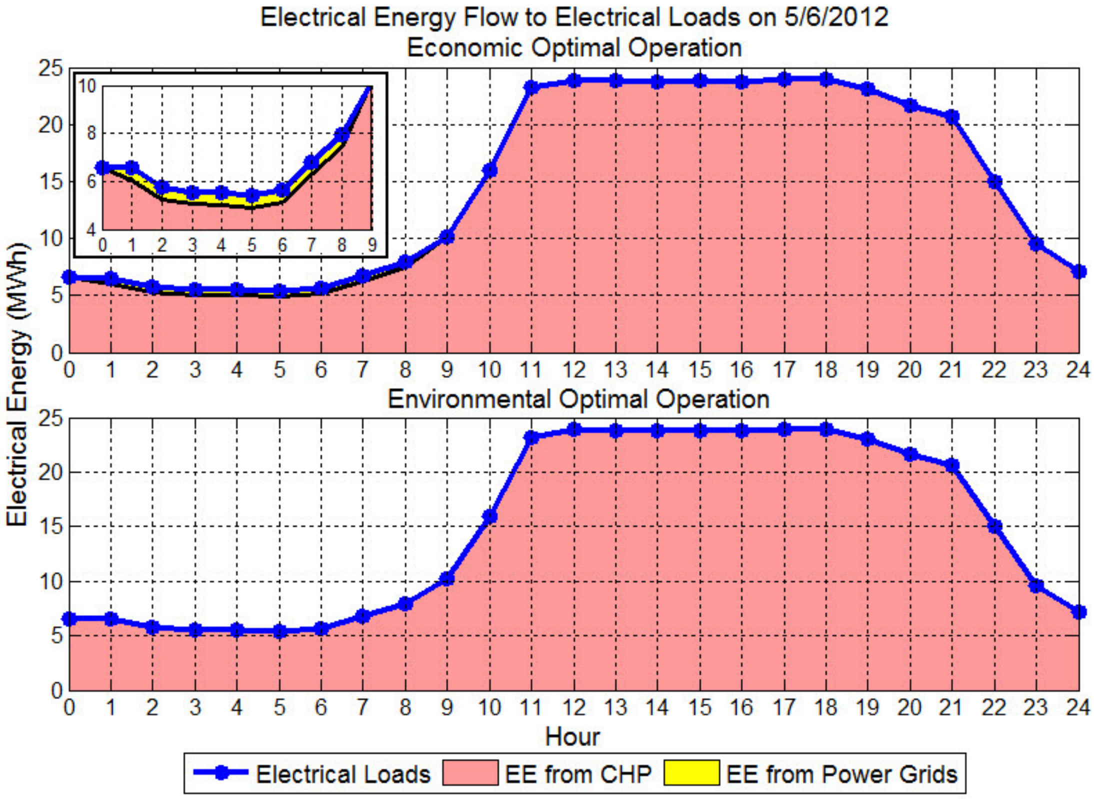

Figure 3.7: EE flow to electrical loads of BEMS1.

Optimal Cooling Energy Flows

Figure 3.8 displays CE flows to cooling loads. It reveals that BEMS1 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, BEMS1 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 will operate in the second mode which causes extra CO_2 emissions a little bit more. If the shortage increases, BEMS1 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, BEMS1 supplies HE to the absorption chiller depending on which HE source offers the minimum CO_2 emissions at that hour.

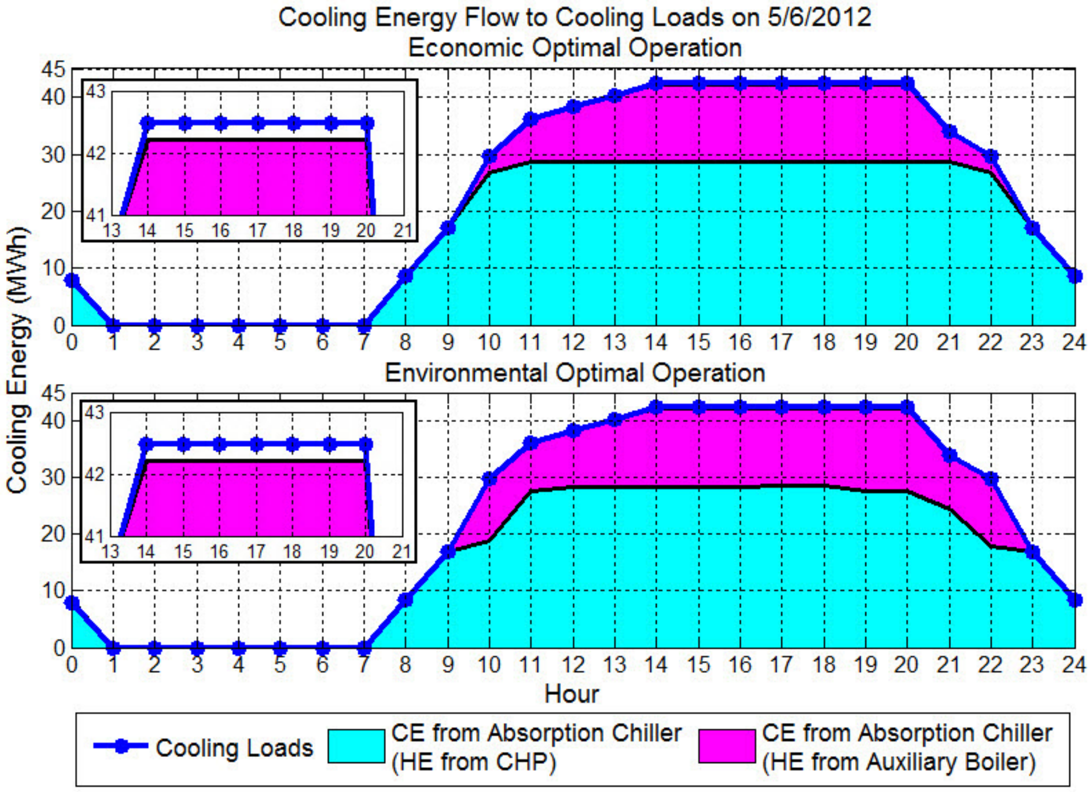

Figure 3.8: CE flow to cooling loads of BEMS1.

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 3.9 demonstrates that the relationship between two optimal operations is a trade-off between TOC and TCOE. If BEMS1 operates with low TOC, it gives high TCOE. This curve is useful for operators in changing operating points of BEMS1 apart from the economic or environmental optimal operating points. For example, if operators want to keep TOC less than 29 million baht, BEMS1 will have TCOE in the range of 6,570-6,671 tCO_2 depending on their decision.

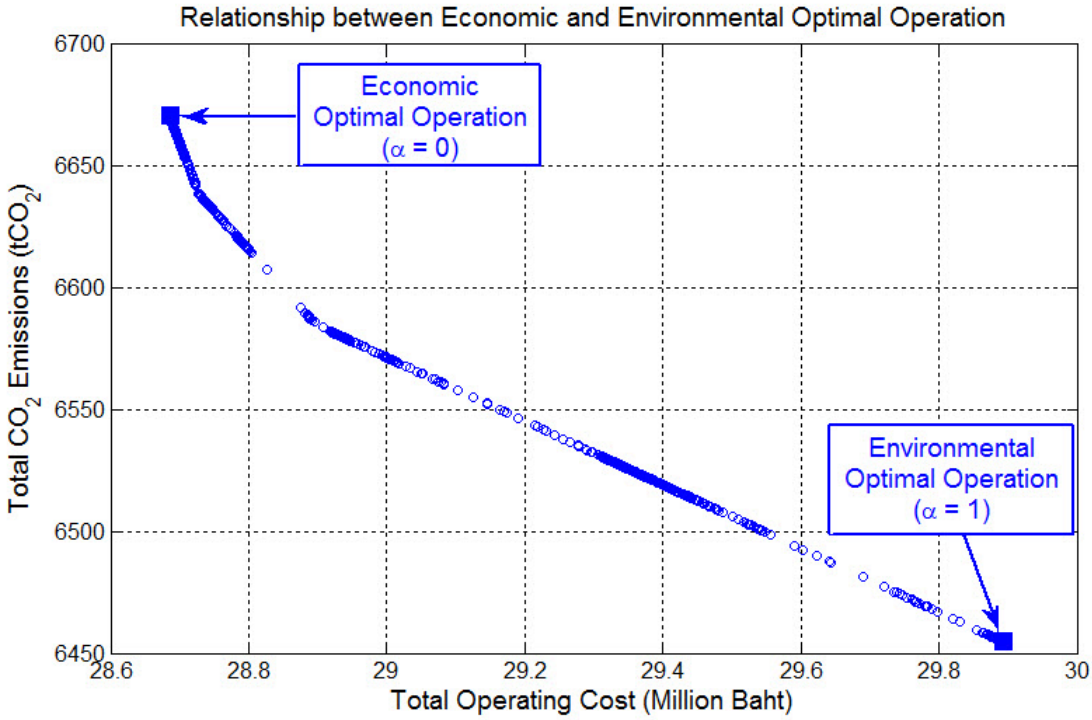

Figure 3.9: Relationship between economic and environmental optimal operations of BEMS1.

3.5.3 Impact of Natural Gas Prices

This subsection investigates the risk in a long-term operation of BEMS1. 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 in the operation because it is an uncontrollable factor for building owners but has a direct and major effect on the operating costs of the equipment like the CHP system and auxiliary boiler in a long run. Figure 3.10 shows APNG in Thailand during 2003-2012 [22]. Obviously, APNG increases almost every year and more than twice in 10 years. Besides, the lifetime of the equipment in BEMS1, typically, is in the range of 20-30 years, so this is the reason why 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 BEMS1, while EE charges, EE selling prices, and CO_2 emission factors are fixed.

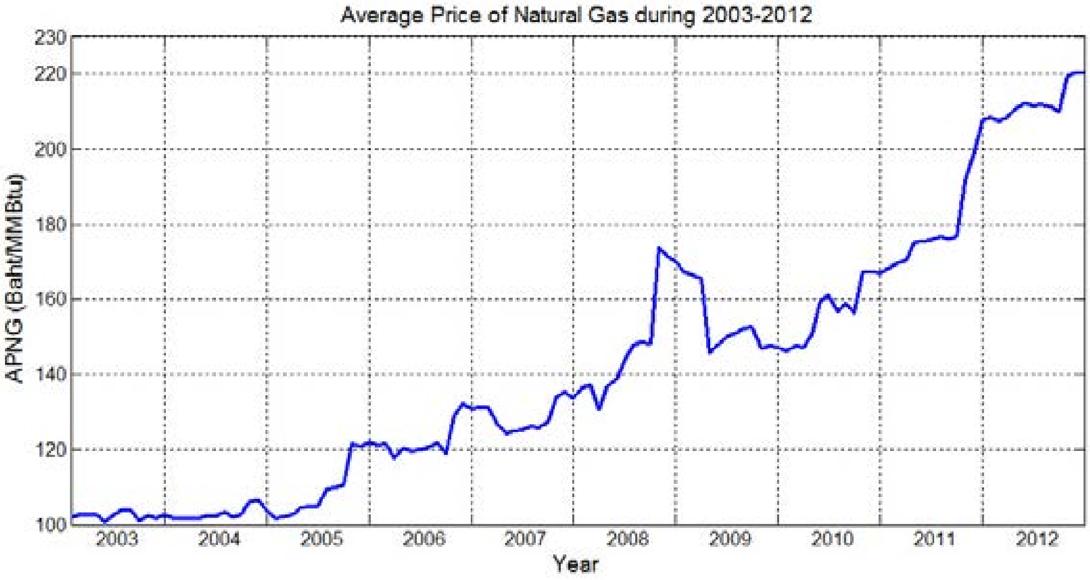

Figure 3.10: APNG during 2003-2012.

Impact on Total Operating Cost

Figure 3.11 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 goes 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 at the same rate of TOC of the environmental one. Moreover, TOCs of BEMS1 are more than TOC of the conventional one when APNGs reach 295 and 303 baht/MMBtu, which means that it is not worth using BEMS1. If we delve deeply into the constitution of TOC, Figure 3.12 shows ECs and DCCs versus APNG. ECs of both optimal operations go up linearly like TOC, but DCCs are 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 which are deciding factors in the environmental optimal operations, and the grid emission factor is still higher than the CO_2 emission factor of the CHP system. As a result, BEMS1 needs to keep utilizing electricity from power grids as little as possible in order to obtain minimum CO_2 emissions.

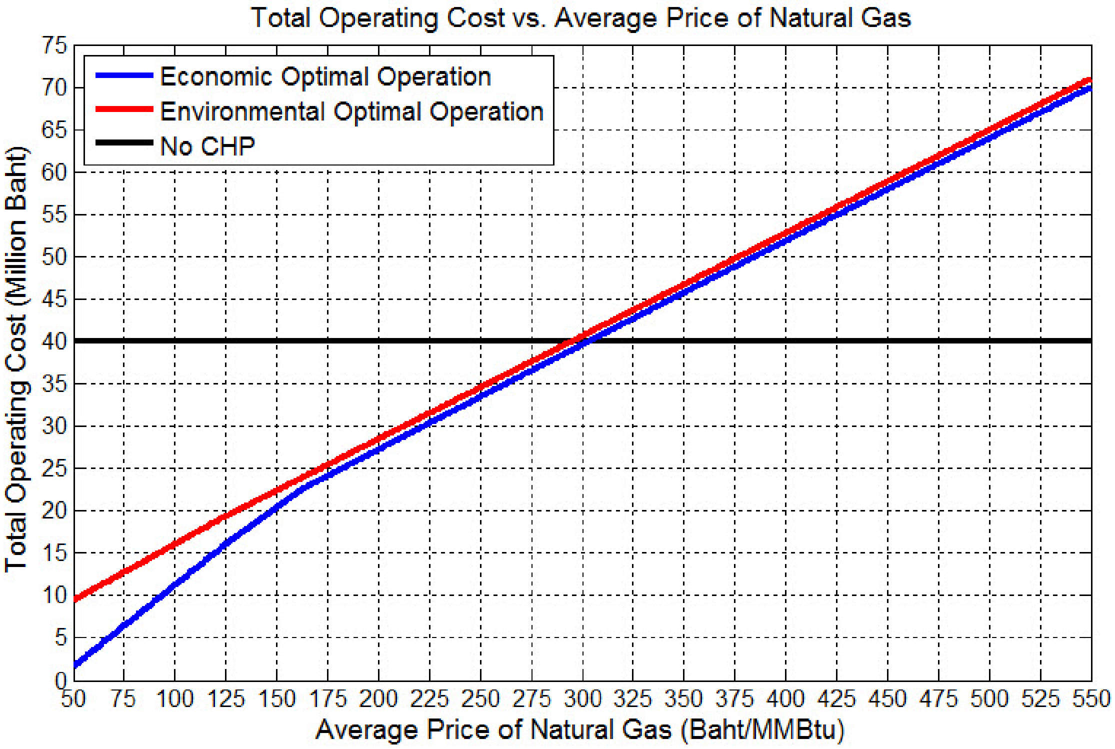

Figure 3.11: TOC of BEMS1 vs. APNG.

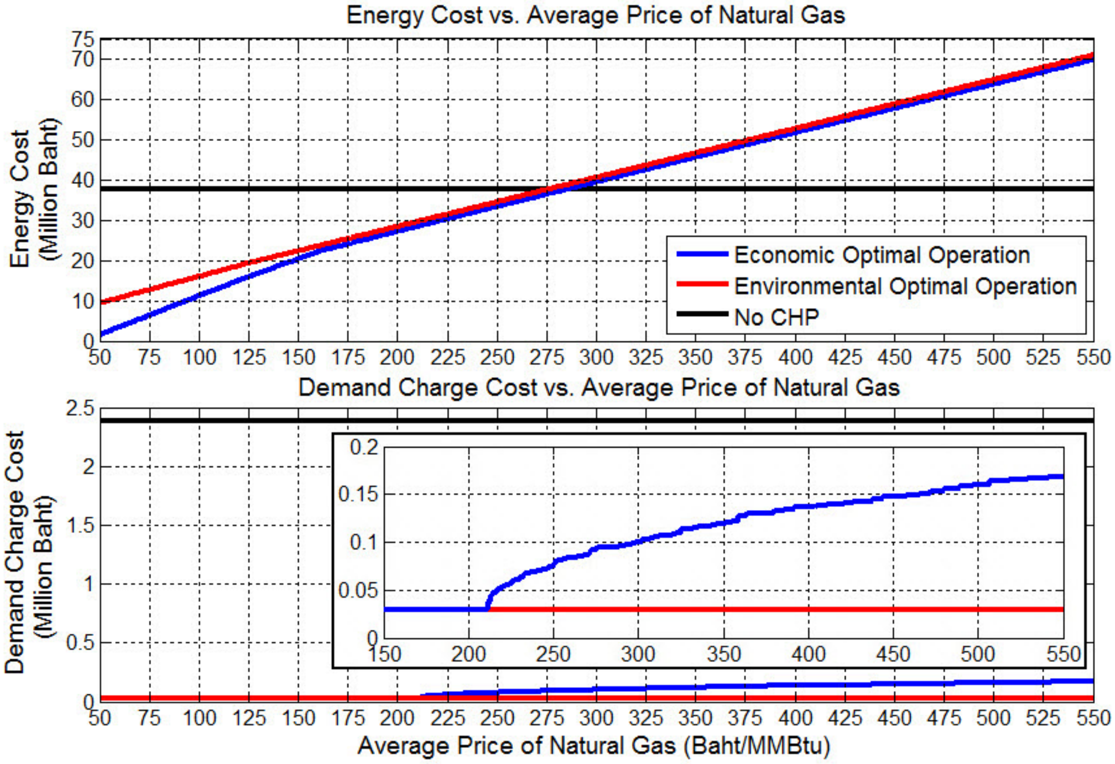

Figure 3.12: EC and DCC of BEMS1 vs. APNG.

Impact on Total CO_2 Emissions

Figure 3.13 shows TCOEs of both optimal operations. Obviously, TCOE of the environmental optimal operation is constant because CO_2 emission factors, which are 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 BEMS1 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.

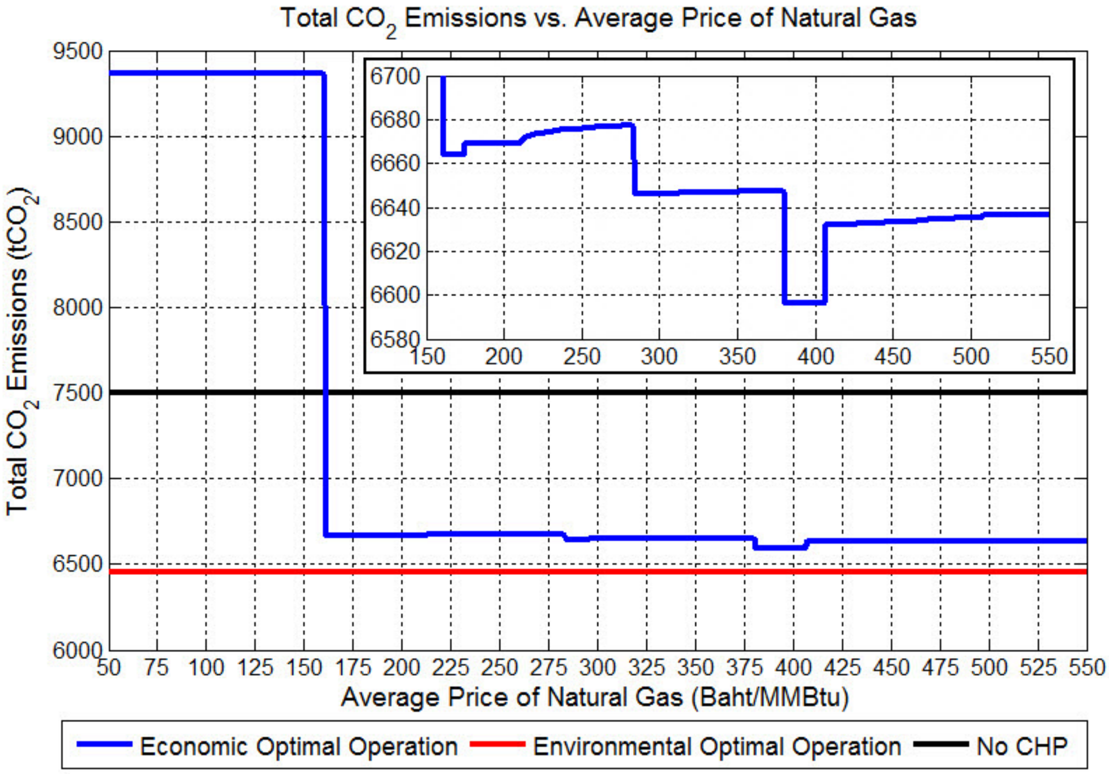

Figure 3.13: TCOE of BEMS1 vs. APNG.

Impact on Electrical and Cooling Energy Costs

Figure 3.14 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, BEMS1 should earn income from selling EE both during off-peak and during on-peak time to reduce operating costs as much as possible. Moreover, BEMS1 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 off-peak time, the CHP system should stop selling EE to power grids and only generate EE electrical loads. During on-peak time, the CHP system still generates EE at the maximum level to earn income from selling EE. Furthermore, BEMS1 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 off-peak time, the CHP system should reduce EE generation to electrical loads, and power grids should take part in supplying EE to meet the demand. In this case, BEMS1 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 on-peak time, the CHP system still generates EE at the maximum 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 off-peak time, the CHP system and power grids should operate like their cooperation in the scheme 3. During 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. BEMS1 compromises the cooperation between the CHP system and power grids based on the EE production cost, the EE charges and the demand charge both during the off-peak and during on-peak time in order to obtain minimum TOC.

Figure 3.15 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, BEMS1 under the economic optimal operation should reduce HE supply from the CHP system and increase HE production from the auxiliary boiler instead when APNG increases.

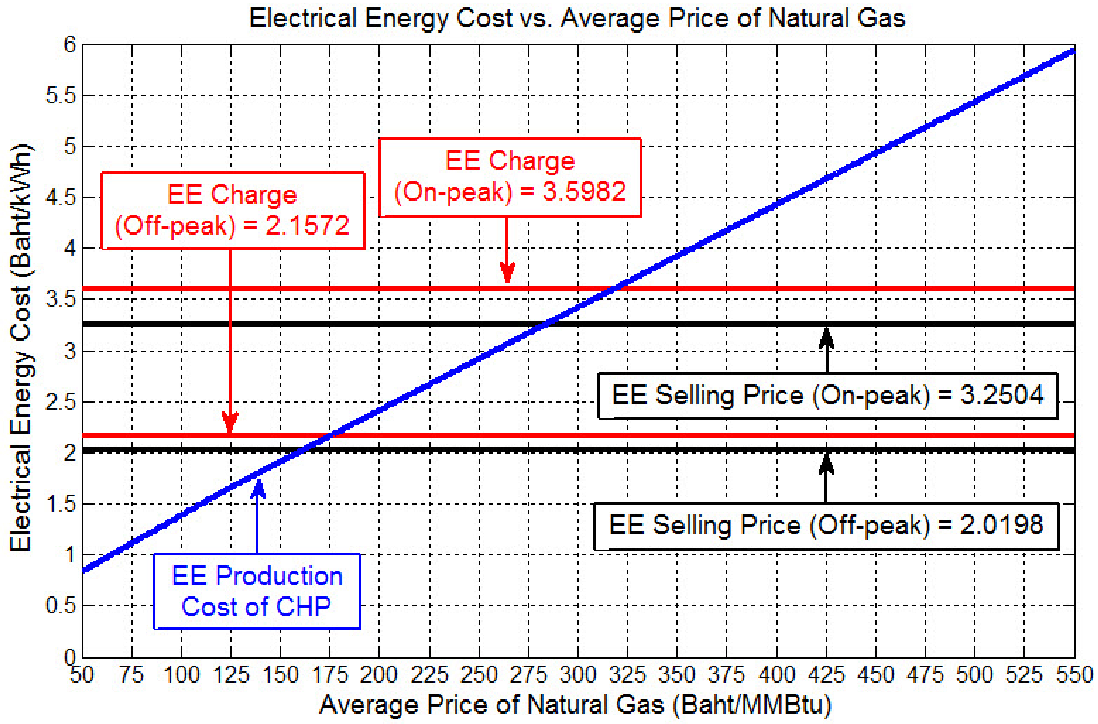

Figure 3.14: EE production cost of CHP system of BEMS1 vs. APNG.

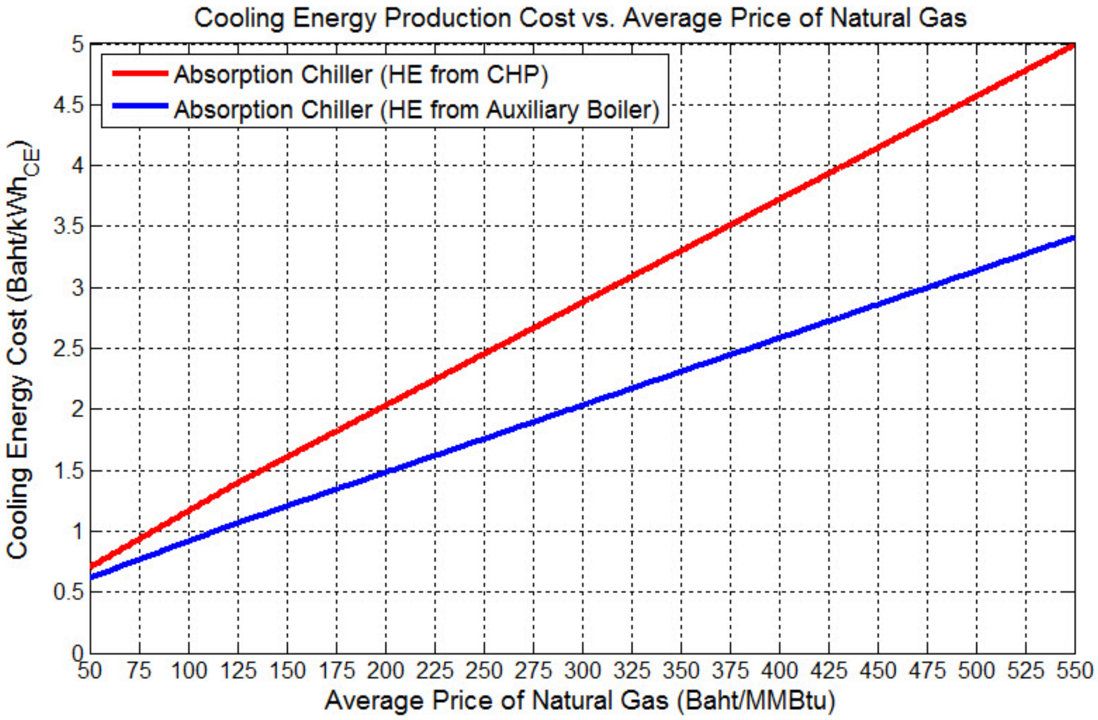

Figure 3.15: CE production cost of absorption chiller of BEMS1 vs. APNG.

Impact on Optimal Operations

Figures 3.16-3.18 show the EE dispatch of the CHP system and power grids and Figure 3.19 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 BEMS1 working under the environmental optimal operation does not change following APNG; therefore, we will not further discuss the EE and HE production of the equipment under this operation. On the contrary, the EE and HE dispatch of BEMS1 working under the economic optimal operation causes 6-step changes in TCOE. Figure 3.16 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 in TCOE. Figure 3.17 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 3.18. Figure 3.19 displays total HE supply to the absorption chiller which contributes to supporting the investigation. In sum, 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 stops selling EE to power grids during off-peak time (see in Figure 3.18). 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 BEMS1 decreases EE supply from the CHP system to electrical loads during off-peak time but increases EE utilization from power grids instead (see in Figure 3.17). As a result, the CHP system reduces total EE production (see in Figure 3.16), but TCOE goes 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 utilization from power grids causes CO_2 emissions more than that from EE generation 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., BEMS1 needs to compromise the cooperation between the CHP system and power grids based on the EE production costs of the CHP system, the off-peak EE charge, and the demand charge in order to obtain 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 3.17). 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 on-peak time (see in Figure 3.18). Consequently, TCOE drops following the decrease in total EE production of the CHP system.

Step 5: At APNG of 380 baht/MMBtu, the CE production costs start having an effect on the economic optimal operation, i.e., BEMS1 reduces HE supply from the CHP system in case of slight heat shortage. In other words, if APNG is lower than 380 baht/MMBtu, and it is worth commanding the CHP system to produce HE a little bit more, from existing HE proportional to EE generation to electrical loads, to supply the little heat shortage. However, if APNG is higher than 380 baht/MMBtu, it is worth using HE from the auxiliary boiler to supply the 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 3.19). Also, such an operation of the CHP system leads to the decrease in EE export during the on-peak time (see in Figure 3.18). 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 BEMS1 needs to consider three factors, namely, the EE production cost, the on-peak EE charge, and the demand charge in the EE dispatch of the CHP system and power grids in order to acquire 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 3.18). Also, such an operation of the CHP system brings about the decrease in HE supply to the absorption chiller, so the auxiliary boiler has to produce HE more to compensate for the shortage (see in Figure 3.19). TCOE increases following the larger utilization of EE from power grids even though the total EE production of CHP decreases.

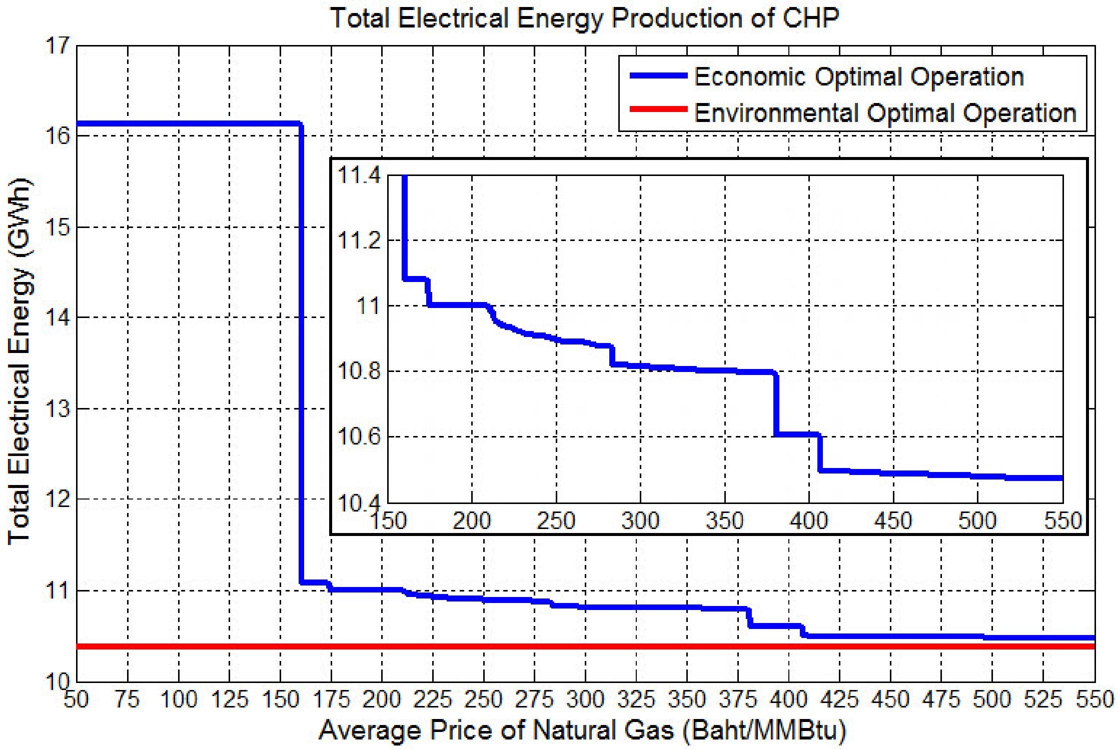

Figure 3.16: Total EE production of CHP of BEMS1 vs. APNG.

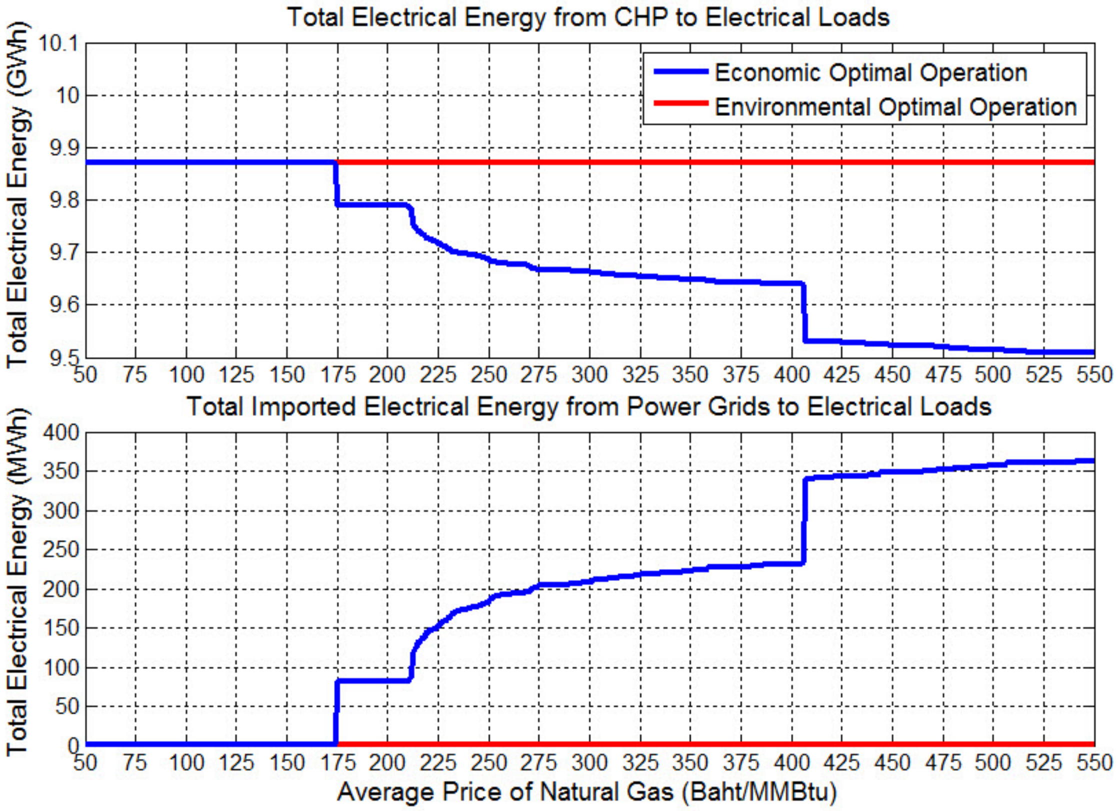

Figure 3.17: Total EE supplied to electrical loads of BEMS1 vs. APNG.

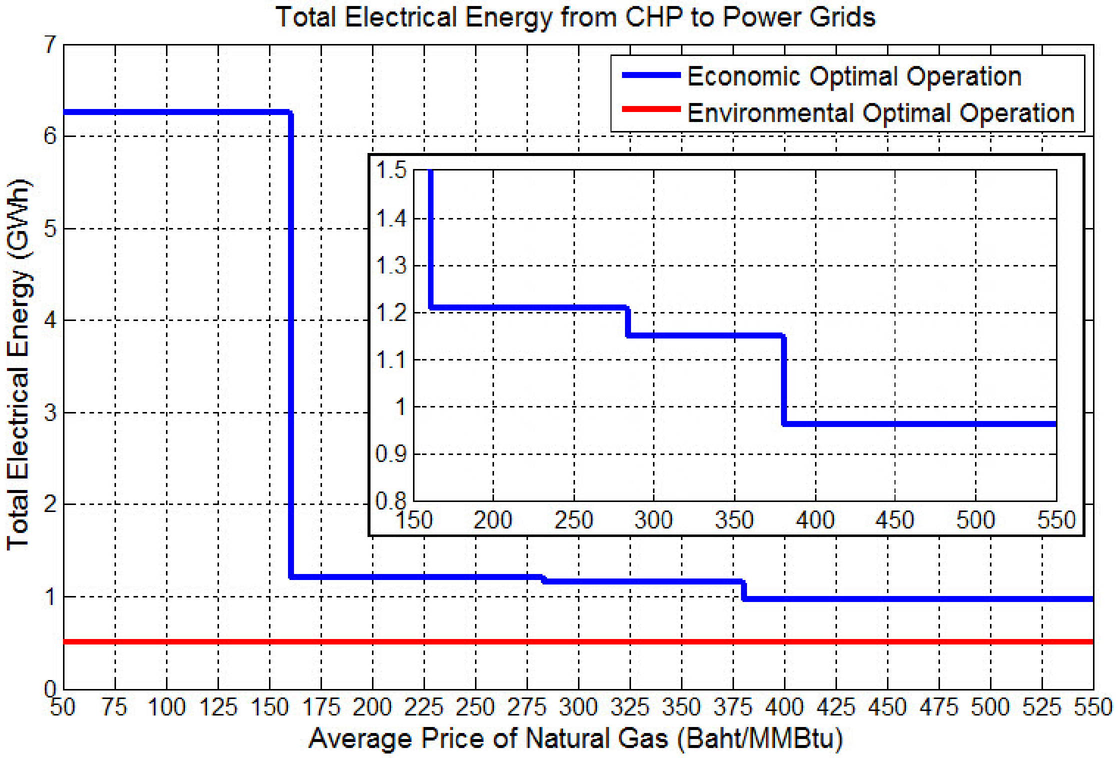

Figure 3.18: Total EE exported to power grids of BEMS1 vs. APNG.

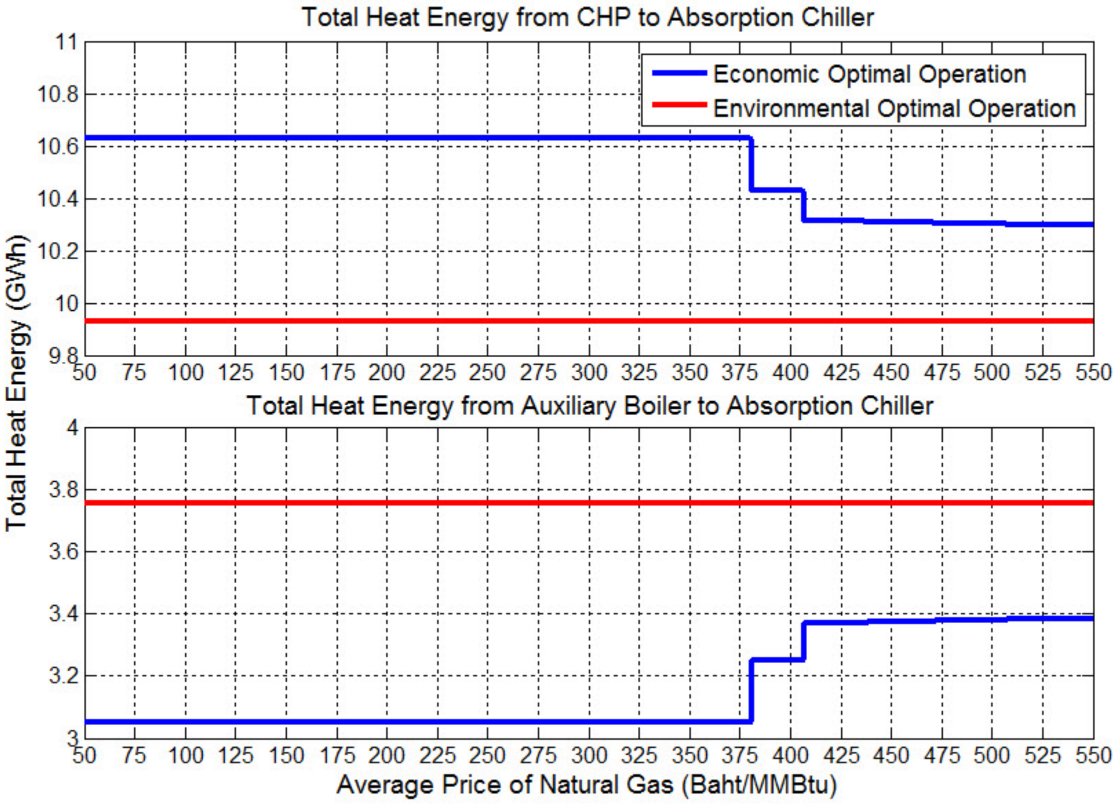

Figure 3.19: Total HE supplied to absorption chiller of BEMS1 vs. APNG.

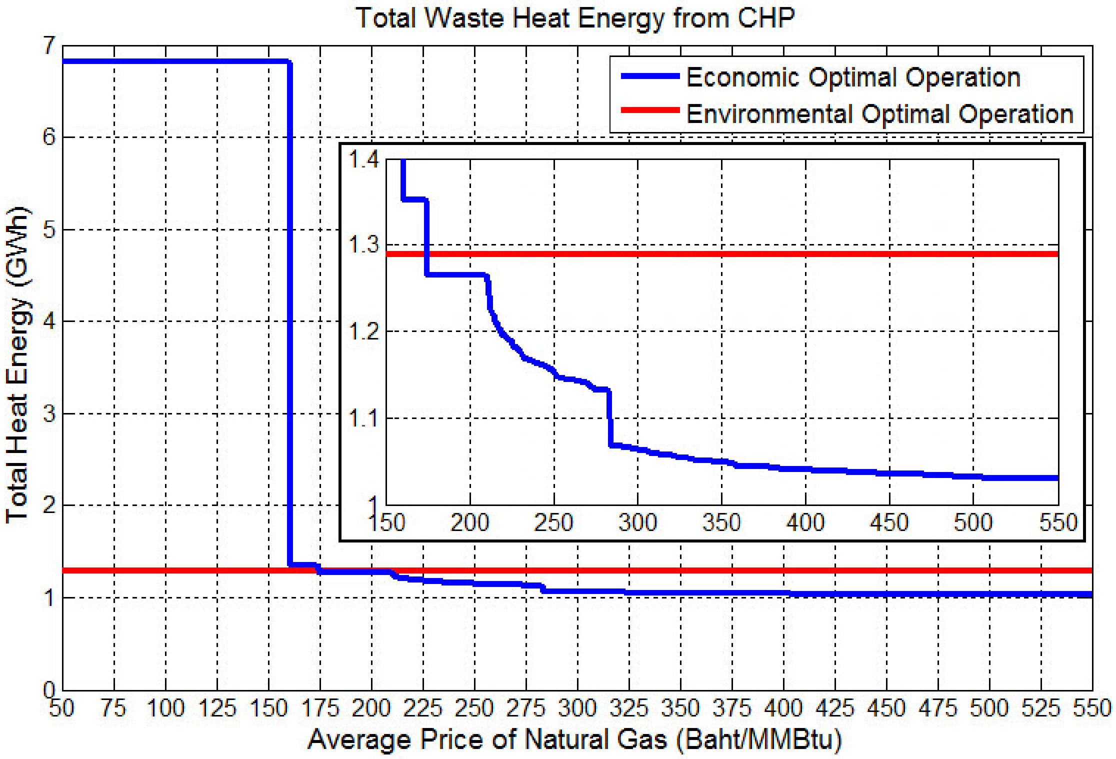

Figure 3.20: Total waste HE from CHP of BEMS1 vs. APNG.

Table 3.12 summarizes the changes in TCOE and total energy production according to the equipment due to the economic optimal operation. We can draw a simple conclusion that the decrease in TCOE results from the decline in total EE generation of the CHP system but the increase in TCOE comes from the rise in EE utilization from power grids.

Finally, although BEMS1 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 3.20. Almost all of waste HE occurs in the off-peak time when there is no CE demand. To improve energy efficiency in BEMS1, 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, BEMS1 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 more 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 3.20. 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.

Table 3.12: Summary of changes in TCOE and total energy production according to the equipment due to economic optimal operation of BEMS1.

APNG (Baht/ MMBtu)	CHP System					EE from Power Grids	HE from Auxiliary Boiler	TCOE
	Total EE Generation	EE to Electrical Loads	EE to Power Grids	HE to Absorption Chiller	Waste HE			
161	↓	–	↓	–	↓	–	–	↓
175	↓	↓	–	–	↓	↑	–	↑
211	↓	↓	–	–	↓	↑	–	↑
283	↓	–	↓	–	↓	–	–	↓
380	↓	–	↓	↓	–	–	↑	↓
407	↓	↓	–	↓	–	↑	↑	↑

Note: 1) ↑ = Increase
↓ = Decrease
– = No change.

2) The changes in TCOE at each step are considered from TCOE in case of APNG lower and higher than each APNG in the table. For example, when APNG is lower than 161 baht/MMBtu, TCOE is 9,364 tCO_2; however, when APNG increases more than 161 baht/MMBtu, TCOE is decreased to 6,664 tCO_2 due to the decline in EE export.

3.6 Summary

In this chapter, we demonstrate that the application of BEMS, which consists of a CHP system, an absorption chiller, an auxiliary boiler, and power grids, is suitable for a large shopping mall due to the pattern of electrical and cooling loads. We design the most suitable capacity of the equipment in BEMS and analyze the economic and environmental optimal operations. The numerical results show that BEMS 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.

CHAPTER IV

BEMS USING COMBINED HEAT AND POWER WITH ELECTRIC CHILLER

This chapter proposes an economic and an environmental optimal operation of BEMS consisting of the CHP system, the absorption chiller, the electric chiller, and power grids. First, we formulate objective functions of BEMS and design dispatch strategies of equipment. Then, the proposed optimal operations of BEMS are applied to a large shopping mall as a case study to determine the most suitable capacity of each component. Lastly, we analyze optimal operations of BEMS via optimal energy flows, and investigate the risk in a long-term operation via the impact of fuel prices.

4.1 System Description

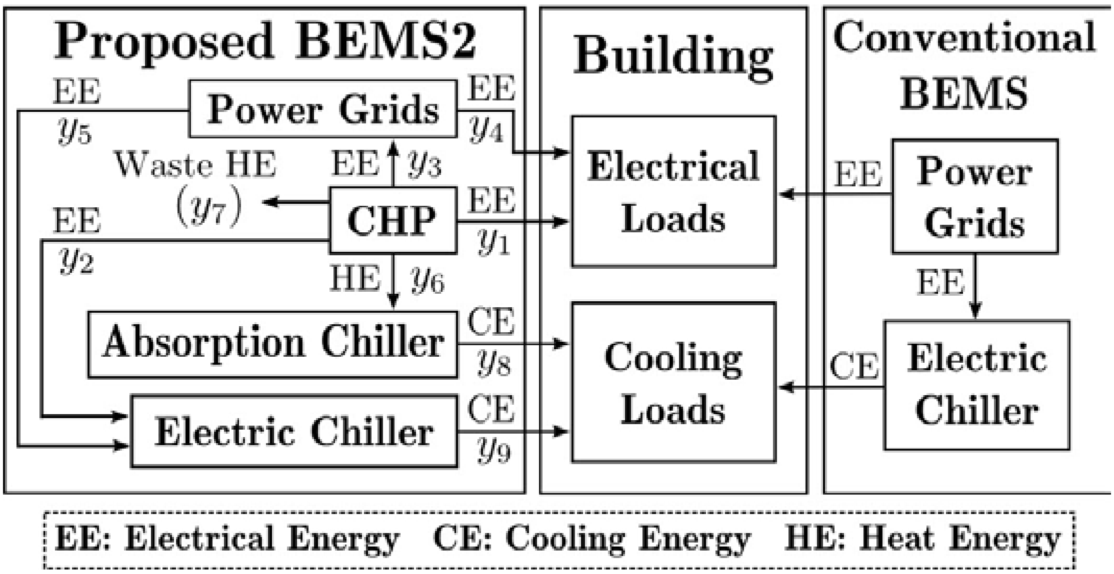

Figure 4.1: Diagram of proposed BEMS2 and conventional BEMS.

The proposed BEMS2, Figure 4.1, controls and optimizes the operation of the CHP generation system, the absorption chiller, the electric chiller and power grids. The CHP system takes primary responsibility for generating EE to electrical loads (y_1) and the electric chiller (y_2), and the coincident HE (y_6) will be supplied to the absorption chiller which converts it to CE (y_8). However, if recovered HE is greater than HE required to meet CE demand, its surplus is released as waste heat HE (y_7). Besides the operation of the CHP system, power grids play a role in purchasing EE from the CHP system in case of excessive EE production (y_3) and in selling EE to electrical loads (y_4) and the electric chiller (y_5) in case of power shortages. Lastly, the electric chiller will start producing CE to cooling loads (y_9) when the absorption chiller cannot provide CE to meet CE demand.

Compared to the equipment in BEMS1 which comprises the CHP system, the absorption chiller, the auxiliary boiler, and power grids, BEMS2 chooses to use the electric chiller instead of the auxiliary boiler. There are two differences between BEMS1 and BEMS2. The first one is the system design process. BEMS1 uses the absorption chiller as the only CE production source, so its size is designed to match cooling loads. However, the size of the CHP system is selected to suit electrical loads, so there is a strong possibility that the CHP system cannot provide HE enough for the absorption chiller. In this case, the boiler is used to produce auxiliary HE and its size is chosen based on the heat shortage. On the contrary, BEMS2 utilizes both absorption and electric chillers in producing CE to cooling loads. The capacity of the absorption chiller is reduced to suit heat that the CHP system can supply, so there is a chance that the absorption chiller cannot supply CE to meet CE demand. In this case, the electric chiller will participate in producing CE and its sized is selected based on the cooling shortage. In addition to the design process, another difference is energy efficiency. Typically, the electric chiller is more efficient than the absorption chiller in term of the cooling production; in other words, the absorption chiller using HE from the auxiliary boiler has cooling production costs and CO_2 emissions more than the electric chiller using EE from power grids. Therefore, we can expect that BEMS2 has total operating costs and total CO_2 emissions lower than those of BEMS1.

4.2 Objective Functions

This section formulates objective functions for the economic and environmental optimal operations of BEMS2 as well as a multi-objective approach to find their relationship.

4.2.1 Economic Optimal Operation

The economic optimal operation is aimed to minimize total operating costs of BEMS2. The objective function is defined as the total operating costs, TOC (baht), which consists of energy costs (EC) and demand charge costs (DCC). EC is the sum of the operating costs of the CHP system and the income and expense from electrical energy trading with power grids throughout the operation. The operating costs of the CHP system is calculated from EE generation to electrical loads, the electric chiller, and power grids. The income from selling EE to power grids contributes to reducing TOC, but there will be an electricity bill if BEMS2 utilizes EE from power grids to supply electrical loads and the electric chiller. DCC is calculated from maximum power imported from power grids to electrical loads and the electric chiller during the operation. Therefore, the economic objective function can be explained as follows:

$$\mathrm{TOC} = \mathrm{EC} + \mathrm{DCC} \tag{4.1}$$

$$\mathrm{EC} = \sum_{k=1}^{n\times d}\Big[c_{\mathrm{CHP}}(y_{1,k} + y_{2,k} + y_{3,k}) - q_k y_{3,k} + p_k(y_{4,k} + y_{5,k})\Big] \tag{4.2}$$

$$\mathrm{DCC} = \frac{d_{\mathrm{PG}}}{\Delta t}\max_{k=1,\ldots,n\times d}(y_{4,k} + y_{5,k}) \tag{4.3}$$

where $y_{i,k}$ is energy flow in the time interval of k. Also, c_{CHP} is operating costs of the CHP system, and 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.

4.2.2 Environmental Optimal Operation

The environmental optimal operation is focused on minimizing total CO_2 emissions, TCOE (tonnes of CO_2, tCO_2), which is comprised of CO_2 emissions from the CHP system and power grids. CO_2 emissions from the CHP system depend on EE generation to electrical loads, the electric chiller, and power grids, and CO_2 emissions from power grids rely on EE supplied to electrical loads and the electric chiller. The environmental objective function can be formulated as follows:

$$\mathrm{TCOE} = \sum_{k=1}^{n\times d}\Big[\mathrm{EF}_{\mathrm{CHP,CO_2}}(y_{1,k} + y_{2,k} + y_{3,k}) + \mathrm{GEF}(\mathrm{y}_{4,k} + y_{5,k})\Big] \tag{4.4}$$

where $\mathrm{EF}_{\mathrm{CHP,CO_2}}$ is CO_2 emission factor of the CHP system, and GEF is grid emission factor.

4.2.3 Multi-objective Approach

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

$$\mathbf{min}\quad (1-\alpha)\frac{\mathrm{TOC}}{\mathrm{TOC}_{\min}} + \alpha\frac{\mathrm{TCOE}}{\mathrm{TCOE}_{\min}}. \tag{4.5}$$

Subsequently, we vary the weighting factor from 0 to 1 and minimize the linear combination in (4.5) to obtain multi-objective optimal operation.

4.3 Dispatch Strategies

The heart 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, BEMS2 operates under the different objective functions but the same constraints. The constraints are mainly divided into EE and CE dispatch strategies.

4.3.1 Electrical Energy Dispatch Strategy

The EE dispatch strategy is linked with the operation of the CHP system and power grids. The operation of the CHP system depends on electrical loads (U_k), that is, it shuts down when there is no EE demand from electrical loads. In this case, power grids are in charge of supplying EE to electrical loads. On the contrary, when cooperating with power grids, the CHP system produces EE within its limitations, $P_{\text{CHP,min}}$ and $P_{\text{CHP,max}}$, and HE proportional to its power-to-heat ratio ($\mathrm{P2H}$). 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

$$y_{1,k} = y_{2,k} = y_{3,k} = y_{6,k} = y_{7,k} = 0$$

else

$$P_{\text{CHP,min}}\Delta t \le y_{1,k} + y_{2,k} + y_{3,k} \le P_{\text{CHP,max}}\Delta t$$

$$\frac{y_{1,k} + y_{2,k} + y_{3,k}}{y_{6,k} + y_{7,k}} = \mathrm{P2H}$$

$$\left|(y_{1,k} + y_{2,k} + y_{3,k}) - (y_{1,k-1} + y_{2,k-1} + y_{3,k-1})\right| \le R_{\text{CHP}}\Delta t$$

end.

$$y_{1,k} + y_{4,k} = U_k$$

4.3.2 Cooling Energy Dispatch Strategy

The CE dispatch strategy is relevant to the operation of all equipment in BEMS2. The CHP system is the only HE supply source of the absorption chiller, but the electric chiller can get EE both from the CHP system and from power grids. Also, the absorption chiller is considered as the primary CE supply source, and the electric chiller is the secondary one. The CE dispatch strategy can be divided into 4 conditions depending on CE demand (C_k). Firstly, if there is no CE demand, the absorption and electric chiller shut down, and HE produced from CHP is released as waste HE. Secondly, if there is CE demand but less than the minimum cooling production level of the absorption chiller ($\mathrm{CP}_{\mathrm{AC,min}}$), the absorption chiller operates at the minimum level so that the temperature in the building is still cool. The CHP system is in charge of supplying HE to the absorption chiller, and the electric chiller still shuts down. Thirdly, BEMS2 still does not use the electric chiller if the absorption chiller can supply CE to meet CE demand. That is, CE demand is less than the maximum cooling production level of the absorption chiller ($\mathrm{CP}_{\mathrm{AC,max}}$) or actual maximum CE depending on maximum HE that the CHP system can supply ($\frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} \times \mathrm{COP}_{\mathrm{AC}}$). Lastly, when the absorption chiller cannot supply CE to satisfy CE demand, the electric chiller starts operating to produce CE to compensate for the cooling shortage. The electric chiller operates in its limitations, $\mathrm{CP}_{\mathrm{EC,min}}$ and $\mathrm{CP}_{\mathrm{EC,max}}$, and the CHP system and power grids cooperates to provide EE to the electric chiller. Both absorption and electric chillers work together to supply CE to meet CE demand but not more than maximum CE that they can produce. In sum, the CE dispatch strategy can be explained with the following constraints.

If $C_k = 0$, then

$$y_{2,k} = y_{5,k} = y_{6,k} = y_{8,k} = y_{9,k} = 0$$

else if $C_k < \mathrm{CP}_{\mathrm{AC,min}}\Delta t$, then

$$y_{6,k}\mathrm{COP}_{\mathrm{AC}} = y_{8,k}$$
$$y_{8,k} = \mathrm{CP}_{\mathrm{AC,min}}\Delta t$$
$$y_{2,k} = y_{5,k} = y_{9,k} = 0$$

else if $C_k \le \min\left(\mathrm{CP}_{\mathrm{AC,max}}\Delta t, \frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} \times \mathrm{COP}_{\mathrm{AC}}\right)$, then

$$y_{6,k}\mathrm{COP}_{\mathrm{AC}} = y_{8,k}$$
$$\mathrm{CP}_{\mathrm{AC,min}}\Delta t \le y_{8,k} \le \min\left(\mathrm{CP}_{\mathrm{AC,max}}\Delta t, \frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} \times \mathrm{COP}_{\mathrm{AC}}\right)$$

$$y_{8,k} = C_k$$

$$y_{2,k} = y_{5,k} = y_{9,k} = 0$$

else

$$y_{6,k}\mathrm{COP}_{\mathrm{AC}} = y_{8,k}$$

$$\mathrm{CP}_{\mathrm{AC,min}}\Delta t \le y_{8,k} \le \min\left(\mathrm{CP}_{\mathrm{AC,max}}\Delta t, \frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} \times \mathrm{COP}_{\mathrm{AC}}\right)$$

$$(y_{2,k} + y_{5,k})\mathrm{COP}_{\mathrm{EC}} = y_{9,k}$$

$$\mathrm{CP}_{\mathrm{EC,min}}\Delta t \le y_{9,k} \le \mathrm{CP}_{\mathrm{EC,max}}\Delta t$$

$$y_{8,k} + y_{9,k} = \min\left(C_k, \min\left(\mathrm{CP}_{\mathrm{AC,max}}\Delta t, \frac{P_{\mathrm{CHP,max}}\Delta t}{\mathrm{P2H}} \times \mathrm{COP}_{\mathrm{AC}}\right) + \mathrm{CP}_{\mathrm{EC,max}}\Delta t\right)$$

end.

4.4 Case Study on a Large Shopping Mall

In a case study, we apply BEMS2 to a large shopping mall which is the same building selected in the case study of BEMS1. BEMS2 exploits natural gas as the primary energy source and electricity from power grids as the secondary one, when compared to the conventional BEMS utilizing electricity from 69-kV distribution grids of MEA as the only energy source. Like the problem formulation process in Chapter 3, this study is conducted based on the same conditions, namely, load profiles, natural gas prices, and electricity prices. However, the procedure for equipment selection is adapted a little bit to suit BEMS using the electric chiller.

Load profiles in the application of BEMS2 are taken from the hourly electrical and cooling load profiles in the study of Chapter 3 which are shown in Figure 3.3 and 3.4. Although all CE demand comes from cooling load profiles, all EE demand does not only result from electrical load profiles but also derive from EE consumption profiles of the electric chiller. In other words, BEMS2 uses the electric chiller to compensate for the cooling shortage, so CE production profiles of the electric chiller can be converted to EE consumption profiles. Generally, EE consumption profiles of the electric chiller depend of types of optimal operations of BEMS2; as a result, we cannot know their daily shapes but can estimate the maximum power required by the electric chiller because it relies on the capacity and efficiency. After knowing the maximum power, we can approximate the maximum peak of all EE demand based on the peaks of electrical loads. Lastly, the maximum peak contributes to selecting the capacity of the CHP system.

On the subject of natural gas prices and electricity prices, this study uses the structure of natural gas tariffs as shown in the equation (3.6) of Chapter 3. Moreover, the parameters of power grids still consist of EE charges, EE selling prices, a demand charge, and a grid emission factor, and all of them are summarized in Table 3.2.

System Design

To design BEMS2, we use the following guideline for equipment selection. Firstly, we consider the type and capacity of CHP systems that match the peaks of all EE demand. Secondly, we choose the type and size of absorption chillers that suit the characteristics of heat production of CHP systems. Thirdly, the type and capacity of electric chillers are selected based on the cooling shortage. Lastly, the well-designed combination will be simulated to find the best BEMS2.

For the selection of the type of CHP system and the absorption chiller, we use information mentioned in the system design of BEMS1 (Subsection 3.3.4) as a guideline. That is, we consider gas turbines as the CHP system of BEMS2 because their sizes are suitable for electrical loads, and the double-effect absorption chiller with coefficient of performance ($\mathrm{COP}_{\mathrm{AC}}$) of 1.1 is chosen as the absorption chiller of BEMS2 because its steam input matches the steam output of the CHP system. The capacity of the CHP system is selected to cover the peaks of all EE demand which comes from the peaks of electrical loads and the maximum power of the electric chiller. However, we do not know the maximum power of the electric chiller because it depends on its type and size which are unknown at first. Therefore, in the beginning, we choose the capacity of the CHP system based on the peaks of electrical loads which are in the range of 22-24.5 MW. For example, if the CHP system has the capacity of 22 MW, it can produce heat of 24.63 MW which can be converted to cooling power of 27.09 MW or 7,703 TR. Hence, we choose the absorption chiller with the size of 7,700 TR; however, total size of the chiller is fixed at 12,000 TR according to the real capacity of the chiller of the shopping mall, so BEMS2 needs the electric chiller with the capacity of 4,300 TR. Lastly, we consider the type of electric chiller to find its maximum power.

Electric chillers suitable for buildings [14, 19] are commercially classified into two types: air-cooled and water-cooled electric chillers. The first type is appropriate for medium buildings, but the second suits large buildings due to bigger sizes and higher efficiency. Moreover, electric chillers with the capacity more than 500 TR should have coefficient of performance ($\mathrm{COP}_{\mathrm{EC}}$) at least 5.67 according to the recommendation of the energy usage regulation in new buildings [19]. In this study, we consider the water-cooled electric chiller with the $\mathrm{COP}_{\mathrm{EC}}$ of 5.67 as the electric chiller of BEMS2 because its size suits the cooling shortage.

After choosing the type of electric chiller, we can calculate the maximum power required by the electric chiller. For instance, in the case of the 22-MW CHP system, the electric chiller with the capacity of 4,300 TR requires electricity input of 2.67 MW, so the maximum peak of all EE demand is 27.17 MW which is more than the capacity of the CHP system. Therefore, we reconsider the size of the CHP system until it covers the maximum peak of all EE demand. That is, when the capacity of the CHP system is 27 MW which matches the 8,800-TR absorption chiller, BEMS2 needs the electric chiller with the size of 3,200 TR whose electricity input is 1.98 MW. In this case, the maximum peak of all EE demand is less than the capacity of the CHP system. In sum, this study considers the CHP system in sizes ranging from 22 MW to 27 MW. Table 4.1 summarizes the CHP system data which are estimated based upon available technical data [10-12]. In the simulation, the minimum and maximum power production of the CHP systems, $P_{\mathrm{CHP,min}}$ and $P_{\mathrm{CHP,max}}$, are set to 20% and 100% of the rated power, and the electrical energy ramp rate (R_{CHP}) is set to 100% of the rated power. Moreover, the operating costs of the CHP system (c_{CHP}) can be computed according to the equation (3.9) of Chapter 3. Table 4.2 demonstrates all combinations of the equipment in BEMS2, including electricity input of the electric chiller. Lastly, Table 4.3 sums up parameters related to the absorption chiller, the electric chiller and others to be used in the study. The minimum and maximum cooling production of the absorption chiller, $\mathrm{CP}_{\mathrm{AC,min}}$ and $\mathrm{CP}_{\mathrm{AC,max}}$, and those of the electric chiller, $\mathrm{CP}_{\mathrm{EC,min}}$ and $\mathrm{CP}_{\mathrm{EC,max}}$, are set to 20% and 100% of the rated cooling power.

Table 4.1: CHP data for BEMS2.

Description		CHP Systems					
Rated Power (MW)	-	22	23	24	25	26	27
Electrical Efficiency (%)	$\eta_{\mathrm{CHP,EE}}$	33.11	33.51	33.90	34.30	34.48	34.66
Power to Heat Ratio	P2H	0.8933	0.9088	0.9244	0.9400	0.9480	0.9560
Maximum Power Production (MW)	$P_{\mathrm{CHP,max}}$	22	23	24	25	26	27
Minimum Power Production (MW)	$P_{\mathrm{CHP,min}}$	4.4	4.6	4.8	5.0	5.2	5.4
Electrical Energy Ramp Rate (MW)	R_{CHP}	22	23	24	25	26	27
CO_2 Emission Factor (tCO_2/MWh)	$\mathrm{EF}_{\mathrm{CHP,CO_2}}$	0.5497	0.5423	0.5349	0.5275	0.5250	0.5224
Operation and Maintenance Costs (baht/MWh)	$\mathrm{OM}_{\mathrm{CHP}}$	0.1598	0.1555	0.1513	0.1470	0.1456	0.1442

Table 4.2: Capacity combinations for BEMS2.

CHP System (MW)	**Absorption Chiller (TR)**	**Electric Chiller**	
		Capacity (TR)	**Electricity Input (MW)**
22	7,700	4,300	2.67
23	7,900	4,100	2.54
24	8,100	3,900	2.42
25	8,300	3,700	2.29
26	8,500	3,500	2.17
27	8,800	3,200	1.98

Table 4.3: Parameters of equipment and other notations for BEMS2.

Absorption Chiller		
Rated cooling power (MW)	-	-
Coefficient of performance (-)	$\mathrm{COP}_{\mathrm{AC}}$	1.1
Maximum cooling production (MW)	$\mathrm{CP}_{\mathrm{AC,max}}$	-
Minimum cooling production (MW)	$\mathrm{CP}_{\mathrm{AC,min}}$	-
Electric Chiller		
Rated cooling power (MW)	-	-
Coefficient of performance (-)	$\mathrm{COP}_{\mathrm{EC}}$	5.67
Maximum cooling production (MW)	$\mathrm{CP}_{\mathrm{EC,max}}$	-
Minimum cooling production (MW)	$\mathrm{CP}_{\mathrm{EC,min}}$	-
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

4.5 Simulation Results

The proposed economic and environmental optimal operations of BEMS2 are formulated as a linear program (LP) which can be efficiency solved by MATLAB optimization toolbox. In the simulation, we investigate three main parts. The first focuses on the questions: can BEMS2 reduce TOC and TCOE and which combination is the best for the BEMS2. Next, after obtaining the best candidate for BEMS2, we analyze the optimal operations of each component working under the economic and environmental optimal operations, including the relationship between them. Lastly, we examine the risk in long-term operation via the question: how does APNG have an impact on TOC, TCOE and optimal operations of BEMS2.

4.5.1 System Design Results

This subsection answers two questions: are TOC and TCOE reduced by the proposed optimal operations, and which combination of the equipment is the most suitable for the BEMS2. We compare TOC and TCOE of BEMS2 with those of the conventional BEMS and BEMS1. Each candidate is simulated under the economic and environmental optimal operations based on APNG as of June 2012 [22], 211.75 baht/MMBtu.

Before answering the questions, we sum up TOC and TCOE of the conventional BEMS. The shopping mall has TOC of 39,924,388 baht and TCOE of 7,503 tCO_2, and if we delve deeply into TOC, EC and DCC are 37,543,604 and 2,380,784 baht or represent 94.04% and 5.96%, respectively. When BEMS2 is applied to the shopping mall, Table 4.4 summarizes TOCs and TCOEs of all candidates working under the economic and environmental optimal operations. It demonstrates that all combinations can reduce TOCs and TCOEs.

Table 4.4: BEMS2 design results.

CHP (MW)	Economic Optimal Operation		Environmental Optimal Operation	
	TOC (Baht)	TCOE (tCO_2)	TOC (Baht)	TCOE (tCO_2)
22	28,173,251	6,139	28,579,156	6,006
23	27,449,853	6,082	27,877,941	5,929
24	26,711,901	6,039	27,126,744	5,885
25	25,973,856	6,051	26,384,591	5,896
26	25,460,572	6,131	25,937,035	5,937
27	24,972,014	6,259	25,581,582	6,011

TOCs of BEMS2 decline by 29.4%-37.5% and 28.4%-35.9% for the economic and environmental optimal operations, when compared to TOC of the conventional system. It is obvious that the increase in the capacity of the CHP system leads to the decrease in TOC of BEMS2. To explain the reason for this cause, we need to consider the constitution of TOC. Table 4.5 shows ECs and DCCs which account for 98.7%-100% and 0-1.3% of TOCs, respectively, for both optimal operations. Clearly, DCCs of BEMS2 working under both optimal operations look quite similar; moreover, when compared to DCC of the conventional BEMS, they decline by more than 84.2% and up to 100% when the capacity of the CHP system is more than the maximum peak of all EE demand. This result reflects that BEMS2 attempts to reduce maximum electricity power from power grids as much as possible in order to obtain the minimum DCC. Furthermore, when compared to EC of the conventional BEMS, ECs of BEMS2 decrease by 24.9%-33.5% for the economic optimal operation and 23.9%-31.9% for the environmental one. Table 4.6 gives details of ECs according to the equipment. It can be observed that total EC of the CHP system goes up greatly following its capacity even if the operation and maintenance cost ($\mathrm{OM}_{\mathrm{CHP}}$) goes down. This means that the CHP system increases EE production, especially EE exported to power grids, which leads to the dramatic increase in earnings; as a result, net EC of the CHP system increases slightly and turns to decrease when the capacities are 26 and 27 MW. Moreover, the rise in EE generation of the CHP system brings about the fall in EE utilization from power grids. Hence, EC of power grids decreases significantly, which contributes to the decrease in EC of BEMS2. In sum, when the capacity of the CHP system increases, TOC of BEMS2 decreases because BEMS2 can reduce EE utilization and maximum electricity power from power grids and earn more income from the increase in EE production of the CHP system.

Table 4.5: Energy and demand charge costs of BEMS2.

CHP (MW)	**Economic Optimal Operation**		**Environmental Optimal Operation**	
	EC (Baht)	**DCC (Baht)**	**EC (Baht)**	**DCC (Baht)**
22	27,798,214	375,037	28,204,119	375,037
23	27,158,154	291,699	27,586,242	291,699
24	26,503,539	208,362	26,918,382	208,362
25	25,848,830	125,026	26,259,565	125,026
26	25,418,884	41,688	25,895,310	41,725
27	24,972,014	0	25,581,582	0

Table 4.6: Energy costs according to equipment of BEMS2.

CHP (MW)	Equipment		Economic Optimal Operation	Environmental Optimal Operation
			EC (Baht)	EC (Baht)
22	CHP	Total EC Income from EE export	25,694,907 (1,296,743)	26,020,093 (489,943)
		Net EC	24,398,164	25,530,150
	Power Grids		3,400,050	2,673,969
23	CHP	Total EC Income from EE export	26,457,217 (1,600,424)	26,564,103 (644,271)
		Net EC	24,856,793	25,919,832
	Power Grids		2,301,361	1,666,410
24	CHP	Total EC Income from EE export	27,197,412 (2,009,341)	27,177,390 (1,035,223)
		Net EC	25,188,071	26,142,167
	Power Grids		1,315,468	776,215
25	CHP	Total EC Income from EE export	27,956,846 (2,715,944)	27,771,322 (1,702,456)
		Net EC	25,240,902	26,068,866
	Power Grids		607,928	190,699
26	CHP	Total EC Income from EE export	28,743,797 (3,540,885)	28,093,637 (2,207,997)
		Net EC	25,202,912	25,885,640
	Power Grids		215,972	9,670
27	CHP	Total EC Income from EE export	29,607,248 (4,635,234)	28,438,049 (2,856,467)
		Net EC	24,972,014	25,581,582
	Power Grids		0	0

TCOEs of BEMS2 drop by 15.6%-19.5% and 19.9%-21.6% for the economic and environmental optimal operations, respectively, when compared to TCOE of the conventional BEMS. Unlike TOC, TCOE of BEMS2 does not decline continuously following the capacity of the CHP system. For both optimal operations, TCOE decreases at first until the capacity of the CHP system is 24 MW and then it turns to increase. To investigate the trend of TCOE, we consider CO_2 emissions according to the equipment as shown in Table 4.7. Clearly, there are two trends in CO_2 emissions: an upward trend of the CHP system and a downward trend of power grids. The CHP system working under both optimal operations has a tendency to increase CO_2

emissions even if the CO_2 emission factor of the CHP system decreases following its size. This means that the CHP system increases EE generation to electrical loads, the electric chiller, and power grids. The increase in EE supply of the CHP system to all EE demand leads to the decrease in EE utilization from power grids; as a result, power grids are likely to decline CO_2 emissions. These two trends cause changes in TCOE in two directions. TCOE begins with decrease because the downward trend is more outstanding, i.e., when the capacity of the CHP system increases from 22 MW to 24 MW, CO_2 emissions from power grids reduce by 408 and 356 tCO_2 for the economic and environmental optimal operations, compared to those of the CHP system which just rise by 308 and 235 tCO_2. After that, TCOE turns to increase due to the influence of the upward trend, i.e., when the size of the CHP system increases from 24 MW to 27 MW, CO_2 emissions of the CHP system grow by 510 and 266 tCO_2, compared to those from power grids which fall by 290 and 190 tCO_2 for the economic and environmental optimal operations, respectively. In sum, BEMS2 has the minimum TCOE when the capacity of the CHP system is 24 MW for both optimal operations.

Table 4.7: CO_2 emissions according to equipment of BEMS2.

CHP (MW)	**Economic Optimal Operation**		**Environmental Optimal Operation**	
	CHP (tCO_2)	**Power Grids (tCO2)**	**CHP (tCO_2)**	**Power Grids (tCO_2)**
22	5,441	698	5,510	496
23	5,599	483	5,622	307
24	5,749	290	5,745	140
25	5,902	149	5,863	33
26	6072	59	5,935	2
27	6,259	0	6,011	0

To compare the performance of BEMS1 and BEMS2, we consider TOCs and TCOEs as criteria. BEMS1 uses the CHP system in sizes ranging from 22 MW to 25 MW as candidates, but BEMS2 exploits the CHP system in the range of 22-27 MW, which makes it difficult to compare. Therefore, the comparison focuses only on the CHP system with the capacity ranging from 22 MW to 25 MW. Regardless of types of optimal operations, BEMS1 can reduce TOCs and TCOEs by 22.0%-30.2% and 10.4%-14.0%; however, BEMS2 is able to cut TOCs and TCOEs by 28.4%-34.9% and 18.2%-21.6%, respectively. Therefore, we conclude that BEMS2 is more efficient than BEMS1 because it offers lower TOCs and TCOEs when working under the same conditions: electrical and cooling loads, natural gas prices, and electricity prices. If we consider the performance of BEMS1 and BEMS2 according to the equipment, Table 4.8 compares energy and demand charge costs, and CO_2 emissions in the overall picture. Irrespective of types of optimal operations, total ECs and CO_2 emissions of the CHP system of BEMS1 are close to those of BEMS2, which means that both BEMS1 and BEMS2 control the CHP system to produce EE in a similar amount. However, when there is power and heat or cooling shortage, BEMS1 utilizes power grids and the auxiliary boiler to supply EE to electrical loads and HE to the absorption chiller, compared to BEMS2 which uses only power grids to supply EE to electrical loads and the electric chiller. There is no doubt that DCC of BEMS1 is certainly lower than that of BEMS2 because BEMS1 needs maximum electricity power from power grids to supply only electrical loads, compared to BEMS2 which requires it to supply both electrical loads and the electric chiller. ECs and CO_2 emissions of power grids and the auxiliary boilers of BEMS1 are higher than those of power grids of BEMS2, which reflects that BEMS2 has more energy efficiency than BEMS1 when dealing with the shortage. In other words, the utilization of the electric chiller is more efficient than the use of the auxiliary boiler and the absorption chiller because the electric chiller has higher COP than the absorption chiller. In short, BEMS2 has more performance than BEMS1.

Table 4.8: Comparison of energy and demand charge costs, and CO_2 emissions of BEMS1 and BEMS2 in overall picture.

Description		BEMS1	BEMS2
Energy Costs (Baht)	Total EC of CHP	25,701,669 - 28,650,953	25,694,907 - 27,956,846
	Grids (and Boilers)	3,564,280 - 5,917,085	190,699 - 3,400,050
Demand Charge Costs (Baht)		0 - 177,298	125,026 - 375,037
CO_2 Emissions (tCO_2)	CHP	5,443 - 6,049	5,441 - 5,902
	Grids (and Boilers)	675 - 1,176	33 – 698

Finally, to find the best combination of BEMS2, we use TCOE of the environmental optimal operation as a decision criterion, like the criterion used in BEMS1. In the case study, the minimum TCOE occurs when the capacity of the CHP system is 24 MW. As a result, we choose the 24-MW CHP system, the 8,100-TR double-effect absorption chiller, and the 3,900-TR water-cooled electric chiller as the best candidate for BEMS2.

4.5.2 Analysis of Optimal Operations

After obtaining the best combination of BEMS2, we analyze the operating behavior of each component under the economic and environmental optimal operations. In particular, we will investigate how each component of BEMS2 works under the economic and environmental optimal operations and whether BEMS2 can supply EE and CE to meet the demand. In the analysis, we choose the optimal energy flows on 5 June 2012 as examples with the same reason in the case study of BEMS1. Also, we find the relationship between the economic and environmental optimal operation via the multi-objective approach.

Deciding Factors in Optimal Operations

Before analyzing the optimal operations of BEMS2, we investigate deciding factors in the economic and environmental optimal operations.

In view of the economic optimal operation, BEMS2 controls the equipment to supply EE and CE based on deciding factors: EE production cost of the CHP system, electricity prices of power grids, and CE production costs of the absorption and electric chillers. The EE production cost, EE charges, EE selling prices, and demand charge are related to the cooperation between the CHP system and power grids in supplying EE. The EE production cost of the 24-MW CHP system based on APNG as of June 2012 is 2.5308 baht/kWh. During off-peak time, the EE production cost is higher than the EE charge and selling price, so the CHP system should not sell EE and power grids should take part in supplying EE to reduce EC. During on-peak time, the EE production cost is lower than EE charge and selling price, so the CHP system should operates at the maximum EE production level in order to supply EE to electrical loads and the electric chiller as the main EE supply source and sell excessive EE to earn income. Power grids do not participate in supplying EE as long as the CHP system can produce EE to meet all EE demand. The CE production costs, which are directly linked to the economic operation of the chillers, are divided according to types of chillers. Generally, BEMS2 uses the absorption chiller before the electric chiller because it obtains free HE which is coincident with EE generation of the CHP system to all EE demand and power grids; in this case, the absorption chiller produces CE without CE production cost. However, if free HE is not enough for the absorption chiller to produce CE to meet CE demand, BEMS2 has two ways in handling the cooling shortage. The first way is to command the CHP system to produce HE more if it does not operate at the maximum EE production level yet; in this case, the absorption chiller has the CE production cost which can be calculated from the amount of HE required to generate one kilowatt-hour of CE (kWh_{CE}), i.e., 2.1268 baht/kWh_{CE}. The second way is to order the electric chiller to produce CE; in this case, the CE production costs are computed based on EE supply sources, i.e., 0.4463 baht/kWh_{CE} for EE from the CHP system, and 0.6346 and 0.3805 baht/MWh_{CE} for EE from power grids during on-peak and off-peak time, respectively. Lastly, Table 4.9 summarizes EE and CE production costs, and electricity prices based on APNG as of June 2012.

In view of the environmental optimal operation, BEMS2 orders the equipment to supply EE and CE based on deciding factors: CO_2 emission factor of the CHP system, grid emission factor, and equivalent CO_2 emission factors of the absorption and electric chillers. The CO_2 emission factor of the 24-MW CHP system and grid emission factor, which are directly associated with EE supply, are 0.5349 and 0.5994 tCO_2/MWh; therefore, BEMS2 should use the CHP system as the main EE supply source to electrical loads and the electric chiller and not sell EE to power grids because it causes additional CO_2 emissions unnecessarily. Power grids participate in supplying EE when the CHP system cannot produce EE to meet all EE demand. Equivalent CO_2 emission factors of the chillers involve the environmental operation of the chillers. BEMS2 supplies CE to cooling loads with CO_2 emissions if CE does not result from CE production of the absorption chiller using clean HE which is coincident with EE generation to electrical loads and the electric chiller. The equivalent CO_2 emission factors are calculated from CO_2 emissions released to produce a megawatt-hour of CE (MWh_{CE}), i.e., 0.4495 tCO_2/MWh_{CE} for the absorption chiller using HE from the CHP system, and 0.0943 and 0.1057 tCO_2/MWh_{CE} for the electric chiller using EE from the CHP system and power grids, respectively. Table 4.10 summarizes the comparison of CO_2 emission factors.

Table 4.9: Comparison of EE and CE production costs of BEMS2 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
CE Production Costs	
CE production cost of absorption chiller using HE from CHP (baht/kWh_{CE})	2.1268
CE production cost of electric chiller using EE from CHP (baht/kWh_{CE})	0.4463
CE production cost of electric chiller using EE from power grids during on-peak time (baht/kWh_{CE})	0.6346
CE production cost of electric chiller using EE from power grids during off-peak time (baht/kWh_{CE})	0.3805

Table 4.10: Comparisons of CO_2 emission factors.

CO_2 Emission 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 electric chiller using EE from CHP (tCO_2/MWh_{CE})	0.0943
Equivalent CO_2 emission factor of electric chiller using EE from power grids (tCO_2/MWh_{CE})	0.1057

Optimal Operations of CHP system

Figure 4.2 and 4.3 show EE and HE production of the CHP system on 5 June 2012. Clearly, the CHP system mainly generates EE to electrical loads and the electric chiller 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.

On the subject of the economic optimal operation, the CHP system operates based on the EE production cost and electricity prices of power grids. During on-peak time or 9.00-22.00, the EE production cost is lower than the EE charge and EE selling price, so the CHP system generates EE at the maximum level in order to supply electrical loads and the electric chiller and export the surplus EE to power grids to reduce EC 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 off-peak time, the CHP system produces EE only to electrical loads and does not attempt to export EE to power grids because the EE production cost is higher than the EE selling price. Most of the coincident HE is released as waste HE because there is no CE demand, especially during 1.00-7.00 which is the time the shopping mall is closed. Moreover, we can notice that BEMS2 exports EE to power grids before 9.00 and after 22.00 even if it cannot earn income from this selling. The reason is that BEMS2 needs extra HE for the absorption chiller to produce CE to meet CE demand. In other words, existing HE which is coincident with EE generation to all EE demand is not enough for the absorption chiller to produce to CE to meet CE demand, but the CHP system does not generate HE at the maximum level yet. Therefore, BEMS2 orders the CHP system to produce HE more according to the CE dispatch strategy, and the surplus EE which coincident with HE production is sold to power grids.

With regard to the environmental optimal operation, the CHP system operates based on CO_2 emission factors. Obviously, almost all of the operation time, the CHP system produces EE to electrical loads and the electric chiller because its CO_2 emission factor is lower than grid emission factor; moreover, the CHP system does not try to export EE to power grids because it causes additional CO_2 emissions unnecessarily. Most of the coincident HE is supplied to the absorption chiller except when there is no CE demand. Such an operation of the CHP system is called operating following EE demand. However, we can observe that the CHP system exports EE to power grids during 8.00-10.00 and 22.00-24.00, like the economic optimal operation of the CHP system. The reason is that the CHP system operates according to the CE dispatch strategy. That is, the CHP system has to provide HE more for the absorption chiller to produce CE to meet CE demand, and the surplus EE which coincident with HE production is sold to power grids. This operation mode of the CHP system is called operating following CE demand.

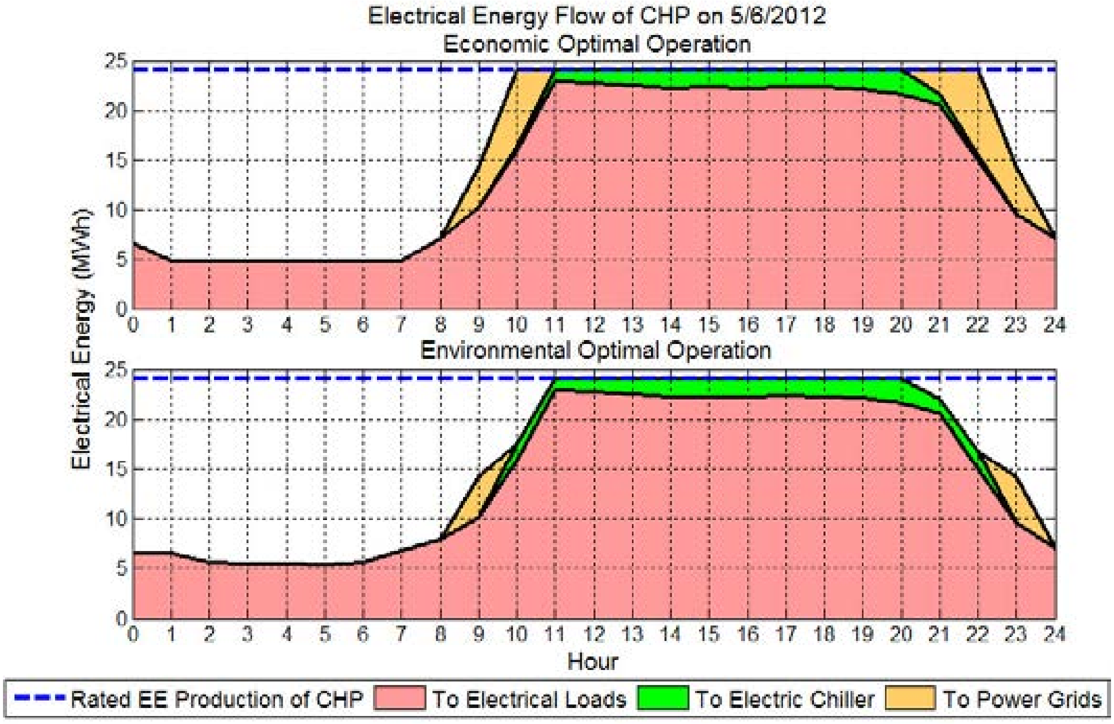

Figure 4.2: EE production of CHP system of BEMS2.

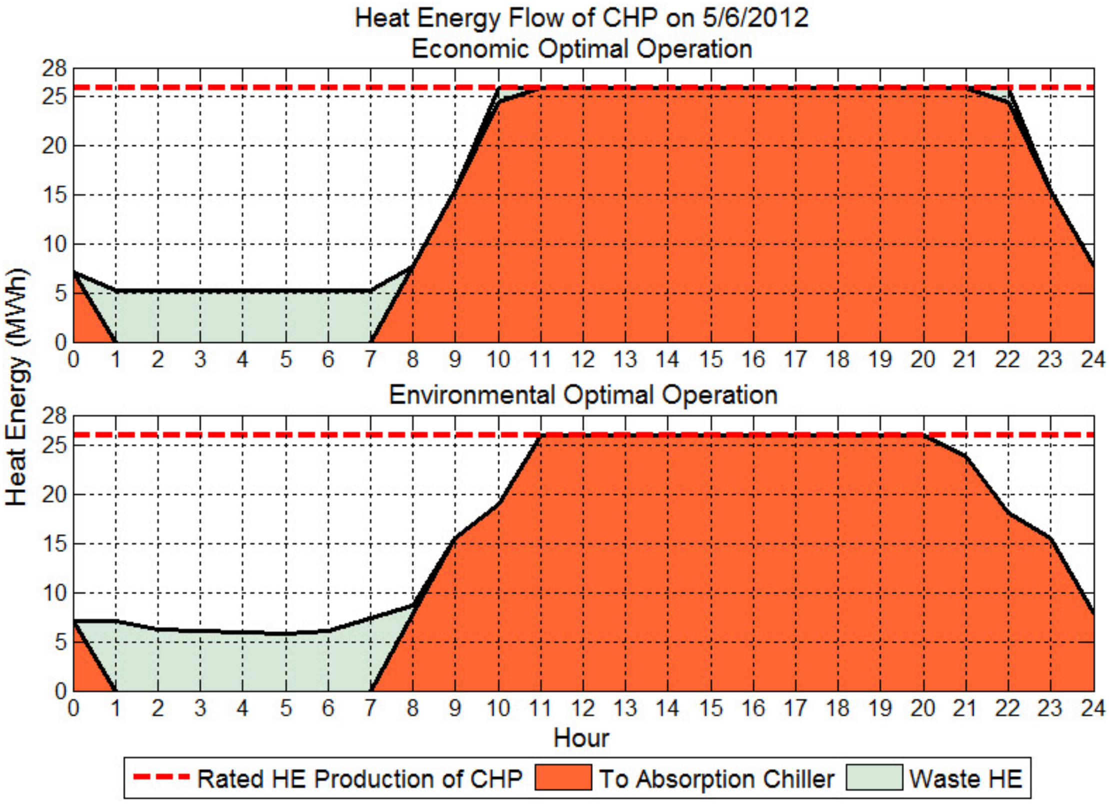

Figure 4.3: HE production of CHP system of BEMS2.

Optimal Electrical Energy Flows

Figure 4.4 and 4.5 demonstrate that BEMS2 can supply EE to meet electrical loads and the electric chiller. Noticeably, EE flows of both optimal operations look quite similar, but the reason why each optimal operation dispatches such EE flows is different.

In view of the economic optimal operation, BEMS2 supplies EE based on the EE production cost of the CHP system, EE charges and demand charge of power grids. During on-peak time, the EE production cost is lower than the EE charge, so the CHP system is the main EE supply source to electrical loads and the electric chiller. Power grids participate in supplying EE when the CHP system cannot generate EE to meet all EE demand. During off-peak time, the EE production cost is higher than the EE charge, so power grids take part in supplying EE to all EE demand in order to reduce EC as much as possible. It is obvious that the CHP system generates EE at the minimum level during 1.00-7.00 which is different than EE production during this time of BEMS1. The reason is that, in BEMS2, all EE demand comes from electrical loads and the electric chiller, so the maximum electricity power from power grids of BEMS2 is more than that of BEMS1. As a result, BEMS2 is allowed to utilize EE from power each hour more than BEMS1, which leads to the minimum EE generation of the CHP system and the maximum EE utilization from power grids to obtain minimum EC.

In view of the environmental optimal operation, BEMS2 supplies EE to electrical loads and the electric chiller based on CO_2 emission factors. Due to the fact that the CO_2 emission factor of the CHP system is lower than the grid emission factor, the CHP system is the main EE supply source to all EE demand both during on-peak time and during off-peak time. Power grids participate in supplying EE to electrical loads and the electric chiller when the CHP system cannot generate EE to meet all EE demand.

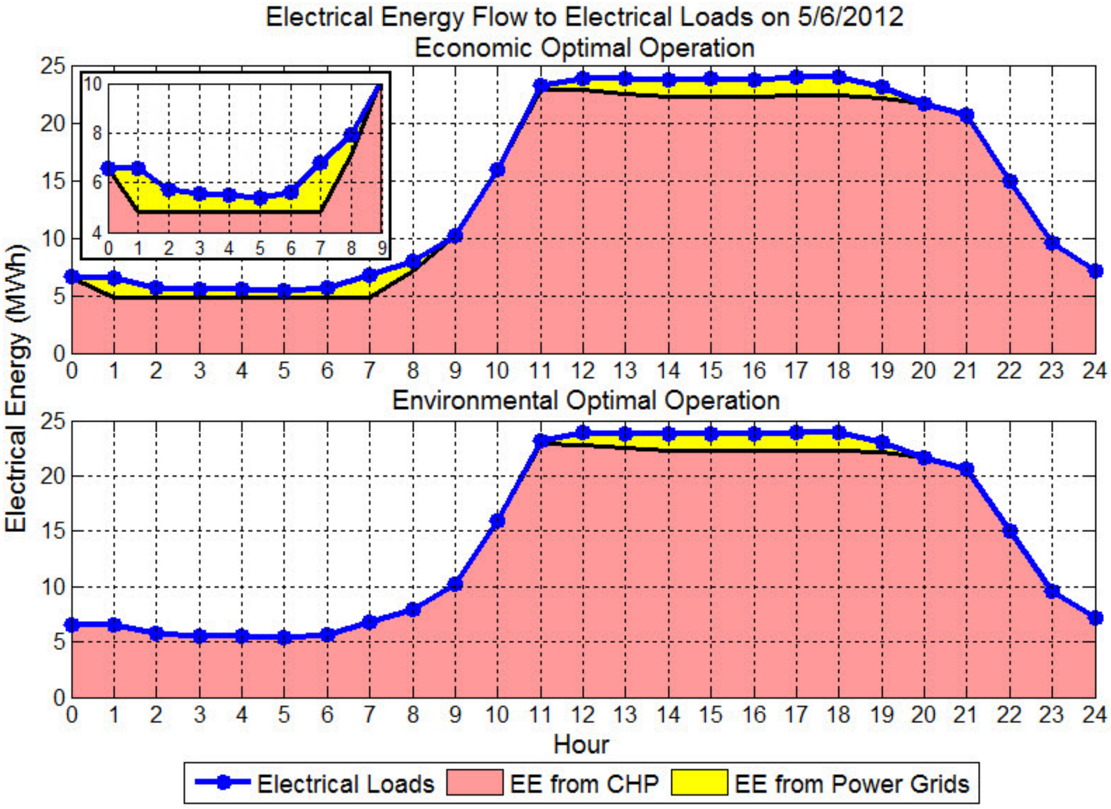

Figure 4.4: EE flow to electrical loads of BEMS2.

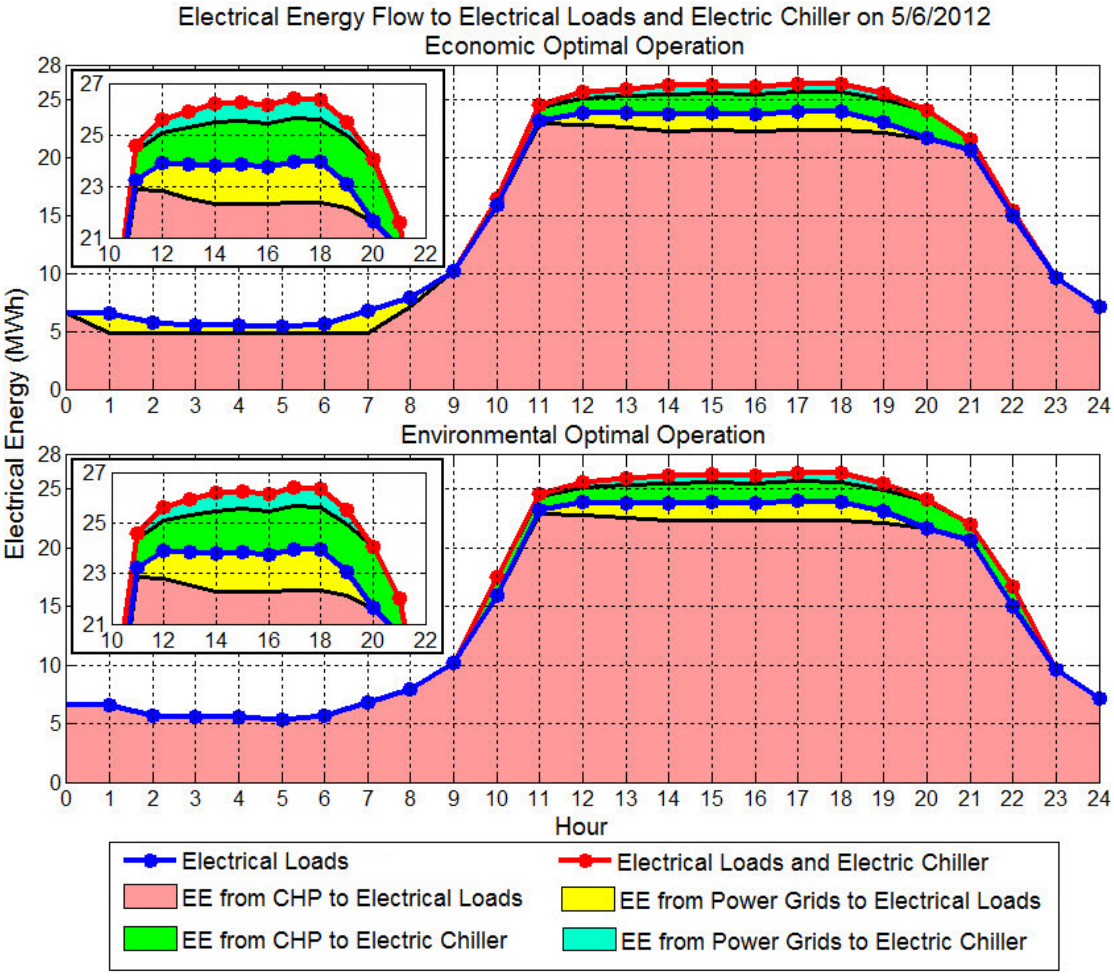

Figure 4.5: EE flow to electrical loads and electric chiller of BEMS2.

Optimal Cooling Energy Flows

Figure 4.6 displays CE flows to cooling loads. It reveals that BEMS2 can supply CE to meet CE demand almost all of the operation time except when peak cooling demand is greater than total rated cooling power of the absorption and electric chillers, i.e. 12,000 TR or 42.2 MW_{CE}. In that case, both chillers produce CE at their maximum level but cannot provide CE to satisfy CE demand. Total CE production of both chillers working under both optimal operations is the same, i.e., trying to supply CE to meet CE demand, but HE and EE supply to both chillers is different.

Regarding the economic optimal operation, BEMS2 provides CE to cooling loads based on CE production costs. Throughout the operation, BEMS2 uses the absorption chiller before the electric chiller because BEMS2 obtains free HE which is coincident with EE generation of the CHP system to all EE demand and power grids; therefore, BEMS2 provides CE without CE production costs. However, as analyzed in the economic optimal operation of the CHP system, during 8.00-9.00 and 22.00-24.00, the CHP system has to produce HE more to the absorption chiller according to the CE dispatch strategy because free HE is not enough for producing CE to meet CE demand, so the absorption chiller supplies CE with the CE production cost. When CE demand is more than maximum CE that the absorption chiller can produce, BEMS2 orders the electric chiller to start operating. Obviously, the electric chiller produces CE only during on-peak time. The CHP system generates EE at the maximum level to supply EE to electrical loads and the electric chiller, which leads to maximum free HE production. Therefore, the absorption chiller produces CE at the maximum level, too. The electric chiller consumes EE from the CHP system before EE from power grids because the CE production cost based on EE from CHP is lower than that based on EE from power grids. Power grids take part in supplying EE to the electric chiller when the CHP system cannot generate EE to meet EE demand of the electric chiller.

Concerning the environmental optimal operation, BEMS2 supplies CE to cooling loads based on equivalent CO_2 emission factors of the chillers. Throughout the operation, BEMS2 uses the absorption chiller before the electric chiller because BEMS2 obtains clean HE which is coincident with EE generation of the CHP system to electrical loads and the electric chiller. Hence, the absorption chiller produces CE without CO_2 emissions except when the CHP system operates following cooling loads according to the CE dispatch strategy, i.e., during 8.00-10.00 and 22.00-24.00, the absorption chiller produces CE with CO_2 emissions. The electric chiller starts operating when CE demand is more than maximum CE the absorption can produce. Due to the fact that equivalent CO_2 emission factor of the electric chiller using EE from the CHP system is lower than that from power grids, BEMS2 supplies EE to the electric chiller from the CHP system before power grids. However, it is obvious that the absorption chiller does not produce CE at the maximum level throughout on-peak time. In particular, during 10.00-11.00 and 21.00-22.00, BEMS2 decides to use the electric chiller to produce CE to compensate for the cooling shortage rather than have the CHP system produce HE at the maximum level for the absorption chiller because equivalent CO_2 emission factor of the electric chiller is lower than that of the absorption chiller. Power grids are involved in supplying EE to the electric chiller when the CHP system already generates EE at the maximum level.

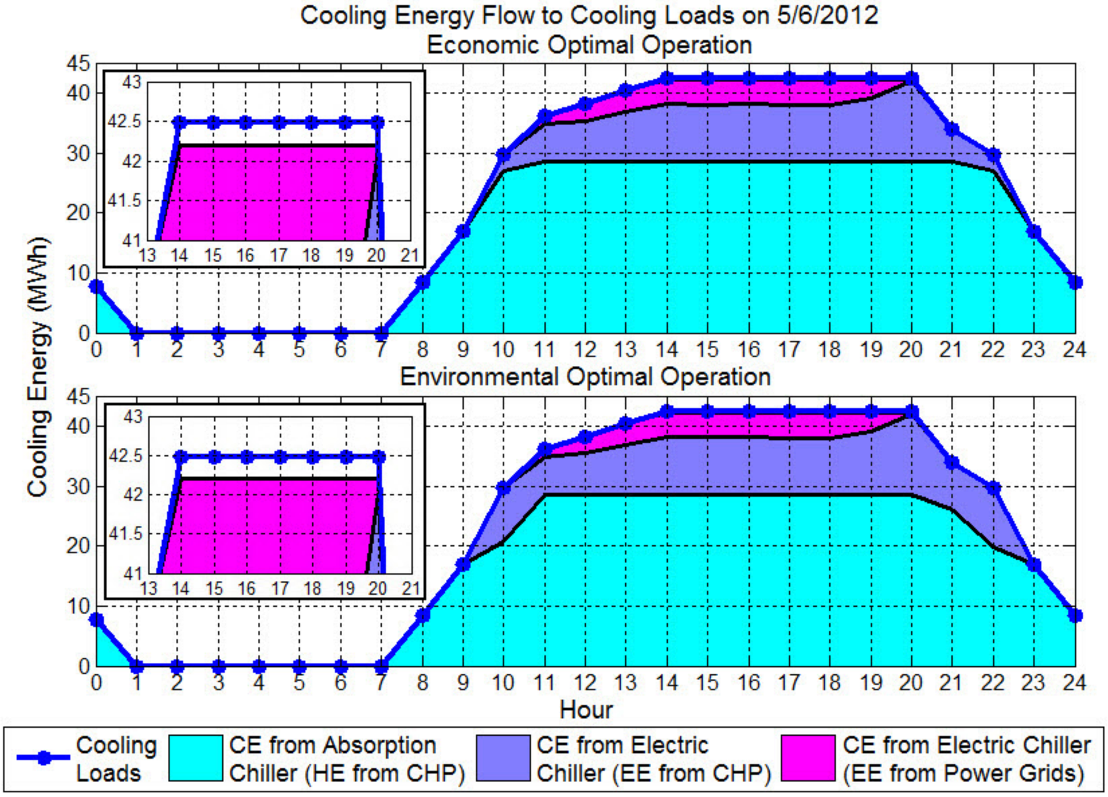

Figure 4.6: CE flow to cooling loads of BEMS2.

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 4.7 demonstrates that the relationship between two optimal operations is a trade-off between TOC and TCOE. If BEMS2 operates with low TOC, it gives high TCOE. This curve is useful for operators in changing operating points of BEMS2 apart from the economic or environmental optimal operating points. For example, if operators want to keep TOC less than 26.9 million baht, BEMS1 will have TCOE in the range of 5,950-6,039 tCO_2 depending on their decision.

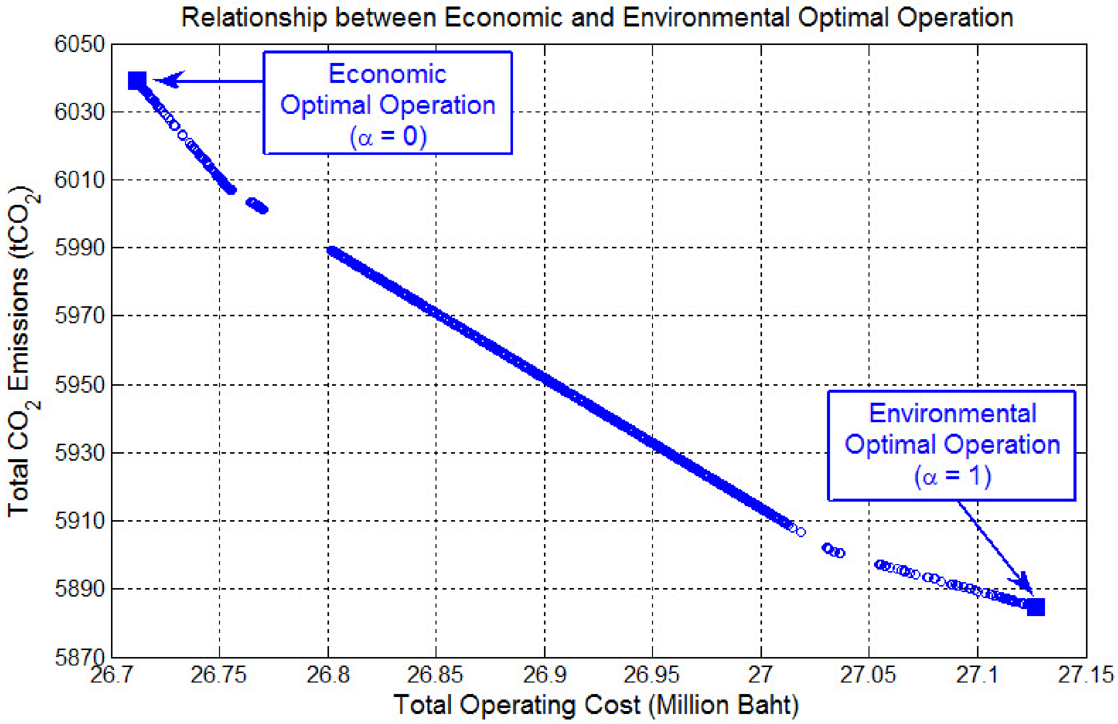

Figure 4.7: Relationship between economic and environmental optimal operations of BEMS2.

4.5.3 Impact of Natural Gas Prices

With the same reason in the case study of BEMS1, this subsection investigates the risk in a long-term operation of BEMS2. In particular, we focus on analyzing an impact of APNG onto TOC, TCOE, and optimal operations of the equipment. In the simulation, we vary APNG from 50 to 550 baht/MMBtu and then solve the economic and environmental optimal operation problems of BEMS2, while EE charges, EE selling prices, and CO_2 emission factors are fixed.

Impact on Total Operating Cost

Figure 4.8 indicates that TOCs of both optimal operations increase linearly when APNG goes up. Although TOC of the environmental optimal operation grows steadily, TOC of the economic optimal operation rises with three rates. In the beginning, it goes up dramatically until ANPG reaches 161 baht/MMBtu due to exporting EE to cut TOC as much as possible; then, it starts reducing EE export and grows at the same rate as TOC of the environmental one does. In the end, it increases slowly when APNG is more than 392 baht/MMBtu. Compared to TOC of the conventional BEMS, TOCs of BEMS2 are higher than it when APNGs reach 330 and 336 baht/MMBtu, which means that it is not worth using BEMS2. If we delve deeply into the constitution of TOC, Figure 4.9 shows ECs and DCCs versus APNG. ECs of both optimal operations go up linearly like TOCs, but DCCs are different. DCC of the economic optimal operation is constant until APNG reaches 392 baht/MMBtu; then, it begins to increase nonlinearly but is still much lower 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 main reason is that APNG does not cause any change in CO_2 emission factors which are deciding factors in the environmental optimal operation; also, the grid emission factor does not change either and is still higher than the CO_2 emission factor of the CHP system. As a result, BEMS1 still keeps utilizing electricity from power grids as little as possible in order to obtain the minimum CO_2 emissions.

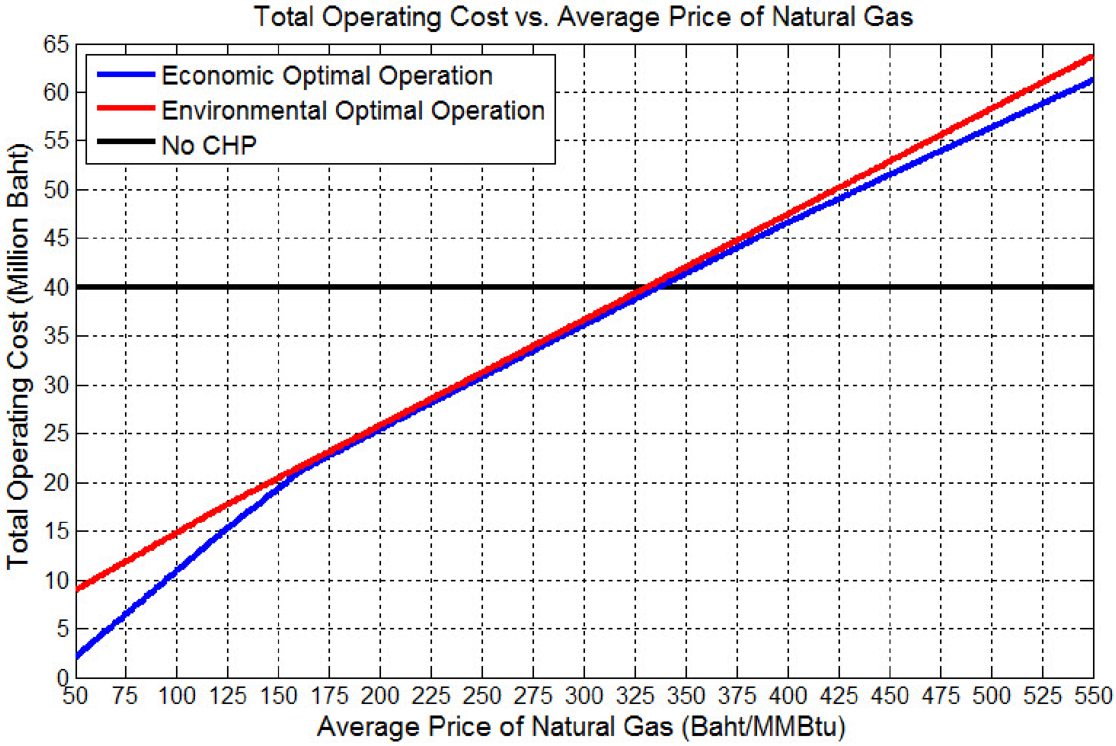

Figure 4.8: TOC of BEMS2 vs. APNG.

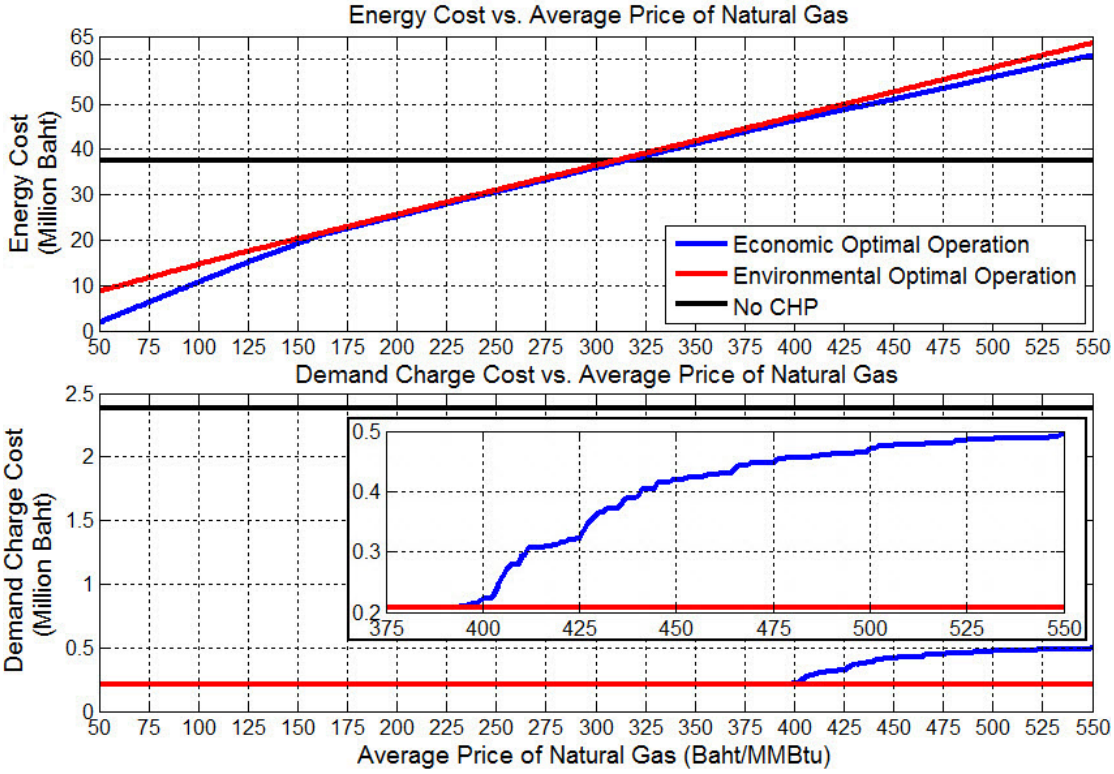

Figure 4.9: EC and DCC of BEMS2 vs. APNG.

Impact on Total CO_2 Emissions

Figure 4.10 shows TCOEs of both optimal operations. Clearly, TCOE of the environmental optimal operation is constant because CO_2 emission factors which are 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 BEMS2 still works at the same environmental optimal operating point. In contrast, TCOE of the economic optimal operation changes in seven steps at APNGs of 161, 175, 203, 219, 283, 351 and 392 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 and electric chillers, 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.

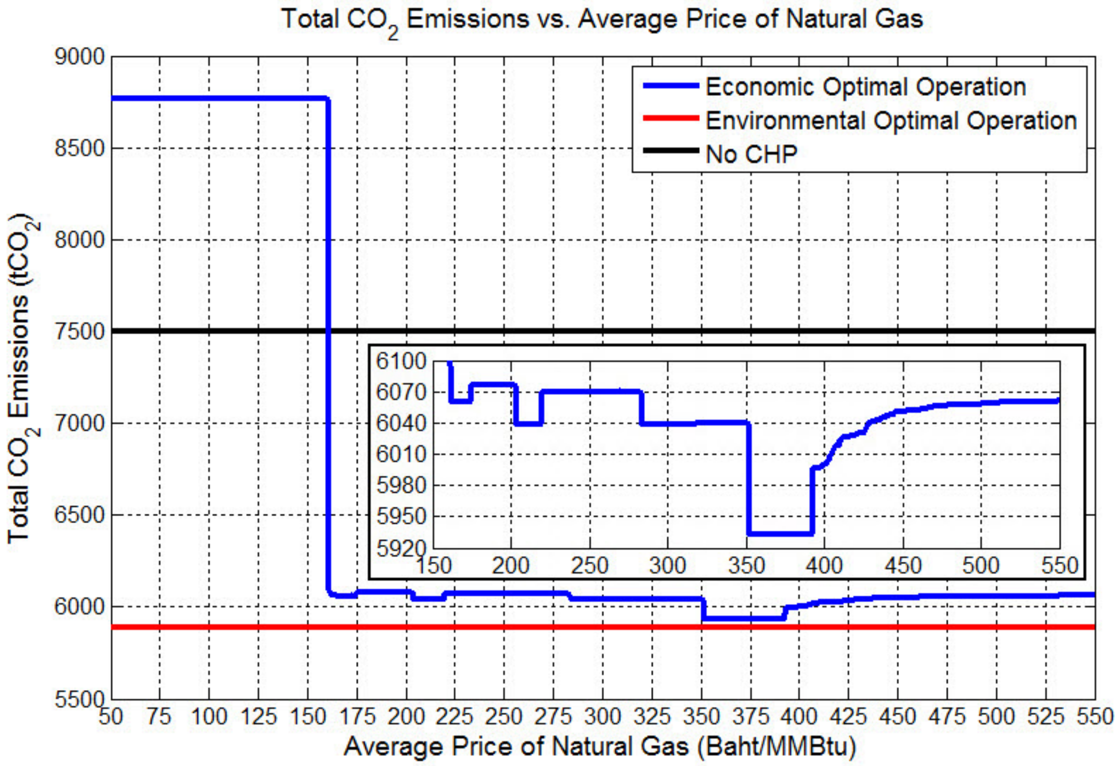

Figure 4.10: TCOE of BEMS2 vs. APNG.

Impact on Electrical and Cooling Energy Costs

Figure 4.11 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 are fixed in the simulation, the result is that there are 4 intersection points at APNGs of 161, 175, 283, and 318 baht/MMBtu. Hence, we can predict that 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, BEMS2 should earn income from selling EE both during off-peak and during on-peak time to reduce EC as much as possible. Moreover, power grids should not participate in supply EE to electrical loads and the electric chiller as long as the CHP system can generate EE to meet all 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 off-peak time, the CHP system should stop selling EE to power grids and only generate EE electrical loads and the electric chiller. During on-peak time, the CHP system still operates at the maximum EE production level to earn income from selling EE. Furthermore, power grids take part in supplying EE to electrical load and the electric chiller when the CHP system cannot generate EE to meet all EE demand.

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 off-peak time, the CHP system should reduce EE production to electrical loads and the electric chiller, and power grids should take part in supplying EE to reduce EC. During on-peak time, the CHP system still generates EE at the maximum level and sells EE to reduce EC; moreover, 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 off-peak time, the CHP system and power grids should cooperate as predicted in the scheme 3. During on-peak time, the CHP system should stop selling EE and only generate EE to electrical loads and the electric chiller; moreover, power grids supplies 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. BEMS2 compromises the cooperation between the CHP system and power grids based on the EE production cost, the EE charges and the demand charge both during off-peak and during on-peak time in order to obtain the minimum TOC.

Figure 4.12 shows the CE production costs of the absorption and electric chiller versus APNG. The CE production cost of the absorption chiller using HE from the CHP system is higher and increases more rapidly than the CE production cost of the electric chiller using EE from the CHP system because the electric chiller is more efficient than the absorption chiller. When the electric chiller uses EE from power grids, the CE production costs are calculated from the fixed on-peak and off-peak EE charges. As a result, the CE production costs of the electric chiller from two sources intersect at APNGs of 175 and 318 baht/MMBtu. However, it is quite difficult to predict that how the absorption and electric chillers should cooperate and which is the best EE supply source for the electric chiller between the CHP system and power grids for each APNG. Therefore, we will analyze the cooperation of both chillers and EE supply sources from net EE production of the CHP system and net CE production of both chillers in the next subsection.

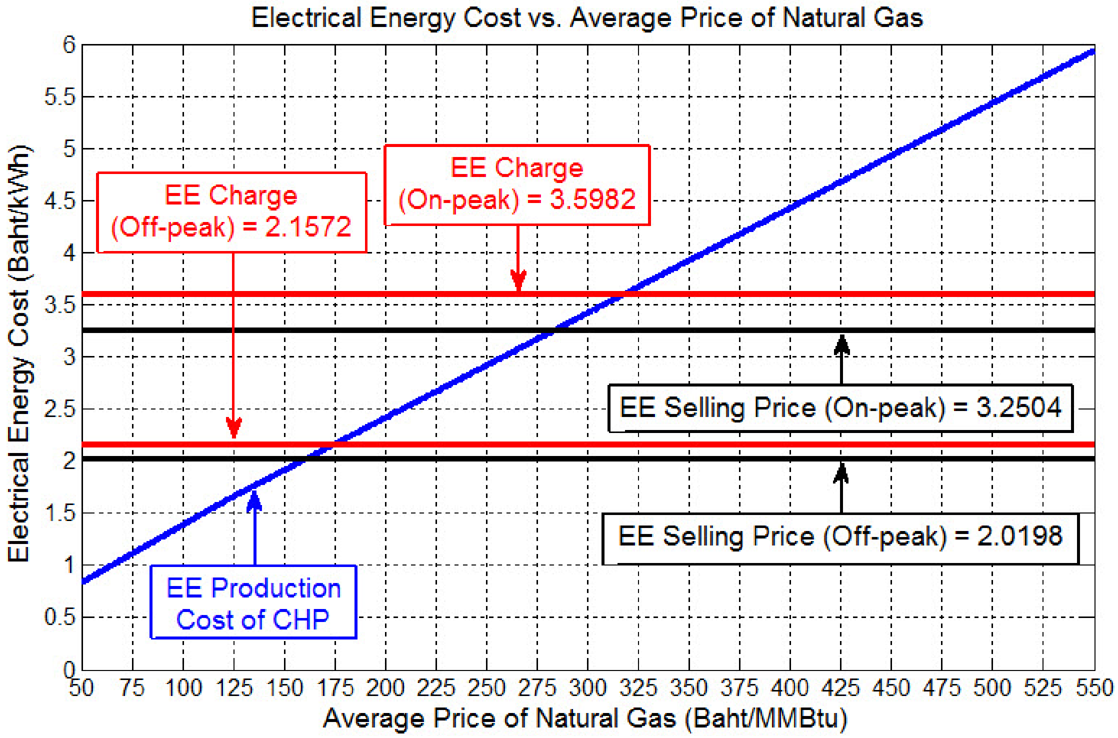

Figure 4.11: EE production cost of CHP system of BEMS2 vs. APNG.

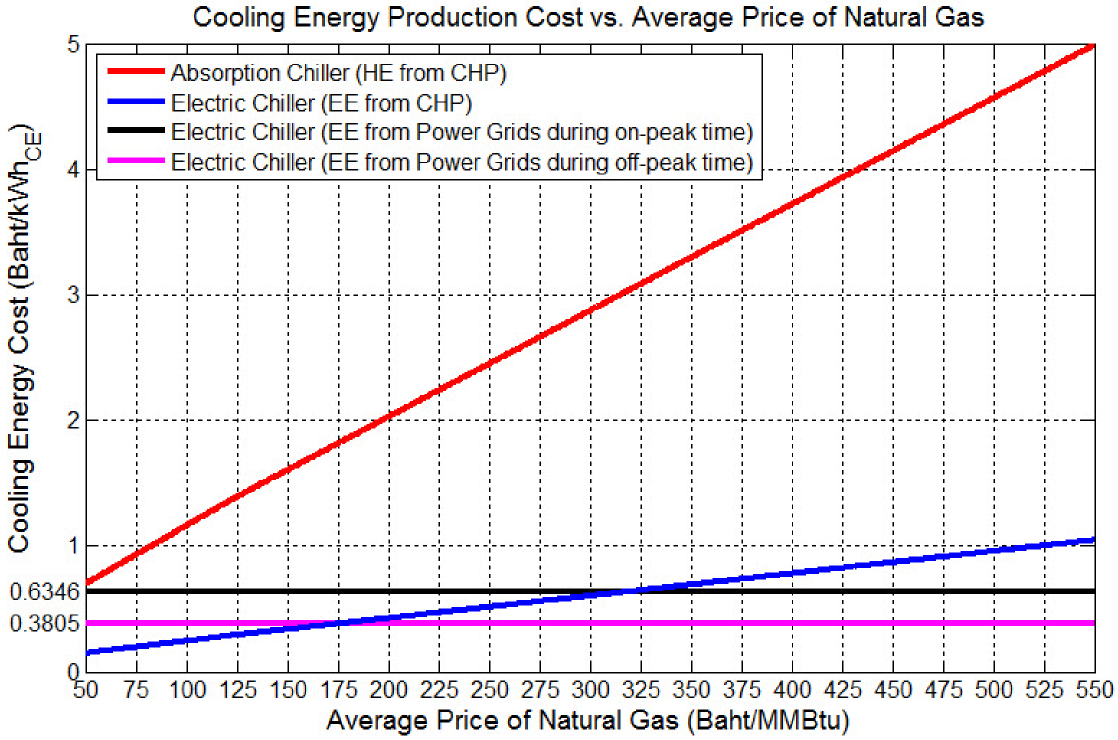

Figure 4.12: CE production costs of absorption and electric chillers of BEMS2 vs. APNG.

Impact on Optimal Operations

Figures 4.13-4.15 show the EE dispatch of the CHP system and power grids and Figure 4.16 displays the CE dispatch of the absorption and electric chillers to cooling loads. Figure 4.17 exposes total waste HE from the CHP system. As analyzed via TCOE earlier, the optimal operating point of each component in BEMS2 working under the environmental optimal operation does not change following APNG; therefore, we will not further discuss the EE and CE production of the equipment under this operation. On the contrary, the EE and CE dispatch of BEMS2 working under the economic optimal operation causes 7-step changes in TCOE. Figure 4.13 reveals that total EE production of the CHP system based on loads as of June 2012 has 7-step changes like the changes of TCOE. In other words, the changes of total EE generation of the CHP system cause the direct changes in TCOE. Figure 4.14 demonstrates that total EE supply from power grids to electrical loads and the electric chiller results in 3-step changes and the other 4-step changes result from total exported EE to power grids as shown in Figure 4.15. Total CE production of both chillers, including total waste HE from the CHP system, contributes to supporting the investigation. In sum, 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 4.15), which leads to the largest decrease in total EE generation of the CHP system as well as total waste HE (see in Figure 4.13 and 4.17). However, the CHP system and power grids do not change EE supply to electrical loads and the electric chiller (see in Figure 4.14); also, total CE production of both chillers does not change either (see in Figure 4.16). Lastly, TCOE falls sharply following the largest decrease in total EE export 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 BEMS2 decreases EE supply from the CHP system to electrical loads but increases the utilization of EE from power grids instead (see in Figure 4.14). As a result, the CHP system reduces total EE production and total waste HE (see in Figure 4.13 and 4.17). Nevertheless, total CE production of both chillers does not change (see in Figure 4.16), which means that the CHP system still supplies total EE and HE to them at the same energy level. Lastly, TCOE goes 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 utilization from power grids causes CO_2 emissions more than that from the CHP system.

Step 3: At APNG of 203 baht/MMBtu, the CHP system decreases total EE production, while power grids do not change EE supply to electrical loads and the electric chiller (see in Figure 4.13 and 4.14). The absorption chiller reduces total CE production, but the electric chiller increases it to compensate for the cooling shortage (see in Figure 4.16). Obviously, the CHP system increases EE supply to the electric chiller a little bit, but it decreases HE supply to the absorption chiller (see in Figure 4.14 and 4.16). This action leads to the decrease in total EE exported to power grids, but total waste HE does not change (see in Figure 4.15 and 4.17). It means that the decrease in total exported EE results from the decline in surplus EE generation which coincident with HE production to the absorption chiller; in other words, the CHP system reduces HE production in the mode of tracking cooling loads. In fact, this incident occurs on holidays as shown in Figure 4.18 as an example. Lastly, TCOE drops following the decrease in total EE production of the CHP system.

Step 4: At APNG of 219 baht/MMBtu, the CHP system reduces total EE generation to electrical loads and the electric chiller, and power grids supplies total EE more to compensate for the electricity shortage (see in Figure 4.14). Absorption chiller decreases total CE production, but the electric chiller increases it instead (see in Figure 4.16). Nonetheless, total EE export and total waste HE of the CHP system do not change, so the decrease in total EE production of the CHP system comes only from the decline in total EE generation to all EE demand (see in Figure 4.13, 4.15, and 4.17). Indeed, the CHP system decreases EE generation to electrical loads and the electric chiller on holidays whose EE charge is the off-peak rate throughout the day; this investigation can be noticed from an example of the EE production as shown in Figure 4.18. Lastly, TCOE rises following the increase in EE utilization from power grids.

Step 5: 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 4.15). Also, it leads to the decrease in total EE production and total waste HE of the CHP system (see in Figure 4.13 and 4.17). However, EE supply from the CHP system and power grids to electrical loads and the electric chiller, including CE production of both chillers, does not change (see in Figure 4.14 and 4.16). Therefore, TCOE drops following total EE export of the CHP system.

Step 6: At APNG of 351 baht/MMBtu, the EE production cost of the CHP system is already greater than the on-peak EE charge. The CHP system reduces total EE generation, but power grids still supplies EE to electrical loads and the electric chiller at the same EE level (see in Figure 4.13 and 4.14). The absorption chiller decreases the CE production, while the electric chiller produces CE more instead (see in Figure 4.16). It is further obvious that total exported EE declines but total waste HE does not change (see in Figure 4.15

and 4.17). However, there is a little bit increase in total EE generation to all EE demand, so we can conclude that the CHP system increases a little bit of EE supply only to the electric chiller (see in Figure 4.14) but decreases HE supply to the absorption chiller, which leads to the large decline in total exported EE. In fact, the CHP system changes EE and HE production to both chillers during on-peak-time on workdays, which can be observed from Figure 4.19 as an example. Lastly, TCOE decreases following the significant decrease in total EE generation of the CHP system.

Step 7: At APNG of 392 baht/MMBtu, the demand charge starts having an influence on the economic optimal operation, i.e., BEMS2 needs to compromise among the EE production cost of the CHP system, the EE charges, and the demand charge in order to obtain the minimum TOC. The CHP system decreases EE supply to electrical loads and the electric chiller continuously while power grids provide EE to them more and more (see in Figure 4.14). However, total exported EE and total waste HE do not change (see in Figure 4.15 and 4.17). Therefore, we can conclude that the decrease in total EE generation of the CHP system causes the direct decline in HE supply to the absorption chiller, and the electric chiller utilizes EE from power grids more and more. Lastly, TCOE increases gradually following maximum electricity power from power grids.

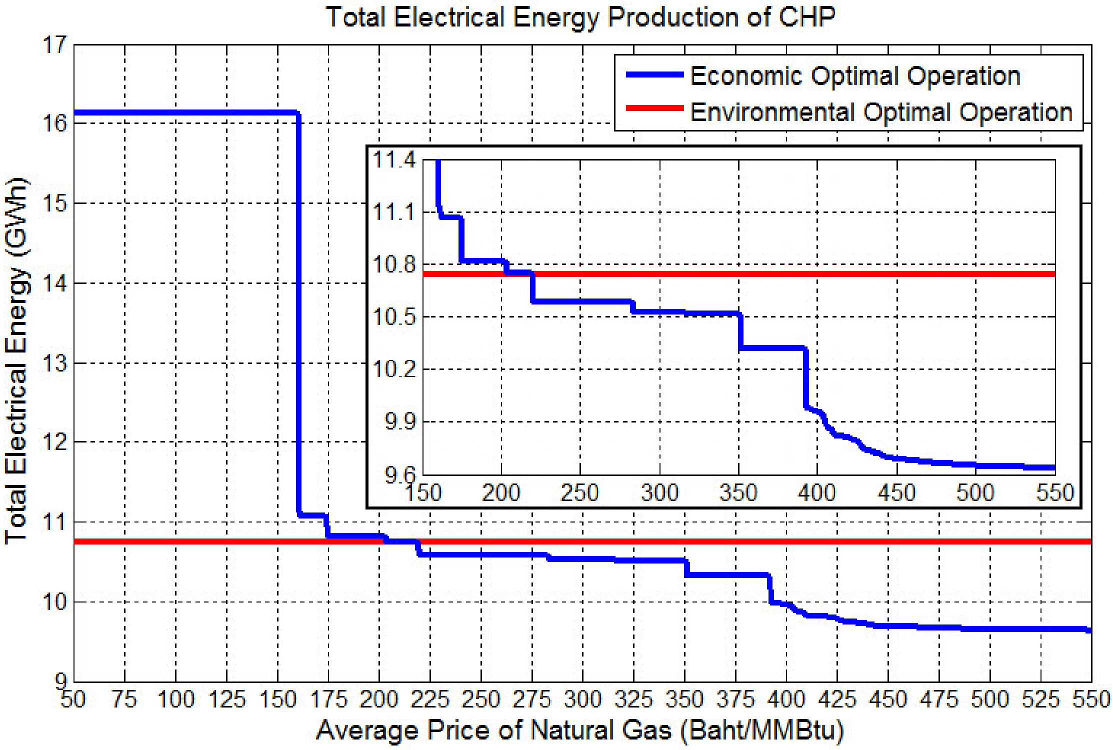

Figure 4.13: Total EE production of CHP of BEMS2 vs. APNG.

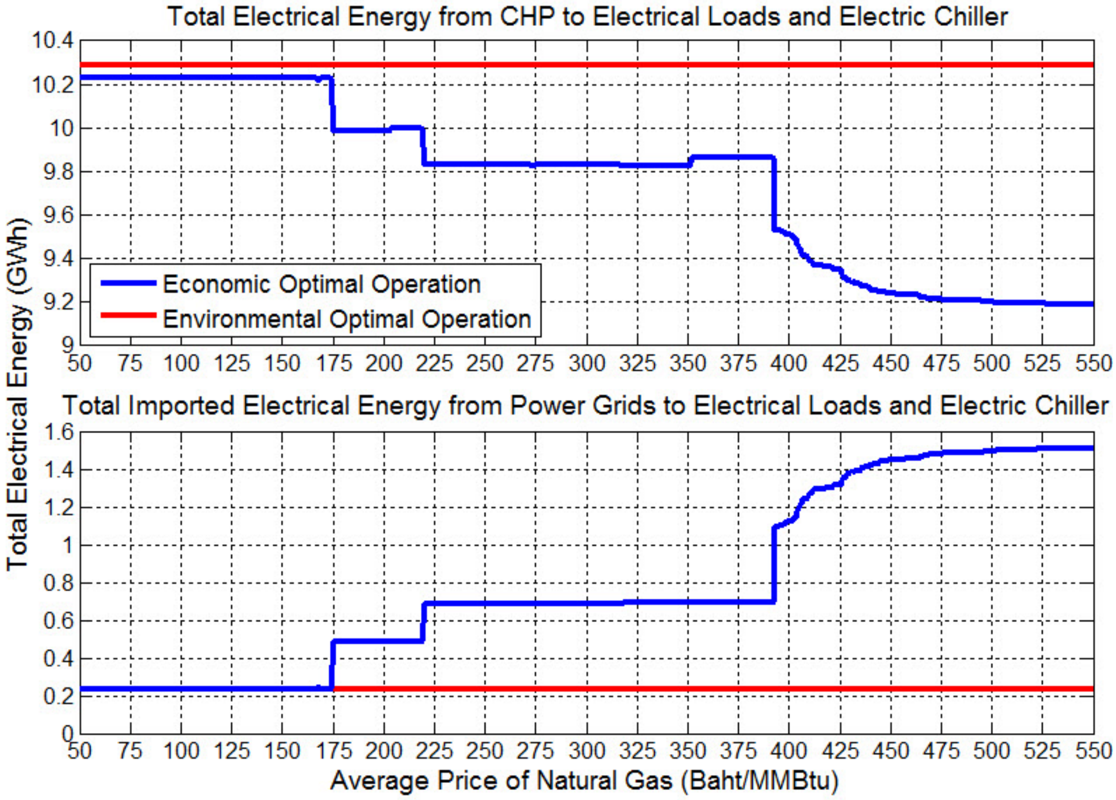

Figure 4.14: Total EE supplied to electrical loads and electric chiller of BEMS2 vs. APNG.

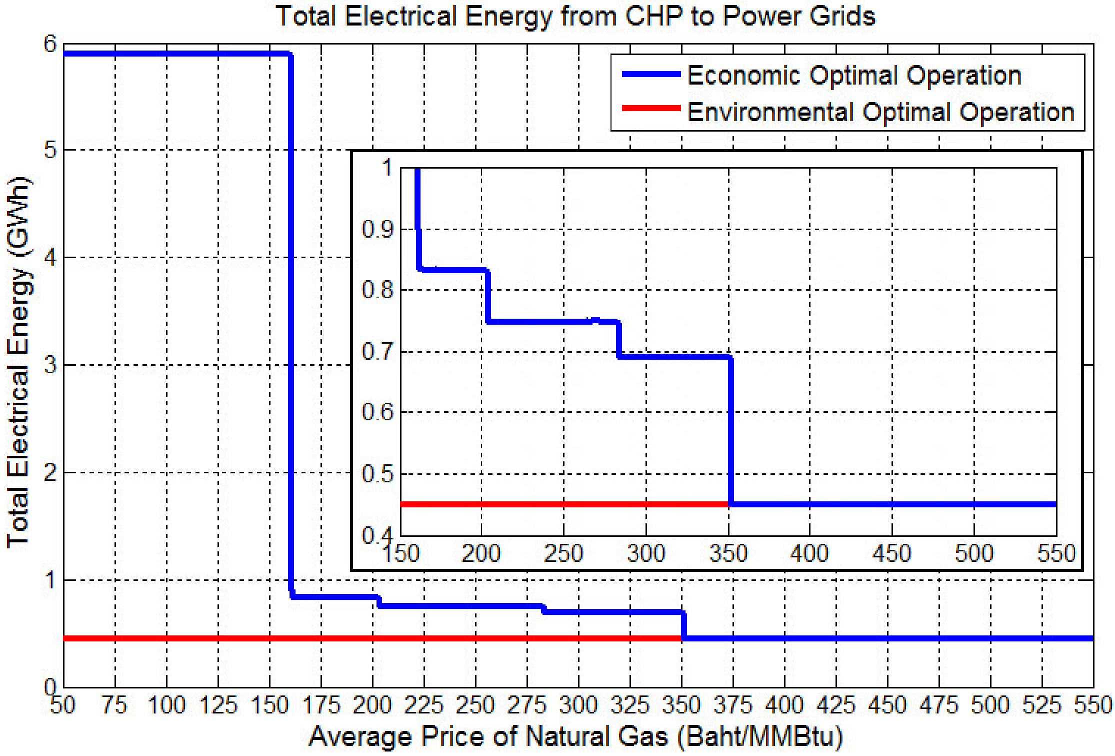

Figure 4.15: Total EE exported to power grids of BEMS2 vs. APNG.

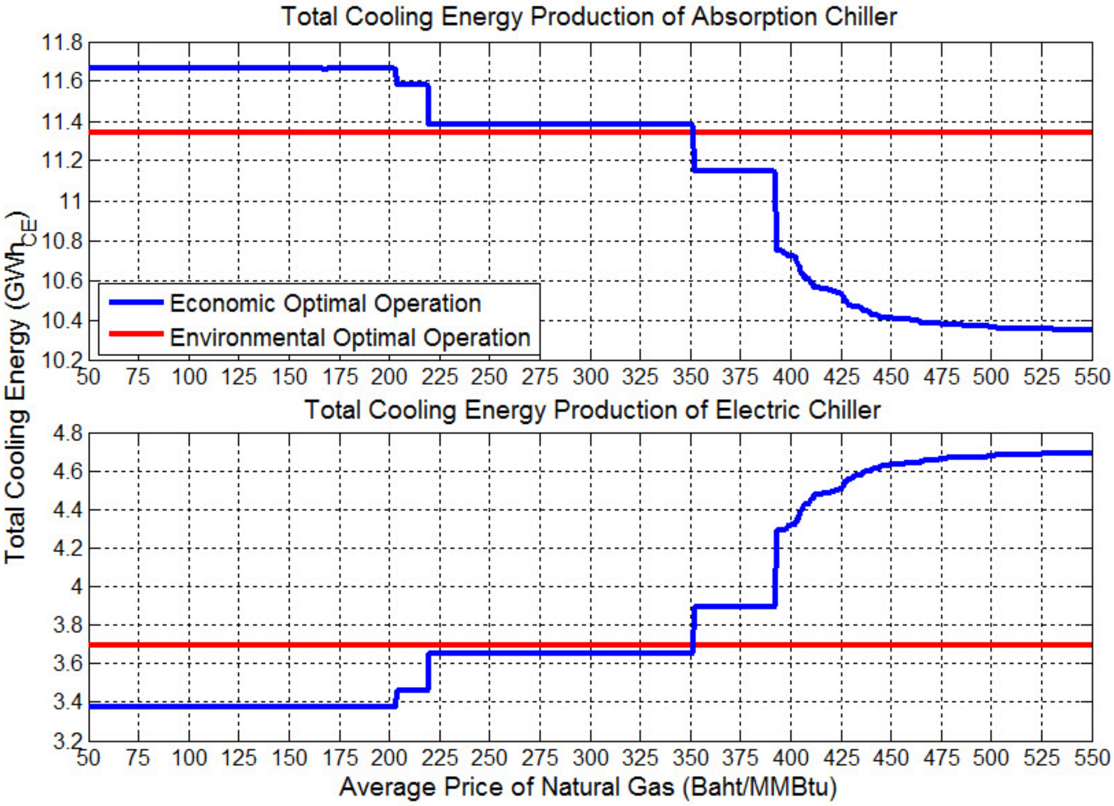

Figure 4.16: Total CE production of absorption and electric chillers of BEMS2 vs. APNG.

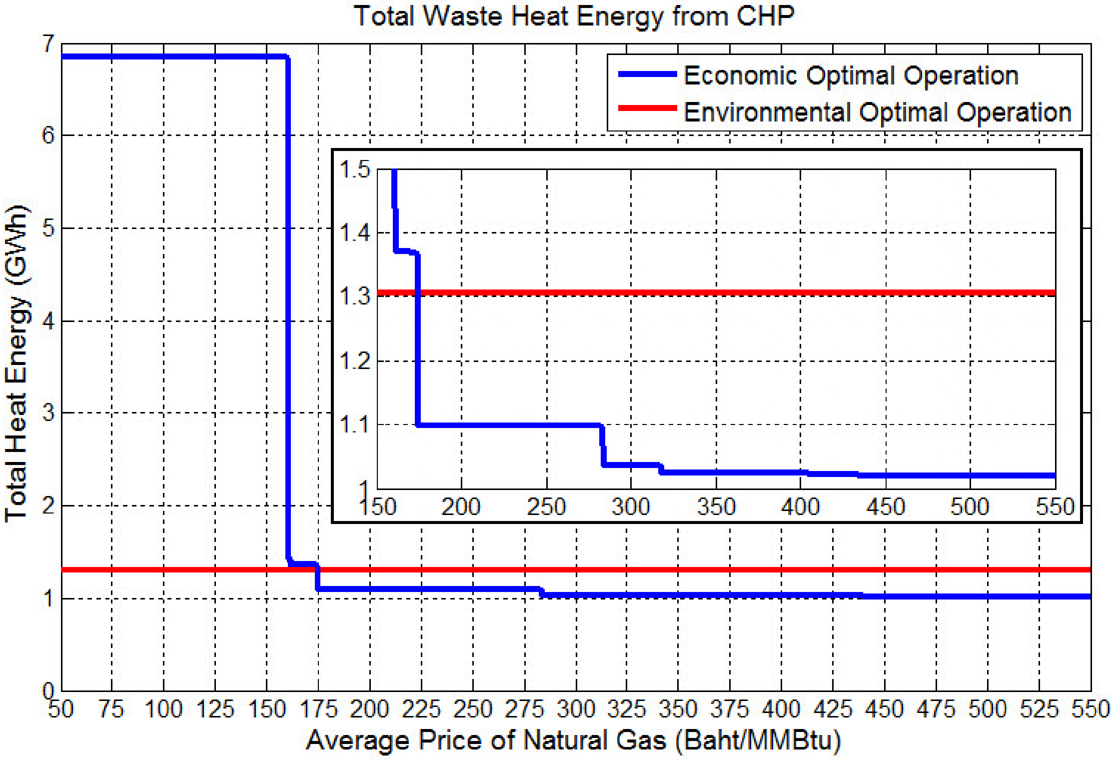

Figure 4.17: Total waste HE from CHP of BEMS2 vs. APNG.

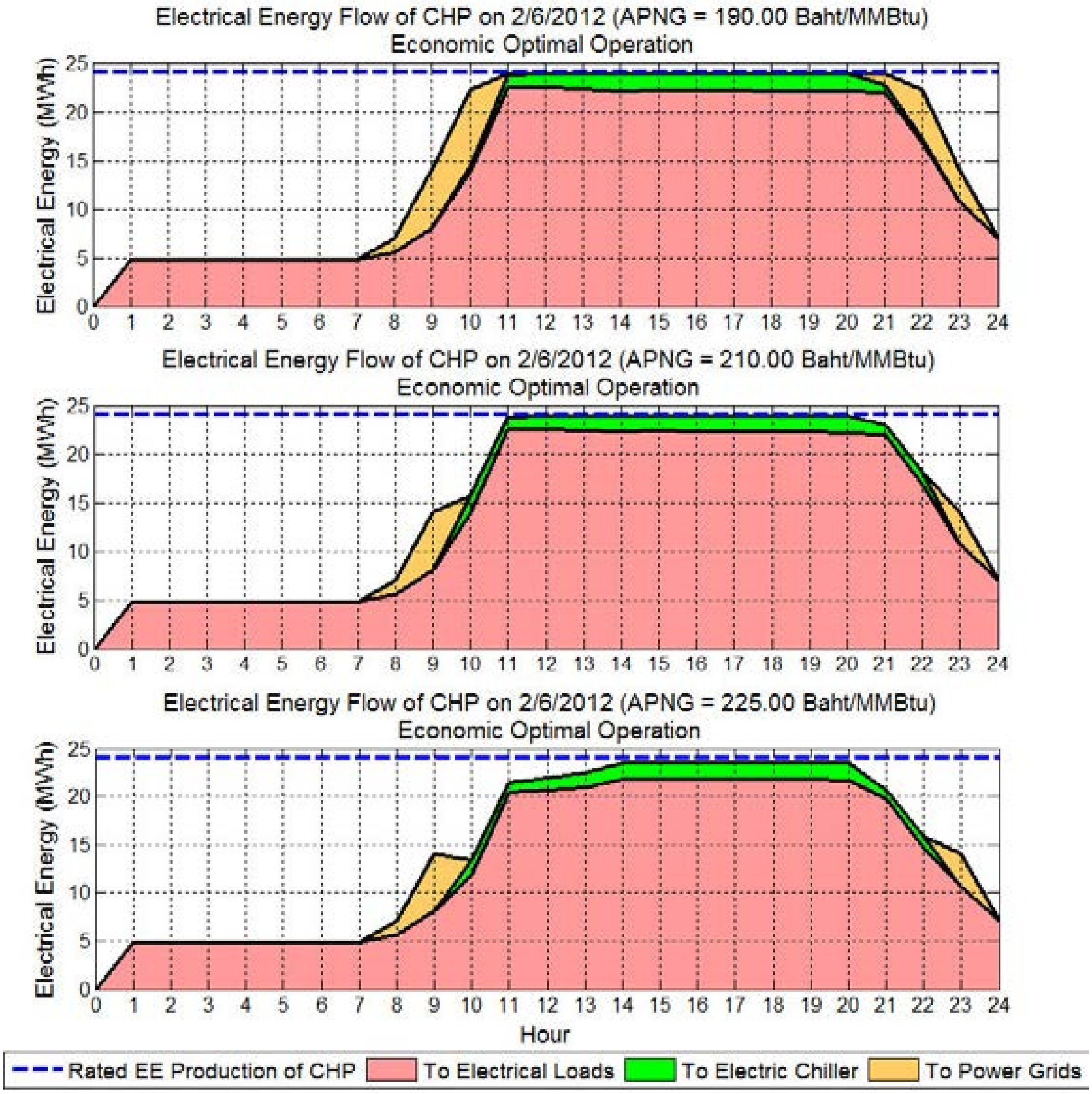

Figure 4.18 Comparison of EE production of CHP system of BEMS2 at APNGs on holiday.

Figure 4.18 compares the EE production of the CHP system on June 2, 2012, a holiday, at APNGs of 190, 210, and 225 baht/MMBtu. At APNG of 190 baht/MMBtu, the CHP system produces HE to the absorption chiller in the mode of tracking cooling loads during 7.00-11.00 and 20.00-24.00, which brings about surplus EE generation sold to power grids. When APNG is higher than 203 baht/MMBtu, the CHP system decreases HE supply to the absorption chiller and increases EE generation to the electric chiller instead, especially during 10.00-11.00 and 20.00-22.00, as shown in a case example of APNG of 210 baht/MMBtu. When APNG is higher than 219 baht/MMBtu, the CHP system reduces EE generation to electrical loads and the electric chiller, especially during on-peak time, which can be noticed in a case example of APNG of 225 baht/MMBtu.

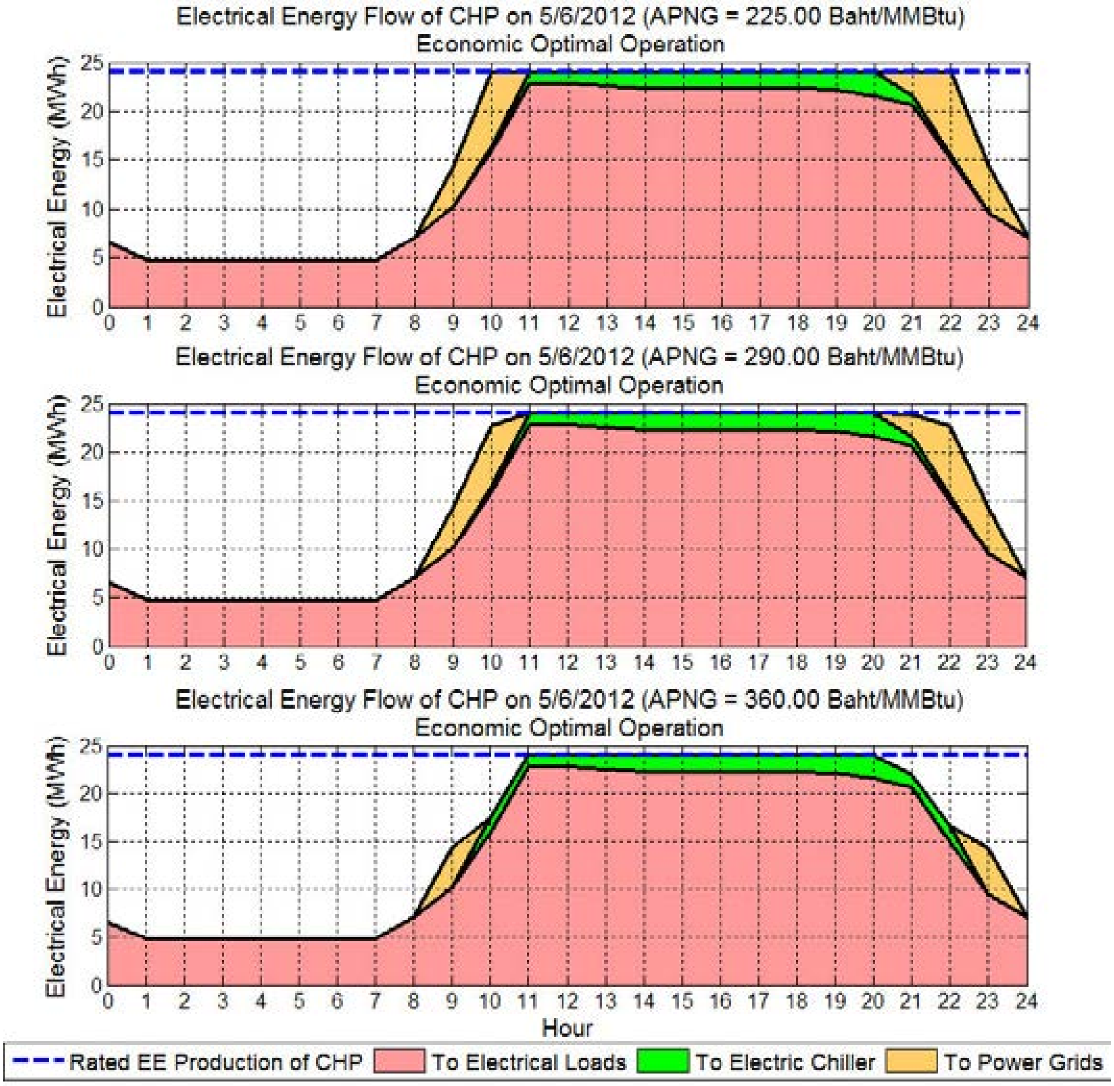

Figure 4.19 Comparison of EE production of CHP system BEMS2 at APNGs on workday.

Figure 4.19 compares the EE production of the CHP system on June 5, 2012, a workday, at APNGs of 225, 290 and 360 baht/MMBtu. At APNG of 225 baht/MMBtu, the CHP system still generates EE at the maximum level and sells EE during on-peak time because the EE production cost is lower than the on-peak EE selling price. When APNG is higher than 283 baht/MMBtu, the EE production cost is higher than the on-peak selling price. Therefore, the CHP system reduces EE sold to power grids, but it still produces HE to the absorption chiller in the mode of tracking cooling, especially during 8.00-11.00 and 20.00-24.00, as shown in a case example of APNG of 290 baht/MMBtu. When APNG is higher than 351 baht/MMBtu, the EE production cost is already higher than the on-peak EE charge. The CHP system reduces HE supply to the absorption chiller and increase EE generation to the electric chiller instead, especially during 10.00-11.00 and 20.00-22.00, as shown in a case example of APNG of 360 baht/MMBtu.

Table 4.11 summarizes the changes in TCOE and total energy production according to the equipment due to the economic optimal operation. We can draw a simple conclusion that the decrease in TCOE results from the decline in total EE generation of the CHP system but the increase in TCOE comes from the rise in EE utilization from power grids.

Finally, although BEMS2 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 4.17. Almost all of waste HE happens in off-peak time when there is no CE demand. To improve energy efficiency in BEMS2, we recommend adding heat storage to keep waste HE, especially in off-peak time, and use it in 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 6.85 GWh. The double-effect absorption chiller can convert it to total CE 7.53 $\mathrm{MWh}_{\mathrm{CE}}$ which is higher than total CE production of the electric chiller. In this case, BEMS2 does not need CE from the electric chiller, which leads to the decrease in TOC and TCOE. However, if APNG is greater than 161 baht/MMBtu, the utilization of waste HE contributes to reducing TOC and TCOE when the electric chiller uses EE from power grids.

To determine a suitable capacity of heat storage, we employ total waste HE shown in Figure 4.17. 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 1.02-1.37 GWh per month or 36.43-48.93 MWh per day. Therefore, we may choose the size of heat storage in the range of 37-49 MWh. If we make a rough estimate on the decrease in TOC and TCOE based on the EE charges and the grid emission factor of power grids, we find that the full utilization of total waste HE contributes to cutting TOCs by 1.1%-1.5% and 0.4%-1.3% and reducing TCOEs by 0.8%-2% and 0.85% for the economic and environmental optimal operations, respectively.

Table 4.11: Summary of changes in TCOE and total energy production according to the equipment due to economic optimal operation of BEMS2.

APNG (Baht/ MMBtu)	CHP System						EE from Power Grids	CE from Absorption Chiller	CE from Electric Chiller	TCOE
	Total EE Generation	EE to Electrical Loads	EE to Electric Chiller	EE to Power Grids	HE to Absorption Chiller	Waste HE				
161	↓	–	–	↓	–	↓	–	–	–	↓
175	↓	↓	–	–	–	↓	↑	–	–	↑
203	↓	–	↑	↓	↓	–	–	↓	↑	↓
219	↓	↓	↓	–	↓	–	↑	↓	↑	↑
283	↓	–	–	↓	–	↓	–	–	–	↓
351	↓	–	↑	↓	↓	–	–	↓	↑	↓
392	↓	↓	↓	–	↓	–	↑	↓	↑	↑

Note: 1) ↑ = Increase
↓ = Decrease
– = No change.

2) The changes in TCOE at each step are considered from TCOE in case of APNG lower and higher than each APNG in the table. For example, when APNG is lower than 161 baht/MMBtu, TCOE is 8,768 tCO_2; however, when APNG increases more than 161 baht/MMBtu, TCOE is decreased to 6,060 tCO_2 due to the decline in EE export.

4.6 Summary

In this chapter, we demonstrate that the application of BEMS, which contains a CHP system, an absorption chiller, an electric chiller, and power grids, is suitable for a large shopping mall due to the pattern of electrical and cooling loads. We design the most suitable capacity of the equipment in BEMS and analyze the economic and environmental optimal operations. The numerical results show that BEMS can reduce both TOC and TCOE up to 37.5% and 21.6%, compared to the original electricity usage. Furthermore, the fluctuation in APNG has impacts on a long-term operation.

CHAPTER V

CONCLUSIONS

5.1 Summary

This thesis proposes economic and environmental optimal operation of BEMS using the CHP system as a main source. BEMS is applied to a selected large shopping mall as a case study with the following procedure. Firstly, we select the equipment in BEMS based on building load profiles and then find the best BEMS. Next, we analyze optimal operations of BEMS, including their relationship. Lastly, we investigate the risk in the long-term operation of BEMS via the impact of fuel prices. To summarize the thesis, we highlight main topics as follows.

Chapter 1 briefly introduces the motivation behind the research. Next, the literature review is given to cover an overview of optimal operations of CHP systems. Afterward, we present the thesis objectives, scope and research contributions.

Chapter 2 is dedicated to background knowledge, especially about CHP technologies suitable for buildings. Also, we present other equipment which can be used in CHP applications, such as HVAC systems and industrial boilers, followed by energy usage in building, including the standard for energy efficiency of air-conditioning systems.

Chapter 3 formulates economic and environmental optimal operations of BEMS consisting of a CHP system, an absorption chiller, an auxiliary boiler, and power grids. The economic optimal operation focuses on minimizing TOC while the environmental optimal operation concentrates on minimizing TCOE. Also, we design electrical and cooling energy dispatch strategies for BEMS. In the numerical example, we apply BEMS to a selected shopping mall with the following steps. First, we create hourly electrical and cooling load profiles from real electrical load profiles, and then we select the type and capacity of the equipment that match peaks of load profiles. After simulating both optimal operations of BEMS on MATLAB, we compare TOC and TCOE with those of conventional electricity use, and the result indicates that BEMS has the potential to reduce both TOC and TCOE. To find the best BEMS, we use minimum TCOE of the environmental optimal operation as a decision criterion. Afterward, we analyze optimal operations of BEMS and find that the economic and environmental optimal operations make a decision based on energy production costs and emission factors, respectively. Moreover, a multi-objective approach shows that the relationship between both optimal operations is the trade-off between TOC and TCOE. Lastly, we assess the risk in the long-term operation of BEMS via the impact of natural gas prices on TOC, TCOE, and optimal operations. The results demonstrates that the fluctuation in fuel prices causes changes in economic optimal operating points of BEMS but does not affect any changes in the environmental optimal operation.

Chapter 4 designs another BEMS by replacing an auxiliary boiler with an electric chiller. Then, we formulate economic and environmental optimal operations of new BEMS, including dispatch strategies. Next, we apply it to the same shopping mall, and conduct the simulation in the same ways. The design results show that BEMS using the electric chiller as a supplement is more efficient than BEMS using the auxiliary boiler because it offers lower TOC and lower TCOE. However, the results from optimal operation analysis and risk assessment lead to similar conclusions of old BEMS. Lastly, we find that both BEMSs still have a room for improvement, i.e., there is still waste heat energy that happens when there is no cooling demand. To improve energy efficiency of both BEMSs we recommend adding heat storage to keep waste heat energy and use it during peak cooling demand.

The conclusions and recommendations for future work are briefly described at the end.

5.2 Recommendations for Future Work

1. BEMS with heat storage

   Due to the existence of waste HE, we recommend adding heat storage to improve energy efficiency of both BEMSs. In order to apply heat storage to BEMS, we need to reformulate economic and environmental objective functions, including electrical and cooling energy dispatch strategies. Moreover, heat storage causes change in equipment selection. Regarding BEMS using a boiler, heat storage contributes to reducing heat production of the boiler; therefore, we need to redesign the size of the boiler to match heat storage and the heat shortage. Concerning BEMS using an electric chiller, heat storage contributes to increasing cooling production of the absorption chiller but decreasing cooling production of the electric chiller; hence, we need to reselect the size of the absorption and electric chillers to suit heat storage and the cooling shortage.

2. BEMS with renewable energy and alternative energy

   Apart from support for energy efficiency with CHP, PDP2010 promotes renewable energy and alternative energy. Renewable energy, like photovoltaic cells and wind turbines, is another option of clean electricity generation to help reduce TOC and TCOE from external electricity dependence like distribution grids. Therefore, we can imagine BEMS based on CHP systems, absorption chillers, electric chillers, boilers, solar cells, wind turbines, batteries, heat storages and power grids. Moreover, alternative energy, like biomass, is an optional fuel for CHP systems to reduce operating costs, emissions, including the risk in fuel price fluctuation. In sum, renewable energy and alternative energy are an interesting option for BEMS improvement.

3. Implementation of BEMS

   The optimal operation models of both BEMSs are suitable for energy generation planning to buildings. However, both proposed optimal operations are designed based on linear models, i.e., output energy and operating costs of the equipment are directly proportional to input energy; in other words, we assume that the equipment operates at full-load efficiency for producing energy from the minimum to the maximum level and ignore part-load efficiency. To implement BEMS in practice, we need to consider the effect of part-load efficiency because it has a direct impact on total operating costs and total CO_2 emissions, including optimal operations of BEMS; therefore, in-depth technical details of the equipment are required to improve economic and environmental optimal operation models. Nevertheless, the proposed optimal operation models of BEMS are still an offline model because BEMS knows load profiles exactly, which enables BEMS to simply obtain minimum total operating costs and total CO_2 emissions. In real-time applications of BEMS, load profiles are not clearly defined especially in the future, and BEMS knows load profiles and optimized the operation of the equipment only at the moment. In order to develop online optimal operation models of BEMS, we need to create an extra function for predicting load in every time of optimization; also, load forecast should cover at least a determined month to estimate demand charge costs of the month. In short, implementation of BEMS in practice requires online optimal operation models which can be developed from offline models by integrating part-load efficiency models of the equipment and load forecast modules.

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BIOGRAPHY

Thanakorn Petkajee received his Bachelor's Degree in Electrical Engineering from Faculty of Engineering, Chulalongkorn University in 2010. He was granted "Sitkonkuti" Scholarship from Electrical Engineering Department to pursue his master's degree in electrical engineering at Control System Research Laboratory (CSRL), Department of Electrical Engineering, Chulalongkorn University, since 2010.

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List of Publications

1. T. Petkajee and D. Banjerdpongchai, "Economic Optimal Operation of Combined Heat and Power Generation for Building Energy Management System," In the Proceeding of the 5th AUN/SEED-Net Regional Conference in Electrical and Electronics Engineering (RC-EEE), February 4-5, 2013, Bangkok, Thailand, pp. 189-192.

2. T. Petkajee and D. Banjerdpongchai, "Multi-objective Approach to Economic and Environmental Optimal Operations of Cogeneration for Building Energy Management System," In the Proceeding of the 10th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), May 15-17, 2013, Krabi, Thailand, pp. 1-6.

3. 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, August 2013 [Online]. Available: http://www.ecti-thailand.org/assets/papers/1351_pub_57.pdf.