DEVELOPMENT AND ASSESSMENT OF AN INTEGRATED ENERGY AND WATER SYSTEM FOR A HOSPITAL

Andreas Prasetyadi

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Engineering in Mechanical and Process System Engineering

Suranaree University of Technology

Academic Year 2019

การพัฒนาและประเมินระบบผสมผสานระหว่างพลังงานกับน้ำ
สำหรับโรงพยาบาล

นายอันเดรียส ปราเสิตติยาดี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมเครื่องกลและระบบกระบวนการ
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2562

DEVELOPMENT AND ASSESSMENT OF AN INTEGRATED ENERGY AND WATER SYSTEM FOR A HOSPITAL

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

____

(Assoc. Prof. Dr. Bundit Krittacom)

Chairperson

____

(Asst. Prof. Dr. Atit Koonsrisuk)

Member (Thesis Advisor)

____

(Asst. Prof. Dr. Keerati Suluksna)

Member

____

(Asst. Prof. Dr. Krawee Treeamnuk)

Member

____

(Asst. Prof. Dr. Pansa Liplap)

Member

____

(Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart)

Vice Rector for Academic Affairs

and Internationalization

____

(Assoc. Prof. Dr. Pornsiri Jongkol)

Dean of Institute of Engineering

อันเดรียส ปราเสิตติยาดี : การพัฒนาและประเมินระบบผสมผสานพลังงานกับน้ำสำหรับโรงพยาบาล (DEVELOPMENT AND ASSESSMENT OF AN INTEGRATED ENERGY AND WATER SYSTEM FOR A HOSPITAL) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร. อาทิตย์ คูณศรีสุข, 281 หน้า.

วิทยานิพนธ์ฉบับนี้มีเป้าหมายศึกษาความสัมพันธ์ระหว่างพลังงานและน้ำที่ใช้งานในโรงพยาบาล โดยเลือกศึกษาระบบของอาคารหลักของโรงพยาบาลมหาวิทยาลัยเทคโนโลยีสุรนารี ซึ่งมีวัตถุประสงค์แรกเพื่อประเมินเชิงคุณภาพของอาคารดังกล่าว โดยใช้โครงร่างสถาปัตยกรรมที่ใช้กันทั่วไปในการอธิบายปัญหาของระบบ โดยการไหลและคุณภาพของพลังงาน และน้ำถูกทดสอบแต่ไม่รวมน้ำร้อนที่ไม่ได้ใช้เพื่อความปลอดภัย ส่วนน้ำที่ใช้ในระบบ ได้แก่ น้ำประปา น้ำโออาร์ น้ำที่ปรับคุณภาพโดยเติมสาร น้ำระบายทิ้งจากระบบคอนเดนเซท และน้ำเสีย ซึ่งพลังงานไฟฟ้าเป็นพลังงานรูปแบบเดียวที่จ่ายเข้าสู่ระบบ ดังนั้นระบบน้ำประปา ระบบปรับอากาศ ระบบระบายอากาศ และระบบน้ำเสียจึงเป็นระบบที่ควรประเมินผล

ส่วนที่ 2 ตรวจสอบระบบปรับอากาศและระบายอากาศ เนื่องจากเป็นระบบหลักที่ใช้พลังงานและน้ำในอาคาร ซึ่งผลการจำลองตลอดทั้งปีของอาคารจำลองโดยใช้โปรแกรม TRNSYS สำหรับการวิเคราะห์เอ็กเซอร์ยีมีลักษณะเหมือนกับการวิเคราะห์น้ำของระบบ พบว่าการตั้งค่าอุณหภูมิที่ 24 °C ทำให้ค่าอัตราส่วนระหว่างอัตราการทำลายเอ็กเซอร์ยีต่ออัตราการใช้ไฟฟ้า (XER) ต่ำที่สุด และพบว่าเครื่องทำน้ำ (Chiller) เป็นระบบที่ใช้พลังงานสูงสุด ซึ่งการใช้น้ำคอนเดนเสทสามารถลดการใช้พลังงานลงอย่างมาก เนื่องจากการให้ปั๊มของเครื่องทำน้ำเย็นสามารถลดอัตราการทำลายเอ็กเซอร์ยีของอาคารได้

วัตถุประสงค์ของส่วนที่สามและสี่คือ (1) เพื่อศึกษาความสัมพันธ์ของระบบน้ำประกอบด้วยระบบน้ำประปา ระบบปรับอากาศ และระบบจัดการน้ำเสีย (2) เพื่อให้วิธีการอธิบายความสัมพันธ์ของระบบ โดยทำการวิเคราะห์เอ็กเซอร์ยีของระบบน้ำ ตามด้วยการศึกษาการอนุรักษ์น้ำของระบบ ซึ่งพบว่าพลังงานและน้ำมีความสัมพันธ์กันในระหว่างกระบวนการบริโภค การผสมผสานทรัพยากรทางเลือกของน้ำสามารถลดพลังงานน้ำได้ 12% นอกจากนี้ยังแสดงให้เห็นว่าสามารถปรับปรุงการทำงานของสภาพปัจจุบันได้ การประยุกต์ใช้ตัวชี้วัดสำหรับความสัมพันธ์ประกอบด้วยประสิทธิภาพเอ็กเซอร์ยี ความพร้อมใช้น้ำ และการเข้าถึงน้ำที่ระบบน้ำประปามีค่า 56.39%, 2.84 และ 1 ตามลำดับ สำหรับประสิทธิภาพเอ็กเซอร์ยี ประสิทธิภาพคุณภาพน้ำ และดัชนีเน็กซัสเท่ากับ 0.68, 0.65 และ 0.44 ตามลำดับ ตัวเลขเหล่านี้แสดงให้เห็นว่าในระหว่างกระบวนการพลังงานอนุรักษ์ 68% ของพลังงานถูกอนุรักษ์ ขณะที่ 65% ของน้ำได้รับการอนุรักษ์ และภาพรวมคือ 44%

ของพลังงานและน้ำได้รับการอนุรักษ์ การศึกษานี้แสดงให้เห็นว่า ยังมีแนวทางให้ปรับปรุงระบบได้อีกมาก

สาขาวิชา วิศวกรรมเครื่องกล

ปีการศึกษา 2562

ลายมือชื่อนักศึกษา________________

ลายมือชื่ออาจารย์ที่ปรึกษา อาทิตย์

ANDREAS PRASETYADI : DEVELOPMENT AND ASSESSMENT OF AN INTEGRATED ENERGY AND WATER SYSTEM FOR A HOSPITAL. THESIS ADVISOR : ASST. PROF. ATIT KOONSRISUK, Ph.D., 281 PP.

ENERGY-WATER NEXUS/EXERGY/HVAC/WATER SYSTEM/NEXUS INDEXING

This dissertation attempted to explore the energy and water interrelation of a hospital. The main building of Suranaree University of Technology Hospital (SUTH) was the object in scope limitation. The purpose of the first study was to evaluate the system of SUTH main building in qualitative methods. Architectural framework as commonly used in system description was applied to describe the problem. Map of flows and quality of energy and water was tested. Hot water which was not used for the safety reason was excluded. Tap water, RO water, soften water, brine, condensate water, wastewater are the types of water flowing among the system. The electricity is the only energy form supplied to the system. Tap water system, HVAC system, wastewater system became the systems that were evaluated.

The 2nd part investigated HVAC as the main consumer of energy and water at the building. A year simulation of the building using TRNSYS was conducted to resemble the hospital HVAC building. Exergy analysis of the system, followed by water analysis of the system is applied. It is found that setting temperature of 24 °C is considered the best in term of exergy destruction rate ratio to electricity supply (XER). The chiller is the highest exergy consumer of the system. Condensate water usage can significantly reduce energy intensity of the costumer. Providing secondary pumps of chiller water can also reduce the exergy destruction rate of the building.

The aims of the third and fourth parts are (1) to investigate the interrelation of the water system comprising tap water system, HVAC, and wastewater system and (2) to provide a method of describing the interrelation of the system. Exergy analysis of the water system was conducted. It was followed by study of water conservation of the system. The work shows that energy and water are interrelated during the process of consumption. Incorporating alternative resources of water can reduce energy of water intensity by 12%. It also shows that the current condition operation can be improved. Application of indicators for the interrelation consisting exergy efficiency, water availability, and water accessibility at the tap water system resulted 56.39%, 2.84, and 1, respectively. The nexus index using advancement of water quality efficiency and exergy efficiency shows 0.68, 0.65, and 0.44 for exergy efficiency, water quality efficiency, and nexus index, respectively. The numbers show how energy is 68% conserved during the process, 65% of the water quality is conserved, and cumulative conservation of energy and water as much as 44%. It implies wide area of improvement can be searched.

School of Mechanical Engineering — Student's Signature ______________

Academic Year 2019 — Advisor's Signature ______________

ACKNOWLEDGEMENT

The thesis could not have been finished without the support of the Suranaree University of Technology scholarship “*Provision of 2016 Postgraduate Scholarships for Foreign Students*”. The author would like to express his sincerest to Suranaree University of Technology for these financial supports.

The author would like to sincerely thank to the academic supervisor, Asst. Prof. Dr. Atit Koonsrisuk, for their encouragement, guidance, and available advices. The advices on both researches as well on his career have been priceless.

A special thanks to all of his committee members Assoc. Prof. Dr. Bundit Krittacom of the School of Mechanical Engineering, Rajamanggala University of Technology Isaan, Asst. Prof. Dr. Krawee Treeamnuk of the School of Mechanical Engineering, Asst. Prof. Dr. Keerati Suluksna of the School of Mechanical Engineering, and Asst. Prof. Dr. Pansa Liplap of the School of Food Technology, Suranaree University of Technology for their available comments and suggestions during the proposal and thesis defenses. Thanks are also extended to Assist Prof. Dr. Chalotorn Thumthae, Head of the School of Mechanical Engineering, for his support during this research.

The author also would like to thank the director, the former director, and engineering department of Suranaree University of Technology Hospital, particularly Dr. Niwatchai Namvichaisirikul, Dr. Likit Matrakul, Mr. Watcharin Singtana, Mr. Songkrit Jitpakdeebordin, Mr Chaleomkiat Kaewkurn, Mr. Prashya Suranachit, Ms. Naphatthira Decheerawas, Ms. Porntip Prapin and all the staffs. The author is particularly grateful to all his lab mates and his friends at Suranaree University of Technology for their useful help during the study. High appreciation is extended for the Yayasan Sanata Dharma for allowing the author for studying and partial support the research, especially in joining conference. Without the support, this study would be impossible. Last but not least, the author must express his gratitude to his family, especially his spouse and kids for their sacrifices. He wishes to thank his family for their tremendous encouragement, support, and love during this endeavor.

Andreas Prasetyadi

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF TABLES (Continued)

Table **Page**

LIST OF TABLES (Continued)

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

SYMBOLS AND ABBREVIATIONS

ACH	=	Air Change per Hour
AHU	=	Air Handling Unit
ASHRAE	=	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTU	=	British Thermal Unit
CAT	=	Continuous Aeration Tank
CCHP	=	Combined Cycle Heating and Power Generation
CDP	=	Condenser Water Pump
CHCP	=	Combined Heating, Cooling and Power Generation
CHP	=	Chilled Water Pump
COP	=	Coefficient of Performance
CCS	=	Carbon Capture and Storage
CSSD	=	Central Sterile Service/Supplies Department
CT	=	Cooling Tower
CT-Scan	=	Computerized tomography scan
DIN	=	Deutsches Institut für Normung
DOD	=	Department of Defense
EER	=	Energy Efficiency Ratio
EPA	=	The Environmental Protection Agency
EPPO	=	Energy Policy and Planning Office
EW_{eff}	=	Energy Water Effectiveness

SYMBOLS AND ABBREVIATIONS (Continued)

FGI	=	Facility Guidelines Institute
HVAC	=	Heating Ventilating and Air Conditioning
IEA	=	International Energy Agency
IEER	=	Integrated Energy Efficiency Ratio
IOA	=	Input Output Analysis
IPD	=	In-Patient Department
IPLV	=	Integrated Part-Load Value
LCA	=	Life Cycle Analysis
MLPW	=	Mean Lumens Per Watt
MRI	=	Magnetic resonance imaging
NEA	=	Network Environment Analysis
NHS	=	National Health Service
NREL	=	National Renewable Energy Laboratory
OPD	=	Out-Patient Department
RO	=	Reverse Osmosis
SAT	=	Sequenced Aeration Tank
SDG	=	Sustainable Development Goal
SUT	=	Suranaree University of Technology
SUTH	=	Suranaree University of Technology Hospital
UML	=	Universal Modeling Language
SYSML	=	System Modeling Language
TMY	=	Typical meteorological year

SYMBOLS AND ABBREVIATIONS (Continued)

XER	=	Exergy Destruction to Electricity Ratio
XLR	=	Exergy Destruction to Cooling Load Ratio
C_b	=	Usage Coefficient of Basin (liter/person day equivalent)
C_f	=	Usage Coefficient of Flushing (liter/person day equivalent)
C_i	=	Coefficient of Energy Processing for the ith ater
C_{pda}	=	Specific Heat of Dry Air
C_{pv}	=	Specific Heat of Vapor
C_{SO}	=	Coefficient for Soften Water (kWh/m^3)
C_r^n	=	Combination of n Fixture and r Usage
D	=	Diameter of Pipe
E_{HVAC}	=	Energy for HVAC Usage
E_W	=	Energy for Supplied Water
$\dot{E}$	=	Energy Rate
EW_{eff}	=	Energy Water Effectiveness
EW_{eff}^*	=	The Second Energy Water Effectiveness (Nexus Index)
f_D	=	Darcy Factor
f_{EC}	=	Energy Cost Factor
f_{WC}	=	Water Cost Factor
g	=	Specific Gravitation
L	=	Length of Pipe

SYMBOLS AND ABBREVIATIONS (Continued)

$\dot{m}$	=	Mass Rate
P	=	Pressure
P_0	=	Pressure of Dead Zone
P_1	=	Pressure of Chilled Water at Evaporator Inlet
P_2	=	Pressure of Chilled Water at CHP Outlet
P_3	=	Pressure of Condenser Water at Condenser Outlet
P_4	=	Pressure of Condenser Water at CDP Outlet
P_{fr}	=	Probability of Fixture Usage
Q	=	Flow Rate of Chilled Water
$\dot{Q}$	=	Heat Transfer
R	=	Resistance
$\dot{S}_{gen}$	=	Generated Entropy Rate
T	=	Temperature, Window Time
T_b	=	Temperature at Boundary
T_0	=	Temperature at Dead Zone
V_{bw}	=	Volume Blowdown
V_m	=	Volume of Make-Up Water
V_{cdw}	=	Total Volume of Condenser Water
$\dot{V}_{cdw}$	=	Condenser Water Flow Rate
$\dot{V}_{chw}$	=	Chilled Water Flow Rate

SYMBOLS AND ABBREVIATIONS (Continued)

$W_{a,j}$	=	Amount of Available Water at j^{th} Story
$W_{ac,j}$	=	Water Accessibility at j^{th} Story
W_{av}	=	Water Availability of the Building
$\hat{W}_{av}$	=	Capped Water Availability
$W_{av,j}$	=	Water Availability of j^{th} Story
W_{avi}	=	Water Availability of i^{th} Type
$\hat{W}_{avi}$	=	Capped Water Availability of i^{th} Type
W_d	=	Daily Water Usage
W_{ds}	=	Water Usage for Domestic Use
W_{efk}	=	k-Type Water Effluent
$\hat{W}_{efk}$	=	Minimum k-Type Water Effluent
W_{fs}	=	Water Usage for Flush at Story
W_m	=	Water Usage for Medical Activities
W_{in}	=	Work Input
W_{ms}	=	Water Usage for Make-Up
W_{out}	=	Work Output
$W_{r,j}$	=	Amount of Required Water at j^{th} Story
W_s	=	Amount of Supplied Water
W_s	=	Amount of Water Usage at a Story
$\dot{X}_a$	=	Exergy Rate of Moist Air

SYMBOLS AND ABBREVIATIONS (Continued)

$\dot{X}_{air,i}$	=	Exergy Rate of Air at Inlet
$\dot{X}_{air,out}$	=	Exergy Rate of Air at Outlet
$\dot{X}_{chw,in}$	=	Exergy Rate of Chilled Water Inlet
$\dot{X}_{chw,out}$	=	Exergy Rate of Chilled Water Outlet
$\dot{X}_{cdw,in}$	=	Exergy Rate of Condenser Water Inlet
$\dot{X}_{cdw,out}$	=	Exergy Rate of Condenser Water Outlet
$\dot{X}_{des}$	=	Exergy Destruction Rate
$\dot{X}_{el}$	=	Exergy Rate of Electricity
$\dot{X}_{in}$	=	Exergy Rate Entering the Control Volume
$\dot{X}_{m}$	=	Exergy of Mass Rate
$\dot{X}_{out}$	=	Exergy Flow Rate Leaving the Control Volume
$\dot{X}_{odair,in}$	=	Exergy Rate of Outdoor Air at Inlet
$\dot{X}_{rmair,in}$	=	Exergy Rate of Room Air at Inlet
$\dot{X}_{W}$	=	Exergy Rate of Work
$\dot{X}_{cooling\_load}$	=	Exergy Rate of Cooling Load
$\dot{X}_{W}$	=	Exergy to Electricity Ratio
XLR	=	Exergy to Cooling Load Ratio
$x_{in,f}$	=	Exergy of Inlet Flow
$x_{out,f}$	=	Exergy of Work

SYMBOLS AND ABBREVIATIONS (Continued)

η_{xcf}	=	Exergy Efficiency of Fan Coil
η_{xcdp}	=	Exergy Rate of Condenser Water Pump
η_{xch}	=	Efficiency of Exergy Rate of the Chiller
η_{xchp}	=	Exergy Rate of Chilled Water Pump
η_{xct}	=	Efficiency of Exergy Rate of the Cooling Tower
η_{II}	=	Exergy Efficiency
ρ	=	Specific Mass
ψ_j	=	Water Quality Efficiency
ω	=	Specific Humidity
$\tilde{\omega}$	=	1.608 ω
$\tilde{\omega}_0$	=	1.608 ω_0 (Specific humidity of dead zone)
Δp_{ev}	=	Pressure Difference of Chilled Water at Evaporator
Δp_n	=	Pressure Difference between CHP Outlet and Chiller Inlet of the Chilled Water Pump
Δp_s	=	Pressure Difference of Main Supply Pipe
Δp_r	=	Pressure Difference of Main Return Pipe
Δp_L	=	Pressure Difference of the Load

CHAPTER I

INTRODUCTION

1.1 Rationale of the Study

Hospital is a kind of institution providing medical treatment and nursing care for sick or injured people (Srinivasan, 2008). There are some classifications of hospitals servicing society. People classified hospitals according to number of beds, operators and services. According to number of beds, there are large, medium, and small hospitals. The public and private hospitals are categorization of hospitals in term of the operator. Single Speciality and Multi Speciality are classification of the hospitals considering its services.

A medical facility provides some medical functions to run it services. A simple health care facility that provides basic health care only needs less than 1000 m^2 space for 30 beds and general medical equipment. A large hospital with many specialities can need more than 10000 m^2 spaces and thousand medical instruments. The functions increases as the number of patients or medical services increase (Bottero et al., 2015). A multi speciality hospital has more facilities than a single one. Each facility needs more requirements to run each functions, such as electricity, steam, ventilation, water, lighting, and space. It implies that more medical facilities consume more energy and water (Christiansen et al., 2015; Christiansen et al., 2016).

Hospital is a building that consumes significant energy and water. In comparison to the other commercial buildings, hospital is the 1^{st} rank in water consumption and the 2nd rank energy consumption over its space. It was reported that in Thailand, a hospital energy intensity was 244 kWh/m^2 (EPPO, 2016). The number is slightly higher than Malaysia's hospitals energy intensity with 234 kWh/m^2 (Saidur et al., 2010). But it was far less than European and American hospitals energy intensity (González et al., 2018). The water intensity of a hospital was reported as 54.8 m^3/year every single bed (González et al., 2016). In 2017, it was reported that the water consumption of healthcare facilities per year ranged from 610 l/m^2 to 5580 l/m^2 (Grumann, 2019). The water is consumed for sanitary, HVAC, medical activities, drinking and food in order of high percentage.

Efficiency energy and water in hospital is common concern. Both resources affect hospital operation cost. Many efforts were applied in order to minimize energy cost (Ascione et al., 2016; Congradac, 2014; Teke and Timur, 2014) or water cost (González et al., 2016; Hospital Energy Alliance, 2011). Challenges of reducing energy and water cost of the hospital were also the topic of policy study (Wang et al., 2016).

In studying energy performance, some measures including cycle methods were applied in reducing the energy consumption of the Greece hospital (Bakaimis and Papanikolaou, 2017). The report shows that air conditioner is significant in affecting electricity consumption of hospital. The report also emphasizes on focusing upon controllable and significant features for reducing energy consumption. In broader scope of hospital operation, Bonnema et al. (2010) studied about the possibility of 50% energy reduction of US hospital in 16 climate zone. Saidur et al. (2010) elaborated the motor effect on electricity consumption of the hospital in Malaysia. Motor retrofitting could reduce significant electricity consumption of the hospital by 36%.

Water efficiency effort in hospital was also subject of concern. Some measures were proposed to reduce water cost of hospital building (González et al., 2016; Hospital Energy Alliance, 2011). The common methods are retrofitting equipment and fixtures, removing one through water cooling, and controlling the user habits. In addition, campaign of reuse, regeneration, and recycle are also proposed methods in order to reduce the water cost of hospital. A cycle consists of identifying water source, habits, and options followed with planning, acting, and evaluating was also applied (Saad, 2007).

Efforts to integrate energy and water issue in hospital has been proposed. Combination of hot water and energy requirement, water usage of the boiler are some area of discussion. Tri generation which includes power, heating and cooling was also analyzed for hospital operation (Santo, 2014).

Systematic integration of energy and water issue of hospital building is not a common work for efficiency energy and water. However, an approach of managing energy and water for engineered water system in UEA was proposed by creating architectural framework and modeling the system (Lubega and Farid, 2014a; Lubega and Farid, 2014b). The architectural framework, qualitative method to understand the engineer field was applied. Mathematical model and its simulation followed (Lubega and Farid, 2014b).

A study of integrating energy and water issue in a hospital building in a systematic way is proposed for the research. The study follows strategy of identifying SUTH building main parts using energy and water, modeling system and simulating it using TRNSYS, analyzing the energy and water consumption, and its distribution at the SUTH main building. Accordingly, exergy analysis and water quality process are proposed as the method to understand the trend of interrelation energy and water in the hospital.

1.2 Research Objectives

1.2.1 To map the energy and water streams in architectural framework and determining the important part of the system affecting energy and water interrelation (Chapter III, and IV).

1.2.2 To model and simulate the HVAC (Heating Ventilating and Air Conditioning) system of the building and analyze it by energy, exergy, and water intensity (Chapter V, VI, and VII).

1.2.3 To model and analyze the water system of the building for determining the pattern of water system (Chapter VIII, and IX).

1.2.4 To study the indexing of water and energy interrelationship in hospital system for describing the energy and water nexus (Chapter X, and XI).

1.3 Research Hypotheses

1.3.1 Energy and water are straggly used in a hospital and have intertwined relation. The dominant water and energy usage can be evaluated to determine the spot of interrelation between energy and water.

1.3.2 The HVAC system consumes most of the energy in the hospital building. It is also source of exergy destruction of the system. Operation of HVAC and retrofitting HVAC pumps can increase the efficiency and reduce the exergy destruction significantly.

1.3.3 Water system of the building shows the interrelation of energy and water. Minimization of energy in water system can be applied for cost minimization of the building.

1.3.4 Hospital consumes energy and water. During the process of consumption, interrelation of energy and water takes place. The interrelation shows existence of quality degradation. Based on quality degradation, the index describing conservation of energy and water can be developed.

1.4 Scope and Limitation of this Study

1.4.1 The main building of Suranaree University of Technology Hospital becomes the object of the study. The other buildings are excluded for limiting the scope.

1.4.2 The main building choice implies the electricity as the only energy of the building to be counted on.

1.4.3 Simulation and application of coefficients become the limitation of the system.

1.4.4 Application of the proposed pattern can be applied in the new hospital building.

1.5 Expected Results

1.5.1 Map of energy and water flows in hospital main building helps to determine the spot of energy and water interrelation in hospital.

1.5.2 A pattern of water system and HVAC system of multistory hospital building.

1.5.3 The pattern of the system can be applied for designing new hospital building.

1.5.4 Index of energy and water interrelation can be applied for describing the conservation level of energy and water in consumption process.

CHAPTER II
LITERATURE REVIEW

2.1 Energy and Water Interrelation

Energy is important and become main issue of the world. The consumption of energy is always increasing. In 2017, 14 million kilo ton oil equivalent was consumed. It was almost 2 times of energy production around the world in 1990. All of energy type consumption increased (IEA, 2019). A lot of organizations, institutions, governments care of the issue. Abundant researches of energy sufficiency were conducted and are still to be proposed. A wide range of energy concerns are spread of over the world. The deep and huge impacts of the energy create people concern to the energy issues from economical perspective to subtle technical aspect. The problem of generation, distribution and the way to consume become part of the energy issue. People become aware of the energy as it is used in every activity they do.

Energy consumption report of International Energy Agency (IEA) shows that industry and transportation dominated energy consumption around the world. Both consumptions score 2.8 million ktoe in 2017. Residential usage and commercial usage follow the position of consumption type of energy. The residential consumed 2.1 million ktoe. The commercial usage was 0.8 million ktoe in the same year. Among these usages, transportation had higher increasing trend of energy consumption. Industry consumption increased its consumption less than transportation did (IEA,2019).

Water is another resource that the world cares of. As the world inhabitant increases, the water need is increasing as well. At the same time, the water is limited and the drought becomes the monster of human living. Even the water covers most part of the earth surface it is known that most of the water is inconsumable. Most of the water is seawater. Less than 2.5% of the water on the earth is fresh water, and less than half of this fresh water is reachable for consumption. In addition, fresh water is not distributed evenly among the countries. There are 9 countries which become home of 60% of the fresh water (Al Fry, 2006). Some of them are because of the large country area such as China, Canada, Russia, India and United States. Some other country becomes the host of the water because their positions give them high yearly precipitation. They are Indonesia, Brazil, Columbia, and Democratic Republic of Congo. It was reported that 49 countries are in water stressed, 9 countries are in water scarcity and 21 countries are in absolute water scarcity with yearly water availability precipitation of <4600 liters/day, <2700 liters/day, and <500 liters/day, respectively (Al Fry, 2006). Asia is reported as the continent with least water capacity per capita (UN-Water, 2020).

Water withdrawal around the world is mostly used for agriculture. It accounted 69% of the total water withdrawal. Industry consumed 20% of the water withdrawal. There are different trends between developed countries and developing countries. The rest was for municipality usage. In Europe, most water is used for industry. It was about 50% of the water withdrawal. The agriculture in Europe consumed half of the water for industry. It is the industrial countries that consume more water for industry than agriculture (Al Fry, 2006). Because of the economic trends, the water for industry is increasing in many countries.

Energy and water are important for the world and become the concern of the world. Sustainable Development Goals (SDG) document also mentions both resources as main focus in development of human living. The water affordability is the 6th target and energy becomes the 7th target of SDG. The 6th goal on the water focuses on accessibility of clean water and sanitation for the population. Water affects greatly the population living quality. Water scarcity, poor water quality, improper wastewater treatment minatory the population in many parts of the world because they create less water affordability. The 7th goal of SDG is targeting on affordability of energy and renewable energy mixture. Increasing energy efficiency is among the targets of SDG on energy in addition to cleaner energy technology and better energy infrastructure (UN, 2015).

Energy and water are considered to have interrelation that is called nexus recently. Water and energy are interrelated such way that the trade-off of energy and water exist (Energy, 2014; Marsh and Sharma, 2007). The interrelation can be in the form of mutualism, commensalism or parasitism. Mutualism takes place as the energy production can increase water availability or quality. Both elements have good impact each other. Commensalism happens as energy process doesn't affect the water sufficiency and vise-versa. Parasitism of energy and water appears as the energy phase process worsens water sufficiency. It also can happen in opposite direction.

Energy and water trade-off can happen in many levels. It can happen on regionals level, such Ethiopian giant dam and Egypt agriculture. The Ethiopian ambition to become energy exporter by building a gigantic dam on Nile tributary affects deeply the water sufficiency of the Egypt. It will especially create drought on Egypt during the dam filling as the tributary is the place where 85% of Nile water flowing (El-nashar and Elyamany, 2018). Similar problem also arises on the Mekong basin (Kittikhoun and Michèle, 2018). Some projects in its tributaries potentially create adverse condition on the delta. The energy and water trade-off can also happen at domestic area. Choice of water processing can become an example of the energy and water trade-off.

Energy is applied in water cycles. The water cycle consists of extracting process, conveying, distributing, treating, using and wastewater treating (Wakeel et al., 2016). Extracting process is effort of moving the water from the water source such as watershed and ground water to storage. The process is a kind of pumping which is basically an adding potential energy. The higher the potential difference is, the more energy is needed for extracting. Generally, extracting from watershed consumes less energy than extracting from ground water source (Wakeel et al., 2016). Water conveying consists of any methods to move the raw water to the reservoir for processing. Distance and methods are very important in energy consumption of the cycle. The common methods for conveying water are channeling, piping and transporting. Distributing water is activities to send the water to the costumers. The method, distance, land contour, and the costumer position are some parameters to differ the energy consumption of water distribution. The treating is methods to process the raw water to be tap water or consumable water. Quality of water, technology, and capacity are the differentiators of energy consumption (Al-Karaghouli and Kazmerski, 2013; Ghaffour et al., 2013; Isaka, 2012). Water using is any people activity of consuming water. Some water consuming need energy such as hot water and sprinkling. Wastewater treating is effort of processing collected wastewater to be acceptable environmentally before it is released. Different level of wastewater treatment means different energy consumption (Wakeel et al., 2016). A biological and chemical water treatment consumes a lot of energy. The biological treatment is applied to minimize hazardous germs that may alive in water after usage. It is also applied to reduce the BOD of the water. Chemical water treatment is performed to reduce the contaminants on the water. Energy becomes integral part of water cycle.

Water in energy phases is inevitable. Water is important for primary energy extraction. During oil, coal, gas mining, water is extracted as well in many cases (Sohns et al., 2016). Some amount of water is needed for extracting the primary energy during the extraction process as well. Water is needed during well boring, conveying the raw material and maintaining temperature of the coal. At the process of oil distillation, water is used for cooling. Gasification of the coal also consume significant amount of water (Ali and Kumar, 2016). Primary energy consuming can also need water, such as the power generating. Thermal power generation consumes significant number of water. The water is needed in almost every phase of power generation. According life cycle analysis, the water is important in the process of power generation building (Yang and Chen, 2016). It is also part of power generation destruction. At the power generation process, water is significantly consumed for cooling system. Except dry cooling, the other process cooling needs water. It was reported that less efficient power generation system consumes more water for cooling system. Additional system to fill the environment requirement such as CCS also adds water requirement.

Renewable energy system also consumes water. Wind power and solar cell are considered as the least water consumer (Spang et al., 2014b). The geothermal and solar thermal systems tend to be water gobbler (Macknick et al., 2012). The hydro systems also consume water in significant number due to it way of collecting water (Mekonnen and Hoekstra, 2012). Creating dams increase the water surface exposed to the sun and it means to increase the evaporation. Biofuel is the system that considered consumes the highest number of water (Gerbens-Leenes et al., 2008; Gerbens-Leenes et al., 2007). Even it is considered as green due to CO_2 balance, it consumes significant number of water during the process of cultivation. Potential conflict arises between biofuel and food in the water and land need (Lele et al., 2013).

The research of energy and water interrelation is started by Peter Gleick with his paper on energy and water in 1994 (Gleick, 1994). In this work, he showed the energy cost of water and water use in energy processing in some countries. He emphasized the importance of considering water in energy processing and considering energy in water processing. Deeper works on water value of energy were performed by many researchers. Babkir Ali proposed values of water consumption of coal production from the mining to processing (Ali, 2017). He also performed researched of water processing for gas power generation (Ali and Kumar, 2016) and renewable energy power generation (Ali and Kumar, 2017). Dalgado proposed model for estimating water consumption of thermal power generation (Martin, 2012; Sohns et al., 2016). Integrating water and energy as a nexus is part of some research works. Energy and engineered water system of a Middle East country was studied by Lubega and Farid (2014; 2013b). They proposed architectural approach (Lubega and Farid, 2014) followed by bond graph modeling (Lubega and Farid, 2014). Marsh and Sharma studied impact of energy and water in economic systems in New South Wales through IO model (Marsh and Sharma, 2007). Network environmental analysis was applied by Yang and Chen in analyzing wind power generation (Yang and Chen, 2016). Fang et al. studied socio-economic aspect of energy and water in Ganzhou (Fang et al., 2014) with the same method. They also presented the cycling index to indicate water use efficiency.

Considering the scope of the object, the study of energy and water interrelationship can be categorized into measuring energy of water cycles (Isaka, 2012; Sanders and

Webber, 2012; Wakeel et al., 2016), measuring water of energy production (Copeland, 2014; Delgado et al., 2015; Eltawil et al., 2009; Lee and Cheng, 2012; Sohns et al., 2016; Spang et al., 2014a; Vakilifard et al., 2017), facing area constraints (Dubreuil et al, 2013; Frisvold and Marquez, 2013; Gold and Webber, 2015; Larson et al., 2017), and policy proposing (Energy, 2014; Glassman et al., 2011; Li et al., 2012; Venkatesh et al., 2014; Yan et al., 2017). The discussed area constraint problems range from building (Bertone et al., 2016, 2018), cities et al., 2011), national (Kenway et al., 2011), regional and international (Holland et al., 2015; Spang et al., 2014b). Among the building, study of energy and water at the same time was reported in order for retrofitting. The study was conducted for formulating a policy to promote building retrofit (Bertone et al., 2016). Integration of energy and water system were formulated to create engineered system (Lubega and Farid, 2014a; 2013a; 2014b). However, measure of energy and water in a building is far from defined.

2.2 Energy and Water in Hospital Building

Hospital is a kind of healthcare institution that provides medical service to the people. The medical service can be a treatment or nursing (Srinivasan, 2008; Bottero et al., 2015). The medical treatment is various activities in order to trace the patient problem or help them to face the illness problem and getting health. Including in this service are clinics, laboratory, operation (surgical), pharmacy, and therapies. Nursing are various activities to prevent a patient from getting worsen condition and providing ancillary support for getting cured. The nursery consists of activities to help patient to get recovery and avoid of death. Wards and various living services are part of nursery. In these services, providing good food, good living condition, and environment are included. The second type medical service is the core of hospitality.

There are many categorizations of a hospital. The first categorization is based on the number of beds. There are small hospital, medium hospital, and large hospital. In India the small hospital has beds less than 30, the medium hospital can accommodate inpatient until 100 people and the large hospital has beds more than that numbers (Srinivasan, 2008). The second categorized hospital into general hospital, single speciality, and multi speciality. This categorization follows the clinics that a hospital provides. According to the operator of the hospital, there are public hospital that is operated by government and private hospital that belongs to private company, organization or person. The categorization of hospital according to the stakeholders of the hospital indicates that there are normal hospital, educational and research hospital. The normal hospital focuses on treatment and nursing function of the hospital. The research hospital usually is also an educational hospital. It becomes research facility of healthcare and student study center. This type of hospital usually belongs to a university or trans-national health organization.

Different hospital type implies different intensity of energy usage and water usage. Two different studies according the capacity classification were performed by Bonnema et al. (2010a; 2010b) for energy saving. Bonnema et al. applied some component metrices for the hospital in purpose of 30% energy savings. They are MLPW (Mean Lumens Per Watts), EER (Energy Efficiency Ratio), IEER (Integrated Energy Efficiency Ratio), IPLV (Integrated Part-Load Value), COP (Coefficient of Performance) in addition to some insulation parameters (Bonnema et al., 2010a; 2010b). Metrics intensities of energy usage of a hospital generally are applied to measure hospital efficiency (Bagnascoet al., 2015;

Congradac et al., 2012; González et al., 2018; Saidur et al., 2010; Singer et al., 2009; Thinate et al., 2017). Size of the hospital is used to become the metrics, such as energy intensity per-bed, energy intensity per staff, energy intensity per-inpatient, and energy intensity per-hospital area. The water usage of hospital can be also measured in similar ways. They are intensities per-bed, per-staff, per inpatient, and per-hospital area.

Thinate et al. (Thinate et al., 2017) analyzed energy consumption of 45 large hospitals across Thailand. It was reported that energy consumption of the large hospital depended on temperature, air conditioning area, non-air conditioning area, inpatient, outpatient, and staff member. Their equation shows that temperature setting, air conditioning area, out-patient number affected positively energy consumption. The result also shows that the patient number didn't affect significantly the energy consumption of a large hospital. Energy consumption of large hospital in Thailand was reported 244 kWh per year for every m^2 (EPPO, 2016). The number is slightly higher than Malaysian public hospital reported consuming 234 kWh/m^2 (Saidur et al., 2010).

2.2.1 Hospital Building Systems

A hospital building has many facilities to run its functions as ancillary system. Generally, facilities in hospital building can be categorized as medical facilities and non-medical facilities. The medical facilities include all equipment and spaces used for running the medical functions. The non-medical facilities include spaces and all of the system of the building to support the hospital system and run medical facilities. Including into medical facilities are the equipment of sterilization (CSSD), medical gas system, hemodialysis, vacuum system, laboratory facilities, pharmacy, operation room, treatments, clinics, and offices. The non-medical facilities are water system, electricity system for lighting and load, HVAC system, food preparation, canteen and offices.

Among the healthcare building facilities, some are considered as the main energy consumer. These facilities are HVAC, lighting, biomedical instruments. It was reported by Thinate et al. (2017) that HVAC consumed more than 51% of the energy consumption. Lighting consumed 14%, and the boiler took part of 12% energy consumption. Chirarattananon et al. (2010) mentioned that HVAC spent 66% of hospital energy consumption. The lighting part of the energy consumption was 20%. Gao et al. (2017) reported that 160-162 kWh/m^2 electricity was spent in Shandong and the boiler consumed 10.2-10.9 $kgce/m^2$. All the report emphasized that HVAC is the main energy consumer of the hospital building. Electricity consumption on lighting is also should be a concern of the energy consumption.

Water consumption of the hospital building was reported by some organizations. The North Carolina Division of Pollution Prevention and Environmental Assistance mentioned in their publication of promoting the water saving that HVAC consumed 53% of water. It was followed by domestic usage counting on 24%. The cleaning, kitchen, and processes consumed 10%, 5%, and 4%, respectively. The rest was consumed by other activities. It was also mentioned that there was nearly 50% water saving potential. Similar report was also published by EIA based on 2012 data. Hospital Energy Alliance showed that sanitary is the water gobbler of hospital with HVAC followed the position.

HVAC are reported to become the main consumer of energy (Teke and Timur, 2014) and water (Kassai, 2017). It is emphasized the important of HVAC system in hospital to be discussed in the term of energy and water system. HVAC has potential of energy saving and water saving at the same time.

In addition to HVAC, as Thinate et al. (2017) reported, electricity of the system consumed 20% of energy. At the same time, sanitary was reported as the water monster for hospital building and has significant saving. Water system of the hospital building can become a potential location of the energy and water trade-off. The water system was composed of pumping system in many places which is very significant in industry energy issue.

2.2.2 HVAC

The HVAC is very important in hospital. It is not only for the comfort of the people staying and working at the hospital, but it is also used for optimizing the hospital function. Practically, the HVAC has function of supporting the recover process, preventing the infection spreading, and keeping the safety of the building. It is noted that HVAC installation of the hospital is tightly connected to the services at the hospital. The more complex services of a hospital, the more complex its HVAC system should be. HVAC installation of the clinics, offices, wards, support system are different in requirement (Owen, 2003).

HVAC in recovering process is used for creating suitable condition for the patient to recover. The suitable condition increases the comfort of the patient that supports their psychological aspect. Moreover, a special condition of the patient may need to be specially treated. Patient with high percentage burns needs around 35% humidity to faster the wound recovery and temperature close to human body to keep the patient temperature. Patient with airborne bacterial diseases has to stay in low humidity condition (Owen, 2003) which is different with necessity of viral diseases.

The HVAC design for a hospital has to fulfill some criteria. The criteria include indoor, outdoor environment conditions, and economical consideration. The indoor requirements are the need of room condition for special function. The outdoor criteria describe the outlet and inlet of the ventilation system. The standard of the criteria for HVAC system of the building are released by some organization dedicated for the building and medical facilities or the institution managing specific health facilities such as ASHRAE, NHS, FGI, DIN and DOD.

Hospital HVAC becomes the subject of the study for the reason of minimizing energy consumption, best condition for patient and worker, and managing the public health. In 2007, Balaras, et al. (2007) reported range of temperature in Helas hospital operation rooms were 14 ^{o}C to 29 ^{o}C. The humidity of the operation room indoor air was 13-80%. Real time optimization becomes the study of increasing the optimization of HVAC system (Wang etal., 2016). Buratti et al. (Buratti et al., 2013) proposed simple model to understand the HVAC conditions proper for the patients. Classification of indicators of HVAC performance was studied by Alves et al (Alves et al, 2016). They found that seasonal indicators were important to apply instead of the basic indicators.

2.2.3 Water System

Water is important in hospital operation. The water is used for many functions. Generally, water is used for domestic use, clinical use, and service use. The domestic use of water in a hospital can be classified as sanitary use, gardening use, and cleaning use. The clinical use is considered as the water for clinical equipment and clinical activities. The water of clinical use has direct contact with patient. The service water is water for providing system a support that useful to patient recovery process. It includes water for cooking, CSSD, and HVAC.

Water of domestic use is the water which has lowest quality as it doesn’t have any contact with patient. Flushing, gardening, and cleaning can use brine water or tap water without any treatment. It is also available to use the recycled water with limited process.

The clinical use needs high quality water which is free of contaminant. Therefore the water for clinical use should be prepared well. Most of the water for clinical use is RO water or distilled water. The water has direct contact with patient and may enter to the body of patient.

The support system water use in a hospital has various water types for its functions. The water for support system is determined by specific function of the support system. The HVAC system needs soften water, but the cooking water needs tap water. The laundry system needs tap water and hot water. The CSSD need soften water to be transformed to be vapor.

A hospital provides its water use in many different ways. The requirement of water supply system for a hospital should accommodate emergency condition. Therefore the hospital water system provides redundant system for the water need (Michigan Department of Licensing & Regulatory Affairs (LARA), 1978). The supply should have double lines support for anticipate failure of a line. Emergency supply is prepared in addition of enough water storage for 2-3 days intermittent and maintenance time.

The water system of a hospital accommodates hospital water requirement in term of water quality. Therefore, a hospital usually has tap water system supply, hot water system supply, soften and RO water system supply. Some hospital has centralized system for all of the function for the reason of efficiency. The others prefer distributed system in order to reduce the nosocomial infection through the water system.

Hospital water minimization is conducted mostly in order to reduce water cost. Water efficiency effort consists of water management system, behavior adjustment, technology and retrofit treatment. The water management system is improvement of water system. It includes activities control, equipment control and behavior adjustment. A behavior adjustment is effort to minimize water use of a facility through evaluating the behavior of the inhabitant. Behavior adjustment is assumed to be a good choice with minimum cost. Technology and retrofit treatment is effort of conserving water through implementing a new technology. It only can be applied as the levelized water cost being acceptable.

2.3 Integration of System

System integration is accumulation of effort to conserve resource through managing many activities so that those activities can use the resource efficiently. An integration process is also intended to increase an efficiency of a system by combining it into another system. The assumption of the method is the existence of by-product of the first system which can be used for another system. The integration can also be application of multimethod for reducing a specific resource cost in a system. Combination of solar thermal and photo voltaic (Chow et al., 2012), combination of heat storage and solar heat (Baniassadi et al., 2018), combination of water distillation and heat pump (Yang et al., 2016) are examples of multimethod.

Integration of the system is implemented many heat systems. Integration of heat exchanger is conducted in heat exchanger network design through many ways. Integration through superstructure approach is applied for heat exchanger consisted many flows (Liu et al., 2018). The model includes hot and cooling flows with optimization conducted in simultaneous way. A heat integration of industrial area is proposed by total site approach (Yen et al., 2017). The total site approach incorporates wide area with multiple heat resources. The basic idea of the method is reduction of thermal effluent assuming it will reduce heat input (Semkov et al., 2014).

Multi resources integration is conducted for optimizing cost. In order to minimizing cost of power generating process, a study of combining CO_2 processing and energy input in power plants was conducted. Some chemical industries, power plant was integrated to minimize cost of CO_2 capture and energy input (Hassiba and Linke, 2017). Combination of thermal and wind for heat and power dispatch was conducted and emphasizing the importance of storage (Zheng et al., 2018).

Trigeneration as an advancement of combine cycle approach was common for a system such as a hospital. Analysis of energy and exergy of trigeneration in Brazilian hospital reported that the method can reduce energy consumption (Santo, 2014). It is also reported that it can reduce power cost of the system.

CHAPTER III

A REFERENCE SYSTEM ARCHITECTURE FOR INTEGRATED ENERGY AND WATER IN A HOSPITAL

3.1 Abstract

Hospitals are considered as an energy gobbler with middle energy intensity compared with other large commercial buildings. It is also water consumer with highest water consumption intensity annually. Interrelation of energy and water as a nexus affects trade-off of energy and water provision. Energy value of water is also characterized on somehow to consume the water at the end user. As a hospital operates continuously, the energy and water are important to be optimized by an appropriate system architecture that identifies its interrelation clearly and can define the parameters. This paper presents a reference system architecture for energy and water system in a hospital. The system is developed with System Modeling Language in intention of providing graphical model for qualitative discussion and planning quantitative model for retrofitting HVAC, medical equipment, energy system, and water system that consists of hot water module, tap water distribution, RO water, soften water and wastewater infrastructure at a hospital. The model shows possibilities of retrofitting to conserve the system where energy for water dominates.

3.2 Introduction

Energy and water systems are inextricably linked in many facets and interrelated in such a way that improper managing of one endangers the sustainability of the other. At the provision side, energy and water are interconnected because providing energy is water consumer activity (Ali and Kumar, 2016; 2017a; 2017b) and water provision needs huge amount of energy (Al-Karaghouli and Kazmerski, 2013; Gleick, 1994; Isaka, 2012). Intensity parameters, such as water footprint (Gerbens-Leenes et al., 2008; Gerbens-leenes et al., 2007; Mekonnen & Hoekstra, 2011), virtual water (Hoekstra, 2003; Allan, 1998; Shin and Zhan, 2015; Velàzquez et al., 2011; Zhang and Anadon, 2014), energy intensity of water and water intensity of energy (Rutberg, 2012; Liu et al., 2016) are some meters that are applied to measure interrelation of both resources. On the other hand, at the consumption, water and energy are also interconnected through managing policy to optimize both resources conservation with economical meter becoming the common reference for optimization (DOE, 2011; Ziher and Poredos, 2006). Environmental parameters are also become the measurement of conservation (Alexis and Liakos, 2013).

A lot of studies were conducted to understand the interrelation of energy and water. In addition to policy (DOE, 2014; DOE, 2006), study about the water and energy intensity dominated the efforts. The intensities are measured through life-cycle analysis (Ali and Kumar, 2016; 2017a; 2017b), input-output analysis (Shi and Zhan, 2015; Zhang and Anadon, 2014; Hawkins et al., 2007), and network environment analysis (Yang and Chen, 2016). The life-cycle analysis portrays the intensity through path of production and consumption. Input-output analysis mentions about the impact of interrelation of system in term of products exchange or trades. Network environment analysis resembles the interconnection of ecosystem components for determining impacts.

Interrelation of energy and water are also studied as network of components that provide or consume energy. Sustainability is the main motivation of the study. Among the methods of studying the interrelation connected to sustainability, building reference system architecture (Lubega and Farid, 2013; 2014) was a rigid model that can be applied in designed engineered system of energy and water. It provides clarity of composition and interconnection of the components at the system. The model can provide possibility of discussion at qualitative and quantitative approach.

The main goal of sustainability discussion of the energy and water is applicable efforts on managing both resources at provision and consumption side. Management of behavior becomes the main effort in conserving resources due to consideration of low cost. In addition to behavior management, retrofitting is a method of conservation on energy and water at consumption level. It needs amount of investment, but it helps to reduce the consumption into specific state that is predictable and can be specified onto planned proper element.

Retrofitting is also a kind of instrument for conserving energy and water in many levels. At the end user, retrofitting is practically applied as a strategy to reduce cost. At the level of policy, law can enforce retrofitting to fit the requirement of environmental convention such as green gas emission that is stated at Paris Protocol (EPPO, 2016).

To implement the national energy conservation measures, commercial buildings have a very high energy-saving potential (EPPO, 2016). Commercial buildings also have a very high-water saving potential. Consequently, energy and water demand management in commercial buildings would be a smart measure. Additionally, the management plan should take the interrelation of energy and water into consideration.

The hospital is a commercial building. Generally, it consumes a large number of energy and water. According to the study (EPPO, 2016), its energy and water intensity are classified as middle and the most intensive, respectively, compared with other types of large commercial buildings. Hospital in Thailand consume 244 kWh/m^2 yearly (Thinate et al., 2017). In Malaysia, it is reported to consume 234 kWh/m^2 (Saidur et al., 2010). The water consumption of hospital is reported as much as 144.8 10^3 gals/bed annually (EIA, 2012).

Understanding the energy and water consumption is important for retrofitting the energy and water facilities in a hospital (Bonnema et al., 2010). Some efforts on energy may be incompatible with the water conservation and vice versa. At minimizing energy consumption, too cool cooling tower output may consume more water than normal condition. Saving water by minimizing wastewater effluent may come at the fact of over energy consumption for over processing.

A tropical area with high temperature and high humidity needs special treatment to fulfill the requirement of hospital. The cooling equipment at the tropical area works at two challenges environment. High temperature implies more cooling load. The high humidity means more energy to force the ambient air flowing. High humidity also limits ability of evaporation.

The paper focuses on discussing method of creating energy and water integration in SUTH main building at the qualitative state. Architecture Reference system is proposed by providing block diagram that describes the structural composition and activity diagrams that provide activities and functions of each module. These diagrams become the main part of the 3rd section that follows this introduction and SUTH description.

After the diagrams, the discussion of the system in term of integrating energy and water is proposed as the following section. The conclusion will be the final part of the paper

3.3 Suranaree University of Technology Hospital (SUTH)

SUTH is a 120-bed hospital and it has 558 staffs. It is affiliated with the Institute of Medicine of Suranaree University of Technology. There are main building, imaging building, health promotion building, service building, and dormitory. The main building is the largest building as indicated in the circle in Figure 3.1. It is an 11-story building with total area 19,000 m^2. The out-patient division, operations, and wards are located in the main building.

The total electricity and water consumption of SUTH are about 9,100 kWh/day and 146 m^3/day, respectively. The main building consumes approximately 70% and 64% of the total consumption of SUTH, respectively.

The required cooling load of the main building when it completely and fully functions is estimated to be 8,000,000 BTU/hr. The building is cooled by a HVAC (heating, ventilation, and air conditioning) system. The system consists of chillers, AHUs, FCUs, and cooling towers.

There are 3 chillers and each chiller have a capacity of 250 TR with a chiller water flow rate of 70.80 m^3/hr. The designed temperature of the chilled water is 7-13.5 ^oC. The main function of the AHU (air handling unit) is to condition and supply the cooled air to the air-conditioned rooms. While the FCU (fan coil unit) draws the air in the rooms, blows it over a cooling coil, and then supplies the cooled air back into the rooms. The AHUs are used to circulate the cooled air for the entire building, while the FCUs are used in some specific areas.

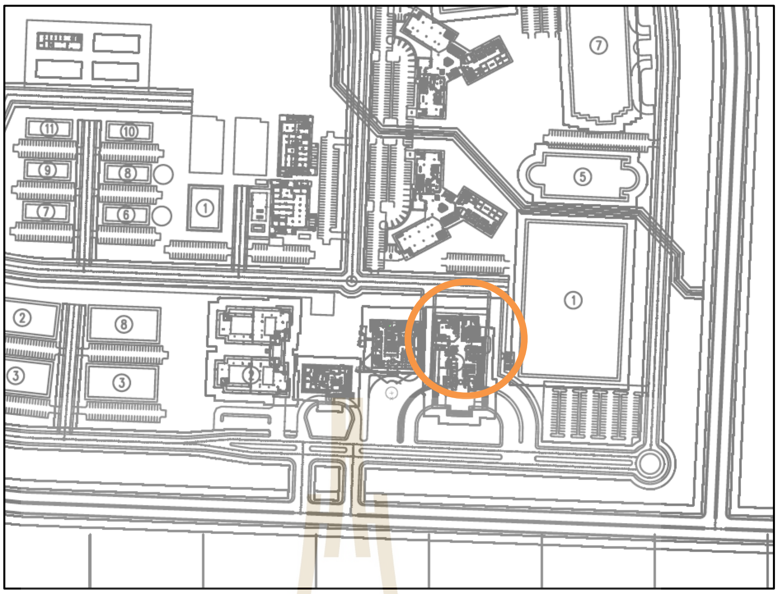


Figure 3.1 Top view of SUTH. Main building is circled in the figure.

The HVAC system rejects heat to the atmosphere through 3 mechanical-draft cooling towers. Each cooling tower has a capacity of 953,904 kcal/hr. The chillers are located in the basement and the cooling towers are on the rooftop of the building.

Water used in SUTH is supplied by the tap water system of Suranaree University of Technology (SUT). The tap water is first stored in a 130 m^3 underground storage in the main building, and then sent to a 50 m^3 water tower on the rooftop on the building using 2 pumps. Each pump has a capacity of 50 m^3/hr and a head of 85 m.

SUTH has a package water treatment plant with a capacity of 220 m^3/day. To treat the wastewater, the plant uses an activated sludge process with a system of continuous and sequential aeration ponds. Currently the plant treats only wastewater from the main building. The treatment level is secondary which can produce water with the BOD (biological oxygen demand) level of 20 ppm.

The electricity system of the hospital is connected to the grid through $2\times 1{,}250$ kW transformers. There is a backup power system with a 1,100 kVA generator. Additionally, there is an emergency power system for the operation rooms, with 30 minutes of backup time.

3.4 The Reference Architecture of Energy and Water System on SUTH

A Reference System Architecture is a set of documents that model a system at which a developer refers to during the development the system. This approach is mostly applied at the software development to communicate among programmers, developer and consumer. Currently such model is also applied to build enterprises, education and other systems. The method is platform independent and visualized by some diagrams. Some common languages of the method are UML (Universal Modeling Language) and SYSML (System Modeling Language). The last is chosen for describing the energy and water system at SUTH.

The main features of energy and water systems of SUTH are the existence of interdependency and they have to provide energy and water for SUTH services continuously. All systems are backed-up with redundancy system to ensure the readiness of the systems. Moreover, some systems are backed-up with emergency system such as operation room system that has emergency power supply.

In the following part, the interdependency of the energy and water system is portrayed in the form of Reference Architecture. This reference architecture of energy and water system on SUTH is provided through internal block diagram and activity diagrams. The block diagram shows the structural composition of systems that composed of modules in term of integration systems and its interconnection. The relations and functions that build a module are figured by activity diagrams.

3.4.1 Block Diagram of SUTH

The block diagram for energy and water system of the SUTH main building is provided in Figure 3.2. The figure shows that the energy source for all the systems is electricity only. According to Figure 3.2, the building uses 5 types of water; they are tap water, hot water, soften water, RO (reverse osmosis) water, and wastewater. The tap water and hot water are used for sanitary, the soften water is used as the make-up water for the chillers and cooling towers. The RO water is needed by the hemodialysis and laboratory equipment. The wastewater of the building is collected, treated, and then released to the environment.

The wastewater from the HVAC system is hereafter referred to as blowdown. It is a high mineral water that has to be blown down to keep the cooling towers work well. To this end, the make-up water is required to compensate the blowdown and the water evaporated at the cooling towers. This make-up water is softened and then feed into the system via a condensate pipe.

To simplify the problem, equipment of the hospital is divided into 3 categories: imaging system equipment, hemodialysis, and sanitary and others. The 1st category represents equipment that needs cooling. The 2nd category is equipment that needs RO water during operation and the last category represents other types of equipment.

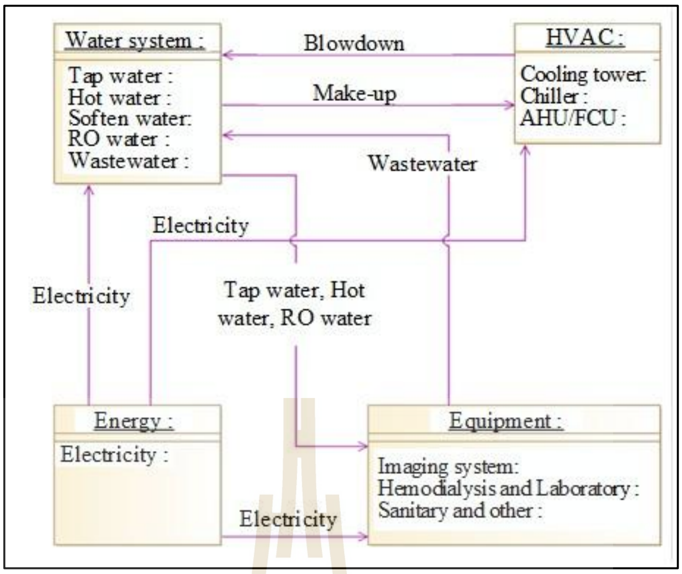


Figure 3.2 Block diagram of energy and water system of SUTH main building.

The HVAC system is composed of cooling tower, chiller and AHU/FCU (Air Handling Unit/ Fan Coil Unit). The AHU and FCU are located in the room for rejecting heat from the room and transferring it to the chiller water. The chiller transfers heat from chiller to condensate water through expansion process. The cooling tower removes heat to the atmosphere.

3.4.2 Activity Diagrams of SUTH Energy Water Systems

The activity diagram of the tap water system is displayed in Figure 3.3. The figure shows that there are two storages, one is in the basement and the other is on the rooftop. It should be noted that the pumps are needed to distribute water in Floors 8-11, while the water is distributed using gravity in other floors.

The hot water is provided by the electrical heaters placed where the hot water is required. Therefore, electricity is the only energy applied for water heating. It implies that the hot water distribution is part of tap water distribution.

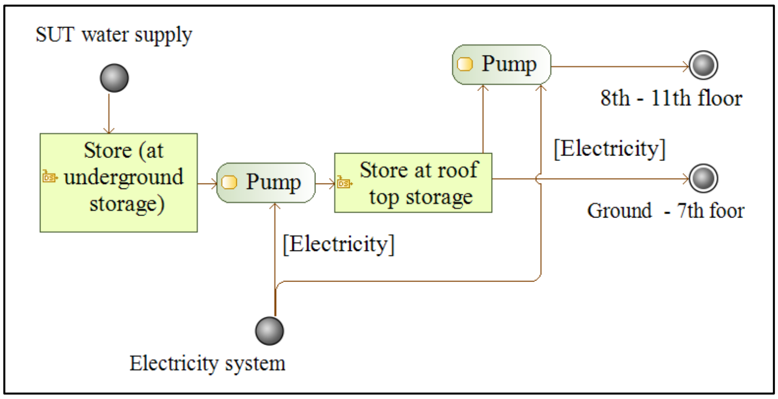


Figure 3.3 Activity diagram of tap water system.

The soften water facility is placed near the chillers and cooling towers. After the facility, the water is pumped and fed into the condensate return pipes as make up water or cooling tower in exchanging blowdown. The activity diagram of this process is displayed in Figure 3.4.

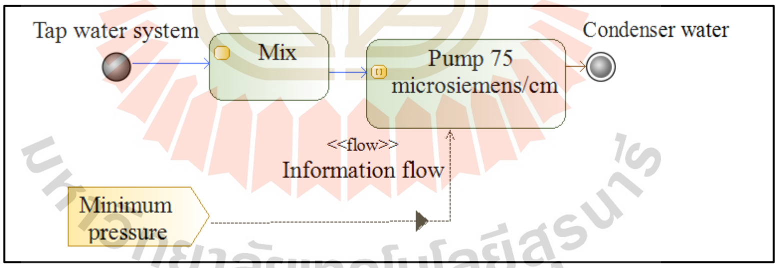


Figure 3.4 Activity diagram of soften water system.

The hemodialysis system needs RO water. The RO production system in on the 8th floor of the main building and has capacity of 600 l/hr. Soften water is supplied to the RO production system. The soften water is demineralized, becomes RO water, and keep in a storage tank. The brine is a waste product and discharged to the wastewater system. The activity diagram of the system is illustrated in Figure 3.5.

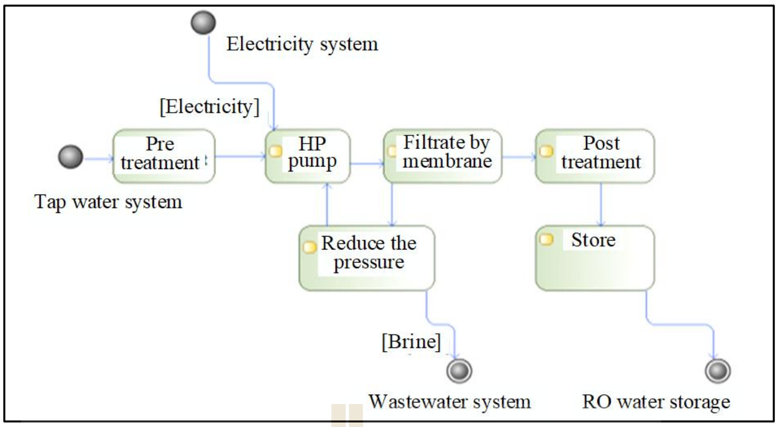


Figure 3.5 Activity diagram of RO water system.

In the wastewater treatment system, wastewater is first treated by sequence and continuous aeration. At this stage, the collected wastewater is mix with activated sludge, aerated and decanted. After that chlorination is done, and then the effluent is directed to the tank for irrigation or outdoor uses. The activity diagram of wastewater treatment system is displayed by Figure 3.6.

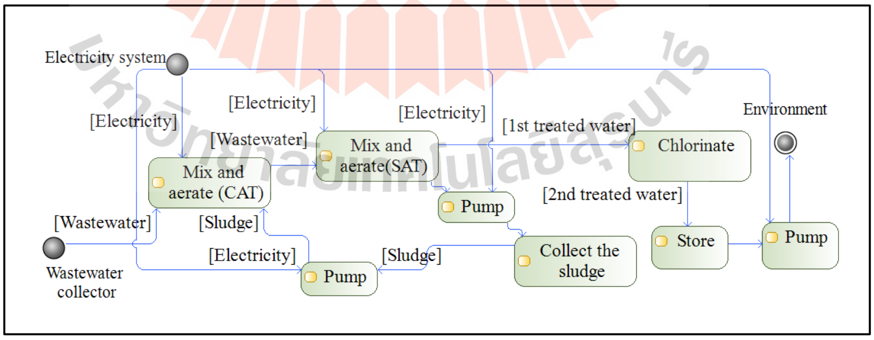


Figure 3.6 Activity diagram of wastewater treatment system.

The pumps are used to move the water among compartments and other treatment activity. The pump is applied for moving the water from sequence aeration to continuous aeration compartment. Pump is the primary mover for mixing the activated sludge and the coming wastewater. Pumps are also the mover of sludge and effluent as the product.

The activity diagram of the cooling towers, chillers, and AHU/FCU systems are displayed in Figures 3.7, 3.8, and 3.9, respectively. Figure 3.7 describes the activities of the cooling towers that consist of pumping and evaporative cooling process. Figure 3.8 provides a relationship of the activities of the chillers. The expansion process takes places for transferring heat from chilled water to condensed water. The pumps are needed because the chillers are placed in the basement of the building. Figure 3.9 shows the activities of the AHU and FCU. The difference between AHU and FCU is that FCU circulates the indoor air, while there is an addition of fresh air in the operation of AHU.

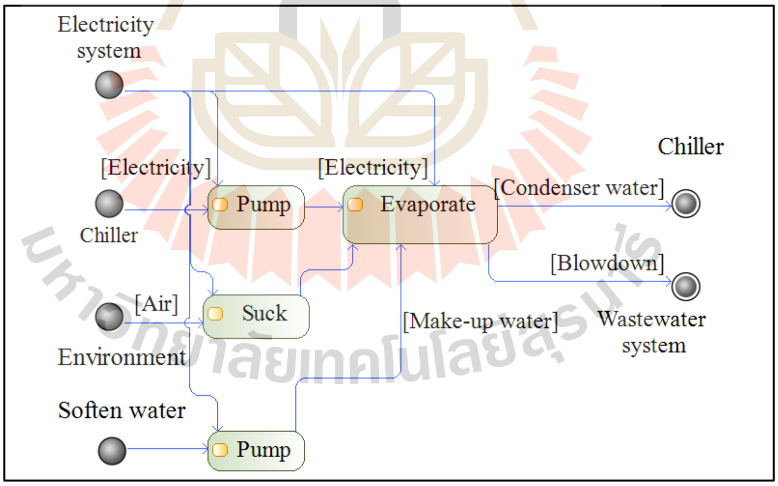


Figure 3.7 Activity diagram of cooling towers.

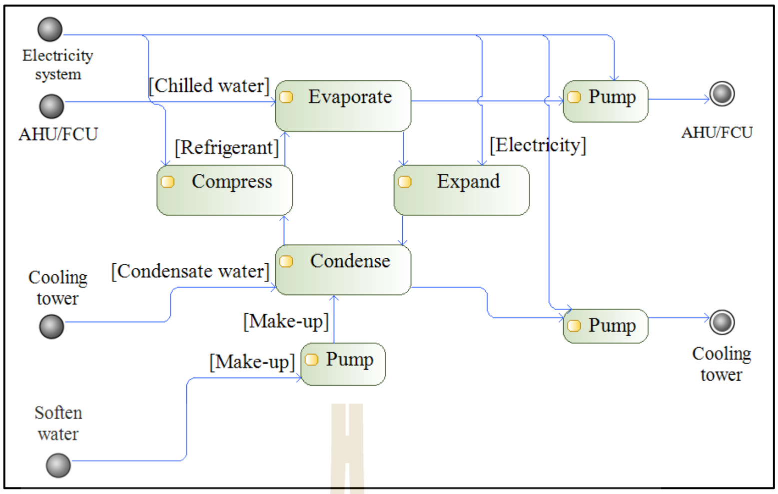


Figure 3.8 Activity diagram of chiller system.

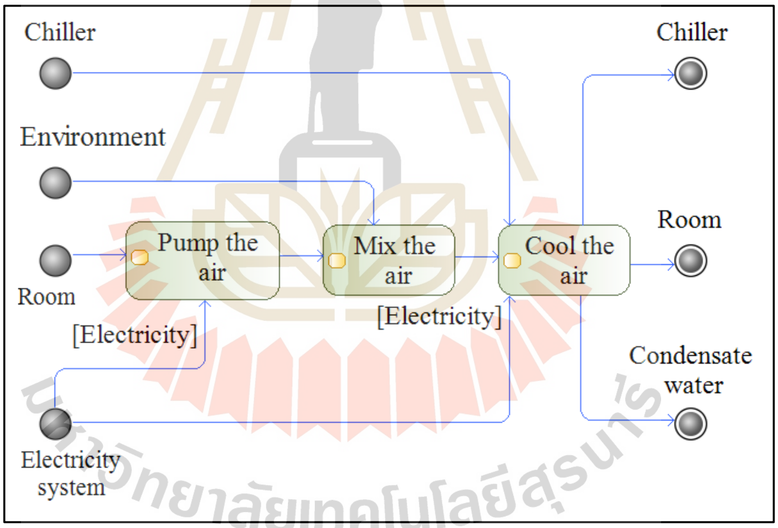


Figure 3.9 Activity diagram of AHU/FCU.

The activities diagram of the electricity system is presented in Figure 3.10. The system consists of distributing the electricity as the main function, generating and storing to meet the emergency conditions. The electricity is 3 phase AC that is controlled by a main control panel in the basement of the building. The control panel also manages the backup system when the grid is shut down. In the diagram, fuel is prepared for a backup power system.

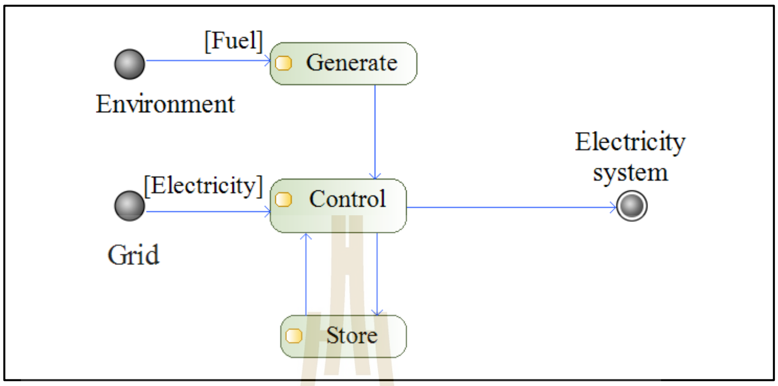


Figure 3.10 Activity diagram of electricity system.

The activity diagram of the hemodialysis and imaging system are shown in Figures 3.11 and 3.12, respectively. At hemodialysis system, heating and pumping are the main activities. At the imaging system, generating X-Ray, pumping and cooling system are the activities of the module.

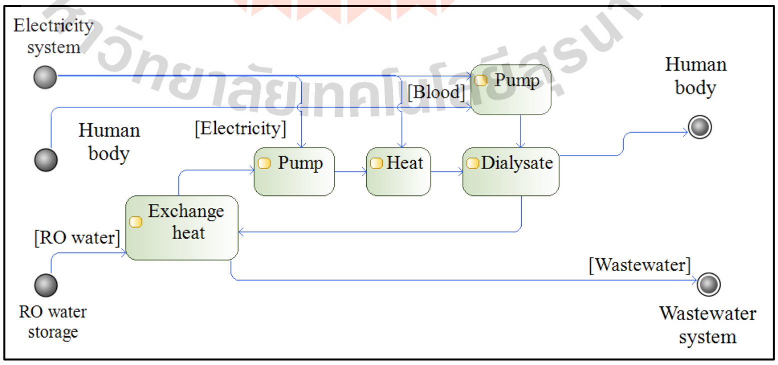


Figure 3.11 Activity diagram of hemodialysis system.

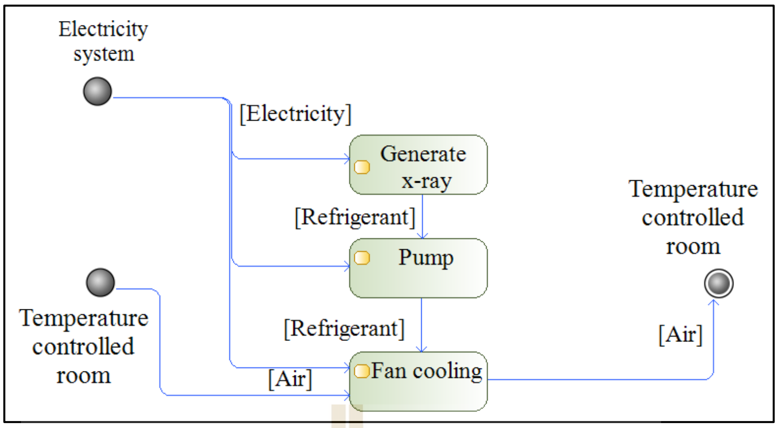


Figure 3.12 Activity diagram of imaging system.

The sanitary and other system consumes more water than the first two systems at the equipment. However, it only consists of pumping. Therefore, the activity diagram of sanitary and other system is not shown here.

3.5 Discussion

Electricity is the only type of energy at the main building of SUTH. The electricity is used for pumping, heating, compressing, and cooling. It is also utilized for generating X-Ray for imaging system and lighting of the building.

This choice has some advantages and disadvantages. The advantage of the choice is that electricity is easy to use, to transfer, to transform and to control. The disadvantage of the choices is that electricity is not easy to store. Electricity has directly to be used as soon as it is produced. To transform the electricity into another type of energy costs some loss due to resistance of network.

Electricity for heating at low temperature is considered very expensive due to its quality (Ziher and Poredos, 2006). The lower the quality of energy is, the more energy types that can be used to fulfill the requirement. To change the heat to electricity, in addition to low efficiency, complex system should be built. Oppositely, changing electricity to heat can be done easily and controlled well. According to the Energy Star Algorithm, the electricity has factor 3.94 (Singer et al., 2009) which mentions that to produce 1 unit of electricity energy, 3.94 unit of primary energy source is needed. Heat for district has factor 1.35 (Singer et al., 2009) that only needs 1.35 unit primary energy for producing 1 unit heat energy directly. It implies that heating by electricity burns the primary energy for creating electricity by factor 3.94 and bears electricity loss for transforming electricity to heat. Heating cost by electricity will be 3 times direct heating from primary energy to heat. Therefore, the hot water production can be redesigned and controlled in an energy-efficient way.

Heating the water by electrical equipment with efficiency 95% can spend huge amount of energy. To increase the temperature of 1 m^3 of water from 25 ^{o}C to 35 ^{o}C, it needs 11.6 kWh. It also implies that increasing the tap water system temperature by 1 ^{o}C can reduce 1.2 kWh every m^3 hot water consumed. Increasing 1 ^{o}C of water tap temperature can be done through simple solar thermal system at proper time (Alvarez et al., 2010).

Increasing the temperature of the raw water by 5 ^{o}C from 25 ^{o}C to 30 ^{o}C is considered possible for reducing the energy consumption by 3.4% for RO water system (Gold and Webber, 2015). Accordingly, the increase of feeding water temperature to the RO water production system can reduce the energy consumption of the system. Consequently, using renewable energy to pre-heat the feeding water should be considered to reduce the energy consumption.

In hospital water systems, pumps are the main energy consumer that delivers water steadily from one place to another. It is also used in mixing and filtration process for water treatment. In addition to capacity, position of some equipment can differ widely energy consumption for water distribution and treatment processing (Ma et al., 2017). Currently, for distributing water, all the water has to be pumped to tower at the rooftop. Addition of 7th floor tower to distribute water for the ground floor until 4th floor may decrease the energy of water pumping.

Condensation is probable way for water harvesting. Generally, for the reason of convenience, room temperature is set to be 24 ^{o}C. The cooling process due to the operations of FCUs and AHUs produces liquid via a condensation process. A room with a high air change rate (ACH) can produce more water. With the set-point temperature of 24 ^{o}C and desire humidity of 55%, a 1 m^3 of air with temperature of 30 ^{o}C and humidity of 80% can produce 11 ml of water. Therefore, a 36 m^3 room with 20 of ACH of 400 cfm can produce 66 ml/min or 3.96 l/hr. A computation reveals that all buildings of SUTH can produce a total of 10 m^3 per day approximately. Therefore, a consideration of using this condensate could reduce the tap water consumption.

The effluent from the wastewater system is treated and can be used for some sanitation purposes and irrigation. Utilization for irrigation can reduce cost of water significantly. This can be done during the summer when the plants need watering. During the rainy season, this activity is not conducted while the plants of the building are located outdoor and the rain water is sufficient for the irrigation. According to the analysis, reuse of wastewater saves 35 thousand Bahts yearly at the current price.

3.6 Conclusion

The energy and water system in a hospital is described by architecture reference system composed of block diagram and activity diagrams of every system or modules. The block diagram tells about the structure and components, they are water systems, energy systems, equipment and HVAC. The activity diagrams mention about the functions of each modules and how they work. The utilized energy at the main building is the electricity that is used for pumping, compressing, heating and transforming. This choice is practical but in some cases may increase energy intensity consumption due to site factor of electricity.

Energy and water are interconnected in many systems. It shows some possibility for retrofitting. Application of pretreatment for RO also can be applied to reduce energy intensity of water. Additional water heater by renewable energy is also possible for reducing energy consumption. Position of some equipment may reduce the overall energy consumption. Collecting water condensed at the HVAC can be a probable activity to reduce water cost. This situation of energy water interrelation is dominated by water impact on energy consumption.

CHAPTER IV

TYPE AND QUALITY OF ENERGY AND WATER IN A TROPICAL HOSPITAL

4.1 Abstract

Chapter III mentions systems of SUTH main building and their activities. Among the systems, it can be inferred that HVAC, laboratory, autoclaves, radiology machine, hemodialysis equipment, and sanitary system use energy and water. The lighting, even it spent significant energy, it doesn't use any water. Therefore, the lighting doesn't change the water usage at the same time.

Mapping the energy and water in term of type and quality is proposed as the starting point in managing energy and water as nexus. This article focuses on that effort in purpose of integrating energy and water system in a hospital. SUTH, a 120 beds hospital located in tropical area in Thailand that operates daily with 146 m^3 water and 1.5 MW of electricity becomes the case of the study. The input and output of energy and water of each subsystem are exposed in addition to subsystems that are described in some different methods. The results show flows of energy and water as by-product that can be used for other systems. Radiology and HVAC release very low enthalpy heat that could not be managed for other utilization, but hemodialysis releases very low heat that is used for its own process. Autoclaves can releases heat that be used for laundry and its own pre-heating. HVAC release brine and distilled water through

blowdown system and condensation respectively. Electricity is very dominant energy supply of the hospital.

4.2 Introduction

Hospital is considered as an energy consumer among large buildings. Hospital energy consumption in Greece was 426 kWh/m^2 (Sayyaadi and Nejatolahi, 2011). In Thailand hospital energy intensity was reported as 243 kWh/m^2 (EPPO, 2016). Hospitals in Malaysia consume slightly less than Thailand as 234 kWh/m^2 (Saidur et al., 2010). Spain hospitals were reported to consume energy annually as much as 270 kWh/m^2(González et al., 2018). The American hospital benchmark for energy consumption is ranging from 160 kWh/m^2 until 310 kWh/m^2 for small facilities (Bonnema et al., 2010) and 437 kWh/m^2 – 668 kWh/m^2 for large hospital at low energy consumption (Bonnema et al., 2010). Among large buildings, energy consumption intensity of hospital is in the middle of the energy consumption for large buildings (EPPO, 2016) and totally hospital represents 6% energy consumption of building sectors (Teke and Timur, 2014). Most of the energy of the hospital goes for air conditioner that can reaches 51% (Thinate et al., 2017). In addition to the HVAC, medical equipment and lighting are the other energy gobbler components of a hospital.

Water is another resource that hospital consumes significantly. According to EPA report, hospital consumes 7% of total water for commercial and institutional building (Epa, 2012). The hospital consumes water 144.8 10^3 gals/bed annually (EIA, 2012). This number is nearly 20% above the lodging consumption at the second position among water consumption intensity of large buildings. The water at the hospital, mostly is consumed at sanitary system (42%) and HVAC (23%) (Hospital Energy Alliance, 2011).

Some efforts are reported for conserving water at the hospitals. EPA proposes some activities to conserve water that include maintenance of the system, applying audit of the consumption, retrofitting equipment and application of alternative resources (Office of Water U.S. Environmental Protection Agency, 2012). The maintenance aim is to achieve optimum operation condition. The retrofitting is applied to reduce the consumption through installing new and more efficient equipment. The application of alternative resources is proposed to reduce traditional supply resources share. It increases the supply resilience.

Energy conservation at hospital becomes main topic of some researches. Rehabilitation of envelope is reported reducing energy demand on HVAC by 49.8% (Ascione et al., 2013). Optimization of retrofitting CHCP at the 714 beds hospital at Parma was simulated to provide 15 months investment payback period (Pagliarini et al., 2012). A 30% energy saving guidance for small healthcare facilities was reported by Bonnema et al. (2010). On the other hand, Buonomano et al. (2014) proposed some retrofitting to a hospital that includes rehabilitation of thermal insulation, applying external temperature dependent controllable water valve, installation of thermostatic valve for radiators, and controlling the AHU operation.

Energy efficiency at building can increase water consumption. Energy efficiency at buildings such as hospitals can be achieved through HVAC efficiency which depends on chiller. To work at high efficiency, the chiller should work at low temperature as possible, but keeping the temperature of chiller too low can imply high cost at cooling tower in term of energy and water due to negative approach operation. Over maintenance of the cooling system consumes amount of water that can imply the cost.

Water efficiency at hospital can affect increasing of energy consumption. Some water saving recommended by the guidance of water efficiency such as to reuse water at laundry system, to recycle water system, to utilize blowdown water, and to use standardized sanitary equipment have main aim to minimize water withdrawal. Unfortunately, these activities may imply more energy consumption for water processing and pumping or infrastructure. For example, to use recycled water for flushing, it needs different water network and pumping. Additional equipment increases investment, maintenance and operation cost.

Integration is proposed as the way for conserving multi resources system. It is applied at the petrochemical system and many industries for optimizing the energy (Gundersen, 2013). At larger scope, total site integration was also proposed to optimize energy consumption at an industrial park and urban (Yen, 2017; Hassiba and Linke, 2017).

Integration is started by mapping the resources which is known as the data extraction. In the data extraction process, resources and its relationship at the facilities are portrayed. At this way, the modules processes are evaluated to understand the resources requirements (Yang et al, 2016). The resources requirements are the base of integrating that becomes the main constraint and possibilities of multi resources integration.

This paper is purposed for providing map of energy and water requirements that can be used for integration of energy and water in a tropical hospital with Suranaree University of Technology Hospital (SUTH) as its model. The description of SUTH becomes the second section which is followed by unit operations in modules constructing the SUTH system. This part also provides definition and relationships that is used for describing the system that are sequenced some principle methods.

The requirements of energy and water are provided at the forth section followed the discussion of its context. The last section is the conclusion.

4.3 Suranaree University of Technology Hospital (SUTH)

SUTH is a 120-bed hospital and it has 558 staff. It is affiliated with the Institute of Medicine of Suranaree University of Technology. The operational hospital consists of 6 buildings. There are main building, imaging (radiology) building, health promotion building, service building, and dormitory. The main building is the largest building as indicated in the circle in Figure 4.1. It is an 11-story building with total area 19,000 m^2. The out-patient division, operations, and wards are located in the main building. The radiology building is provided for imaging equipment such as X-Rays, MRI and CT Scan. The health promotion building is former hospital that is functioned as outpatient clinic at over time and conference. The service buildings composed of building for sterilization and laundry, and food preparation building.

Total electricity and water consumptions of SUTH at August 2017 are 9,100 kWh/day and 146 m^3/day, respectively. The main building consumes approximately 69.3% and 63.6% of the respective total electricity and water consumption. Building for sterilization and laundry consumes 15.3% of electricity. The radiology building electricity consumption is 11.4% of total electricity consumption. The food preparation building shares nearly 2.8% of electricity need. The waters consumption of laundry and sterilization building, and food preparation building are 33.4%, and 2% respectively. The radiology building only consumes minute water, less than 1%.

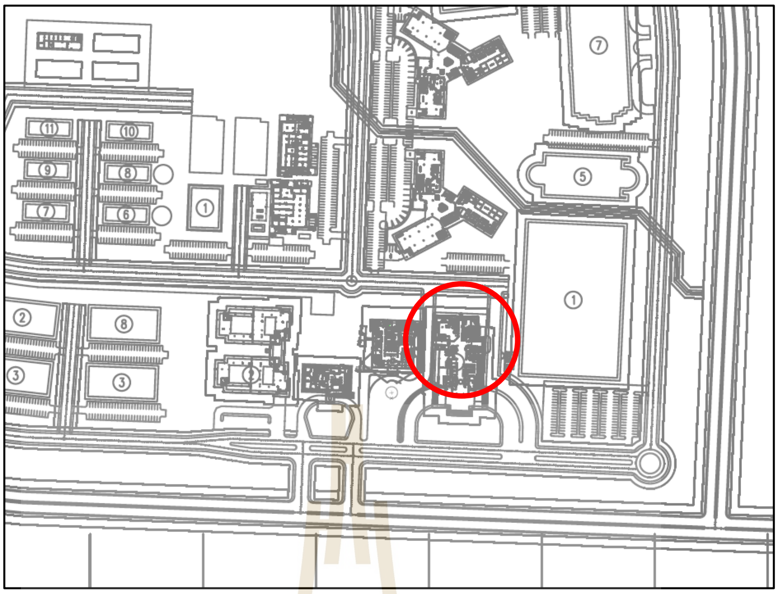


Figure 4.1 Top view of SUTH. Main building is circled in the figure.

The HVAC systems for the buildings are built independently. Every building has its own HVAC system. The main building, and the sterilization and laundry building have centralized HVAC with cooling capacity 8,000,000 btu/hr and 3,208,000 btu/hr, respectively. The main building applies water chiller system and has wet cooling tower as its heat rejection equipment. The sterilization building has dry cooling system. The other buildings apply split system for the HVAC with cooling capacity around 1 million btu/hr for each building.

At the basement of main building, there are 3 chillers and each chiller has a capacity of 250 TR with a chiller water flow rate of 70.80 m^3/hr. The designed temperature of the chilled water is 7 – 13.5^{o}C. The chillers are supported by 3 chilled water pumps for distributing the chilled water. There are 3 water pumps that transfer condenser water from the chillers to cooling tower at rooftop.

The HVAC system of the main building rejects heat to the atmosphere through 3 mechanical-draft cooling towers. Each cooling tower has a capacity of 953,904 kcal/hr or 3.8 million btu/hr. It has water flow rate 750 gpm. The air flow rate of a cooling tower is 1,850 m^3/min with fan speed 350 rpm. A motor for fan of the cooling tower is 10 HP.

Water used in SUTH is supplied by the tap water system of Suranaree University of Technology (SUT). The tap water is first stored in a 130 m^3 underground storage in the main building, and then sent to a 50 m^3 water tower on the rooftop on the building using 2 pumps. Each pump has a capacity of 50 m^3/hr and a head of 85 m.

SUTH has a package water treatment plant with a capacity of 220 m^3/day. To treat the wastewater, the plant uses an activated sludge process with a system of continuous and sequential aeration ponds. Currently the plant treats only wastewater from the main building. The treatment level is secondary which can produce water with the BOD (biological oxygen demand) level of 20 ppm.

The electricity system of the hospital is connected to the grid through $2 \times 1{,}250$ kW transformers. There is a backup power system with a 1,100-kVA generator and a 220-kW generator for data center. Additionally, there is an emergency power system for the operation rooms, with 30 minutes of backup time.

4.4 Modules and the Operation Units

The following section consists of two parts, they are the definition, and the systems of energy and water descriptions. The first part discusses about some terms that connect integration term and the common term of modelling. The second part describes the work of the systems and their requirements.

Some methods are applied to describe the modules. They are input-output of mass flows, table of input-output, block diagram, black box and activity diagram. The input-output of mass flows diagram only describes the material flowing at the modules. Input-output table mentions the energy and water input and output at every modules of the system. Black box diagram describes the activity of a system as hidden process that provides energy and material input and output. The block diagram depicts a module, its energy and water input-output at diagram format instead of table. Activity diagram is used to portray in relative detail activities taking places at the module.

Structural diagram is applied to describe relation among the term concepts. Relations of system, modules, unit operation are provided in a block diagram. Hierarchical relation is the basic principle of this.

4.4.1 Definition

Module at the term of integration is functional steps that consist of operation units. A module can have some steps of specific function and may represent sequence activities. For example, a chiller module consists of evaporation unit, compressing unit, condensing unit and expansion unit. If a module consists of single operation unit, it is also an operation unit. This definition of a module implies that a system is composed of some modules. The relation of a system, modules and operation units is mentioned in Figure 4.2. It also shows that they have structural relationships.

A facility at a hospital consists of modules that form a system. Every system has some activities that can occur serially or in parallel. HVAC system consists of AHU/FCU modules, chiller module, cooling tower and soften water module. These modules operate together in parallel and sequential ways to fit the function of a HVAC system.

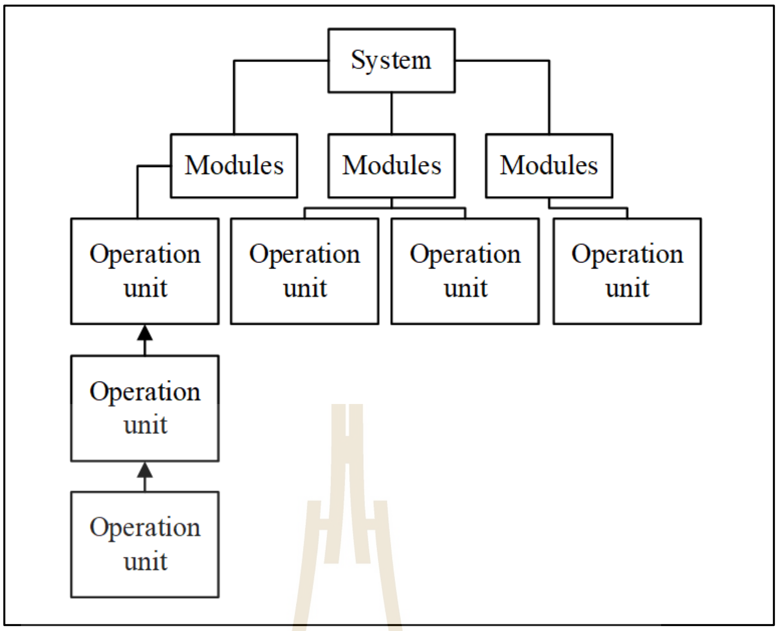


Figure 4.2 Structural relation of system, modules and operation units.

The definition of hospital facility does not mean medical function, but it refers to technical or equipment facility, such as HVAC system, sanitary system, and sterilization system rather than out-patient clinic, wards and offices. Therefore the hospital facility is considered as technical functional equipment systems. The activities of hospital are represented by some functions of equipment. This equipment can be a module such as AHU, FCU, and chiller. The other equipment could be an operation unit such as pump and water heater.

4.4.2 SUTH Systems and Modules

The systems of SUTH that will be discussed at this paper are HVAC, sanitary system, autoclaves system, laboratory system, radiology system, and hemodialysis system. The choice is based on energy consumption and water consumption of the system. Lighting, even usually it consumes 12% of energy consumption (Yang et al., 2016) is out discussed because it is not connected directly to water.

The discussion of every module is focused on input-output energy and water. Input energy represents the energy for the module operating. Output energy represents every types of energy released by the operating module. Similar principles are also applied to the water of modules. Input-output energy and water are categorized to be existing and probable. The output includes by-product of operation.

4.4.2.1 HVAC

The HVAC system consists of AHU and FCU, chiller, cooling tower and soften water system. All of the modules apply electricity as the energy source. Therefore, the only input energy is electricity. But some modules produce by-product energy (heat) and by-product mass that is type of water.

At the chiller module, there are two main mass flows in addition to refrigerant. They are chilled water flows and condenser flows. The chilled water flows connect the chiller and the FCU/AHU or refrigerator. The condenser water connects chiller to the cooling tower. The chiller transfers heat from chilled water to condenser water. The chilled water flow is closed system without significant water alteration. The condenser water has alteration due to evaporation at the cooling tower which increases the conductivity and reduces the volume of condenser water. To compensate the volume and conductivity, additional soften water should be added as make-up water. This additional make-up water volume depends on the cycle design. Therefore, the quality of chilled water is relatively constant, but the quality of condenser water is ranging from 75 – 225 µS/cm.

The AHU and FCU have two main flows, they are air flows and chilled water flows. Both modules need electricity as the energy input and can be considered not producing by-product energy. The AHU mostly produces condensed water as by-product because it has additional outdoor air that has higher temperature and relative humidity than room temperature and humidity. The process at AHU consists of temperature cooling and dehumidifying. On the other hand FCU does not produce water as by-product due to small change of humidity because the air flow is relatively closed.

Volume of distilled water as by-product of psychrometric process at AHU depends on air change and the different temperature and humidity between the outdoor air and room air. The more air change rate is the more by-product water can be produced while the outdoor air is more humid.

The cooling tower needs electricity to operate and release heat to the atmosphere through evaporation principle. It has water input that is condenser water coming from the chiller. It returns the condenser water with alterations, they are conductivity increase and volume decrease. The volume alteration is compensated by make-up water, but the conductivity alteration should be compensated through blowdown water.

The blowdown water is released as brine water from the cooling tower to environment. To keep the cooling tower operate optimally, the blowdown water should be released when the conductivity reaches 225 µS/cm or the water is categorized as slightly hard. Additional equal volume soften water is made after the water blew down. Through this method, the condensate water for cooling tower and chiller is kept at operation range.

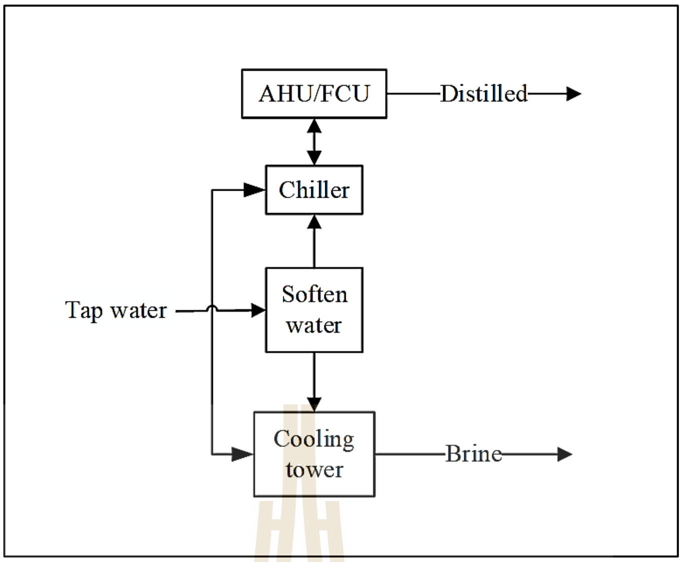


Figure 4.3 Input and output mass flow of HVAC modules.

4.4.2.2 Sanitary

The main function of sanitary system is to provide water for domestic daily use, such as toileting, showering, teeth brushing, and hand washing for the patient, staffs and attendances. Input-output of energy and water at the sanitary system is provided in Table 1. Most of the water is going for flushing and hand washing due to people activities. Hot water system also important at this point, even it is shown as different module.

To provide the sanitary system, pumps are applied for moving the water from ground water storage to roof-top storage. Booster pumps are also prepared for the last 4 stories. Some valves are applied to control the flow of the water, therefore the faucets can flow water at 1.5 – 3.5 gallons/min.

Table 4.1 Energy and water input-output of sanitary modules

Modules	Input	Output
Showering, Teeth brushing, Hand washing	Electricity, Tap water	Wastewater
Hot water	Electricity, Heat, Hap water	Wastewater
Flushing	Electricity, Tap water, Recycled water	Wastewater

Hot water is provided by the electric heater in every place that needs it. The reasons of safety base this choice. Hot water network becomes problems in a hospital due to scalding and legionella problems. Managing hot water to keep at safe temperature can imply the legionella bacteria proliferation.

This simple sanitary system has input energy of tap water and output wastewater. Electricity is the only energy input. The temperature of water input is 27 ^{o}C in average, which is less then legionella proliferation window.

Flushing can be done by less quality of water. It can use recycle water with level 2 treatment criteria. The water should be clean, odourless and free of pathogen bacteria.

4.4.2.3 Radiology

The radiology system of SUTH consists of x-rays, MRI, CT-scan equipment and their support systems which are located at radiology building. This 2-story building is dedicated for radiology equipment and does not have any ward for patient. Some conferences and offices are provided. Therefore, the radiology equipment only consumes energy for running the equipment and cooling system. The water is consumed for sanitary which is very few due to its operation time and low occupancy area.

Cooling system for the building is provided by split HVAC system and one single dry cooling condenser for removing heat from MRI. The split cooling system provides 1 million cooling capacity totally. The condensers of the equipment are located inside of the building with air cooling system. At that room, additional cooling apparatus is prepared to remove heat released by condenser. Higher cooling capacity is applied for condenser room.

The only energy supplying the system is electricity. It does not produce energy by-product. Because it only has split system, HVAC of the building does not produce any by-product mass. The heat released from the equipment is directly surpassed by the HVAC.

The radiology system at SUTH is already digitalized, the results are provided in digital format and sent by network. It implies that the system does not need any water for image processing. But it needs additional electricity to run data-centre and its cooling.

4.4.2.4 Hemodialysis and Laboratory System

The hemodialysis modules and laboratory represent similar requirement. The modules consume electricity energy for running the equipment. Both system also consume some water requirement. They need ultra-purified water. Therefore both modules need ultra-purification water treatment by RO system. A block diagram of hemodialysis system equipment is mentioned in Figure 4.4. The system has RO system apparatus and hemodialysis instrument. In addition to the ultra-purified water, both also need tap water for cleaning some equipment.

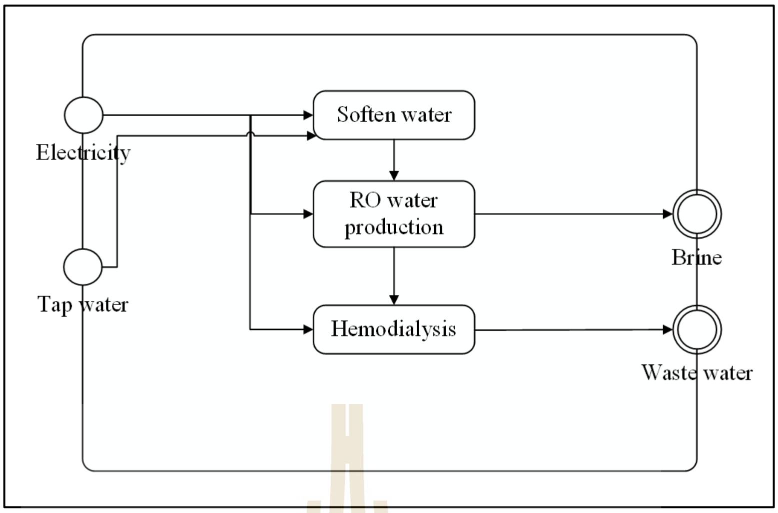


Figure 4.4 Block diagram of hemodialysis apparatus.

The energy for equipment of the modules is electricity. Electricity is applied for hemodialysis and RO water system. The equipment produces a few heat that is not collected due to economical consideration. Sensitive water heater is applied during the process of hemodialysis especially to heat the RO water to be equal to patient body temperature. Some heat is also produced by the equipment that currently is removed by the HVAC. The black box of the hemodialysis module is provided in Figure 4.5.

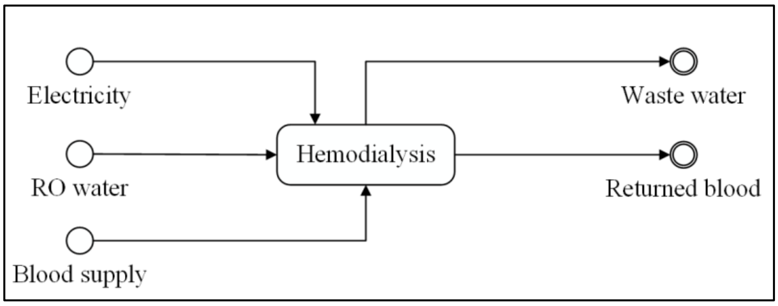


Figure 4.5 Black box of hemodialysis module that describes its activity.

4.4.2.5 Autoclaves and Sterilization

The autoclaves are prepared to provide steam at the sterilization and laundry. It has operation temperature range of 140 – 165 ^{o}C. The total capacity of a boiler is 11.7 million btu/hr. The fuel consumption of the system is 350 litres/day. The system also applies electricity for pumping the water to the boiler and returning the used steam to the boiler.

The autoclaves have softened water input with conductivity of 75 µS/cm. The soften water is supplied the boiler as make-up water, while some of steam is released due to leakage and blowdown. It implies that the autoclaves need soften water as its mass input. It also releases hot brine which is considered as useful hot water in term of energy.

Some of the steam from the autoclaves is reused for laundry system after it is used for sterilization. This steam is used for ironing, drying and providing hot water. The steam flows from autoclaves to sterilization equipment. Some of the steam is condensed due to the temperature, but some of the steam still has high temperature to dry the laundry, to iron and produce hot water for washing and pre-treatment at sterilization unit.

Therefore, the autoclaves consume electricity and fuel as its energy input. It also produces energy by-product and water by-product. The energy by-product is the form of heat. The water by-product is the form of blowdown that should be treated. The complete activity of autoclave is presented in Figure 4.6.

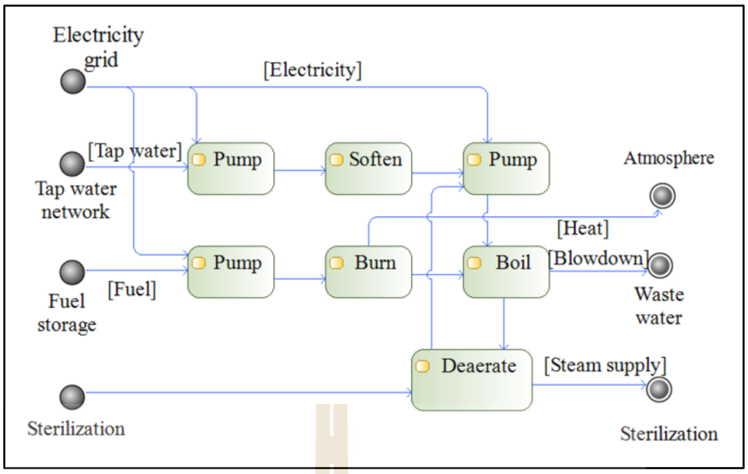


Figure 4.6 Activity diagram of autoclave.

Table 4.2 Water input and by-product of system.

System (modules)	**Consumption**					**Released Water**		
	Tap Water	Hot Water	RO Water	Soften Water	Recylced water	Waste-water	Brine	Distilled Water
HVAC	√			√			√	√
Laboratory	√	√	√			√		
Flushing	√				√	√		
Showering and Teeth brushing	√	√				√		
Autoclaves				√			√	
Laundry	√	√			√	√		
Food Preparation	√	√	√			√		
Drinking			√					
Hemodialysis	√		√			√		
Dish washing	√	√				√		
Outdoor irrigation					√			
Fire Supression	√							

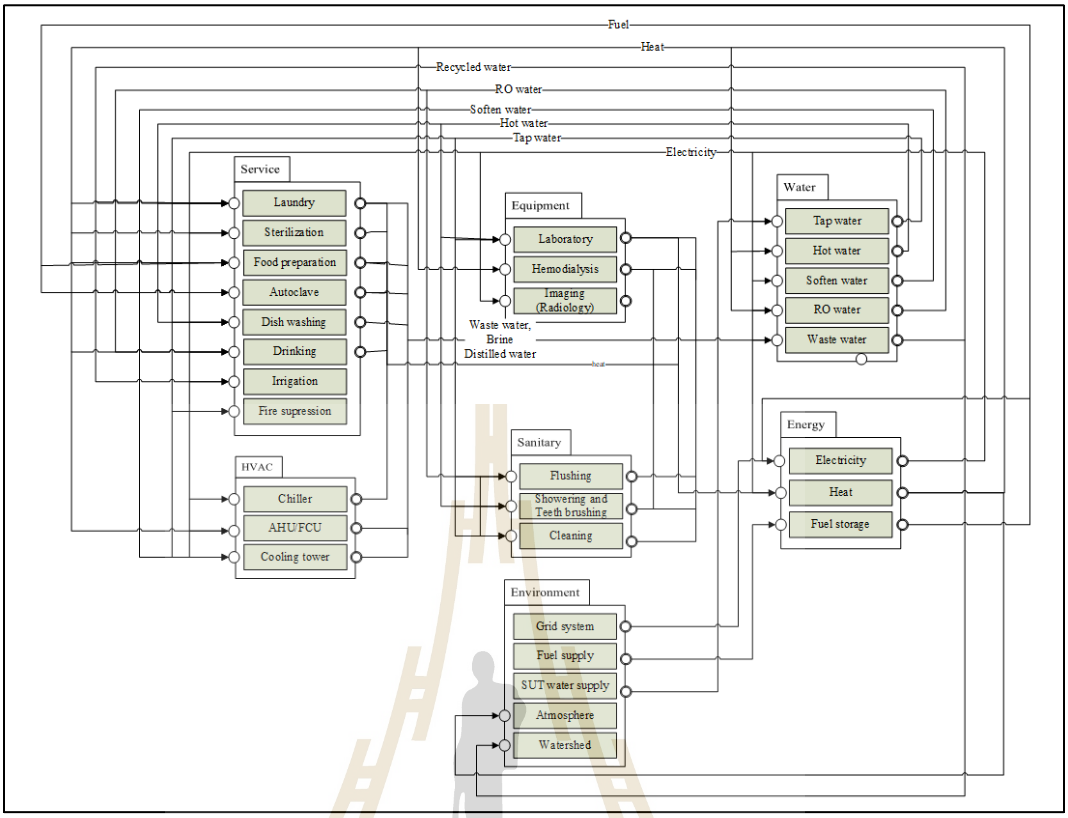


Figure 4.7. Energy and water flows at the hospital.

4.5 Discussion

Energy and water flows at SUTH are mentioned in Figure 4.7. It shows map of energy and water at the hospital. The figure mentions Soften Water, RO Water, and hot Water as single modules even they are practically distributed at several modules. The aggregation is also applied for the AHU/FCU. The detail of the flows can be referred to the block diagram or activity diagram of the module as mentioned in Figure 4.4 and Figure 4.6.

Map of water of the SUTH is provided in Table 4.2. In this table, the probable water that can be used for every system is shown as well as the water that can be collected at the system or module. These probable resources are added as the addition to the existing condition. For example, a cooling tower can use also tap water as its make-up water as long as the tap water is soft enough. Harder water for cooling tower increases the deposition of salt on the surfaces. This crust decreases the cooling tower performance.

If the tap water with higher conductivity is chosen for make-up water, the water cycle of the system will be very low. For example soft water with 100 µS/cm is used for the make-up water and the cooling tower evaporates 10% of water, the cycle of water is 10 if the limit is 200 µS/cm. If 150 µS/cm water is used, the cycle is 7. It means that the cooling tower with 150 µS/cm should blowdown when the cooling tower has already added make-up water 7 times. Less cycle water means more water that is consumed and more brine released.

Table 4.2 also mentions that some activities can use partially or totally recycled water. Irrigation can apply totally recycled water. But laundry only use partially recycled water for the reason of hygienist. The recycled water can be managed for pre-treatment of laundry system. Flushing can use recycled water totally, but differing flushing water network and showering water network implies more investment.

Heat is released at autoclaves as by-product through steam, blowdown and burning process. It can be used at the laundry system for pre-treatment or producing hot water. The steam can be used for ironing, drying and producing hot water through heat exchanger. Blowdown water can be used for increasing the low temperature hot water. This process should consider about the legionella proliferation (Marchesi et al., 2011). Pinch processes in detail should be regarded.

Some system released heat, but in very low enthalpy. Radiology, HVAC, hemodialysis systems are the systems that release heat which is not economical for other system utilization. Table 4.3 shows the heat released by system or module and its necessity.

In Table 4.3, it is shown that HVAC can release very low temperature heat, but need at least low heat. It implies that HVAC never uses its own heat for reducing energy for heating that is used at HVAC. For the tropical area, where the HVAC is focused on cooling, heat can be used for absorption cooling system or dehumidifying system.

Laboratory and hemodialysis modules have different character of heat. Laboratory releases very low heat but need at least low temperature heat. This low temperature is used for some cleaning activity or for heat exchanging processes. Hemodialysis module needs only very low heat for increasing the temperature of RO water for dialysis process. The RO water has to have equal temperature to the blood.

Sanitary system only releases very low temperature heat and need low or medium. It needs temperature above 70 ^{o}C that makes sure the safety of the product. At temperature above 70 ^{o}C, the legionella bacteria do not exist. Having the temperature below 70 ^{o}C, it increases risk of legionella proliferation at the equipment.

The autoclave can release heat that is higher than heat necessity temperature for economizing its own process and other processes. Very low temperature heat is useful to increase the pre-treatment process. The legionella is not considered in this process, while the total provides temperature far above the legionella windows. The autoclave also releases heat with temperature that can be transferred to other modules. To utilize this potentiality, consideration of quantity should be taken into account.

Food preparation needs low or medium heat for reducing heating process in addition to autoclave and sterilization. Consideration of such temperature is based on the pathogen germ that should be limited at the processes or related process. Such temperature is used for pre-treating food or first dish washing.

The sterilization can use its own released heat for its own processes. Cleaning equipment before sterilization can utilize waste heat of sterilization machine.The process can fasten condensation. But this procedure can imply additional pump and deaerator for the condensed water.

Table 4.3. Heat necessity and released by system or module.

System / Module	Heat Release	Heat Necessity
HVAC	VL	L, M, H
Laboratory	VL	L
Hemodialysis	VL	VL
Sanitary	VL	M, H
Autoclave	L, M	VL, M, H
Laundry	VL, L	M, H
Food preparation	L, M	VL, L
Drinking	VL	VL, L, M
Sterilization	L, M	L, M, H

VL: very low T < 40 ^{o}C, L: low T < 90 ^{o}C, M: medium T < 140 ^{o}C, H: high T > 140 ^{o}C

4.6 Conclusion

The hospital utilizes tap water, hot water, RO water, soften water and recycled water for processes, and releases wastewater, brine and distilled water. Some released by-product can be used for other system. The recycled water can be used for irrigation, laundry, and flushing. HVAC also produces distilled water through psychrometric process at AHU. HVAC and hemodialysis release brine that can be recycled without a lot of treatment.

Electricity is main energy that is applied at all of the systems. Some of the system can use low quality of energy, such as heat. Laundry system uses waste heat released by autoclaves. Consideration of hot water production should be applied for preventing legionella proliferation.

Heat is energy that can be used for reducing primary energy consumption. Some system or modules can reuse its own released heat in term of quality. Some other system or modules are impossible to utilize its own waste heat. In addition to the quality of energy, quantity has to be calculated in detail for the future work.

CHAPTER V

SECOND LAW ANALYSIS OF THE CENTRALIZED HVAC SYSTEM OF SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL

5.1 Abstract

The previous chapter addressed systems affecting energy and water in SUTH main building. They are HVAC, tap water system, and wastewater system. Hot water system, hemodialysis is not included as they are not centralized applied and release small amount of energy. Radiology, autoclaves are not part of evaluated systems as they are in other buildings. The evaluated water system will include tap water systems and wastewater system.

A study of a centralized HVAC system is conducted in the aspect of the second law of thermodynamics. The main objective of the study is to find the pattern of exergy destructions of the HVAC operation at Suranaree University of Technology Hospital (SUTH). The year-round transient simulation of the system was done using the TRNSYS program. The justification of the simulations was validated by using the recorded hospital maintenance data. The thermodynamic properties in the simulations were determined using the data from ASHRAE. The cooling load, exergy destruction, and exergy efficiency of the system were calculated. The exergy destructions of the fan coil units, chilled water pump, condenser water pump were proportional to their exergy efficiencies. The pattern of the exergy destruction at the chiller was the same as the

pattern of the cooling load. The cooling tower's exergy efficiency depended mainly on the weather conditions and the number of inhabitants, while its exergy destruction was dominated by the weather conditions. The highest exergy destruction of 37% was at the fan coil units. The average ratios of exergy destruction and the load required were 9.07, 2.12, 1.61, and 0.69 for the chiller, the fan coil units, the chiller water pump, and the condenser water pump, respectively.

5.2 Introduction

Hospital is a kind of utility building with high energy consumption. Uninterrupted operational time and highly requirement of its facilities are considered the main factor for its high energy intensity. EPPO published that energy intensity of Thailand hospital was 244 kWh/m^2 (EPPO, 2016). Saidur et al. (2010) mentioned that Malaysia public hospital have slightly less energy intensity than Thailand's. Highest energy intensity consumption is recorded in United States hospitals reaching 1329.9 kWh/m^2 (Bonnema et al., 2010a; Bonnema et al., 2010b). Generally, the hospital energy consumption is in the middle of the commercial building energy consumption intensity (EPPO, 2016). Education building lays on the bottom due to limited operational time and the retail facilities consume the most as consequence of high density of the inhabitant.

In purpose of censerving energy, some researches of hospital energy have been performed. Cogeneration and trigeneration are the main issue of the researches in the area. Alexis and Liakos (2013) performed analysis of main and back up power system ratio in Greece hospital. An electricity and thermal profile based analysis of energy consumption for cogeneration was conducted by Gimelli and Muccillo (2013) for San Paulo Hospital in Naples. They found that weekly electricity consumption profile exists at the hospital in addition to daily cycle. TRNSYS simulation became the data source for Pagliarini et al.(2012) in optimizing the CCHP at hospital in Parma. Multizone model for the hospital was utilized to acquire heat and cooling gain of the hospital. In addition to cogeneration and trigeneration, HVAC also becomes the main object of hospital energy conservation. Buonomano et al. (2014) mentioned that radiator thermostatic valves and AHU regulations can save energy consumption significantly. Compilation of potential HVAC energy conservation is provided by Teke and Timur (Teke and Timur, 2014).

HVAC is the main energy consumer part of the hospital. The HVAC has function to provide convenient ambient for people and health environment that help the patients recovered. In addition, the HVAC system is also purposed for preventing infection spreading. The functions imply high and various air quality parameters provision of hospital HVAC. They are temperature, pressure, particles removal, humidity, air change and outdoor air composition of the ventilation (Owen, 2003). According to the model developed by Thinate et al. (2017), temperature is the main factor determining energy consumption of the hospital. Level of enviroment temperature positively affects energy consumption of 45 researched Thailand hospitals. The result of Gonzales et al. (2018) shows that total temperature days affect energy consumption of the hospital.

HVAC operation affects energy consumption in many ways. Generally, the chiller is the main energy consumer of the HVAC system. Improvement on this part implies significantly total efficiency of the system. Temperature set point, time operation, and air flow rate control are considered other main features of increasing the efficiency of HVAC. Increasing set point can reduce HVAC energy consumption because of less approach. Air flowrate of the HVAC also significantly makes the energy consumption lower for the reason of increasing heat transfer effectiveness that reduces pump power consumption. It was reported as well that maintenance of the coil becomes important factor of HVAC energy consumption (Teke and Timur, 2014).

Second law analysis of a system provides detail impact of parts on energy consumption of the system. The method, namely exergy analysis allows considering the quality of energy in a process. The quality of energy resembles ability of doing work. Basically, a heat source with higher temperature has more ability to do work rather than equal heat source with less temperature. The exergy analysis employs environment temperature as the reference. The analysis is based on the 2nd law of thermodynamics. This law shows irreversibility that happens due to temperature differences and chemical reaction.

The 2nd law analysis has been applied for many fields. Formerly, it was commonly applied for power plant and chemical reactions. Since 1990s it has been started for heating and cooling system analysis. Recently it also has been applied for control system, economical analysis (Jawad et al., 2018) and non-steady state condition (Choi et al., 2018).

In the HVAC system, the exergy analysis is applied for analyzing the main factors of the system performance, multi types of cooling system cascade, co-generation and tri-generation system (Santo, 2014). The analysis usually is applied by taking refrigerant flow at the chiller system. This method needs detail data of the refrigerant states at the chiller. However such analysis is only suitable for designing the new system. A medium level analysis which consists of components and its performance is still needed. This analysis can be very helpful to understand the interactions of load and the HVAC system as for the control system (Wang et al., 2016). Moreover 2^{nd} law analysis of the hospital HVAC is not performed yet. Based on aforementioned reasons the analsis of SUTH HVAC using medium level of exergy analysis is proposed.

The exergy analysis of hospital HVAC of SUTH is intended to understand exergy streams of the HVAC operation at the hospital located in tropical area. These streams are utilized to show the conservation level of the components. The study is divided into 4 sections. Following the introduction, the method is commenced by SUTH HVAC in a glance and ended by the model of TRNSYS as the 1^{st} part. The second part of the method offers the model of 2^{nd} law analysis approach. The result as the 3^{rd} section starts with validation of the cooling load from the TRNSYS. The TRANSYS results are applied into 2^{nd} analysis steps. The exergy destruction of the system components is presented in accompanion of the exergy efficiency. The discussion becomes part of the section and are put to clear the aroused phenomena. This part is followed by conclusion that emphasizes the main factor for operating the HVAC efficiently. It is the final part.

5.3 Methods

The section consists of 2 main parts representing the object and procedure of the anlysis. The 1^{st} part is about SUTH which becomes the object of the study. The second part offers the strategy of connecting the TRNSYS data and exergy analysis. The simulation provided data of the coils, pumps, chiller, cooling tower, and weather. Additional measured data of the hospital maintenance is formulated for providing thermodynamics properties during the exergy analysis based on ASHRAE table.

The 2^{nd} part is structured into 3 parts, namely model framework, exergy formulation, and measurement indicators.

5.3.1 HVAC at SUTH

Suranaree University of Technology Hospital is a unit affiliated to Faculty of Medicine which is dedicated for Campus Hospital and public services. The hospital has 558 staffs and operates 5 building for 120 beds capacity. These wards are located in main building that has area 19,000 m^2 in 11 stories. In 2017, the daily average OPD is 784. There was average of 68 inpatients staying on the wards at the same year.

The main building is the center of hospital operation. Currently, all the clinics, wards, and other facilities are located in the building excepting the radiology equipments. The building only consumes the electricity as its energy source. The hospital boilers, sterilization equipments, laundry, and cooking facilities are located in another building. Hot water facilities is applied in splits systems. In average, electricity consumption of the building was 9 MWh/day. The electricity consumption of the main building is provided at Figure 5.1. Two peaks of the electricity consumption presents impact of the weather and number of patients. Eventhough summer is considered as the highest temperature peak time, number of patient in April 2017 was not the highest one as shwon in Figure 5.2.

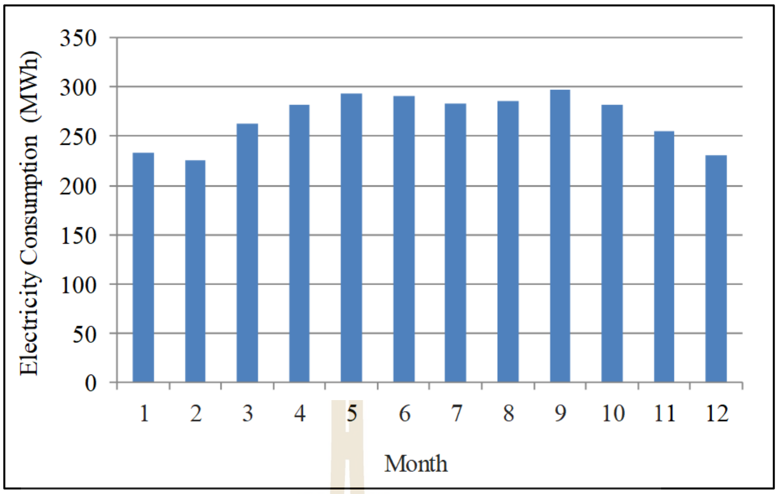


Figure 5.1 Electricity consumption of the SUTH main building.

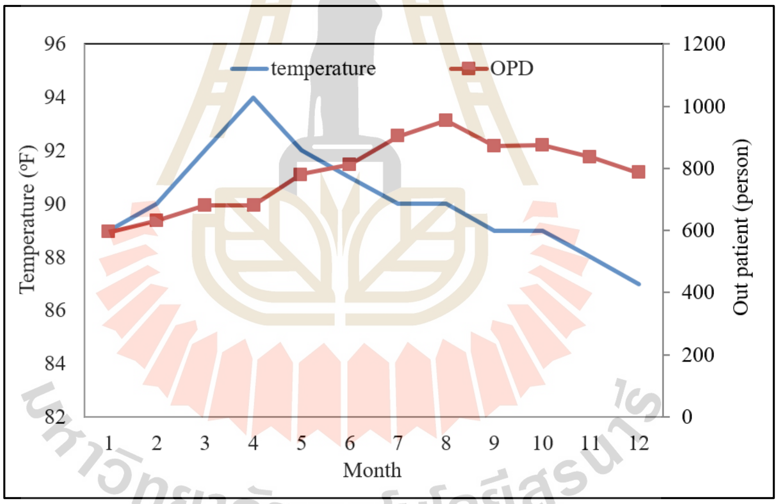


Figure 5.2 Average temperature of Thailand and out patients of the hospital trend.

The HVAC of the main building is provided by 3×250 TR water cooled chiller which is connected to 68 kW coil unit with total capacity 104 m^3/s. The system is supported by 3×37 kW chilled water pumps and 3×30 kW condenser water pumps. Three cooling towers with capacity of 953,904 kcal/hr each are located on roof top, 54 m above the chiller. The condensed water pumps system provides

276 kPa pressure compensation of the pressure loss head and the chilled water pumps circulates the chiller water through 448 kPa network pressure loss. The operational condition of the HVAC is provided at Table 5.1.

Table 5.1 HVAC operational condition parameters

Parameter	Value
Coil air flow rate	104 m^3/s
Chiller type	Rotary, Water cooled, Variable speed
Chiller fuel	Electricity
Chiller capacity	3 × 250 TR
Chiller COP	5.29
Chiller water outlet temperature	44 °F (6.7 °C)
Cooling tower type	Cross flow, Single speed
Capacity of cooling tower	3 × 953,904 kcal/hr
Max chiller water flow rate	83.9 liter/s
Max cooling water flow rate	2,250 gpm
Max cooling tower air flow rate	75.6 m^3/min

The TRNSYS simulation was conducted on the real specification of the hospital HVAC conditions. The building was assumed to be a box with total floor area 15,210 m^2 and comparable air volumes with height of 4 m. The functions and its requirements according to Bonnema et al. (2010) work were used for determining the ventilation requirement costing average 3.3 outdoor air. Some areas were not cooled for the reason of their functions, such as ambulance park lots at basement, vacuum system, chiller room, and shading on the mezzanine. Heat gains of the system were calculated from people on the average daily patient and the staff basis. They were assumed to do very light work with 120 W heat gain. Another heat gain source was the equipment counting 10,149 kJ/hr, computers for data center and daily operation reaching 84 kW.

TRNSYS simulation was performed in a year-round. Ten minutes time step was chosen for the reason of out-patient waiting time which is targeted to be 15 minutes. The patient numbers were scheduled as shown in Table 5.2. The value represents number of the out-patient density. Zero means that there is not any out-patient, while 1 represents all of out-patients are considered at the hospital at that time. Every patient was considered being accompanied by single person.

Table 5.2. Schedule of load according to patient number model.

Start time	**End time**	**Value**
00.00	08.00	0
08.00	09.00	0.7
09.00	10.00	0.75
10.00	14.00	0.8
14.00	16.00	0.5
16.00	18.00	0.25
18.00	20.00	0.1
20.00	24.00	0

TRNSYS is a software for simulating transient behavior of a system which can be efficiently used for thermal system simulation. The software is released by Thermal Energy System Specialist, LLC. It has kernel and libraries that can be configured to the necessity and specific condition. The weather database around the world supplied by NREL is also provided in the form of TMY2 file. The weather data were collected in 1998 - 2014.

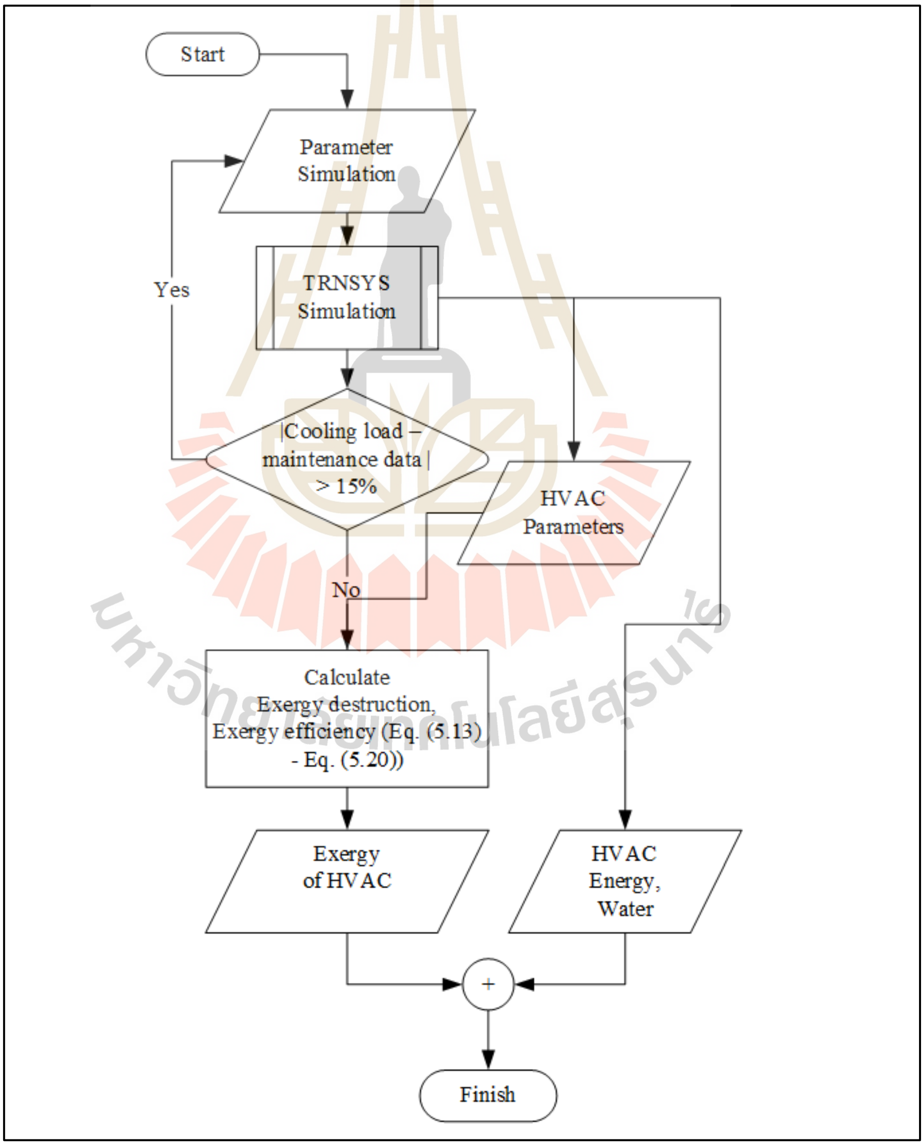


Figure 5.3 Main flowchart of the procedure.

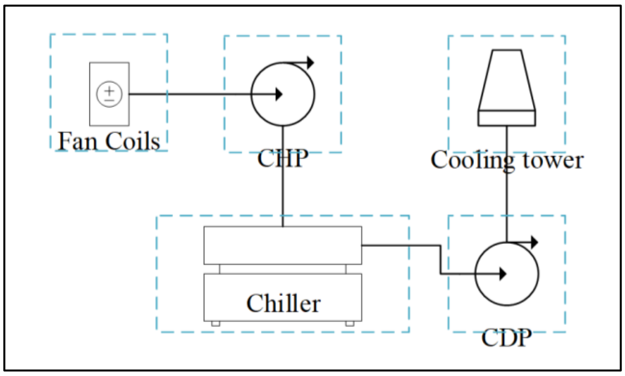


Figure 5.4 The HVAC system of SUTH and the boundaries of the elements.

5.3.2 Model Analysis

The first part of the model analysis is the model framework. In this part a diagram of whole model and each component are presented. The stream variables are shown in addition to the diagrams. Detailed parts of the components are provided for pointing the exergy formulation and analysis strategy. The structure of this part is Model Framework, Basic Exergy, Exergy Formulation and Conservation Indicators.

HVAC system simulation and analysis consists of some steps following the flowchart shown in Figure 5.3. The HVAC system simulation was conducted using TRNSYS and validated with the collected maintenance data of the HVAC using cooling load. A system with reasonable result as shown in Figure 5.10 was analyzed using exergy analysis using MATLAB program. The details flowcharts of the exergy method flowcharts are provided at appendix.

The maintenance data of the HVAC is collected four times daily. It is used for checking the performance of the chiller system. It consists of pressure CHP pressure inlet and outlet, CDP pressure inlet and outlet, and chiller performance. Examples of the maintenance data is provided at the appendix.

5.3.2.1 Model Framework

The model framework is presented to show the global aspect of the system. The system consists of Fan Coil Unit, Chilled Water Pump (CHP), Chiller, Condenser Water Pump (CDP), and cooling tower. Every component is assumed to stand separately and become the boundaries of the volume control. The complete system is shown at Figure 5.4.

Fan Coils have input and output streams of air and water. The air inlet consists of room air and outdoor air which follows the ventilation requirement. In addition to the air inlet, chilled water inlet exists in this part. But there are only two types of outlet, the air and chilled water. At this time, the condensed water is neglected.

The fan coils have three functions. They are adiabatic mixing, cooling and pumping. The cooling and pumping can be considered to happen at the same time, when the adiabatic cooling happens in advance. The processes can be seen in Figure 5.5. These processes imply the formulation of the exergy model.

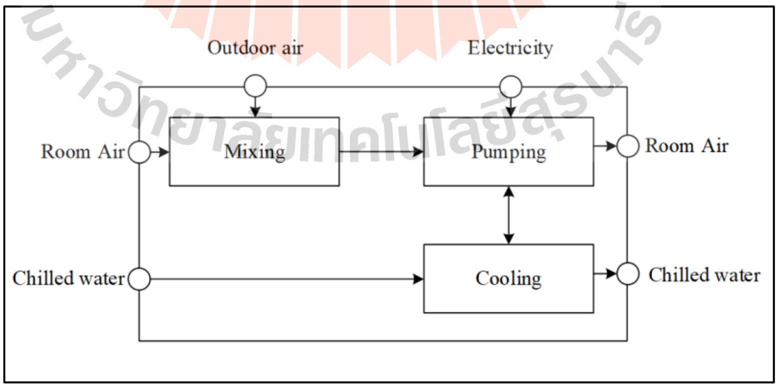


Figure 5.5 The processes in coil fan.

Chilled Water Pump (CHP) is functioned to circulate the chilled water to all the building. This CHP capacity depends on the flow rate which is controlled by the chiller by Equation (5.1) as provided on the manual of the chiller. The inlet pressure of the pump is always kept to be 65 psi. Pressure of the outlet depends on this capacity. The model of the pump and its connection to the AHU network is presented in Figure 5.6. Considering that the TRNSYS simulation provided flow rates rather than pressure, Equation (5.1) can be formed to be Equation (5.2) and Equation (5.3) for P_1 and P_2 respectively.

$$\dot{V}_{chw} = -0.0226\Delta p_{ev}^2 + 8.9826\Delta p_{ev} + 136.65 \tag{5.1}$$

$$P_1 = -0.0042\dot{V}_{chw}^{\ 2} - 0.0784\dot{V}_{chw} + 65.298 \tag{5.2}$$

$$P_2 = -0.00002\dot{V}_{chw}^{\ 4} + 0.0017\dot{V}_{chw}^{\ 3} - 0.0243\dot{V}_{chw}^{\ 2} + 0.2645\dot{V}_{chw} + 67.363 \tag{5.3}$$

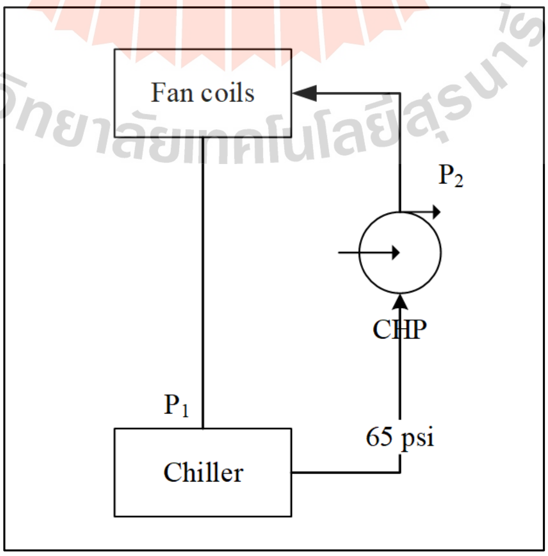


Figure 5.6 Model of the chilled water network. Input of the CHP is 65 psi.

The chiller is the heart of the HVAC system. It has to transfer the heat load to the condenser water. Generally, it is a vapor-compression type. For the reason of simplification, the model of the chiller consists of pump at the evaporator side and a heat exchanger between condenser and evaporator. The model of the chiller is presented in Figure 5.7. The chiller water outlet pressure is 65 psi and the pressure inlet depend on the flow rates of the chilled water as shown in Equation (5.2).

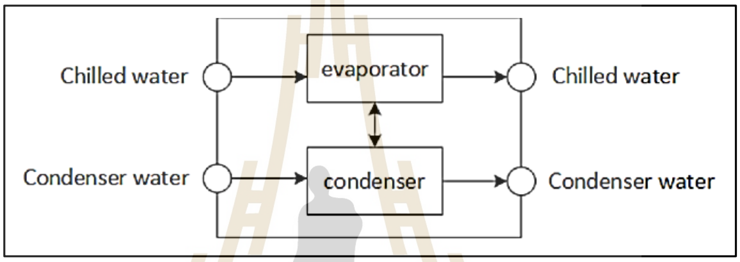


Figure 5.7 The chiller processes. Relation of the evaporator and condenser is simplified as a heat exchanger.

The condenser water pump work to provided sufficient pressure for compensating the pressure head of the cooling tower position. It has to provide 40 psi pressure gain for the condenser water. The inlet pressure is equal to outlet pressure of the condenser. The pressure varies on flow rates basis. Basic relation of flow rates and pressure different of the condenser is provided in Equation (5.4). The model and its pressure variable are presented in Figure 5.8. Adjusted Equation (5.4) is provided as Equation (5.5). There is 5 psi pressure loss in the condenser.

$$\dot{V}_{cdw} = -0.0044\Delta p_{cd}^{\ 2} + 12.898\Delta p_{cd} + 161.31 \tag{5.4}$$

$$P_3 = -0.0028\dot{V}_{cdw}^{\ 2} - 0.069\dot{V}_{cdw} + 62.099 \tag{5.5}$$

The cooling tower is assumed as evaporative cooling system. In addition to the model as provided by Dincer and Rosen (2015), it also has electricity supply. This electricity supply is used for fan of the cooling tower. The model of cooling tower is shown in Figure 5.9. The model does not include blowdown water.

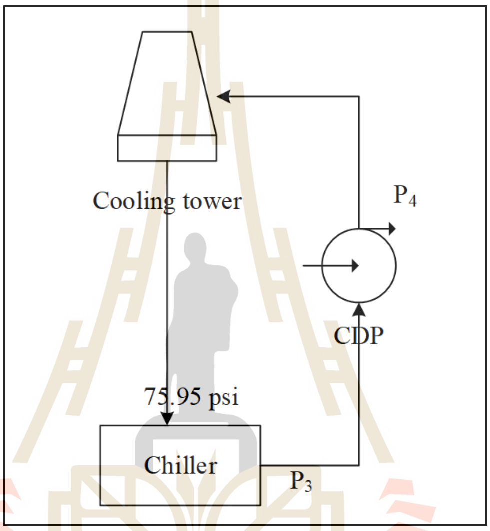


Figure 5.8 The condenser water network and the CDP.

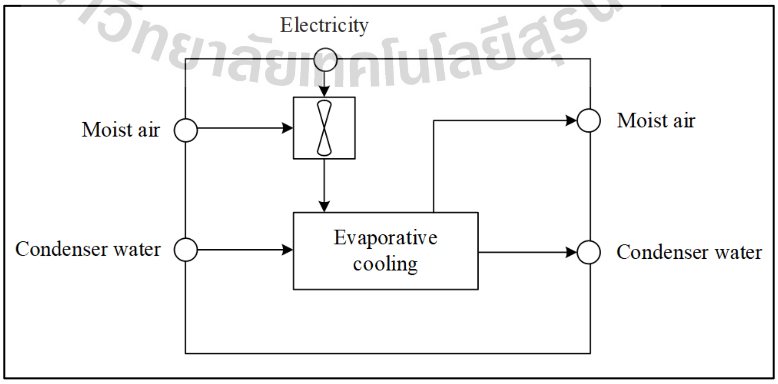


Figure 5.9 The evaporative cooling for the cooling tower model.

5.3.2.2 Exergy Base

The 2nd law analysis is based on the notion that there would not be any spontaneous heat transfer from any less temperature object to higher temperature one. This notion implies that different temperature is also important at heat transfer process effectiveness. Therefore the difference of the system temperature toward the environment temperature represents possibility of work ability. At term of thermo process, the more temperature difference removal means the more exergy of a system destroyed.

The basic equation of the exergy is presented in Equation (5.7) which is called as exergy balance equation. This exergy balance is additional feature where basically mass balance and energy balance can be used for determining the thermodynamic relation.

$$\sum \dot{X}_{in} - \sum \dot{X}_{out} - \sum \dot{X}_{des} = \frac{dX}{dt} \tag{5.7}$$

$\dot{X}_{in}$, $\dot{X}_{out}$, and $\dot{X}_{des}$ are defined as exergy rates entering the control volume, exergy rates leaving the control volume and exergy destruction, respectively. If the system is considered steady, the right side of Equation (5.7) is zero. It implies that exergy destruction will equal to the difference of total exergy entering the control volume and leaving it.

The exergy consists of exergy of heat transfer, work and mass flow. The exergy of heat transfer is defined as Equation (5.8), which shows the Carnot approach of the heat transfer problem.

$$\dot{X} \equiv \dot{Q}\left(1-\frac{T_0}{T_b}\right) \tag{5.8}$$

The temperatures are in absolute values. T_0 is the temperature of reference or dead state. T_b is the temperature of boundary where the heat transfer takes place. The exergy of mass flow is defined as

$$\dot{X}_m \equiv \dot{m}\left(x_{in,f} - x_{out,f}\right) \tag{5.9}$$

Equation (5.9) represents exergy difference conveyed by mass flow entering and leaving to the control volume. The exergy of work is determined by

$$\dot{X}_W \equiv W_{in} - W_{out} + P_0 \frac{dV}{dt} \tag{5.10}$$

This equation shows the exergy of work as total work and the volume change rate of the system at the environment pressure. The exergy destruction is proportional to entropy generation, and determined by

$$\dot{X}_{des} = T_0 \dot{S}_{gen} \tag{5.11}$$

The moist air exergy stream is determined by the model as shown in Wang and Li (2011). The model shows physical exergy stream in the 1st and 2nd terms. The last term is reserved for chemical exergy. The physical exergy stream conveys heat transfer part in the 1st term and work part in the 2nd term. The equation of the moist exergy stream is presented in Equation (5.12) as

$$\dot{X}_a = \left(C_{pda} + \omega C_{pv}\right) T_0 \left(\frac{T}{T_0} - 1 - \ln\frac{T}{T_0}\right) + \left(1+\tilde{\omega}\right) R_{da} T_0 \ln\frac{P}{P_0} + R_{da} T_0 \left[\left(1+\tilde{\omega}\right)\ln\frac{1+\tilde{\omega}_0}{1+\tilde{\omega}} + \tilde{\omega}\ln\frac{\tilde{\omega}}{\tilde{\omega}_0}\right] \qquad (5.12)$$

While there is no change of chemical composition, the last part of Equation (5.12) will disappear. The second part is also neglected when the process is isobaric.

The water exergy stream can be calculated through thermodynamic relation $dS = dQ/T$ and $dQ = C_{pw} dT$. The thermodynamic properties of 1 ^{o}C as ASHRAE table provided were used for determining other temperature properties.

5.3.2.3 Exergy Formulation

The exergy equations were applied to the hospital HVAC components as given in Figures 5.4-5.9. According to the model, the chiller exergy equation can be formed in Equation (5.13). Assuming the chiller is a combination of pump and heat exchanger, the efficiency of the chiller can be determined as Equation (5.14).

$$\dot{X}_{chw,in} - \dot{X}_{chw,out} + \dot{X}_{cdw,in} - \dot{X}_{cdw,out} + \dot{X}_{el} + \dot{X}_{des} = 0 \qquad (5.13)$$

$$\eta_{xch} = \frac{\dot{X}_{chw,\mathrm{out}}}{\dot{X}_{chw,\mathrm{in}} + X_{el,ch}} \cdot \frac{\left(\dot{X}_{chw,in} - \dot{X}_{chw,\mathrm{out}}\right)}{\left(\dot{X}_{cdw,\mathrm{out}} - \dot{X}_{cdw,\mathrm{in}}\right)} \qquad (5.14)$$

The exergy balance at the cooling tower, with the streams of electricity, air flow and water flow, is presented in Equation (5.15). While the process is evaporative cooling, then the efficiency can be provided in Equation (5.16).

$$\dot{X}_{air,in} - \dot{X}_{air,\mathrm{out}} + \dot{X}_{w} + \dot{X}_{\mathrm{cdw},in} - \dot{X}_{cdw,out} + X_{el} + \dot{X}_{des} = 0 \qquad (5.15)$$

$$\eta_{xct} = \frac{\dot{X}_{air,out}}{\dot{X}_{air,\mathrm{i}} + \dot{X}_{W} + X_{el}} \tag{5.16}$$

Chiller water pump and condenser water pump have similar formulation of the exergy equation. The exergy balance of the pump system is presented in Equation (5.17). The related efficiency of the pump is provided in Equation (5.18).

$$\dot{X}_{\mathrm{cdw/chw,}in} - \dot{X}_{cdw/chw,out} + \dot{X}_{el} + \dot{X}_{des} = 0 \tag{5.17}$$

$$\eta_{xchp/xcdp} = \frac{\dot{X}_{\mathrm{chw/cdp,}out}}{\dot{X}_{\mathrm{chw/cdp,in}} + X_{el}} \tag{5.18}$$

The coil fans have three processes as shown in the model of Figure 5.5. They are adiabatic mixing, pumping and cooling. The exergy equation can be presented in Equation (5.19). The efficiency of exergy during the processes in this part is expressed in Equation (5.20). The 1st part is efficiency of pumping and mixing. The 2nd part is efficiency of heat exchanging.

$$\dot{X}_{rmair,in} + \dot{X}_{odair,in} - \dot{X}_{air,\mathrm{out}} + \dot{X}_{w} + X_{el} + \dot{X}_{des} = 0 \tag{5.19}$$

$$\eta_{xcf} = \frac{\dot{X}_{air,\mathrm{out}}}{\dot{X}_{rmair,in} + \dot{X}_{odair,in} + X_{el}} \cdot \frac{\left(\dot{X}_{chw,\mathrm{out}} - \dot{X}_{chw,\mathrm{in}}\right)}{(\dot{X}_{rmair,in} + \dot{X}_{odair,in} - \dot{X}_{air,\mathrm{out}})} \tag{5.20}$$

5.3.2.4 Indicators

Two ratios were added to show the trends of the exergy and load streams. The 1st is ratio of maximum exergy destruction and the electricity power of related components. This indicator tells about minimum exergy that can be conserved at each component. The second is comparison of the exergy destruction and cooling load. The calculations were done monthly.

The electricity is the only source of energy in every component of the HVAC. Each component has electricity supply. Electricity is assumed to be the exergy with unity factor. The ratio of maximum exergy destruction and electricity supply can show the conservation of the energy supplied to the system in each component. Maximum of exergy destruction shows the destroying of work availability. Even every component has exergy supply from other component, it is electricity which is the only energy supply. This ratio show how the instant energy supplied is conserved at the component. The ratio of maximum exergy destruction and electricity supply can be seen in Equation (5.21).

$$XER = \frac{\max(\dot{X}_{dest})}{X_{el}} \tag{5.21}$$

Cooling load shows the quantity of heat should be removed. Therefore, the ratio of the exergy destruction and the cooling load tells about the impact of load to exergy destruction. The higher of the impact means higher loss of exergy destruction. The equation of this measurement is presented in Equation (5.22).

$$XLR = \frac{\dot{X}_{dest}}{\dot{X}_{cooling\_load}} \tag{5.22}$$

5.4 Results and Discussion

Cooling load profile of the model follows the daily cooling load profile. A comparison of the model daily load profile and the data collected from the maintenance process for August 2017 is presented in Figure 5.10. The typical daily load profile is provided in Figure 5.11. Average difference of model and the collected data is less than 5%. In the evening and night the differences of the model results with the data are less than 5%. But for the morning and noon, the difference of the model and the data are more than 15% and 30%.

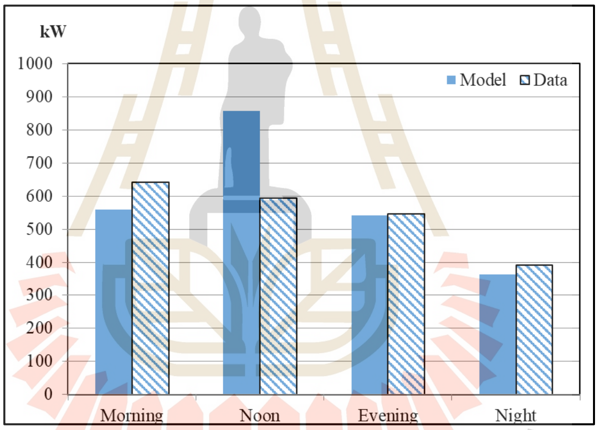


Figure 5.10 Comparison of the data and model load profile in August.

The cooling load profile of the model shows that noon and evening are the peaks of cooling load and they tend to be constant during that time. This load represents the number of people at the hospital as scheduled according to Table 5.2. Early morning is the time when the load is considered as zero. It happens when the daily temperature is lowest. At that time, equipment and people gain is also at the lowest amount.

The energy consumption of the HVAC was 1.1 GWh in 2017. This number was 34% of the total energy consumption of the building of the same year. The building consumed electricity 3.22 GWh at that year. The daily average electricity consumption of the building was 9 MWh. Peak of electricity consumption took place in September with daily consumption as much as 9.89 MWh as shown in Figure 5.1. Figure 5.2 shows that the peak temperature occurred in April. But, at this time, the average of electricity consumption was 9.38 MWh. Average out patients number in August was 953, while the average out patients number in April was 681. At the very light work, the difference is proportional to 32 kW of gain.

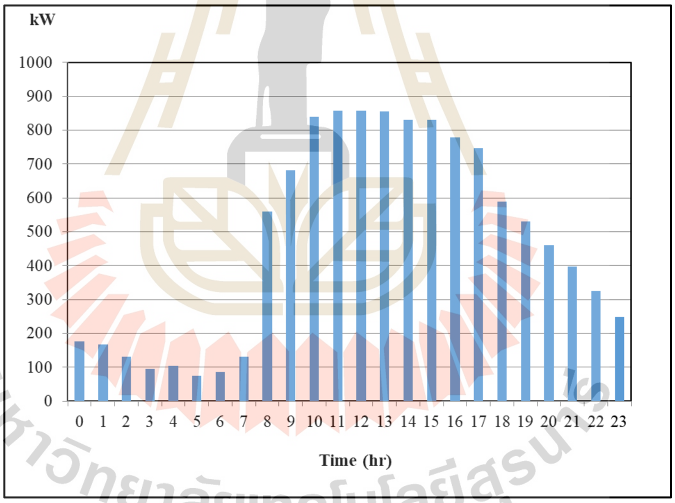


Figure 5.11 Typical daily cooling load of the HVAC.

The exergy of the HVAC calculation was based on the average condition hourly. Then, averaging of the exergy in a month was conducted. The average exergy of the components is provided in Table 5.3. Chiller has highest number or exergy destruction scoring nearly 86 kJ/s. The cooling tower has smallest number of exergy destruction rate. Both components are also the top and bottom of power rate and electricity consumption rate. The coil fans have higher electricity consumption rate than chilled water pump even it has less power rate.

Table 5.3 HVAC components, exergy destruction rates, power rate and its electricity consumption rate

Component	Exergy destruction (kW)	Power rate (kW)	Electricity Consumption (MWh/d)
Chiller	79.8	316.6	1.88
Coil Fans	20.0	68	0.43
CHP	15.1	74	0.36
CDP	6.4	60	0.38
Cooling Tower	0.0	20	0.00

Coil Fan, Chilled Water Pump, and Condenser Water Pump exergy destructions are very similar. The exergy destruction and the exergy efficiency of those components are similar and follows the cooling load profiles. Figure 5.12 shows the efficiency exergy profile. Cooling tower has the highest exergy efficiency and the chilled water pump is the worst. Efficiency of the cooling tower is above 90%. The efficiency of chilled water pump is less than 10%. Chilled water pump circulates high pressure chilled water.

In comparison to the rated power, exergy destruction rates of the condenser water pump, chilled water pump, chiller and the coil fans are 0.14, 0.26, 0.34 and 0.37, respectively. Those number are XERs of the respective components. The cooling tower has ratio of exergy destruction to electricity rate less than 1%. It shows that the coil fan is the component which destroys its exergy mostly. It destroys 37% of its supplied exergy.

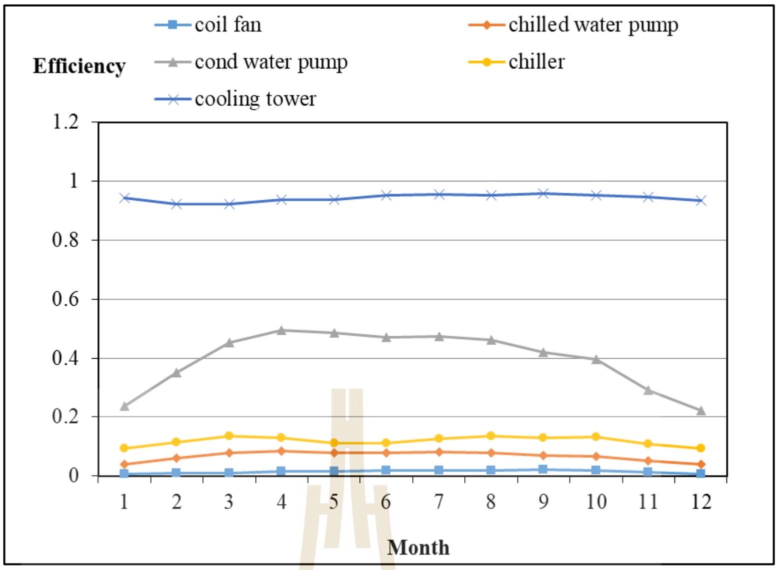


Figure 5.12 Exergy efficiency profile of the components.

Exergy destruction of the chiller fits into cooling load pattern. Figure 5.13 shows that normalized chiller exergy destruction is the fittest to load profile. It implies that the more is the cooling load, the more the chiller exergy destruction is. While temperature and inhabitant affect positively cooling load, they also make the chiller work in similar way.

Generally, those four components exergy destruction agree with the cooling load of the system. The differences only take places on the corners of the graph by 10%. On that reason, it could be inferred that ratios of the components exergy destruction and cooling load are 2.12, 1.61, 0.69, and 9.07 for coil fans, chiller water pump, condenser water pump, and the chiller respectively. These numbers are also XLRs for the components in respective sequence.

The 10% different of the chiller on the corners of the graph shows the impact of lower temperature to the chiller work. Less exergy destruction at the cool seasons represents less work of the chiller. The other rest components (coil fan, chilled water pump and condenser water pump) still have normal work, but the chiller can manage to reduce the capacity. The coil fans, chilled water pump, and condenser pump are limited by the minimum flow of the model. Chiller water pump is limited to 43 l/s to make the pressure of the chiller inlet under 65 psi as the operation set.

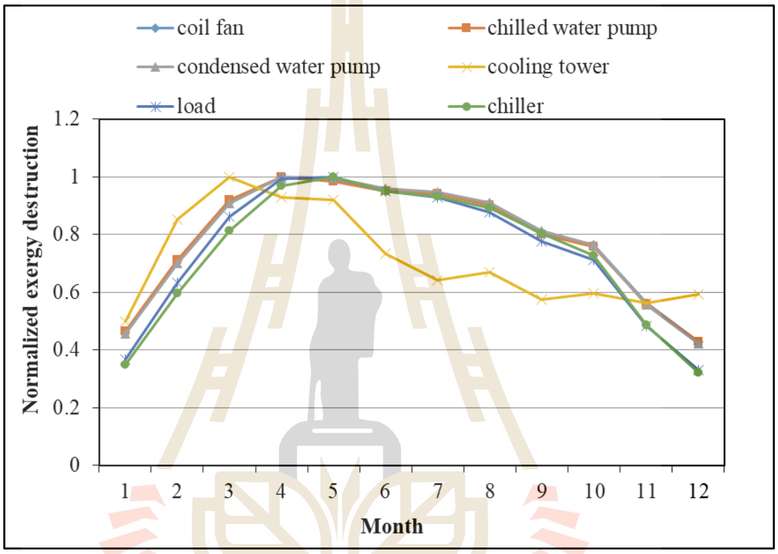


Figure 5.13 The profiles of normalized exergy destruction of HVAC component.

Exergy destruction of the cooling tower shows impact of weather cooling load rather than people cooling load. As it is shown in Figure 5.13, when the temperature dominates, the exergy destruction of the cooling tower follows the profile of the temperature. On the other hand, when the people cooling load dominates, there was less exergy destruction, even more exergy efficiency takes place. Higher efficiency of the exergy in cooling tower represent load of the system. The more is load of the system, the higher exergy efficiency is.

The exergy efficiencies show that the system was still working below its capacity. In this part, increasing of the cooling load implies the increasing of the power needed. When cooling load increases, the coil fans, motor and chiller response it by increasing chilled water flow and condenser water flow. The increase of these flows affects the pressure loss of the network. The pressure loss is proportional to the velocity of the fluid as Darcy-Weisbach equation. The pressure of the chilled water on the chiller is nearly 2.5 bar.

5.5 Conclusion

The 2nd law evaluation of the SUTH HVAC system was conducted with the model assuming that the system work yearly with the condition load of 2017. The result shows that the coil is the part that highest exergy destruction part. Exergy destruction of chiller, coil fan, chilled water pump and condenser water pump are 9.07, 2.12, 1.61, and 0.69 times cooling load that should be removed. The exergy destruction of the cooling tower depends on the temperature and load. The result also shows that currently, the system run in its linear range.

CHAPTER VI

ENERGY AND WATER CONSERVATION EVALUATION OF THE CENTRALIZED HVAC SYSTEM FOR SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL (SUTH)

6.1 Abstract

Former chapter explores simulation of the SUTH main building HVAC using TRNSYS, validation of cooling load and exergy analysis. Evaluation of exergy in previous chapter shows weak parts of HVAC system. Higher load makes better exergy efficiency of the components. Except the cooling tower, exergy efficiency of the HVAC components is less than half. It shows condition of overdesign.

The HVAC of hospitals is the main energy and water consumer. Energy and water conservation of the HVAC system at Suranaree University of Technology Hospital (SUTH) was evaluated in this study. A year-round numerical simulation of the system was conducted using TRNSYS, a transient simulation program. Exergy and water recycling analyses were applied assuming the setting temperature of the HVAC were 22 °C, 24 °C, and 26 °C. To reuse the blowdown water from the cooling towers, the treatments by RO filtering, mixing with RO water, and mixing with harnessed condensed water were evaluated. The results show that usage of 24 °C temperature setting provides least exergy destruction, compared with those of the temperature setting at 22 °C and

26 °C. The percentages of average exergy destruction at Chiller, FCU/AHU, CHP, CDP and Cooling Tower are 72.2%, 11.6%, 10.8%, 5.3% and 0.02%, respectively, when the temperature setting is 24 °C. The water consumptions and water withdrawals at 22 °C, 24 °C, and 26 °C temperature setting are 32.1 and 38.52 m^3/day, 23.3 and 27.96 m^3/day, and 17.4 and 20.88 m^3/day, respectively. It can be seen that the water consumption is about 0.83 of the water withdrawals. Recycling blowdown water by mixing it with condensed water provides the least energy intensity scoring 0.1 kWh/m^3. Mixing brine with the condensed water reduced the electricity and water cost by 1.6% of the system operation cost.

6.2 Introduction

Hospitals are considered as buildings with high energy and water consumptions. Hospital is comparable with hotel and lodging in water consumption intensity. In average hospital consumes more than double of the education energy consumption intensity (EPPO, 2016). Among the hospital facilities, HVAC becomes the main energy (Thinate et al., 2017;Teke and Timur, 2014) and water (Hospital Energy Alliance, 2011) consumer. HVAC is top percentage of energy consumer and second position of water consumer in hospitals. Managing HVAC of hospital can affect the energy (Buonomano et al., 2014) and water consumption significantly.

Twenty four hours operation of highly HVAC requirement is the main reason of energy greediness of hospital HVAC. At the same time, high amount of heat rejection is positively correlated to water consumption (Martin, 2012). This heat rejection mainly comes from heat gain and ventilation. Heat gain is determined by cooling load as function of weather, inhabitant, equipment, and lighting. Ventilation is source of heat that is related to outdoor air requirement. In the reason of minimizing uncontrolled heat gain, enveloping is important aspect of the building energy consumption (Ascione et al., 2013).

Water consumption of hospital HVAC is mainly determined by cooling tower operation (Al-Bassam and Alasseri, 2013). There are two water consumption types of the wet cooling tower. Make-up water as the water for replacing the water evaporated during cooling process is the first type. The make-up water depends mainly on the rejected heat. The complement of this process is blowdown water. The blowdown water replaces the water of the cooling tower system. This water is utilized to keep the water soft enough which keeps the system from the mineralization. Therefore, the blowdown water is function of process cycle amount (Rutberg, 2012).

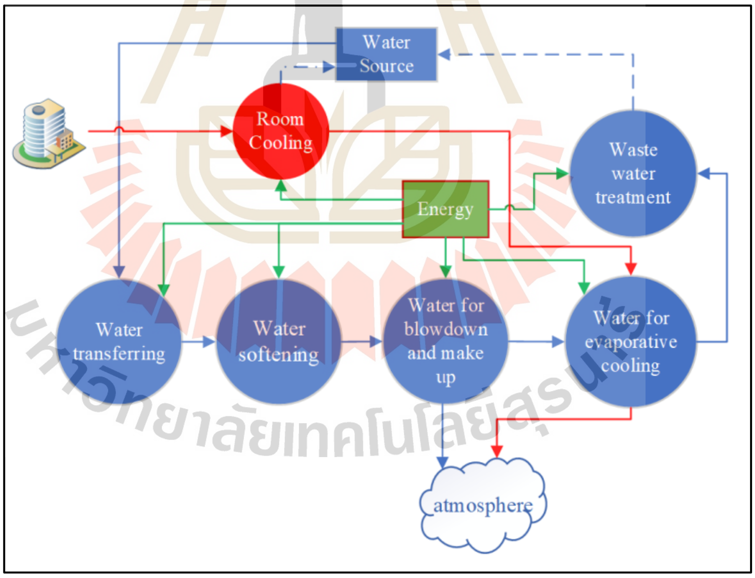


Figure 6.1 Energy and water flow at HVAC. Water, energy and heat flows are presented in blue, green and red respectively. Potential flows are depicted by dashed arrows.

Energy usage of an engineered water system takes place in every step of the cycle. It is used at the extracting, conveying, transferring, treating and consuming (Spang et al., 2014). At a hospital, a water system needs energy for transferring, consuming and treating. The energy is needed for distributing sanitary water for the building. Various qualities of water usage need energy for treating it. Energy is utilized for heating the water and steaming. The wastewater treatment consumes energy to manage the polluted water to be acceptable environmentally before discharging.

Energy for water at HVAC system is determined from its usage of blowdown and make-up. It is composed of energy for distribution and treatment. If the raw water doesn't fit in with the quality of the condenser water, pre-treatment is important. Additional energy for softening is needed before the usage. A diagram presenting water and energy interrelation in hospital HVAC is provided at Figure 6.1.

Figure 6.1 also mentions possibility of harvesting water from cooling process. The cooling process implies less water vapor can exists at air due to lower temperature of the result. To lower temperature makes the air contain less water vapor at the same relative humidity. Specific relative humidity requirement, lower temperature than the ambient and specific outdoor air change of the ventilation can be sources of harvesting water during the cooling process and dehumidifying to fit in the HVAC requirement.

Recycled water as the product of the wastewater treatment can be returned to water source. Amount of energy for recycling water depend on the quality of water and targeted product. At the HVAC system, hard water is the waste of wet cooling tower. This kind of water is not hazardous water and characterized by high calcium and magnesium minerals content. However, the water can easily form crust on the surface of the equipment. The treatment for kind of water can be chemical or physical. Chemical treatment for the water is done by sodium carbonate and calcium reactions followed by filtration. Zeolite coagulation can also be an alternative to reduce the hardness of the water. Another popular method is Reversed Osmosis which produces tap water and wastewater with higher salt concentration.

Combination evaluation of energy and water at HVAC system is far from discussion even the energy evaluation of the HVAC were conducted by many researchers. Congradac et al. (2012) conducted assessment of the hospital cooling and heating energy including hot water need, but didn't count the water effect. They counted on the heat and cooling load of rooms including the dehumidifying for energy saving. The water related to the system was neglected. Alves et al. (2016) classified the energy efficiency of HVAC. Energy efficiency ratio, coefficient of performance, seasonal EER and COP were applied to evaluate the performance of HVAC system in European market. Energy efficiency potentials at hospital HVAC system were proposed by Teke and Timur (2014). Evaluation of cooling tower for HVAC and HGSHP was conducted using exergy evaluation by Singh and Das (2017) with regardless water aspect. Pagliarini et al. (2012) used TRNSYS for optimized the building efficiency with CHCP. At this case, water aspect was still untouched.

Evaluation of energy and water conservation at centralized SUTH HVAC becomes the purpose of this article. The conservation of water is indicated by water consumption for a year. At the same time, exergy evaluation of the HVAC is conducted for energy conservation indicator. Combination of yearly water consumption and exergy evaluation is applied at the final evaluation. Price and cost of energy and water for operating HVAC was evaluated.

The article is structured into 4 parts consisted introduction, methods, results and discussion, and conclusion. At introduction, the reason and the main concept review are presented. The methods tell about the steps of evaluating the HVAC. TRNSYS simulation was applied for yearly data. A comparison with maintenance data energy consumption is conducted. Indicators of water and exergy are provided for clarifying the strategy at some scenarios. The results of simulation and its discussion are provided after the method. Conclusion is provided at the final part of the article.

6.3 Methods

There are 4 main steps of the method proposed in this article. The 1^{st} is simulation of the system for extracting data of water and energy for the SUTH HVAC system. In this part, specific conditions of simulation related to the SUTH building operation are provided. The 2^{nd} step is evaluation of the energy conservation through exergy analysis of the HVAC. The exergy destructions of the HVAC subsystems are determined. The 3^{rd} part is water evaluation of the HVAC system. The water usage of the cooling tower is utilized for determining total water need. The fourth step is analysis of water and energy conservation together. Combination of temperature setting and cooling tower wastewater processing methods is applied for finding the trend of energy and water conservation patterns across the setting variations. A cost and price analysis of water and energy for HVAC operation is presented.

6.3.1 Simulation of the SUTH Main Building Model

SUTH main building is the 11 stories center building of SUTH functioned as clinics, laboratory, treatment centers, wards, and offices. Therefore, the building becomes the center of hospital activities. Average daily visitors of the building were 784 out-patients and 65 in-patients in 2017. At the same year the building consumed 3.2 GWh of electricity and 3.02×10^4 m^3 water in a year. Excluding the sterilization system, laundry, radiology instruments and food preparation, the energy intensity of the building reached 230.4 kWh/m^2 per year.

Simulation of HVAC operation was performed using TRNSYS with a model represented the SUTH main building. The TRNSYS is software for simulating transient of thermal system with some built in functions coded in FORTRAN as libraries. The software libraries include HVAC components and weather condition for a year-round in many locations around the world. The simulated building model is a thermal zone with air volume as the main building of SUTH located in Nakhon Ratchasima Thailand. It was also applied for the simulation weather. The simulation was conducted with 10 minutes steps as compromise of speed and accuracy and presented in hourly steps.

The building model has 15,120 m^3 air zone with 2160 m^2 floor. It has 420 m^2 and 252 m^2 walls on north- south sides, and west-east sides, respectively. The walls have overall heat transfer coefficient 0.541 W/m^2K. The windows parts of the north, east, south and west in respective sequence are 63%, 57%, 53%, and 53%. The numbers are in accordance with actual condition of the building. The overall heat transfer coefficient of the windows is 1.27 W/m^2K. These coefficients are fit into advanced building envelope as the building was built in 2013 when the new standard of the building has been applied (Chirarattananon et al., 2010).

The air condition of the zone is determined from the function of the building. The main building of the SUTH had functions shown in Table 6.1. The table also provides information about the function percentage area and its ventilation requirement. The air change per hour describes amount of air circulated and filtered in volume unit. One ACH means that in an hour, air of one room volume is circulated through the ventilation. Ideally, all air in room is changed. The outdoor air mentions amount of air that should be changed with another air from the ambient in room volume unit. These requirements imply the temperature and humidity of the ventilation.

Table 6.1 Rooms function and their ventilation requirements.

Function	%	OA	ACH
Nurse station, Waiting room, Office, Conference room	57.75	0	0
Transition	2.98	0	2
Equipment and Medical supply	4.62	0	4
Clinics	10.26	0	6
Rest room	5.33	0	10
Patient room	12.62	2	6
Emergency	2.37	3	15
Procedure room	2.26	3	20
Operation room	4.20	4	20

Heat gain of room was determined by number of inhabitants, computer, lighting and medical equipment. The number of inhabitant consists of Out Patient, In Patient and the Staff. Out Patient and In Patient are determined monthly from the patient data in 2017. The daily out-patient arrival was assumed to follow Poisson Distribution. The staffs are set to be 300 people in active days.

The simulation condition of the equipment represents the real condition of main building HVAC system. The simulation was conducted flowchart in Figure 6.2. The HVAC of the SUTH main building is centralized with operation condition is provided in Table 6.2. However, there are 3 chillers, 3 CHPs, 3 CDPs and 3 Cooling towers, only two of the equipment are operated at a time. The rest of the equipment is prepared for emergency. Other specific condition of the equipment is that the chiller water pressure output 65 psi, the condenser water pumps compensate 40 psi head loss for the condensate water to cooling tower, and the chiller water pump works to circulate chiller water with pressure loss up to 138 psi.

Table 6.2 Operation condition of the SUTH HVAC system

Parameter	Value
Max coil air flow rate	104 m^3/s
Chiller type	Rotary, Water cooled, Variable speed
Chiller fuel	Electricity
Operation Chiller Capacity	2×250 TR
Chiller COP	5.29
Chiller water outlet temperature	44 ^{o}F (6.7 ^{o}C)
Cooling tower type	cross flow, single speed
Operation Capacity of cooling tower	$2\times953{,}904$ kcal/hr
Max chiller water flow rate	83.9 liter/s
Max cooling water flow rate	2,250 gpm
Max cooling tower air flow rate	75.6 m^3/min

The volumetric flow rate and pressure different of the chiller water is provided in Equation (1). The volumetric flow rate is in gallons per minute and the pressure different of the evaporator input-output is in psi. The complement specification for condenser water is presented in Equation (2). The pressure different is also in psi and the volumetric flow rate is in gallons per minute. At the simulation, the volumetric flow rates are known. The conditions of previous paragraph are applied for calculating the pressures.

$$\dot{V}_{chw} = -0.0226\Delta p_{ev}^2 + 8.9826\Delta p_{ev} + 136.65 \tag{6.1}$$

$$\dot{V}_{cdw} = -0.0044\Delta p_{cd}^2 + 12.898\Delta p_{cd} + 161.31 \tag{6.2}$$

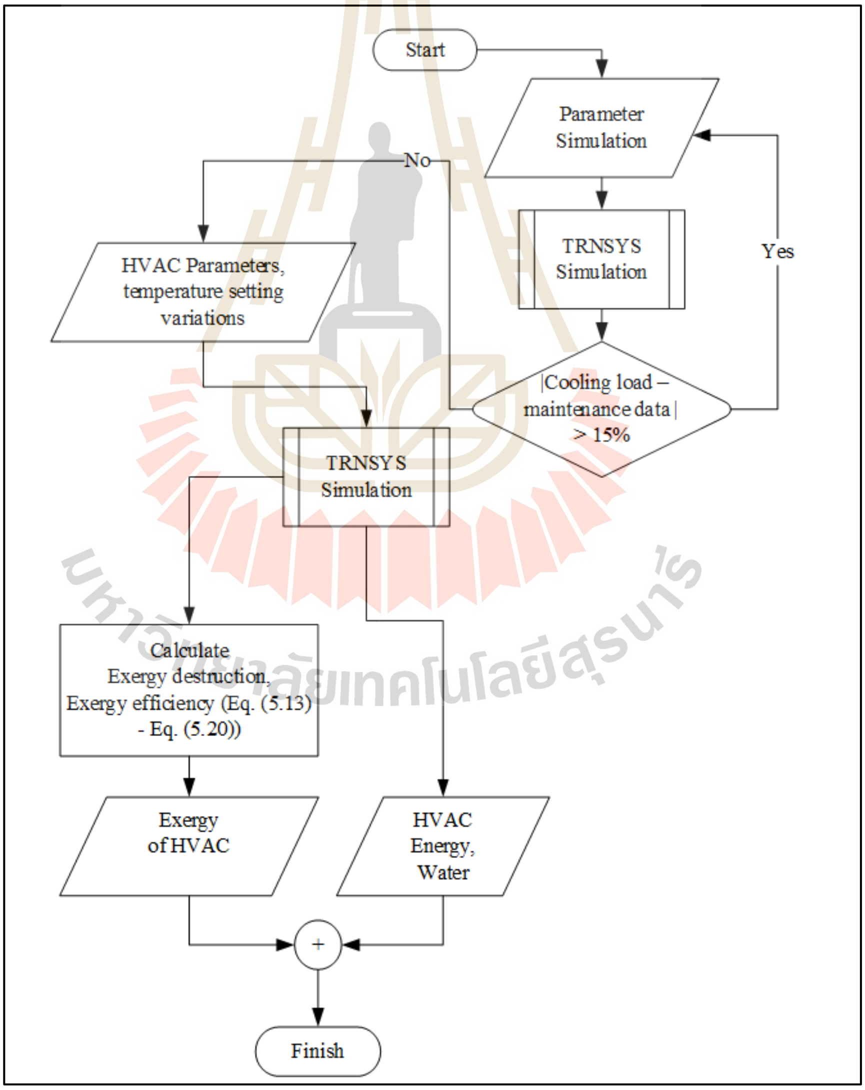


Figure 6.2 Flowchart of HVAC simulation with temperature setting variations.

6.3.2 Exergy of the HVAC System

The HVAC system has 5 main components. They are FCU/AHU (Fan Coil Unit/Air Handling Unit), CHP (Chiller Water Pump), Chiller, CDP (Condenser Water Pump), and CT (Cooling Tower). The FCU/AHU is utilized for pumping heat from room to chiller water. The CHP circulates the chiller water and transfers rejected heat to evaporator of the chiller. The chiller pumps this waste heat from chiller water to condenser water where the CDP transfer it to cooling tower. The cooling tower conducts evaporative heat transfer from condenser water to atmosphere where the waste heat is released.

To simplify the processes, FCU/AHU is assumed to be a combination of pump and heat exchanger. Adiabatic mixing, pumping and heat exchanging are the processes in this part. The exergy and its efficiency equations are provided in Equations 3 and 4. The exergy destruction of the system is determined by Equation (6.3). The Equation (6.4) is equation for calculating the exergy efficiency of the system. $\dot{X}_{rmair,in}$, $\dot{X}_{odair,in}$, $\dot{X}_{air,\mathrm{out}}$, $\dot{X}_{w}$, $\dot{X}_{el}$, and $\dot{X}_{des}$ are the exergy rate of air input from room, outdoor air input, air output from the coil, condensed water electricity, and exergy destruction, respectively.

$$\dot{X}_{rmair,in} + \dot{X}_{odair,in} - \dot{X}_{air,\mathrm{out}} + \dot{X}_{w} + \dot{X}_{el} + \dot{X}_{des} = 0 \tag{6.3}$$

$$\eta_{xcf} = \frac{\dot{X}_{air,\mathrm{out}}}{\dot{X}_{rmair,in} + \dot{X}_{odair,in} + \dot{X}_{el}} \cdot \frac{\left(\dot{X}_{chw,\mathrm{out}} - \dot{X}_{chw,\mathrm{in}}\right)}{(\dot{X}_{rmair,in} + \dot{X}_{odair,in} - \dot{X}_{air,\mathrm{out}})} \tag{6.4}$$

Dehumidifier existence can be applied in this function. However, for the reason that dehumidifier is applied as separated equipment, the energy consumed by the equipment is applied for calculating the FCU/AHU exergy efficiency function. The exergy of electricity is combination of the FCU/AHU and dehumidifier.

The CDP and CHP are used to pump the chiller water and condenser water respectively. Therefore they have similar function of the exergy. The formulation of the exergy function and its efficiency are presented respectively in Equations (6.5) and (6.6). The $\eta_{xchp/xcdp}$ is exergy efficiency of condenser water or chiller water. The $\dot{X}_{\mathrm{cdw/chw},in}$ and $\dot{X}_{cdw/chw,out}$ are exergy rate of condenser water or chiller water input and output respectively.

$$\dot{X}_{\mathrm{cdw/chw},in} - \dot{X}_{cdw/chw,out} + \dot{X}_{el} + \dot{X}_{des} = 0 \qquad (6.5)$$

$$\eta_{xchp/xcdp} = \frac{\dot{X}_{\mathrm{chw/cdp},out}}{\dot{X}_{\mathrm{chw/cdp,in}} + \dot{X}_{el}} \qquad (6.6)$$

The chiller function is to exchange heat from chiller water to condenser water. As the real condition of the chiller, where the internal pump is provided in evaporator only, the combination of pump and heat exchanger for representing the chiller are provided in Equations (6.7) and (6.8). The $\dot{X}_{chw,in}$ and $\dot{X}_{chw,out}$ are the exergy rate of chiller water input and the exergy rate of chiller water output. $\dot{X}_{cdw,in}$ and $\dot{X}_{cdw,out}$ are the exergy rate of condenser water input and condenser water output.

$$\dot{X}_{chw,in} - \dot{X}_{chw,out} + \dot{X}_{cdw,in} - \dot{X}_{cdw,out} + \dot{X}_{el} + \dot{X}_{des} = 0 \qquad (6.7)$$

$$\eta_{xch} = \frac{\dot{X}_{chw,\text{out}}}{\dot{X}_{chw,\text{in}} + X_{el,ch}} \cdot \frac{\left(\dot{X}_{chw,in} - \dot{X}_{chw,\text{out}}\right)}{\left(\dot{X}_{cdw,\text{out}} - \dot{X}_{cdw,\text{in}}\right)} \tag{6.8}$$

The cooling tower conducts evaporative cooling with condenser water, air input and electricity as the inputs. The output of the process is air at outlet. Therefore the exergy equations formulation for the cooling tower can be provided in Equations (6.9) and (6.10). The $\dot{X}_{air,in}$, $\dot{X}_{air,\text{out}}$, $\dot{X}_{w}$, $\dot{X}_{\text{cdw},in}$, and $\dot{X}_{cdw,out}$ are input air exergy rate, output air exergy rate, evaporated water exergy rate, condenser water input exergy rate, and condenser output exergy rate in addition to electricity exergy rate and exergy destruction rate.

$$\dot{X}_{air,in} - \dot{X}_{air,\text{out}} + \dot{X}_{w} + \dot{X}_{\text{cdw},in} - \dot{X}_{cdw,out} + X_{el} + \dot{X}_{des} = 0 \tag{6.9}$$

$$\eta_{xct} = \frac{\dot{X}_{air,out}}{\dot{X}_{air,in} + \dot{X}_{W} + X_{el}} \tag{6.10}$$

Exergy destruction and electricity ratio is applied for evaluating the energy conservation of the HVAC. Electricity is the only utilized energy of the HVAC system at SUTH. The ratios of every HVAC components were calculated using Equation (6.11).

$$XER = \frac{\max(\dot{X}_{dest})}{X_{el}} \tag{6.11}$$

6.3.3 Water Evaluation of HVAC System

The water used for HVAC is composed of water consumption which is released as vapor and water consumption due to alteration of water quality. The make-up water is monitored, but blowdown water is unmonitored. Prediction of blowdown water can be calculated assuming equal concentration of make-up water and blowdown water.

At every n[th] cycle of cooling tower water which is assumed that a make-up water addition is n times the volume of condenser water, the impurities concentration of the magnesium and calcium particles on the water can be shown in Equation (6.12). C_0 is the impurities concentration of make-up water which is assumed to be soft water. m_{cdw} is mass impurities in condenser water at the beginning and V_{cdw}^2 is the square of condenser water volume.

$$C_n = C_0 + n\left(\frac{m_{cdw}}{V_{cdw}^2}\right)V_{cdw} \tag{6.12}$$

with number of cycle $n = \frac{\dot{V}_m}{V_{cdw}}$ and $m_{cdw} = C_0 V_{cdw}$, where $\dot{V}_m$ is the total volume of make-up water after n[th] cycle. The impurities concentration can be formulated in Equation (6.13) as

$$C_n = C_0 + C_0\left(\frac{\dot{V}_m}{V_{cdw}^2}\right)V_{cdw} \tag{6.13}$$

Therefore, the blowdown water in equal unit time with make-up water can be determined as shown in Equation (6.14). The V_m, $\dot{V}_{m\max}$,and V_{bw} are volume of recorded make-up water in specific time unit, maximum allowable make-up water before blowdown, and volume of blowdown water in specific time unit.

$$V_{bw} = \frac{V_m}{\dot{V}_{m\max}}.V_{cdw} \tag{6.14}$$

It should be noted that $V_{bw} = (V_m/\dot{V}_{m\max}).V_{cdw}$. While the conductivity is the method for determining water hardness, it can be inferred that $\dot{V}_{m\max} = (\sigma_{hard}/\sigma_{soft})V_{cdw}$ or $\dot{V}_{m\max} \approx 5V_{cdw}$,then

$$V_{bw} \approx \frac{V_m}{5} \tag{6.15}$$

It means that water consumption for cooling system with wet cooling tower can be determined as shown in Equation (6.16) below.

$$V_w = V_m + V_{bw} \approx \frac{6}{5}V_m \tag{6.16}$$

6.3.4 Energy and Water Conservation of the HVAC

Flow of the water in Equation (6.16) determines energy for water transferring and water softening. The make-up water and the blowdown water need to be transferred from the water source to the water tank on rooftop. They also need to soften for preserving crust. On the other hand, the flow of water in Equation (6.15) determines the wastewater processing of the HVAC.

The energy for HVAC water that consists of transferring and softening can be determined in

$$E_{wt} = V_w \left(C_t + C_s \right) \tag{6.17}$$

with C_t and C_s is the energy coefficient of the pumping and softening, respectively. Assuming the single pass RO process is chosen for the softening, $C_s = 0.36$ kWh/m^3 (Wakeel et al., 2016). The coefficient of pumping can be determined from the efficiency of the pump at working condition, in the case C_t = 0.173 kWh/m^3 (Spang et al., 2014). The total efficiency of the pump is 85%.

There are 2 choices for managing the blowdown. They are releasing it to environment after treatment or recycling it. The wastewater energy intensity of recycling water is determined in Equation (6.18). The coefficient of blowdown wastewater treatment can be summarized in Table 6.3.

$$E_{wwt} = V_{bw} \left(\frac{C_{wwec}}{C_p} \right) \tag{6.18}$$

The electricity and water cost of HVAC is determined by operation electricity consumption of the HVAC operation, water cost of the HVAC operation, electricity consumption for water recycling and price of recycled water. The electricity prices are determined on TOU for public facilities which are 3.44 Baht/kWh and 2.61 Baht/kWh for on peak and off peak, respectively. Therefore, the basic cost of electricity can be determined in Equation (6.19). EC_b , EP , and $ECon$ stand for electricity cost of the HVAC operation neglecting water, electricity price per unit in Baht/kWh, and electricity consumption in kWh. The subscribe P and OP respectively stand for on peak and off peak.

$$EC_b = EP_P \times ECon_P + EP_{OP} \times ECon_{OP} \tag{6.19}$$

Table 6.3 Methods for treating blowdown brine and its energy coefficient

Methods	**Product Coefficient**	**Energy Coefficient/ Input volume (kWh/m^3)**	**Note**
Direct single stage RO	0.6	0.36	0.4 volume is brine with 2.5 times concentration, the product can be used for other necessity
Mixing with RO	6	$5C_t$+ 1.8	no brine, the product can be used for flushing and watering
Mixing with condensed water	5	$4C_t$	Available as long as sufficient condensed water

Water price of SUTH is very low. It only paid 10 Baht per m^3 of raw water. This price is less than half of the current municipal water price. To fit the cooling tower requirement, the water raw should be treated and moved to the tank. The total price of water at SUTH neglecting the water price should include water distribution and treatment. The water cost of the HVAC water is determined in Equation (6.20). WC_{HVAC}, W_{HVAC}, WP, and EP are cost of water for HVAC, water for HVAC withdrawal, water price per m^3 and electricity price, respectively.

$$WC_{HVAC} = W_{HVAC} \times (WP + EP) \tag{6.20}$$

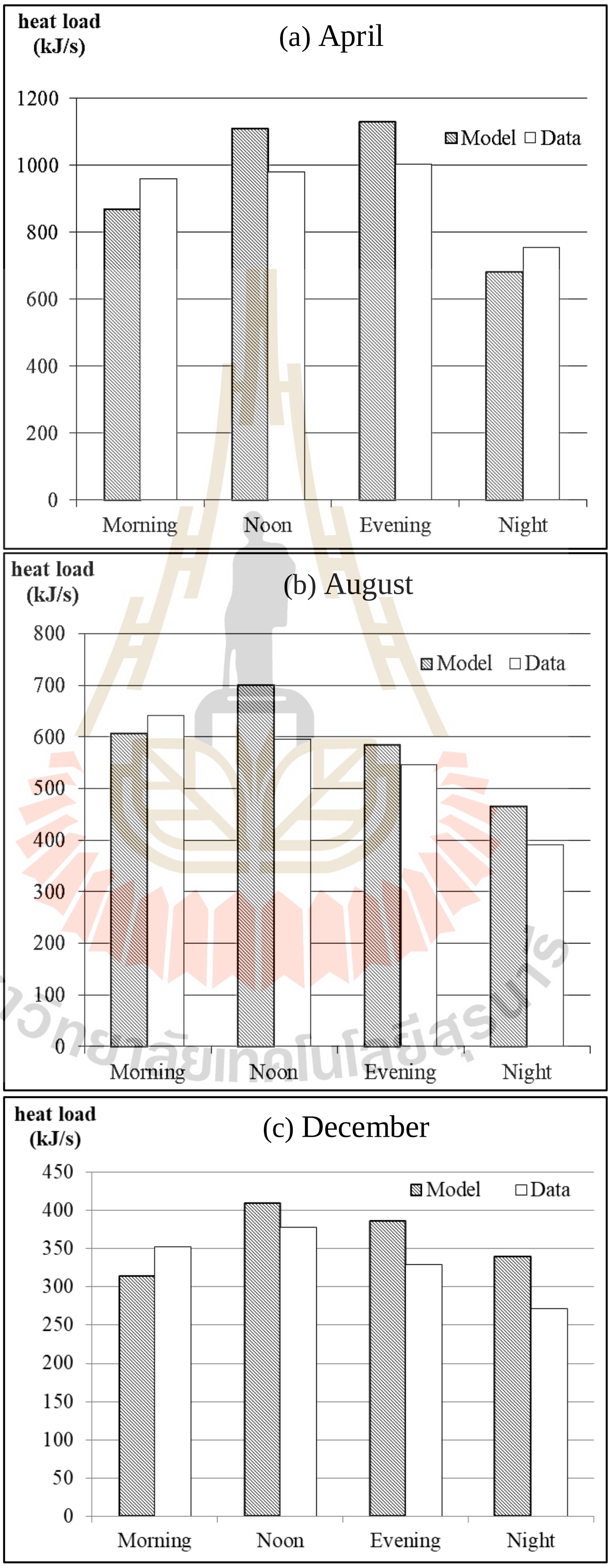

heat load (kJ/s)
(a) April
Model
Data
0
200
400
600
800
1000
1200
Morning
Noon
Evening
Night
heat load (kJ/s)
(b) August
Model
Data
0
100
200
300
400
500
600
700
800
Morning
Noon
Evening
Night
heat load (kJ/s)
(c) December
Model
Data
0
50
100
150
200
250
300
350
400
450
Morning
Noon
Evening
Night

Figure 6.3 Comparison of cooling load of HVAC.

Electricity cost of the water recycling is composed of electricity cost at peak time and off-peak time. The equation of electricity cost for recycling water is presented in Equation (6.21), with EC_{RW}, E_{WWtP}, and E_{WWoP} are electricity cost for recycling water, electricity consumption for recycling water at peak time, and electricity consumption for recycling water at off peak time, respectively.

$$EC_{RW} = E_{wwtP} \times EP_P + E_{wwtOP} \times EP_{OP} \tag{6.21}$$

The water price of water recycled is used for reducing the energy and water cost of HVAC. The cost of water is assumed to be flat at the current price 10 Baht per m^3. Therefore the energy and water cost for HVAC operation can be calculated as presented in Equation (6.22). E_{HVAC} is the electricity and water cost of HVAC operation.

$$EWC_{HVAC} = EC_b + WC_{HVAC} + EC_{RW} - WP_{RW} \tag{6.22}$$

6.4 Results and Discussion

The simulation produced reasonable result with average energy consumption difference to maintenance data 12%. The differences in April, August, and December are 6%, 14%, and 16%, respectively. Comparison of the model cooling load at 24 ^{o}C temperature setting and its maintenance data is provided at Figure 6.3. April represents month with high ambient temperature. August shows the pattern of normal month with high humidity. In 2017, daily out-patient number in August was 950. It was the highest among the months of that year.

Cooling load difference between the model and the data are varied. In the morning, the model produced less coaling load than the data. At noon and evening, the model produced cooling load higher than the data. In the evening, the data of April was higher, but the other months had less cooling load than the model. As April is the month with high ambient temperature, the effect of ambient temperature is dominant. Evening load was higher than noon load. This weather dominance to other load also appears in morning data where the difference between maintenance data and the model was highest in April. Deficiency of morning in April was almost 3 times of deficiencies on other months.

The weather dominant also can be inferred from the difference model and data at night. The model tends to provided higher cooling load than the data except in April. In August and December, the model provided higher cooling load. Assuming the impact of the equal dynamic load, the temperature response of model can be blamed.

Energy consumption for HVAC system, with 24 ^{o}C temperature setting and 50% relative humidity was 1.8 GWh. This number is 56% of electricity consumption of the building in 2017. Almost 55% of the HVAC electricity consumption was used by the chiller. The FCU/AHU, CHP and CDP electricity consumptions were 25.8%, 9.3% and 10.1%, respectively. The cooling tower consumes minute electricity recorded 1.65×10^{-3}%. Except for the CHP and CDP, these numbers are far different from the conclusion of Teke and Timur (2014). The electricity for pumping the condenser water at cooling tower was neglected in this system while it belonged to CDP part.

The chiller is also the equipment with highest exergy destruction. The chiller destroyed exergy as much as 121 MJ every month. The destroyed exergy at other equipment were 19.48 MJ/month, 18.12 MJ/month, 12.96 MJ/month, and 0.03 MJ/month for FCU/AHU, CHIP, CDP, and Cooling Tower respectively. The percentage of average destructed exergy at chiller, FCU/AHU, CHP, CDP and Cooling Tower were 72.2%, 11.6%, 10.8%, 5.3% and 0.02% respectively.

A relative huge number of water was used for HVAC. At the 22 ^{o}C, 24 ^{o}C, and 26 ^{o}C temperature settings, the average water consumptions for HVAC were 32.1 m^3/day, 23.3 m^3/day, and 17.4 m^3/day, respectively. These numbers are equal to 6,369 m^3, 8,506 m^3, and 11,723 m^3 respective sequences of yearly water consumption. The water consumptions also represent amounts of water that were evaporated at respective temperature settings. The water withdrawals as total water used for the HVAC were 38.52 m^3/day, 27.96 m^3/day and 20.88 m^3/day at respective 22 ^{o}C, 24 ^{o}C and 26 ^{o}C temperature settings. The differences of the water withdrawals and water consumptions are the blowdown water.

Table 6.4 The exergy destruction percentage: its ratio to electricity.

Temperature (° C)	**Chiller**	**FCU/ AHU**	**CHP**	**CDP**	**Cooling Tower**	**Total Exergy (MJ/h)**	**Total XER**
	XER	XER	XER	XER	XER		
26	45.6	29.9	25.5	15.3	0.2	143.48	26.3
24	57.1	41.0	36.7	21.6	0.2	167.51	22.6
22	96.9	67.7	68.5	37.8	0.3	332.90	35.4

Table 6.5 Energy intensity and daily average of water production of the blowdown water treatment.

Temperature (°C)	RO		Mix with RO		Mix with condensed water	
	E_{wwt} (kWh/m^3)	Water (m^3)	E_{wwt} (kWh/m^3)	Water (m^3)	E_{wwt} (kWh/m^3)	Water (m^3)
22	0.6	3.85	0.41	38.52	0.099	35.52
24	0.6	2.80	0.41	27.96	0.098	25.96
26	0.6	2.09	0.41	20.88	0.091	20.88

The lower the temperature is, the higher possible harnessed water and the water evaporated at cooling tower are. At 26 ^{o}C, it was 17.4 m^3/day water can be harvested from cooling room. It is also amount of water lost at the cooling tower during evaporation process. Ratios of possible harvested and evaporated loss for 24 ^{o}C and 22 ^{o}C are 21.3:23.3 and 29.1:32.1, respectively. Additional one-fifth of the amounts should be added for blowdown water. It can be inferred that lower temperature setting consumes more net-water for HVAC system.

Providing daily water necessity needs energy intensity 0.497 kWh/m^3 for the direct water. The energy is composed of energy for transferring the water and energy for softening the water. This number implies, more water needs more energy proportionally. It means less temperature setting needs more energy. But it also releases more brine of the blowdown water. The energy for water (E_{wt}) for temperature setting of 22 ^{o}C, 24 ^{o}C and 26 ^{o}C in respective sequence are 19.14 kWh/day, 13.90 kWh/day, and 10.38 kWh/day with water needs 38.52 m^3, 27.96 m^3, and 20.88 m^3, respectively.

The energy need for wastewater treatment of the blowdown brine depends on the scenario of the brine treatment. At temperature setting range, energy per m^3 water product is 0.6 kWh. It still also releases higher mineral concentration brine. Mixing the brine with RO water to produce flushing water has energy intensity 0.4142 kWh/m^3. The mixing blowdown water with condensed water needs less energy intensity. The methods intensities are 0.091 kWh/m^3, 0.098 kWh/m^3, and 0.099 kWh/m^3 for 26 ^oC, 24 ^oC, and 22 ^oC, respectively. Table 6.5 shows relation of temperature setting and its energy intensity for recycled water.

Mixing the blowdown water with RO needs additional water from the source. At 24 ^oC temperature setting, to produce 27.96 m^3 water for flushing, 23.3 m^3 extra water should be withdrawn. At the same time, 21.3 m^3 condensed water is uncollected and unused. But this method provides final wastewater reduction by 4.66 m^3 and reduction of flushing water preparation by the same number. Unfortunately, the method only has water energy intensity slightly less than direct water withdrawal from the source.

Mixing with condensed water potentially reduces water withdrawal, wastewater and water energy intensity. Producing water flushing 25.96 m^3 per day as combination of the blowdown brine and condensed water at 24 ^oC setting implies 25.96 m^3 reduction of water withdrawal and wastewater treatment. Having flushing water energy intensity 0.098 kWh/m^3 less energy intensity of the water can be reached.

Cost of water and electricity for HVAC operation can be reduced through mixing the brine water and condensed water. As the water price was very low and flat, cost reductions of integrating water into HVAC system is 1.71%, 1.62%, and 1.78% at temperature settings 22 ^oC, 24 ^oC, and 26 ^oC, respectively. The numbers are equal to 126, 92, and 74 thousands Baht at respective temperature settings. If the price of water increases, more cost benefit can be earned. The condition shows that energy is more dominant than water in this case.

Table 6.6 Electricity and water consumption and cost of the HVAC

	Temperature (°C)		
	26	**24**	**22**
$ECon_P$ (MWh)	812	1,150	1,601
$ECon_{OP}$ (MWh)	517	652	685
W_{HVAC} (m^3)	7,642	10,207	14,068
E_{wwtP} (kWh)	2,370	3,467	5,037
E_{wwtOP} (kWh)	1,428	1,606	1,955
W_R (m^3)	6,356	7,778	10,617
EC_b (Baht)	4,143	5,658	7,295
WC_{HVAC} (Baht)	88,304	118,187	163,107
EC_{RW} (Baht)	2,077	2,821	3,942
EWC_{HVAC} (Baht)	4,157	5,684	7,333

Table 6.6 also mentions that energy consumption of HVAC operation is dominant at the on peak time. This on peak domination significantly increases cost of the HVAC electricity consumption. The wastewater recycling as treated equally to HVAC operation was also on peak dominant. A simple scheduling can easily reduce its cost.

6.5 Conclusion

The result of this work has some trends that can be inferred. They are

1. The TRNSYS could provide good result model of SUTH main building HVAC system. The cooling load difference with the maintenance data was around 15%.

2. Managing the setting of the temperature can be used to conserve energy and water at the same time. Higher temperature setting needs less energy and water consumption. But less temperature setting can produces more potential water that can be harnessed to reduce the water energy intensity consumption through mixing the condensed water with blowdown water of the cooling tower. However, the ratio of potential harvested water and evaporated water at lower temperature setting was less than higher temperature setting. At 24 ^{o}C setting, electricity need for the system was 1.8 GWh counting 56% of the electricity consumption of the building. Total exergy destruction was 22% of the electricity consumption. Yearly HVAC system water consumption of 24 ^{o}C and 50% humidity setting was 8,506 m^3. The daily average water that can be harvested at the 24 ^{o}C temperature setting and 50% humidity was 21.3 m^3. The evaporated water at the equal setting was 23.3 m^3. The blowdown water need at the same setting was 4.66 m^3. At 26 ^{o}C temperature setting, the potential harvested water and the evaporated water was nearly equal.

3. The chiller is the equipment where most of the exergy destructed at HVAC system of SUTH. The chiller at 24 ^{o}C setting contributes 72.2% of the exergy destruction. The AHU/FCU, CHP, and CDP have portions of 11.6%, 10.8%, and 5.3%, respectively. The cooling tower part is only negligible minute.

4. Mixing blowdown water with collected condensed water significantly could reduce water withdrawal and energy water intensity. The electricity intensity of the water

result is nearly 0.1 kWh/m^3. The number is 1/6 of the energy water intensity of operating HVAC from the current tap water source. Cost of water and electricity of the system reduces by 1.6% - 1.8% through mixing the blowdown water with condensed water at 10 Baht price of water and TOU of electricity.

5. The reduction of electricity intensity of water for operating HVAC system and water withdrawal become guidance to consider providing installation of collecting the condensed water from the HVAC system as alternative water source in large building. A further works should be conducted in specific condition.

CHAPTER VII

EVALUATION OF THE CENTRALIZED HVAC CHILLED WATER PUMPS OF SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL MAIN BUILDING

7.1 Abstract

HVAC system evaluation of Chapters V and VI indicate that the HVAC systems are overdesigned. Exergy efficiency of the HVAC parts is less than half, except the cooling tower. Operation condition of the HVAC implies condensate water that can be collected. Chilled water pump lost exergy higher than 1 which indicates that exergy destruction rate is higher than cooling load.

Pumps are the main issue of the chilled water distribution in a centralized system. In purpose of evaluating the chiller pump system of the centralized HVAC for Suranaree University of Technology Hospital (SUTH) main building, a model comprised evaporator, pump and pipe network was proposed. An analysis of energy rate losses due to pressure losses was applied in a model composed of vertical and horizontal distribution pipes. Pressure loss in pipes was assumed to follow Darcy-Weisbach equation. The resistances of the systems were also calculated. The results show that distribution of losses in vertical shaft and stories were unequal. The pressure loss and energy rate loss were function of flow-rate. But the resistance was an inverse function of the flow-rate. The difference distribution emphasized the need of reconfiguring chilled water pump for accommodating flexibility of usage.

7.2 Introduction

Centralized HVAC is a common method for large building as it has high cooling load. The centralized HVAC works more efficiently than split system when the system needs high heat rejection at the same time. A centralized system works with less moving parts, higher heat working fluid capacity and higher COP (Perez-Lombard et al., 2011). Less moving parts mean less maintenance. Higher heat working fluid capacity allows to handle more heat rejection load. The COP tells energy consumption over heat rejection. Therefore, the centralized HVAC system is preferable for large system. However, the high capacity system has vulnerability of load variation range.

Variation of load in a HVAC system can degrade the efficiency of the system. If a system works at off designed working point, its efficiency mostly decreases. Because the centralized HVAC depends on pumps for transferring heat among its components, increasing load above its design forces the pumps to increase the flow rate of working fluid. It implies higher flow rate and less efficient motor. When the load is less than it designed, the pump can work better, but the motor might work at less efficient condition.

Variable speed motor is proposed for variable load system. Variable speed motor can work over long range speed with high efficiency (Tirmizi et al., 2012). Therefore, load variation does not affect the performance of motor. When the load increases, the motor can adjust the speed to provide higher pressure and vice versa. To set at high performance, control system of the motor is important. Unfortunately, the variable speed motor is still has drawback of the high range variety and the price could be very high for a high capacity motor and its controller.

Constructal law emphasizes a design to follow the nature pattern in order to get high efficiency. In nature, in order to survive, flow should be more and more efficient. Combination of few larges and many smalls is considered the best design as the nature shows in many nature flows (Bejan and Lorente, 2011). It has been studied in many engineering area such as cooling system (Adewumi et al., 2013; Ghodoossi and Eğrican, 2004; Kalbasi and Salimpour, 2015), heat storage (Miguel, 2008), and energy harnessing (Lorente et al., 2010). These studies focused on design base and not for retrofitting the established system.

The objective of the study is to evaluate the chilled water pumps of HVAC system in a multi-story building, the main building of Suranaree University of Technology Hospital (SUTH). Evaluation of centralized HVAC system pump can be considered as the compromise between high variety of load and large system (Perez-Lombard et al., 2011). Moreover, it is also a new field of constructal law area to be more practical in established system. In order to evaluate the HVAC system in large building with high load variety in term of constructal study, a case of SUTH main building is proposed.

The structure of the article is mainly composed of introduction, methodology, result and discussion, and conclusion. At the introduction, the state of the problem is presented to show the research gap of the proposed topic. The methodology part consists of description of the HVAC system of SUTH main building and its performance records. In this part, the model of the system will be presented for evaluating the performance. Result will have some data that show analysis of the performance at the current condition. Optional setting adjustment of the operation condition will be proposed. Conclusion will close the paper with some main trend found.

7.3 Methodology

7.3.1 Centralized HVAC of SUTH Main Building

Rattanajapevat was the operational main building of Suranaree University of Technology Hospital (SUTH). It had 12 floors which have been functioned as the administration building, OPD clinics, wards, operation rooms, emergency, pharmacy, laboratories and some support systems. The clinics areas are distributed in the 1st, 2nd, and 3rd floors. The administration office was centered at the 4th floor. The operation rooms were located in the 5th floor. The 6th floor was dedicated for delivery, while the 7th floor was the place for intensive care units. Hemodialysis machines and its recovery rooms were located in the 8th floors. The rest floors; they are the 9th – 11th, were wards for women, men, and VIP, respectively. The ground floor was the place for some support systems, they were engineering, CSSD, pharmacy stocks, securities, and morgue.

Total HVAC system capacity of the building was 750 TR which consists of 3 chillers with 250 TR each. The system is also supported by 3×30 kW CDPs (condenser water pumps), 3×37 kW CHPs (chilled water pumps) and 3×3.8 million BTU/hr of cooling towers. The coil unit's capacity of the building was 7.2 million BTU/hr. The chilled water flow-rate capacity of the building was 83.9 l/s. The chilled water was designed to work at 7-13.5 ^{o}C. The chilled water output pressure was set to be 65 psi. The condenser water pumps have to manage 40 psi pressure head loss compensation. The model of the chilled water system is shown in Figure 7.1.

The chilled water was distributed to the building by 3×37 kW pumps operated alternately. Every time, only two of the three pumps worked. These pumps were connected to vertical main shaft of 10” pipe. The shaft was connected to distribution pipes in every floors. Different sizes of pipes were applied for the distribution pipes. Some floors had equal size of the supply and return pipes. Some of them had different sizes for the reason of price and the capacity. The size of the pipes for the HVAC and the chilled water flow-rate of the system are provided in Table 1. The Table 7.1 designation of the stories followed the building condition. The 0 and 12 were used for the basement and rooftop, respectively. This chilled water flow-rates also showed the cooling capacity in respective floors.

Table 7.1. Story, chilled water flow rate, inhabitant, and pipe sizes. S and R stand for supply and return, respectively.

Story		**Water (l/min)**	**Inhabitant (day equivalent)**	**Pipe size S (inch)**	**Pipe size R (inch)**
Name	**Designation**				
Ground	0	77.84	18	3	3
1	1	236.10	55	4	4
2	2	203.43	23	4	4
3	3	137.43	23	2	3
4	4	110.60	7	2	3
5	5	120.34	13	2	3
6	6	123.26	5	2	3
7	7	100.65	14	2	3
8	8	86.66	17	2	3

Table 7.1. Story, chilled water flow rate, inhabitant, and pipe sizes. S and R stand for supply and return, respectively. (Cont.)

Story		Water (l/min)	Inhabitant (day equivalent)	Pipe size S (inch)	Pipe size R (inch)
Name	Designation				
9	9	22.10	25	2	3
10	10	22.10	29	2	3
11	11	74.36	17	2	3
R	12	15.00	1	2	3

The chilled water was assumed to be distributed in proportional velocity at steady state condition. The valves were set to provide proportional water flowing at every floor according the capacity of the cooling system. The relationship of the chilled water flow-rate and pressure difference at the evaporator was determined by Equation (7.1) as provided by the provider company (Trane, 2012). The pressure difference was in psi and the flow-rate was in gallon per minute. The model of the chiller system is provided at Figure 7.1. As the input of the pump was set to be 65 psi, the pressure loss of the pipes network followed Equation (7.2).

$$Q_{chw} = -0.0226\Delta p_{ev}^2 + 8.9826\Delta p_{ev} + 136.65 \tag{7.1}$$

$$\Delta p_n = -3\times10^{-10}Q^4 + 4\times10^{-7}Q^3 + 1\times10^{-4}Q^2 + 0.0309Q + 0.6721 \tag{7.2}$$

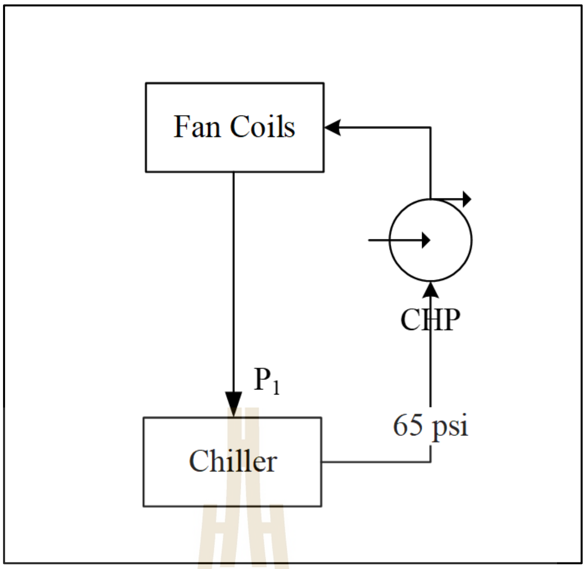


Figure 7.1 Model of the chilled water loop of the HVAC. Output pressure of the chiller was 65 psi. P_1 and P_2 were determined by flowrate.

7.3.2 The Evaluation of the Chilled Water Pump Configuration

There are two questions of the configuration in chilled water distribution problem. The first question is distributing cooling water as load needed. The second question is minimum energy to flow the chilled water to the load which has horizontal and vertical parts. The first question can be considered as sufficiency problem of the chilled water. Assuming load as proportional to number of people and its density is proportional to the area, it can inferred that the scale of the load is L^2 (Bejan and Lorente, 2006). At the same time the chilled water flow-rate expresses the cooling capacity of the network in a story. Higher water flow-rate means higher cooling capacity and vice versa.

To evaluate the chilled water pump, distribution of chilled water is mapped. To simplify the system, a model as shown in Figure 7.2 is proposed. The model consists of evaporator, pump, and pipe networks which their flow rates and pressure differences. The pipes network is composed of shafts (main pipes), and story distribution pipes. Every story pipe line is described as a single equal diameter line connecting inlet main shaft and outlet main shaft. It is assumed to be a single segment which has pressure difference between its inlet and outlet. Every main shaft segment connecting two adjacent stories is assumed to be a single segment. In the model, the segment has its own pressure difference and flow rate.

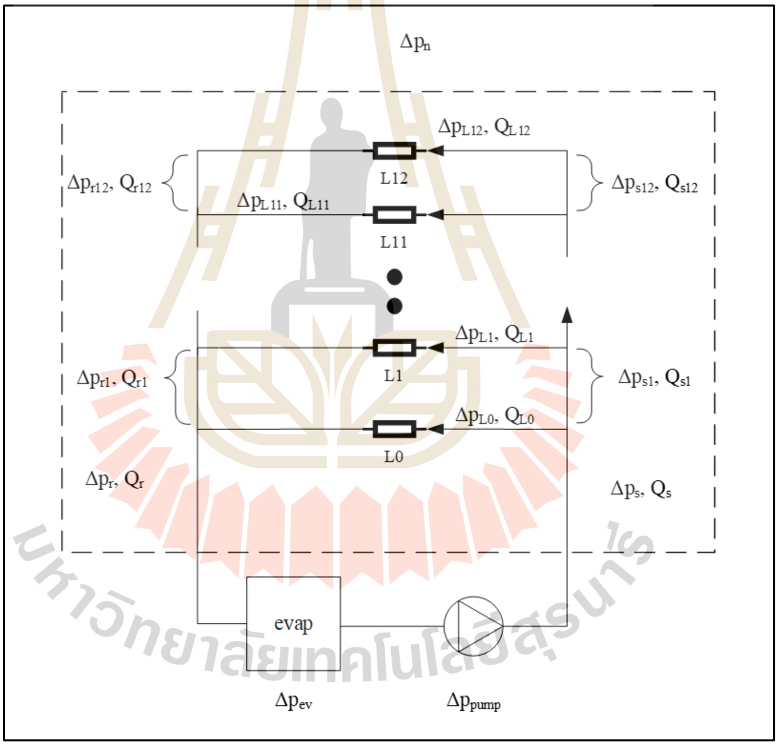


Figure 7.2 The model of chilled water loop and its pressure and flow-rate. Δp, Q represent pressure difference and volumetric flow-rates, respectively. The 1st subscribes show the types (s: supply, r: return, L= story load) and the 2nd subscribes tell about the stories.

The pressure of the loop can be shown in Equation (7.3) with η as the total efficiency of pump and motor. As the Figure 7.2 shows, the Δp_n is the pressure of the network and the Δp_{ev} is the pressure difference of evaporator inlet-outlet.

$$\Delta p_n + \Delta p_{ev} = \eta \Delta p_{pump} \tag{7.3}$$

The pressure of network is composed of pressure of main pipes (Δp_s and Δp_r) and pressure of a story load (Δp_L), that generally can be formed as Equation (7.4).

$$\Delta p_n = \Delta p_s + \Delta p_r + \Delta p_L \tag{7.4}$$

The total load pressure is equal to load pressure at ground Δp_{L0} and accumulation of other load pressure added by pressure loss at shaft between the ground and the 1st floor. Equations (7.5) and (7.6) show the relationship of the pressures.

$$\Delta p_L = \Delta p_{s1} + \Delta p_{r1} + \Delta p_{n1} \tag{7.5}$$

$$\Delta p_L = \Delta p_{L0} \tag{7.6}$$

At the branches, Equations (7.7) and (7.8) take place.

$$Q_{Li} + Q_{S(i+1)} = Q_{Si} \tag{7.7}$$

$$\Delta p_{Li} = \Delta p_{si} + \Delta p_{ri} + \Delta p_{ni} \tag{7.8}$$

It can be inferred, that Equation (7.4) can be formed as Equation (7.9).

$$\Delta p_n = \sum_i \Delta p_{si} + \sum_i \Delta p_{ri} + \Delta p_{L12} \tag{7.9}$$

The flow-rate can be also shown as Equation (7.10).

$$Q_S = \sum_i Q_{Li} \tag{7.10}$$

According the Darcy Weisbach equation for the pipe, $\Delta p = f_D \rho 8LQ^2 / \pi^2 D^5$, therefore it can be formed Equations (7.11) and (7.12) that resembles the electricity equation with the current as volume flow-rate rather than mass flow-rate as Bejan did (Xia et al., 2010) for the reason of incompressibility of the fluid.

$$\dot{E} = \frac{f_D \rho 8LQ^3}{\pi^2 D^5} \tag{7.11}$$

$$R = \frac{f_D \rho 8LQ}{\pi^2 D^5} \tag{7.12}$$

The pressure head difference of the adjacent stories can be inferred as Equation (7.13). The first term is the height effect and the second is length effect.

$$\Delta p_{si} = \rho g \Delta h_i + \frac{f_D \rho 8 \Delta h_i Q_i^2}{\pi^2 D^5} \tag{7.13}$$

The Equation (7.13) emphasizes that the pressure difference of the shaft is proportional to the acceleration of the fluid flow along the vertical shaft. It also happens in horizontal pipes. While at the vertical shaft the potential part is in opposite direction between supply and return, therefore this part collapses in calculation.

Derivation of the pumping power against the pressure different can be shown as in Equation (7.14).

$$\frac{\mathrm{d}\dot{E}}{\mathrm{d}\Delta p} = 3C_1\Delta p^{\frac{1}{2}} \tag{7.14}$$

Equation (7.14) implies that power of pump is a function of pressure difference by power of 3/2. The derivation of power against flowrate gives Equation (7.15). The derivation of flow-rate against pressure difference is shown in Equation (7.16).

$$\frac{\mathrm{d}\dot{E}}{\mathrm{d}Q} = C_2Q^2 = 3\Delta p \tag{7.15}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}p} = C_1\Delta p^{-\frac{1}{2}} \tag{7.16}$$

For vertical pipe in multistory building, the flowrate of the vertical main pipe between two adjacent stories can be assumed as iterative function as Equation (7.17).

$$Q_{si} = \sum_{j=i}^{n} Q_j \tag{7.17}$$

Equation (7.13) implies that the pressure difference of vertical pipe is proportional to the height difference and the acceleration, then it can be formed Equation (7.18).

$$\frac{\mathrm{d}\dot{E}}{\mathrm{d}Q} = C_2 Q^2 + C_4 \qquad (7.18)$$

The first term comes from the pressure different of the kinetic and the second from the potential.

7.4 Results and Discussion

At current operational condition the power of pumping is the function of the total flow-rate. The total flow-rate is determined from Equation (7.1). The total flowrate is quadratic function of the pressure difference at evaporator. Therefore a pressure difference at evaporator determines power of the pump for distributing the chilled water. Applying single primary pump only for the system, the power of the pump for distributing the chilled water according the flow-rate is shown in Figure 7.3. The function of the pump can be determined from Equations (7.1), (7.2) and (7.3).

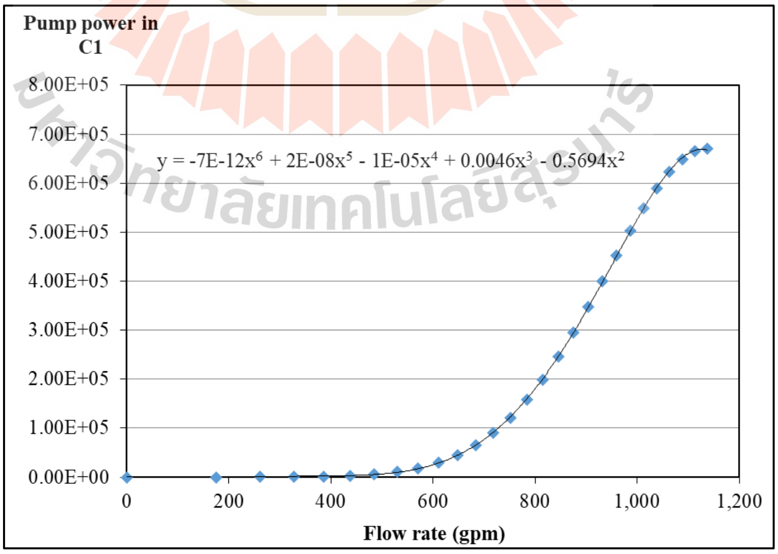


Figure 7.3 Pump power as function of chilled water flowrate. The power is scaled into C1.

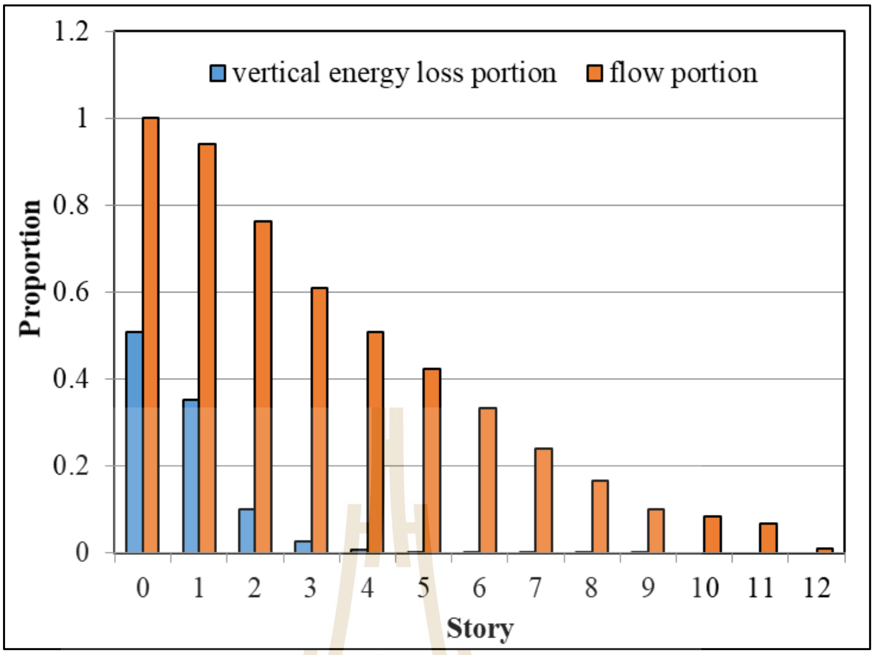


Figure 7.4 The distribution of energy loss in vertical shaft.

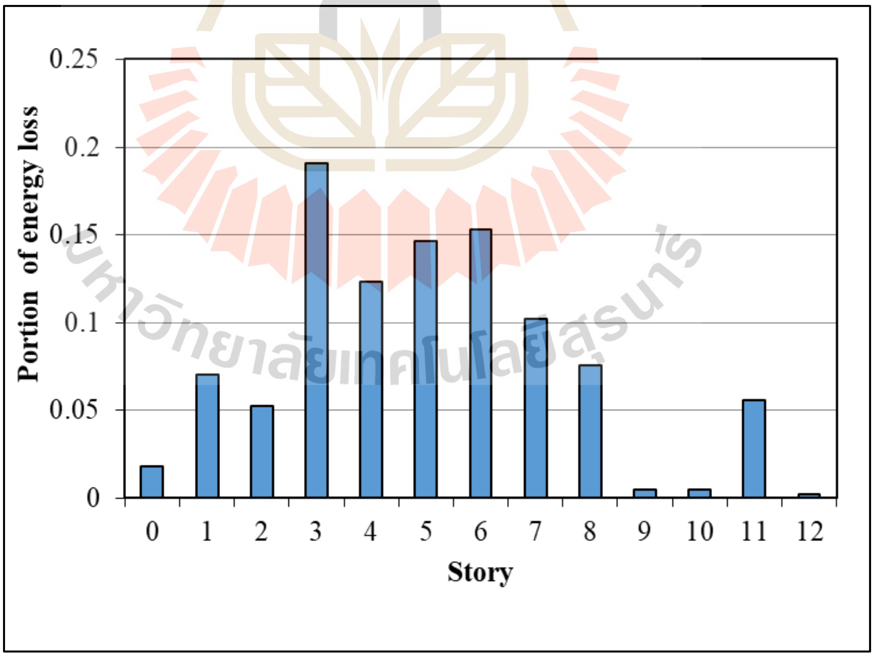


Figure 7.5 The distribution of energy loss in story.

The energy loss at vertical shaft and at the stories can be traced from Equations (7.13) and (7.15). Assuming the proportions of the flow rate are equal to the maximum capacity, the energy lost at vertical shaft can be shown in Figure 7.4. Transferring chilled water from the evaporator to the ground story chilled water network is the place where most of the vertical energy loss happened while transferring chilled water to the roof-top is the least energy consumer.

The energy loss at vertical shaft depends on flow-rate and the height. The distribution of the energy loss according the story shows that vertical effect is far less than energy loss at the story. The pressure loss at vertical shaft for the ground story is ranging from 0.0% - 0.25% of the total pressure loss. Flow rate is more dominant in determining energy loss in distribution of the chilled water than the height.

The maximum delta pressure of the story took place at the ground floor, but the minimum delta pressure happened at the rooftop. Range of the delta pressure between the inlet and outlet at the story is 565.1 - 568.1 kPa at 50 liter/second flow rate of the chilled water. The resistance of the flow at the equal chilled water flow rate shows different trend. The range of the resistance is 64.39 kPa s/m^3 at the 1st story until 1012.68 kPa s/m^3 at the rooftop. It is clear that the chilled water flow-rate at the 1st story is the highest and the lowest took place at roof-top. The complete pressure difference among inlet and outlet of the stories, flow rates of the chilled water at the stories, and the respective resistance are shown in Table 7.2.

Table 7.2. The pressure, flow rate, and resistance of the stories at 50 liter/second flowrate.

Story	Δp_{Li} (Pa sec/m^3)	Q_{Li} (liter/sec)	R_{Li} (Pa sec/m^3)
0	5.6611×10^5	2.90×10^0	1.95×10^5
1	5.6581×10^5	8.78×10^0	6.44×10^4
2	5.6555×10^5	7.57×10^0	7.47×10^4
3	5.6537×10^5	5.11×10^0	1.11×10^5
4	5.6526×10^5	4.11×10^0	1.37×10^5
5	5.6518×10^5	4.48×10^0	1.26×10^5
6	5.6513×10^5	4.59×10^0	1.23×10^5
7	5.6510×10^5	3.74×10^0	1.51×10^5
8	5.6508×10^5	3.22×10^0	1.75×10^5
9	5.6507×10^5	8.22×10^{-0}	6.87×10^5
10	5.6507×10^5	8.22×10^{-0}	6.87×10^5
11	5.6507×10^5	2.77×10^0	2.04×10^5
12	5.6506×10^5	5.58×10^{-0}	1.01×10^6

The pressure loss at stories is function of the chilled water flow rate. Figure 7.6 shows the relation of the pressure loss and the flow rate as a linear function. Increasing the chilled water flow rate increases the pressure loss at the stories linearly. The normalization of the system shows that the increasing takes place proportionally according to the flow rate.

Horizontal energy rate loss does not depend on the story position. But it depends on the flow rates and diameter of the pipes as shown in Table 7.1 and Table 7.2. The relation of the energy rate loss and the flow rate of chilled water is also presented in Figure 7.7. The resistance of the story is also a function of flow rate as shown in Figure 7.8. Considering relation of Equation (7.13), it shows that the coefficient is a function of flow rate which is confirming Figure 7.6. This condition emphasizes necessity of considering the constructal configuration at the story as mentioned by Xia et al. (2010).

Unequal distribution of the vertical and story energy loss shows the importance of reconfiguring the pumps of the chilled water in order to minimize the effect of loss. Controlling single primary pump as the current operational condition assumed equal distribution of the vertical and story losses. Increasing power of the pump will increase the water flow rate proportionally according to the valves setting. At this condition, losses at stories are assumed in accordance with the position. Adjustment of valves should be conducted to allow the change of flow rates. Optimum condition is hardly achieved as the reason of the distribution. In this case, flexibility is important due to interrelation as shown in Figure 7.6, Figure 7.7, and Figure 7.8. Secondary pumps in stories are suggested (Tarmizi, 2012).

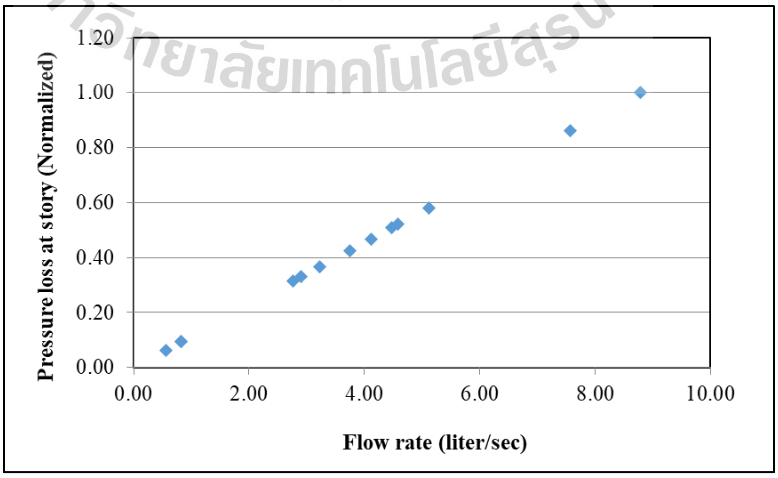


Figure 7.6. Pressure loss at stories as function of flow rate.

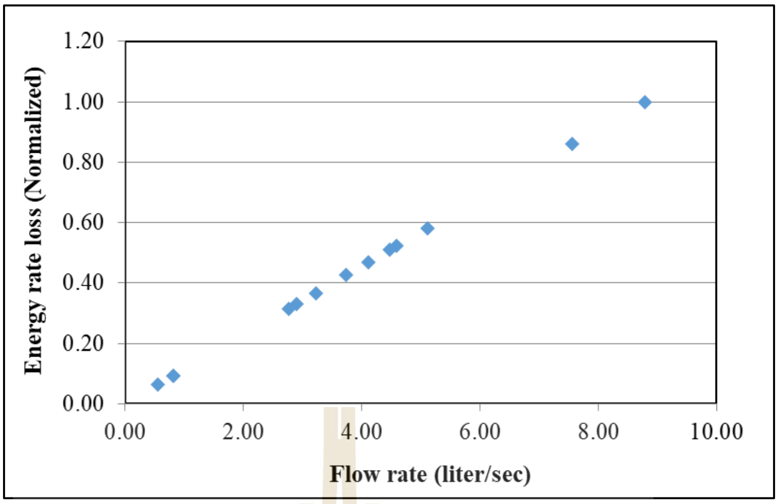


Figure 7.7 The energy rate loss as function of flow rate.

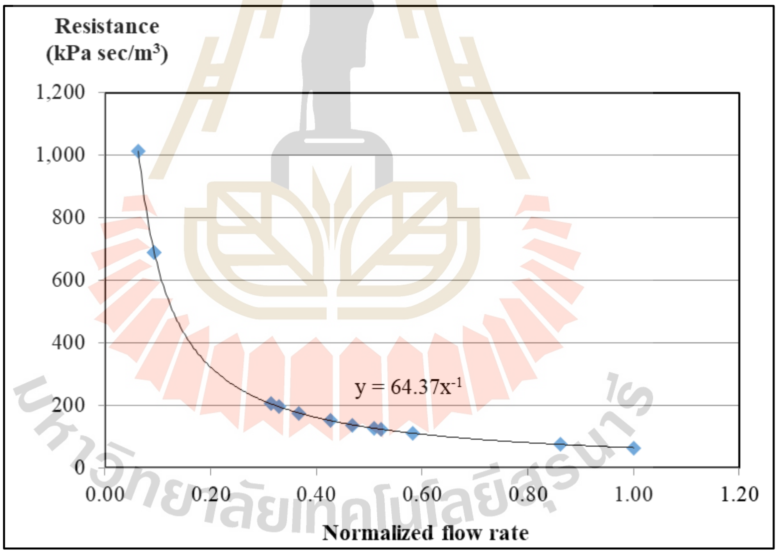


Figure 7.8 Resistance of the stories as function of normalized flow rate.

7.5 Conclusion

The constructal evaluation of the centralized HVAC system at SUTH main building was conducted in order to consider retrofitting the pump configuration. The work shows that distribution of losses at vertical shaft and stories are unequal.

The energy losses and pressure losses at the stories are linear function of flow rate in normalized way. The resistances of stories are inverse function of normalized flow rate. Simple configuration using single primary pump for the system has drawback of losses at some stories which do not need it. It is suggested applying secondary pumps in every stories

CHAPTER VIII

EXERGY ANALYSIS OF A WATER SYSTEM IN THE MAIN BUILDING OF SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL

8.1 Abstract

The other part of the SUTH main building consuming energy and water is the water system as shown in Chapter IV and V. This system consists of tap water system and wastewater system in addition to HVAC water system which has been evaluated in previous chapters. The following Chapter focuses on analysis of exergy toward the water system of the main building of SUTH.

Exergy is common for portraying the irreversibility existence in a thermal process and can be advanced with mechanical aspect. The analysis is very useful for describing the weak parts of process chain of a system. The water allocation of hospital buildings is characterized by high range of energy intensity that comes from multi water type requirement, level position and wastewater treatment. An analysis of water allocation network exergy was conducted for scrutinizing the weak part of the water system of the main building of Suranaree University of Technology Hospital (SUTH) and probing the pattern of exergy destruction over the system. The exergy of the system was based on the combination of thermodynamic and mechanical approaches for three options, i.e. existing system, 2 water tanks option, and harvesting condensate water from the HVAC. The room setting temperatures were 22 °C, 24 °C, and 26 °C.

The humidity was assumed to be 50% relative humidity. The current condition of 24 °C setting temperature became the reference for evaluating the system. The result shows that exergy destruction of distributing water is higher than water transferring and water processing. It also shows that HVAC is the user where most of exergy destruction takes place, accounting 94% of the total exergy destruction. HVAC setting affected on the energy of water consumption by 8.5% - 12.8%, but the number is insignificant in comparison to HVAC electricity consumption. The result emphasizes that flow rate is significant in reducing energy loss.

8.2 Introduction

Exergy analysis is considered as fairer method to evaluate the performance of a system than energy analysis method (Dincer and Rosen, 2007). The exergy analysis can provide thorough information of the performance quality as the method includes irreversibility which limits performance of a system. On the other hand, energy performance indicator such as energy efficiency neglects irreversibility that naturally takes place according the nature law. Therefore, energy analysis can mislead to a conclusion where the possibility does not exist. On the other hand, an exergy analysis has capability to point out the weak component of the system that can be applied for retrofit consideration or new design.

Exergy analysis has been applied for many fields in engineering but the water system of a building is still out of discussion. Exergy was applied in thermal energy system. It was reported that mixing of collector and heat pipes had higher efficiency than conventional collector system (Kargarsharifabad et al., 2014). The evaluation of thermal collector processes and some other processes were presented by Kalogirou et al. (2016). Their study included desalination and distillation. The exergy analysis effectively evaluated the exergy destruction at cooling system (Dincer and Rosen, 2015). It was reported that replacing R22 with R422D in air cooler decreased its efficiency by 20% (Aprea et al., 2014). An optimization of the cooling tower in a hybrid system consisting ground heat pump and HVAC system was studied by Singh and Das (2017) using exergy. The exergy analysis also became tool for evaluating power generation system using Kalina cycle (Nag and Gupta, 1998), combination of steamed coal power and Kalina cycle (Singh and Kaushik, 2013), combination of wind turbine power, heating and cooling storage (Mohammadi et al., 2017).

The study of a water system problem needs to involve of energy and water optimization. The water system is composed of water network problem and its operation. Some methods have been developed for solving the water network problem. Linear programming was conducted by Alperovits and Shamir (1977) for water distribution comprising elevation, pipe diameters, pumps capacity, and operational parameters. Hydrodynamics parameters and economic parameters were also used for optimization by genetic algorithms (Montesinos et al., 1999). Gray code for genetic algorithm was applied instead of binary (Dandy et al., 1996). Another heuristic method such as simulated annealing with economic parameter was applied for the problem (Da Conceição Cunha and Sousa, 1999). According to analysis type, the multiple objectives have been developed with Pareto Algorithm (Baños et al., 2011). The study of the water network problem with equipment constraint was conducted by energy analysis using pump operating as turbine (Carravetta et al., 2012). The exergy analysis has not been applied for the water network analysis yet, especially in a multi-story building.

The aim of the work is to propose application of a method of exergy analysis of water system and to apply it at the multi-stories hospital building water system involving water for HVAC, tap water transfer and distribution, and wastewater treatment. The building is SUTH (Suranaree University of Technology Hospital) main building. The water in the main building of SUTH is considered as important factor of the energy consumption. Consuming 82.7 m^3/day of water, the building scored 62% of the total SUTH water use. The electricity consumption of the water transfer and distribution was around 13% of the total electricity consumption of the building. The electricity consumption of the appliances was excluded.

Portraying water system analysis by exergy method is expected to extend understanding of the water system in a building. This understanding can be used to evaluate the water system of the building. Therefore, the exergy destruction and its locations can lead to better network and water system engineering in many levels. It is also expected to give insight of operation strategy.

Structure of the work consists of reason, method, result and conclusion. The reason shows the gap of the research of the field. The method section describes in detail the framework of water system, the way of estimating the water use of the stories, predicting the flow-rates of stories based on fixtures, calculating exergy destruction of water flows of the water transfer, water distribution system, and wastewater system. The total exergy destruction of the system is defined as the cumulative of the exergy destruction in each sub systems. The result and discussion as the sequenced part consists of energy and exergy destruction of the systems and its maps. Evaluation of the exergy flows is presented as the last part of the discussion. Finally, the conclusion as the wrap up of the system closes the work.

Exergy analysis has been applied for many fields in engineering but the water system of a building is still out of discussion. Exergy was applied in thermal energy system. It was reported that mixing of collector and heat pipes had higher efficiency than conventional collector system (Kargarsharifabad et al., 2014). The evaluation of thermal collector processes and some other processes were presented by Kalogirou et al. (2016). Their study included desalination and distillation. The exergy analysis effectively evaluated the exergy destruction at cooling system (Dincer and Rosen, 2015). It was reported that replacing R22 with R422D in air cooler decreased its efficiency by 20% (Aprea et al., 2014). An optimization of the cooling tower in a hybrid system consisting ground heat pump and HVAC system was studied by Singh and Das (2017) using exergy. The exergy analysis also became tool for evaluating power generation system using Kalina cycle (Nag and Gupta, 1998), combination of steamed coal power and Kalina cycle (Singh and Kaushik, 2013), combination of wind turbine power, heating and cooling storage (Mohammadi et al., 2017).

The study of a water system problem needs to involve of energy and water optimization. The water system is composed of water network problem and its operation. Some methods have been developed for solving the water network problem. Linear programming was conducted by Alperovits and Shamir (1977) for water distribution comprising elevation, pipe diameters, pumps capacity, and operational parameters. Hydrodynamics parameters and economic parameters were also used for optimization by genetic algorithms (Montesinos et al., 1999). Gray code for genetic algorithm was applied instead of binary (Dandy et al., 1996). Another heuristic method such as simulated annealing with economic parameter was applied for the problem (Da Conceição Cunha and Sousa, 1999). According to analysis type, the multiple objectives have been developed with Pareto Algorithm (Baños et al., 2011). The study of the water network problem with equipment constraint was conducted by energy analysis using pump operating as turbine (Carravetta et al., 2012). The exergy analysis has not been applied for the water network analysis yet, especially in a multi-story building.

The aim of the work is to propose application of a method of exergy analysis of water system and to apply it at the multi-stories hospital building water system involving water for HVAC, tap water transfer and distribution, and wastewater treatment. The building is SUTH (Suranaree University of Technology Hospital) main building. The water in the main building of SUTH is considered as important factor of the energy consumption. Consuming water of 82.7 m^3/day in 2017 the building water scored 62% of the total Suranaree University of Technology Hospital (SUTH) water usage in the same year. The electricity consumption of the water transfer and distribution was around 13% of the total electricity consumption of the building. The electricity consumption of the appliances was excluded.

Portraying water system analysis by exergy method is expected to extend understanding of the water system in a building. This understanding can be used to evaluate the water system of the building. Therefore, the exergy destruction and its locations can trigger better network and water system engineering in many levels. It is also expected to give insight of operation strategy.

Structure of the work consists of reason, method, result and conclusion. The reason shows the gap of the research of the field. The method section describes in detail the framework of water system, the way of estimating the water usage of the stories, predicting the flow-rates of stories based on fixtures, calculating exergy destruction of water flows of the water transfer, water distribution system, and wastewater system.

The total exergy destruction of the system is defined as the cumulative of the exergy destruction in each sub systems. The result and discussion as the sequenced part consists of energy and exergy destruction of the systems and its maps. Evaluation of the exergy flows is presented as the last part of the discussion. Finally, the conclusion as the wrap up of the system closes the work.

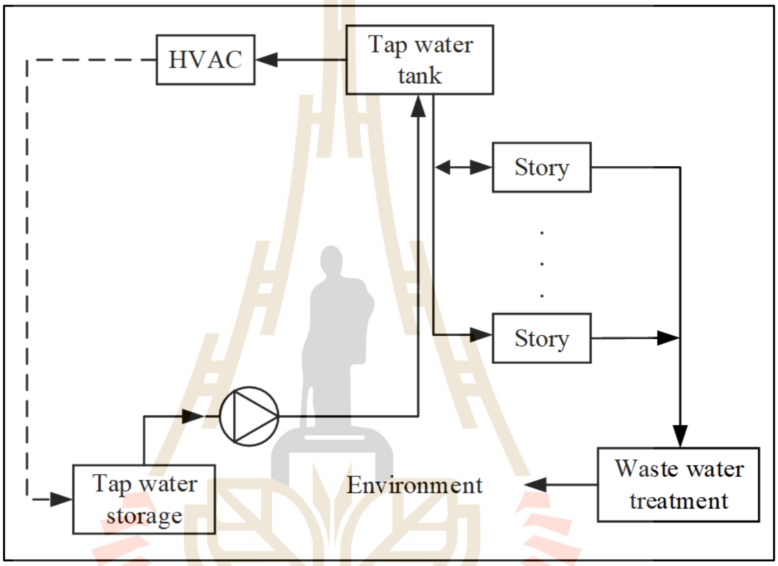


Figure 8.1 The water system of SUTH main building. The dashed line shows the potential process that currently does not exist.

8.3 Methodology

8.3.1 The Water System Framework

Analyzed water system of the SUTH main building consisted of water transfer and distribution system, water use and production of the HVAC system, and wastewater treatment as shown in Figure 8.1. All water used for the building operation was extracted from the raw water system of Suranaree University of Technology and stored at the tap water storage. This tap water storage was located on the ground. Then the water was transferred to the rooftop tank and distributed to all users. After use, the water was collected and transferred to the wastewater treatment facility, except the water that went to the cafeteria. It was collected and managed separately in another facility.

Two pumps of 11 kW capacities alternately worked to transfer the water from the ground storage to the tower tank at the rooftop through main pipes. The route was started by 4-inch pipe of 2 m length. Then, the water moved to vertical 6” pipes connected ground floor and the rooftop tank through 48 m of 6” pipes with 7 of 90^o elbows. All these pipes were schedule-40 type pipes. The rooftop tank was located 52 m above the ground. These pumps worked in single speed which its efficiency depends on the head. According to the manual, the head determined the flow-rate rated at 11 liter/sec with efficiency of 66% (Regent Pump Australia, 2008). The pressure loss at the transferring pipe was calculated using Darcy-Weisbach equation and its equivalent length for the components. The pressure head equivalent of the potential was added for calculating the power of pump. The invers of efficiency was applied for calculating the electricity power supplied for the pumps. Therefore, the energy consumed for transferring the water can be shown in Equation (8.1).

$$E_c = \frac{(\Delta P.Q)}{\eta} T_{op} \tag{8.1}$$

Amount of water distributed to stories depended on inhabitant number of the stories and other use determined by some weighting factors as shown in Table 8.1. The unit of the inhabitant was people day equivalent (pde) which is equal to a person staying 24 hours in the hospital. The inhabitant was calculated from the number of staff, number of inpatient and number of outpatient. A staff was assumed to stay 8 hours per day as time of a worktime shift. The inpatients stayed for 24 hours a day. An outpatient was assumed to spend 2 hours in a visit. The water use per person coefficient was taken from case of Tata medical center (Collett et al., 2016) in Kalkota, India. The water use in a story was differed into water for flushing, hand washing, showering, and other necessity which depended on type of clinics. Water for other functions of the hospital operation such as delivery, surgery, dental, hemodialysis was also calculated by similar weighting method. The laboratory weight was based on the staff number per hour. The HVAC water was taken from the simulation of the building HVAC operation. The cafeteria weight was calculated as the rest of the water consumed. The number was nearly cafeteria water requirement reported (Bonnema et al, 2010). Numbers of inhabitant, types of coefficient of water use and the amount of the water consumption in stories are presented in Table 8.1. The water use of the story was be calculated by Equation (8.2).

$$W_s = I\left(C_f + C_b + C_s\right) + W_a\left(C_{lb} + C_d + C_{sur} + C_h + C_m + C_{cafe}\right) \tag{8.2}$$

The water distribution into users at stories was supported by 3 inches vertical main pipe. In every story, the main pipe had branches for distributing the water at the story. Different sizes of the pipe were applied. Valves adjustments were provided to fit the water flow at the fixture according to the codes. Distribution of the fixture at every story is shown in Table 8.2. There are basin, flush and shower as the types of fixtures. The basin is used for hand washing function representation. The flush represents the water for cleaning the closets or urinals. The water flow rate for the basin and flush was 9 liter/minute (BIS and Cranfield University, 2009). This flow rate was slightly less than a shower flow rate of 9.5 liter/minute (BIS and Cranfield University, 2009). Other in Table 8.2 represents another use of water at the story such as producing RO for laboratory, preparing water for baby delivery, HVAC and cafeteria use. These uses were calculated based on flush flow-rate codes. The 11th story of Table 8.2 includes roof top (RT) use for HVAC as shown in Table 8.1. Practically, roof top room was used for medical equipment storage with minimum inhabitant.

Table 8.1 The story, inhabitant, coefficient and the story water use.

Story	**Inhabitant (pde)**	**Additional Weight (W_a)**	**Used Coefficient**	**Story Use (m^3)**
UG	18	11.9	C_f, C_b, C_s, C_{cafe}	14.53
1	55		C_f, C_b, C_s	8.24
2	23	4.67	C_f, C_b, C_s, C_{lb}	3.76
3	23	39	C_f, C_b, C_s, C_d	3.71
4	7		C_f, C_b, C_s	0.99
5	13	3.3	C_f, C_b, C_s, C_{sur}	2.27
6	5	1.6	C_f, C_b, C_s, C_{sur}	0.96
7	14		C_f, C_b, C_s	2.13
8	17	15	C_f, C_b, C_s, C_h	7.55
9	25		C_f, C_b, C_s	3.77
10	29		C_f, C_b, C_s	4.30
11	17		C_f, C_b, C_s	2.57
RT	1	23.9	C_f, C_b, C_s, C_m	27.96

By C_f = Flush coefficient (50.4 l/pde)

C_b = Basin coefficient (29.84 l/pde)

C_s = Showering coefficient (42.2 l/pde)

C_{lb} = Laboratory use coefficient (68.9 l)

C_d = Coefficient of dental (6.5 l)

C_{sur} = Surgery/Delivery coefficient (100 l)

C_h = Hemodialysis coefficient (200 l)

C_m = Makeup coefficient (1 m^3)

C_{cafe} = Cafeteria coefficient (1 m^3)

The daily water use of the story was transformed into average flow rate of the story. Distribution of fixtures determined the average flow rate at story. The probability distribution of the same type fixtures use followed binomial equation as shown in Equation (8.3) which was proposed by Hunter as in Ref (Buchberger et al., 2015).

$$P_{fr} = \left(C_r^n\right)\left(\frac{t}{T}\right)^r\left(\frac{T-t}{T}\right)^{n-r} \tag{8.3}$$

By t = time of one fixture use, T = window time, n = number of fixtures, r = number of fixtures in use. C_r^n is the combination of n fixture with r number in use.

$$T = \frac{T_{op}n}{N_{usage}} \tag{8.4}$$

Window time was determined from the story fixture use in operation time of the building. The building was assumed to operate 14 hours a day for out-patient clinics, and 24 hours for the wards. The clinics were open at 08.00 a.m. – 10.00 p.m. Even the wards operated 24 hours, but probability calculation time used 14 hours base. The window times of the fixture were calculated by Equation (8.4). T_{op} was operation time of the story and n being the number of fixtures at the story. N_{usage} was number of fixture use at the story.

The number of uses was calculated from coefficient of use per person a day by Equation (8.5). N_{in} was person daily equivalent number inhabitant in a story and C_{usage} was the coefficient of daily use by a person in a day (CSE, 2010). This use was equivalent to fixture flows as shown in Ref (BIS and Cranfield University, 2009).

$$N_{usage} = C_{usage} N_{in} \tag{8.5}$$

Table 8.2 Fixtures of SUTH main building and its daily average water use.

St	Fixtures			Use (liters/day)			
	B	**F**	**Sh**	**B**	**F**	**Sh**	**O**
UG	4	5	2	527.1	890.4	1211.1	11900.0
1	46	39	1	1651.9	2790.6	3795.6	
2	33	30	3	689.2	1164.2	1583.4	321.6
3	24	16	5	692.7	1170.2	1591.7	253.2
4	11	19	1	198.9	336.0	457.0	
5	16	11	2	386.5	652.9	888.0	330.0
6	25	17	4	160.3	270.8	368.0	160.0

Table 8.2 Fixtures of SUTH main building and its daily average water use. (Cont.)

St	Fixtures			Use (liters/day)			
	B	F	Sh	B	F	Sh	O
7	26	17	4	427.6	722.4	982.6	
8	15	16	1	511.4	863.5	1175.0	5000.0
9	9	11	4	755.8	1276.9	1736.7	
10	8	15	2	862.6	1457.1	1981.9	
11	34	20	16	515.2	870.2	1183.6	27960.0

St : Story, B : Basin, F : Flush, S : Shower, O : Others, the 11th story includes roof top (RT)

The total flow of the fixture was cumulative of the probability configuration of every fixture in a story. The total flow was determined as shown in Equation (8.6).

$$\dot{V}_f = \sum_r \left(P_{fr} C_{fr}\right) \tag{8.6}$$

C_{fr} was code for r number fixtures in use. Then, the flow rate of the water at a story could be calculated by Equation (8.7)

$$\dot{V}_s = \sum \dot{V}_f \tag{8.7}$$

The water flow rate of the story as shown in Equation (8.7) determined use time of water at the story. Combining Equation (8.2) and Equation (8.7) provided time of use. The flow rate of every story was also applied for calculating the vertical main pipe rate. Flow of water at vertical main pipe was cumulative of the stories flows. For example, flow at vertical pipe to 8th floor consists of flows of ground to 8th floors. Therefore flow on vertical pipe was able calculated by Equation (8.8).

$$\dot{V}_{vs} = \sum_{i=0}^{s} \dot{V}_s \tag{8.8}$$

8.3.1.1 HVAC Water

The HVAC water consisted of water softening, blowdown, and condensate water. Water softening provided make-up water for cooling tower. The make-up water was equal to amount of water evaporated at cooling tower and the blowdown. According the former work (Prasetyadi and Koonsrisuk, 2019), the amount of the make-up water followed Equation (8.10) with the blowdown presented in Equation (8.9). V_{bw} and V_m were the blowdown water and make-up of evaporated water, respectively. The evaporated make-up water was determined from the simulation of the HVAC as in former work (Prasetyadi & Koonsrisuk, 2019).

$$V_{bw} = \frac{V_m}{5}.V_{cdw} \tag{8.9}$$

$$V_w = V_m + V_{bw} \approx \frac{6}{5} V_m \tag{8.10}$$

The centralized water chiller HVAC system was applied at the SUTH main building. The water of the chiller was closed system except the condenser water which can be evaporated at the cooling tower and added by make-up water. The chiller system analysis was conducted following the former work (Prasetyadi and Koonsrisuk, 2019).

The potential water production was applied in simulation of the HVAC. It could become alternative source of water. The condensate water was potential water that was potential to be collected from the HVAC as the result of temperature and humidity adjustment. As shown in former work (Prasetyadi & Koonsrisuk, 2019), requirement of outdoor air and air change of HVAC in combination with setting temperature reduced amount of water vapor in the air.

The hospital HVAC was assumed to work at 26 ^{o}C, 24 ^{o}C, and 22 ^{o}C. The 24 ^{o}C setting temperature was the current operational setting. Alternative setting temperature of 22 ^{o}C, and 24 ^{o}C were proposed as alternative setting. The dead band of the temperature was ±2 ^{o}C. The relative humidity of the system was set to be 50%. The average outdoor air for the system of 15,120 m^3 air volume of the HVAC was 0.3 with air change rate of 3.3. It meant that every hour 0.3 of air volume or 5,000 m^3 of outdoor air was pumped into room with its temperature and humidity parameter. The coil system circulated around 50,000 m^3/hour air.

8.3.1.2 Wastewater

The wastewater treatment of SUTH main building is a kind of two steps wastewater treatment composed of primary and secondary treatments (Wakeel et al., 2016). The system has two aeration treatment tanks where the wastewater is aerated and mixed with activated sludge. At both places, aeration is intended to increase oxygen contain of the wastewater in order to degrade the organic contain and oxidize some metals or minerals. These parts are called continuous aeration tank (CAT) and sequence aeration tank (SAT). Both systems operate 4 kW motor for pumping. After aerated, the wastewater is pumped to chlorination tank for chlorine addition and sludge removal. The activity diagram of the wastewater processing is shown in Figure 8.2.

CAT and SAT had pump capacity 150 m^3/hr for circulating the wastewater. The circulator injected 1.1 kg/kW oxygen every hour. The CAT operated 2 hours every batch. The SAT was set to work for 1 hour in a batch. A transfer pump of 150 m^3/hr capacity with 3 kW motor was applied to transfer the water among the tanks. The decanter capacity to separate the water from the sludge worked with the capacity of 64.8 m^3/hr. The capacity of the decanter limited and determined the operation time of the system.

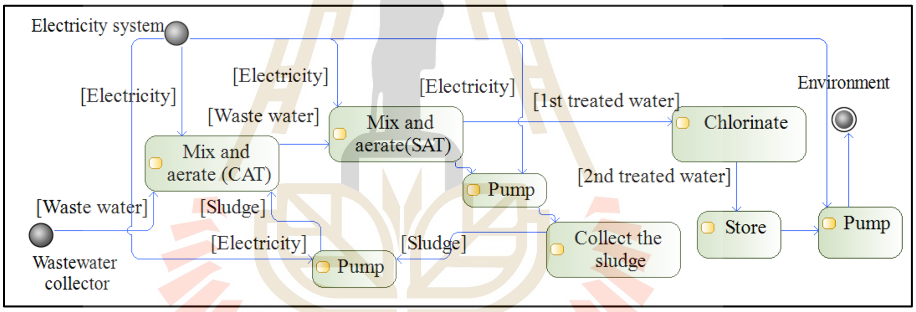


Figure 8.2. The activity diagram of wastewater treatment (Prasetyadi & Koonsrisuk).

Amount of water treated at the wastewater treatment was the total water use of the building excluding the cafeteria and the water evaporated at the cooling tower. At current operation condition, it also did not account on condensate water as it was not collected yet. The water of the cafeteria was treated in different method and place. Therefore, amount of the water treated at the wastewater treatment was calculated by Equation (8.11).

$$V_{ww} = V_u - V_{cafe} - V_m \tag{8.11}$$

8.3.2 The Exergy of the Water System

The exergy analysis of water system comprised exergy analyses of HVAC system, water transfer and distribution system, and wastewater system. The exergy of HVAC was a kind of exergy of moist air and water system. The HVAC component, basically were composed of heat exchanger and pump systems. The water distribution and wastewater system was a kind of exergy of water system only. Pump was the only component for the water system in addition to piping. Therefore, transferring water in pipe was also a kind of exergy source.

Heat exchanger had function to transfer heat from a fluid to other fluid. The exergy destruction of a heat-exchanger was provided in Equation (8.12). $\dot{E}x_{f1,in}$ and $\dot{E}x_{f2,in}$ were the exergy of the input fluid 1 and fluid 2, respectively. $\dot{E}x_{f1,in}$ and $\dot{E}x_{f2,in}$ were the exergy of the output of the fluid 1 and fluid 2, respectively. Exergy destruction in a heat exchanger consisted of thermal and mechanical exergy.

$$\dot{E}x_{f1,in} + \dot{E}x_{f2,in} - \dot{E}x_{f1,out} - \dot{E}x_{f2,out} - \dot{E}x_{des} = 0 \tag{8.12}$$

Pump was kind of active element where energy was added for work. The exergy destruction of pump system was calculated by Equation (8.13) which also indicates that the pumps were electric pump. $\dot{E}x_{in}$, $\dot{E}x_{out}$, $\dot{E}x_{el}$ and $\dot{E}x_{des}$ were input exergy rate, output exergy rate, electricity exergy rate, and exergy destruction rate, respectively.

$$\dot{E}x_{in} - \dot{E}x_{out} + \dot{E}x_{el} - \dot{E}x_{des} = 0 \tag{8.13}$$

For the water transfer and distribution, pump was applied in supplying the water system from the ground tank to the rooftop tank. Then the water is distributed to the stories according to their needs.

Wastewater system consists of some pumps to do its function as mentioned in previous section. It was clear that Equation (8.13) was also applied for the wastewater system. Pumps were applied for aeration and transforming wastewater to chlorination tank and vice versa. Assuming that the pressure of the system did not change and the speed of the system was constant before it was released to the environment, the exergy destruction was equal to the electricity used for water treatment. The wastewater system was a dissipative system where the exergy added will loss.

The exergy destruction at the pipe for water distribution was determined from pressure loss and velocity loss. While the water was considered as incompressible fluid, the effect of volume difference due to pressure was neglected. Therefore, it was possible to calculate the exergy destruction of the water distribution as the energy loss of distributing water.

The pressure loss at the main pipes was calculated using Darcy-Weisbach equation with coefficient 0.019. Assuming that velocity of the main pipe was cumulative as shown in Equation (8.15), the pressure loss should be calculated piece by piece according to the flow rate. The Darcy-Weisbach was applied in every adjacent stories pipe.

The energy loss of water distributing in a story was determined from the pressure difference between the main pipe pressure and output pressure at the fixture. The output pressure of the fixture was 8 psi as the code asked. The outlet pipes in stories were assumed ¾". The pressure of the input for a story was calculated by Equation

(8.14). P_{rt} was assumed 1 bar, while $P_{s,in}$ and ΔP_{mp} were the pressure at inlet of the story and pressure difference between roof top tank and inlet of the story.

$$\Delta P_{mp} = P_{rt} - P_{s,in} \tag{8.14}$$

The pressure and velocity differences between inlet of story water network and the outlet were applied to determine the energy loss at the story. The Bernoulli's equation was performed to calculate the energy loss assuming there were pressure and kinetic aspect.

To determine the pressure loss during transferring water from the storage tank on the ground to the rooftop distribution tank, Equation (8.15) was used. Equation (8.15) was interpolation of the pressure drop of schedule 40. Δh_{rs} was the height difference between rooftop tank and the storage, the elbows length equivalent and horizontal pipe length. $\dot{V}_{pump}$ was the flowrate of the pump.

$$\Delta P = 806.89\, \dot{V}_{pump}^{1.868}\, \Delta h_{rs} \tag{8.15}$$

The pump efficiency was determined from the performance of the pump as provided by the manufacturer. The efficiency of the pump (η_{pump}) was applied for calculating the energy consumption for the transferring water from the ground storage to the roof tank. Electricity consumption for the system could be calculated by following Equation (8.16). $\dot{E}_{pump}$ was the electricity power of the pump and T_{op} was the operational time.

$$E_C = \eta_{pump} \dot{E}_{pump} T_{op} \tag{8.16}$$

The operational time was determined from the daily water necessity and the flow rate that was supplied by the pump in operational condition. The operational time was calculated by Equation (8.17)

$$T_{op} = \frac{W_d}{Q_{pump}} \tag{8.17}$$

8.4 Results and Discussion

Electricity use of the water transferring from the underground storage to the rooftop tank according to Equation (8.1) was 18.5 kWh in a day. The energy transfer coefficient for the water was 0.22 kWh/m^3. Rated power of the pump was 11 kW and it had 66% efficiency for the current operational condition. Pump worked for 2.1 hours averagely in a day to provide 82.7 m^3 of water at the rooftop tank storage. For the head of 52 m, the flow rate of the installed pump is 11 liter/second (Regent Pump Australia, 2008). The pressure difference for compensating pressure loss and potential head was 5.14 bar. With addition of kinetic energy difference of the water flowing inside the 4-inch pipe, it was calculated that the power of the flow was 5.81 kW. The number was the effective of supplied electricity power.

Applying Equation (8.2) with respective weight of the story was used to calculate story water use as shown in the last column of Table 8.1. The total water use of the stories excluding the cafeteria use and HVAC was 43 m^3. A total of 11.9 m^3 water went to cafeteria use and 27.96 m^3 water was used for HVAC. The cafeteria water use is in accordance with the water use of a dense cafeteria of 107 person per 100 m^2

(Bonnema et al., 2010). The current operation only had 47.7 m^3 wastewater going to wastewater treatment facility. The wastewater consisted of wastewater of story use and blowdown of the cooling tower. Flow of water in the system of the current operation is shown in Figure 8.3.

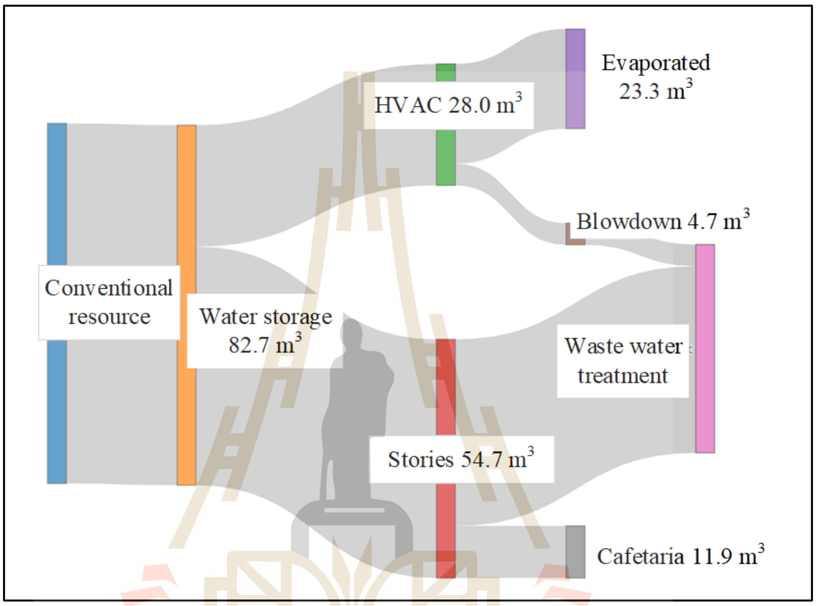


Figure 8.3 Flow of the water at current operation.

The fixtures distribution at stories could be used to estimate average water flow rate of the stories. Probability of the distribution was calculated for every type of fixture using Equation (8.3). Fourteen hours daily operation was applied in calculating the distribution of water use at the fixtures. Neglecting the rest hours due to operation time of the hospital, the flow rates of the water at stories are provided on Table 8.3. Flow rate of a story was accumulation of fixture flow rates as calculated by Equation (8.7) and additional weight of Table 8.1.

Table 8.3 The flow rates of the story according to the fixture.

Story	Basin (lpm)	Flush (lpm)	Shower (lpm)
UG	0.63	1.10	1.44
1	1.97	3.32	4.52
2	0.82	1.38	1.88
3	0.82	1.39	1.89
4	0.24	0.40	0.54
5	0.46	0.78	1.06
6	0.19	0.32	0.44
7	0.51	0.86	1.17
8	0.61	1.03	1.40
9	0.90	1.52	2.07
10	1.03	1.73	2.36
11	0.61	1.04	1.41

The exergy destruction rate as the energy loss rate at the story during distribution water from the distribution tank to users was 0.59 kW. The loss rate can be decomposed into vertical flow loss, horizontal potential loss and horizontal kinetic loss. The vertical loss was energy loss in vertical main pipe. The amount of vertical loss was far smaller than horizontal loss because of the pipe size of vertical was larger than horizontal pipe. Control valves to limit the pressure and flow rate of the fixture were causal factor. Pressure loss in horizontal network at the story was more significant than velocity loss. Controlling pressure was the reason of this condition. Exergy destruction due to pressure loss is linear to the story. The higher is the story, less exergy destruction is because of the pressure loss. The pressure loss in a story is determined by the position of the story inlet which depends on the position of the story as shown in Figure 8.4 which presents the pressure loss exergy destruction rate in secondary vertical axis. This axis shows exergy destruction rate (W) because of pressure loss for every m^3 transferred of 1 story. As the story height is 4.2 m, therefore the pressure loss exergy destruction per m is -1.9×10^{-1} W/liter. The output pressure was determined by the code of the fixture. Most fixtures have outlet pressure requirement 8 psi BIS & Cranfield University, 2009.

The exergy destruction of velocity loss increases according to the story position as shown in Figure 8.4 using primary vertical axis. The axis shows the exergy rate in watt. The graph is power function in order of 3. As the velocity is proportional to flow rate, the exergy destruction related to velocity is quadratic of the velocity. The exergy destruction rate of the velocity becomes zero as the velocity of the flow is 0.074 m/s.

The exergy destruction due to pressure loss is more dominant in lower stories than the exergy destruction affected by velocity loss. At the higher stories, the exergy destruction because of velocity loss is more significant. The floor 6th becomes the places where exergy destruction rates because of pressure loss and velocity difference are comparable. Therefore, minimizing exergy destruction because of the pressure loss can be done with creating water tank every 6 stories. Too many stories difference can create exergy destruction because of pressure loss. Applying tank storage for more than 6 stories also creates inefficiency.

Generally, the exergy destruction of water distribution is function of inhabitant as shown in Figure 8.5. Excluding the ground floor and the rooftop, the graph shows a linear relation of exergy destruction and inhabitant number. Every inhabitant a day contributes 1 W of exergy destruction of the water distribution.

Exclusion of the ground floor and rooftop is because the cafeteria and HVAC use. The ground floor has cafeteria use which is very dominant. It also happens to the rooftop as it also places of water for HVAC. Both numbers are very dominant to the use of hospital. Cafeteria and HVAC water use are 14% and 34% of the building water use respectively. The water use of inhabitant was 54.3% of the total water use of the building.

There is also pressure loss during transferring water from the tap water storage to the roof top tank storage. This pressure loss created power loss as much as 39 watt. At the same time, the pump increased the pressure by 5.1 bar which is proportional to transformed power of 5.6 kW. While the efficiency of the pump was 66%, the electricity for the pump was 8.8 kW. As the system needed to operate pumps 2.08 hours, the electricity consumption of the pump was 18.5 kWh daily.

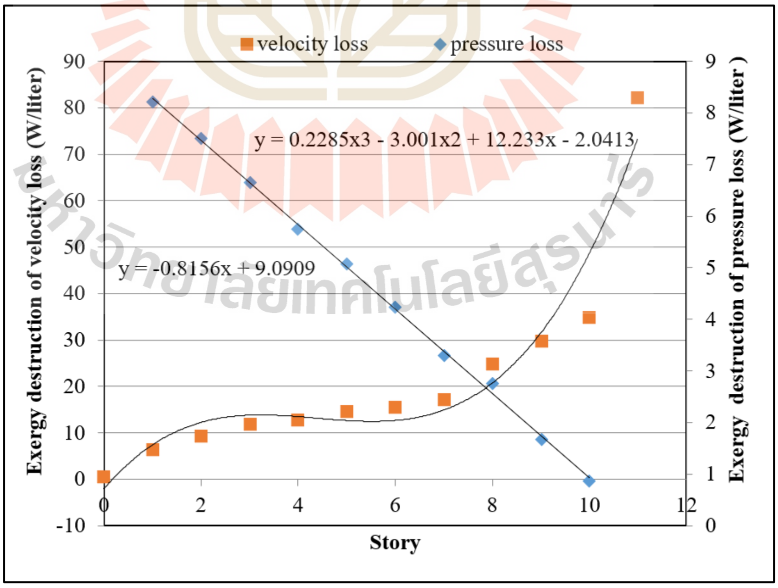


Figure 8.4 The exergy destruction of pressure and exergy velocity.

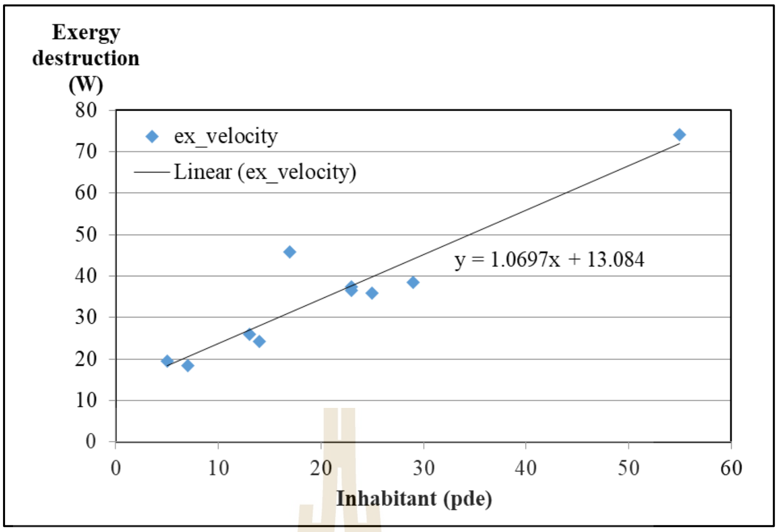


Figure 8.5 Exergy destruction as the function of inhabitant.

The intensity of recorded wastewater treatment was 0.343 kWh/m^3. It spent nearly 20 kWh of electricity per day for treating wastewater. The wastewater treatment system had two steps aeration. Each aeration system had a pump of 4 kW and had capacity 1-1.2 kg O_2/kW hr. It had also a 3 kW pump for returning the sludge and decanting. The aerations had capacity of 150 m^3/hr. The decanter had capacity of 64.8 m^3/hr. While every batch process was set to be 2 hours to make the smallest capacity fit into maximum daily processed wastewater.

The HVAC system destructed exergy with rate of 167 kW. As shown in Table 8.4, the distribution of exergy destruction according to the equipment of the system were 19.5 kW, 18.1 kW, 8.9 kW, 12.10 kW and 0.0 kW for coil fans, chiller pumps, condenser pump, chiller and cooling tower, respectively. The chiller was the system destructing most of the exergy supplied as it is also the main energy consumer of the system of water cooling type (Perez-Lombard et al., 2011). The chiller pumped heat from chiller water to condenser water by vapor compression refrigeration. The vapor compression system comprises of evaporator, condenser, expansion equipment, and compressor. Generally, compressor is the equipment where most exergy destruction of the chiller takes place (Jain and Alleyne, 2014). All the system worked below the environment temperature as the dead state.

Adjustment of room temperature setting affected HVAC exergy destruction rate. It is shown in Figure 8.6 that reducing setting temperature into 22 ^{o}C from the current setting of 24 ^{o}C increased the exergy destruction rate of FCU, CHP, CDP, Chiller and Cooling tower by 87%, 116%, 100%, 98%, and 46%, respectively. It means that all of the equipment became work harder by reducing temperature setting by 2 ^{o}C. The chiller water pump has the highest increasing of exergy destruction rate. Energy consumption rate in this condition increases from 1.8 GWh per year to 2.3 GWh per year or 27%. It implies that reducing setting temperature made the system work less efficiently. Increasing of exergy destruction rate is higher than increasing of the energy consumption.

Figure 8.6 also shows that increasing setting temperature from 24 ^{o}C to 26 ^{o}C reduced the exergy destruction rate. FCU, CHP, CDP, Cooling Tower reduce its exergy destruction by 24%, 27%, 25%, and 27% respectively. The chiller, where most of exergy destruction rate happens, reduces its exergy destruction rate by 10%. As the energy consumption of the HVAC system decreases by 26%, the system in 26 ^{o}C shows slightly higher efficiency than the operation at 24 ^{o}C. The FCU, CHP, CDP and Cooling Tower relatively worked in similar efficiency. But the chiller became less efficient in this condition. It reduces only 10% exergy destruction rate. While energy consumption of the chiller is dominant (Prasetyadi and Koonsrisuk, 2019), it can be inferred that generally, increasing setting temperature from 24 °C to 26 °C slightly reduces efficiency all of the system.

Alternative water production increases by reducing temperature setting into 22 °C from 24 °C current setting. The setting temperature change does not change the exergy destruction rate for the water transferring, but increasing exergy destruction rate for water distribution. It happens as the pumping process condition does not change. But the amount of water increases. The exergy destruction rate increases by 3%. Energy consumption for water increases by 12%. It shows that water system becomes more efficient.

Table 8.4 The exergy destruction rates of the water network equipment.

System	Equipment	Exergy rate (kW)
HVAC	Coil Fans	19.48
	CH Pumps	18.12
	CD Pumps	8.92
	Chiller	120.98
	Cooling Tower	0.03
Tap water	Distribution	3.26
	Transferring	0.59
Wastewater	CAT	2.79
	SAT	2.79
	Transferring pumps	2.04

Increasing temperature setting to be 26 °C from current setting of 24 °C reduces alternative water production. It also reduces exergy destruction rate during distribution by 2% and does not change the exergy destruction rate of water transferring at the same time. Energy consumption of the water transferring decreases by 8.5%. It also shows that the system is less efficient as energy consumption decreasing higher than decreasing of exergy destruction rate.

Alternative operation was proposed with 2 tank storage system for water as shown in Figure 8.7 on the right side. The current operation had 1 tank on the rooftop which supplied all the stories as shown in Figure 8.7 on the left side. At the current operation, the tap water was transferred to the rooftop tank by single pump. Then it was distributed to the stories through single main pipe. Alternatively, an additional tank on 8th floor was applied for supplying the ground until 4th floor. It implied additional main pipe for transferring water and its pump. Therefore, there were two pumps for pumping to the rooftop tank and 8th floor tank.

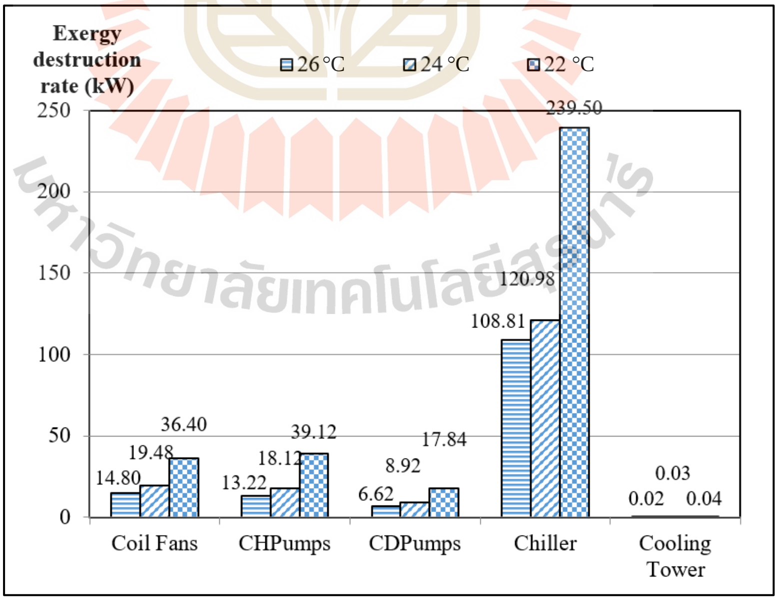


Figure 8.6 Effect of temperature adjustment to exergy destruction rate of HVAC Equipment.

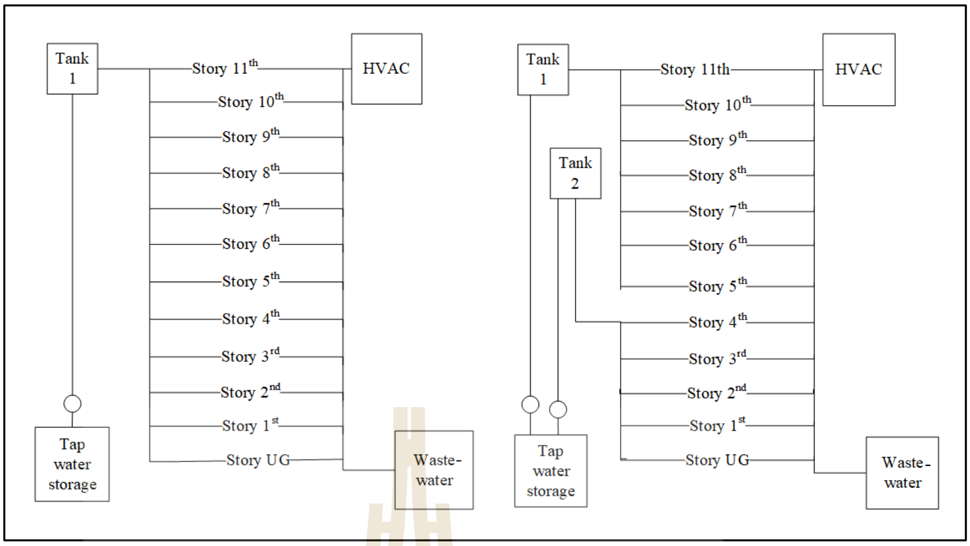


Figure 8.7 The water system with single tank storage (left) and its alternative of 2 tank storage (right).

Two tanks use has different trend with current operation. Increasing temperature setting increases the exergy destruction rate for water distribution. The energy consumption of single tank for 26 ^{o}C, 24 ^{o}C and 22 ^{o}C temperature setting are 16.9 kWh/day, 18.4 kWh/day, and 20.8 kWh/day, respectively. The system with 2 tanks has electricity consumption for water transferring 14.7 kWh/day, 16.3 kWh/day, and 18.6 kWh/day for 26 ^{o}C, 24 ^{o}C and 22 ^{o}C temperature setting, respectively. The energy consumption for water transferring increases as the temperature setting reduces. It needs more energy to transfer more water. The exergy destruction of water distribution at 2 tank storage system has increasing exergy destruction rate as the temperature setting decreases as shown in Table 8.6. Less setting temperature needs more water for cooling tower. As the cooling tower is located at the rooftop, then effect of water distribution becomes less significant. Therefore, exergy destruction of the water distribution only has slight difference affected different temperature setting. The difference takes place only on exergy destruction of transferring water to the rooftop and distribution on the roof top floor.

There would be 2 kWh electricity saving in a day by applying 2 storage tank system. As the price of electricity is capped as much as 4.6 Baht, it only saves 9 Baht a day. This number is insignificant with the price of installation to apply 2 storage tanks. This installation includes additional tank and additional pumps. Application multi tanks for tap water distribution can be applied since the design as it will less index of energy excess as shown in Ref (Baños et al., 2011).

Applying temperature setting has significant effect into operation cost of HVAC and water use. Changing the temperature setting into 26 ^{o}C can reduce electricity cost of HVAC by 2.1 million Bahts yearly. Reducing temperature setting to be 22 ^{o}C increases electricity cost by 2.2 million Bahts yearly. At the same time, it only affects less than 4,000 Bahts in a year at the electricity cost of water. Economically adjusting HVAC temperature setting is more significant than water system adjustment. In term of condensate water, adjustment of temperature setting of HVAC changes water deficits. As shown in Table 8.5, HVAC water use increases by 37.5% with decreasing temperature setting by 2 ^{o}C from 24 ^{o}C setting at current operation. Adjusting setting temperature to be 26 ^{o}C decreases HVAC water use by 25.4%. As the HVAC water use is 34% of the building water, it affects energy water use by 8.5% - 12.8%.

Wastewater treatment of SUTH main building works on batch type. The wastewater amount in a day was less than the wastewater treatment capacity. The daily average wastewater was 43 m^3, while the capacity of the system at the current operation was 130 m^3. Total oxygen injected during process aeration was 13.2 kg. Therefore, cost of wastewater processing in current condition was the highest cost of water processing.

The wastewater processing electricity consumption per day was 36 kWh. It costed 165 baht/day. This wastewater electricity consumption was almost two times of electricity consumption for water transferring and distributing.

Table 8.5 HVAC water use and potential harnessed.

HVAC water	**Setting temperature (°C)**		
	26	**24**	**22**
Evaporated water (m^3/day)	17.4	23.3	32.1
Condensate water (m^3/day)	17.4	21.3	29.1
Blowdown water (m^3/day)	3.5	4.7	6.4

Table 8.6 Exergy destruction rate of water distribution according to room setting temperature.

Operation option	Setting temperature (°C)		
	26	24	22
1) Storage tank system (kw)	0.58	0.59	0.61
2) Storage tank system (kw)	0.31	0.31	0.32

8.5 Conclusion

The exergy analysis can be applied to evaluate the water system of SUTH main building. The exergy destruction rate of equipment in HVAC system, tap water system, and wastewater can be shown. The exergy destruction rates show that flow rate of the water distribution was more significant in managing energy loss in comparison to transferring water to the roof top tank storage. The HVAC setting temperature also affects the exergy destruction significantly. Reducing setting temperature means increasing exergy destruction rates and makes the system less efficient. It also increases electricity consumption.

Centralized HVAC system was the location of most of exergy destruction of the water system of the main building of SUTH. The exergy destruction rate of the HVAC accounted 94% of exergy destruction rate of the water system. The chiller was the equipment among the HVAC system where most of exergy was destructed. Even, the exergy destruction at the chiller was very dominant. The exergy destruction of the chiller was 72% of the HVAC exergy destruction.

The work shows that the water use in every story could be predicted from the inhabitant and it is related to exergy destruction of the story. The predictive flow rate of the story could be calculated from the water use and probability of the fixture use. The exergy destruction because of pressure loss depends on the difference of the story and water tank position linearly. The exergy destruction rate because of velocity loss has order 3 function of story position. The minimum exergy destruction happens on 6^{th} floor. Therefore, two tank storage system can reduce exergy destruction. But applying 2 storage tank system for distribution doesn't affect significantly into cost of tap water operation.

The wastewater system had exergy destruction rate higher than tap water system transferring and distribution accumulated. Wastewater system consumed electricity almost twice of electricity consumption of tap water system transferring and distribution. Exergy destruction of the wastewater system can be reduce as the system work in fully load.

CHAPTER IX

MINIMIZATION OF ENERGY AND WATER COST FOR THE MAIN BUILDING OF SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL (SUTH)

9.1 Abstract

The previous chapter evaluates water systems using exergy approach. The distribution water is more important to manage rather than transferring water. It is also found that the 6th floor is the place where minimum exergy destruction of the tap water system takes places. Applying two water tanks can reduce exergy destruction of the tap water system. A deeper analysis concerning energy and water cost of the water system is conducted in this part.

Hospitals consume a significant amount of energy and water. Energy and water are intertwined that an improvement of one can worsen the other one. However, as the water price was relatively cheaper in comparison to energy, several studies paid their attention to the minimization of energy usage of the building only. In this study, study of energy and water for the main building of Suranaree University of Technology Hospital (SUTH) was conducted in order to find minimum cost of energy and water of the building using proposed a new method namely variables pair. The investigation showed that a single meter of electricity usage as the only energy consumption of the building was applied. Meanwhile, the water usage was composed of tap water, flush water, and distilled water. Therefore, a method to determine the cost of energy and

water was proposed. A variables pair in a form of (water usage, electricity consumption) was used in the proposed method to determine cost of energy and water for the main building. Several water saving options were proposed and examined. It was found that the water and electricity consumptions in the form of variables pair were (82.9 $m^{3/}$day, 26.3 kWh/day) for a current system, while they were (82.9 m^3/day, 21.2 kWh/day) for an option without water regeneration with minimum energy. Meanwhile, they were (82.9 m^3/day, 24.4 kWh/day) for a system with water supply tanks allocated at rooftop and 8th floor of the main building, instead of using only single supply tank installed at the rooftop as in the current system. A system that collects the condensate of the vapor from HVAC system and uses it, had consumptions of (77.3 m^3/day, 16.3 kWh/day). Applying the current cost of energy and water at 4.5 Baht/kWh and 10 Baht/m^3 respectively it was found that total cost of water system could be reduced up to 11% with this water regeneration. The water cost contributed 7.1% of total cost reduction, while the energy part reduction was 38.2%. It shows water volume saving is more significant than energy of water processing saving. The proposed method could separate process and cost parts. Therefore, it is easy to handle and provides boarder perspective of the saving strategy.

9.2 Introduction

Energy and water become main factors of a building conservation. Intensities of energy and water usage portray the building conservation level (Saidur et al., 2010) in addition to the cost. The more efficient a building is, it consumes less energy or water and has less metric intensity. Energy and water usage over space and over inhabitants are two main metrics that people usually use for evaluating the building. Codes

(Chirarattananon et al., 2010; Chirarattananon et al., 2007) and benchmarking (Singer et al., 2009) are applied to set standard of intensity. The codes also relied on planning the energy needs of an area or a country (Chirarattananon et al., 2010).

Energy and water conservation were investigated separately in many cases. The discussions only focused on conservation of energy or water neglecting the other. Domestic hot water was the main issue of energy related to water (Singer et al., 2009) where energy consumption of hot water preparation was the single object of concern (Bujak, 2010). The system consuming a lot of water generating abundant energy requirement of the cycle was still far from discussing water aspect of the energy. Even, about a system consuming abundant water such as a cooling tower, the discussion just focused on energy conservation (Al-Hadban et al., 2018). Effectiveness of the evaporation cooling became the main issue of the proposal as minimum energy consumption and exergy destruction. Highly efficient of the energy consumption can aggravate the water usage of the building. In a broader view, the condition can imply into disadvantage of the energy conservation.

Some studies about energy and water in hospital have been performed. Some organizations and governments conducted study about energy and water in hospital and produced benchmark (Chirarattananon et al., 2007; Bujak, 2010; González, 2018). Nevertheless, a deeper analysis on measure for optimizing energy and water is still rare. Neural network method was applied for energy optimization in operational through forecasting the consumption (Bagnasco et al., 2015). Improvement of the intensity consumption by evaluation of energy and water usage was proposed in facilities audit by merit system approach (Bottero et al., 2015). Multi objective approach using genetic algorithm was elaborated for optimizing CHP (*cooling heating and power generating*) system in hospital. It showed that a primary energy saving should be accompanied by payback analysis for economical optimum (Gimelli and Muccillo, 2013).

Strategy for optimizing two different materials can be categorized into 2 main approaches. The first method is projecting to one of the forming material and the second is projecting to another material. The 1st category includes mapping water to energy and vice versa. In analyzing energy and water of the wind power generation, water was nominated into energy (Yang and Chen, 2016). Then analysis was conducted in energy unit. The reason of the method was that the water cycle needs energy. Therefore, the energy can be used as water metric. The economical unit (Sanders et al., 2014) and CO_2 (Ackerman and Fisher, 2013) evaluation belong to the 2nd type of the method. Economical unit was determined in fixed cost unit or its derivations. CO_2 was applied in order to trace the green-house impact which is mostly presented in CO_2 accumulation equivalence (Racoviceanu et al., 2007). The 1st method can be applied if the interrelation between both materials can be determined clearly. In other words, it can be said that the interrelation has fixed relations. The advantage of this method is its adaptability for another comparison and parameters existence. The contra of the 1st type is inability to determine the policy directly while the price of the material is instable, the material is irrelevant, or the amount is insignificant. The 2nd type method cannot be adapted when the economic states are changing and may mislead in term of non-economic purposes. However, the second method is very practical and useful.

Purpose determines the way of energy and water interconnected. LCA (*life cycle analysis*) was applied for calculating the intensity of wind power (Yang and Chen, 2016). NEA (*network environmental analysis*) was applied to show the interdependency (Yang and Chen, 2016) as an alternative of input output analysis (IOA) methods. IOA was applied to understand the impact over boarder system by inter sectoral interdependence (Fang and Chen, 2017). It implies that there is not any single strategy being able to depict both economic and environmental basis thoroughly. Optimization on economic often has to cross the environmental issue that an adjustment of economic structure should be conducted to save the environment (Shi and Zhan, 2015). Integrating heat exchanger network can neglect the economical aspect of the investment (Liu et al., 2018). The optimization in environmental aspect sacrifices cost of the system. According to extreme value theorem, it can be guessed that the optimum condition ranges the environmental condition to the cost minimization.

Some methods have been proposed for integrating energy and water in industries. Wang and Smith (1994) proposed a method advancing pinch method for water allocation problem of the contaminant system. They searched for optimum wastewater treatments number and capacities. This work has been improved by Kuo and Smith (1997) for multiple treatment case. Both methods were based on graphical approach and had assumptions of single contaminant system and steady state system (Ataei et al., 2009). The advancement of water and heat problem of integration does not yet cover the problem of mechanical which comes from combination of static and dynamic conditions as mechanical generates driving force of mass flow. The driving force problem is more dominant in low quality thermal flow as the thermal aspect becoming less significant.

The aims of this article are to propose a method of energy conservation considering water factors in a building and to propose a method for evaluating energy of water system using paired variables consisting of energy consumption and water usage. The proposed method fits the hospital main building problem categorized as low quality thermal system. A modification of commonly used composite curve is proposed and called as pair variables. Energy evaluation of water was calculated as important part of energy optimization. Therefore, mapping of energy and water flow and its energy projection became the main part of this work. A new method separating the process and material parts was developed. Some options of reconfiguring water streams were presented. Finally, cost of water was provided as an evaluation.

To meet its aims, the article is composed of 4 sections. It is started with setting the problem in introduction as the 1^{st} section, then it is followed by the method as the 2^{nd}. The method has two main parts. The first part is about presenting the energy and water pair variables model. The second focuses on applying the variables pair approach for energy and water in SUTH main building. This part consists of strategy in estimating water usage in hospital, energy estimation of the system and streams of energy and water. An evaluation of energy consumption of the water flow is proposed as the third section followed by some advancement options. The last section shows the conclusion of the work.

9.3 Method

To meet its aims, the article is composed of 4 sections. It is started with setting the problem in introduction as the 1^{st} section, then it is followed by the method as the 2^{nd}. The method has two main parts. The first part is about presenting the energy and water pair variables model. The second focuses on applying the variables pair approach for energy and water in SUTH main building. This part consists of strategy in estimating water usage in hospital, energy estimation of the system and streams of energy and water. An evaluation of energy consumption of the water flow is proposed as the third

section followed by some advancement options. The last section shows the conclusion of the work.

9.3.1 Energy and Water Variable Pair Model

A description of a water allocation problem can be done using streams requirement as shown in Table 9.1. The requirement consists of stream number, flow rate, and concentration. The stream number designates the streams of the problems. The flow-rate indicates amount of each stream. The concentration shows amount of the contaminant over the mass of water at respective inlet stream. The concentration of the contaminant released to the environment was 30 ppm (Kuo and Smith, 1997).

Table 9.1 The streams requirement of the allocation problem (Kuo and Smith, 1997).

Stream number	Flow rate (t/h)	Concentration (ppm)
1	20	800
2	30	400
3	50	200

To find minimum concentration removing in water allocation problem, a composite curve is generated to complete the requirement diagram. The concept of composite curve bases on assumption that the overlapping processes can reduce the total water streams. The composite curve is managed to find minimum. The gradient of the slope represent rate of contaminant over the water flow rate. The higher the gradient means less water need for each contaminant rate. Optimum condition can be found as line connecting output requirement and pinch point. This line should only cross in single point or equal to any line without crossing the rest. The more complex a system is, the more difficult to find the pinch point is. A thorough examination has to be done to find the minimum. Various algorithms can be applied to compare the gradients in order to find the minimum. An example of composite curve of the problem from Kuo and Smith (1997) is shown in Figure 9.1a.

There are two main metrics of the composite curve method showing that conservation of contaminant is the base of requirement. The first is capacity of the wastewater treatment that is represented by flow rate of contaminant (X axis). The second is range of removal (Y axis). Higher capacity and range represent higher cost (Wang and Smith, 1994). Therefore, minimization is an effort to reduce cost in term of the capacity of wastewater treatment and the removal range. Ideal range shows minimum single range wastewater treatment that can be used for the system.

Based on these metrics, the variables pair composed of energy and water flow rate is proposed to exchange the removal range and flow rate. The removal range limits the contaminant mass removed in specific flow rate. The difference of the contaminant between input and output determines cost linearly. The flow rate in addition to limiting the capacity of system also determines cost in linear way. Then, it can be inferred that cost constraint can be exchanged with another function that is linear to the cost. The relations can be formed mathematically as shown in (9.1).

$$\forall \mathrm{C}(x,y) \wedge E(x,y) \rightarrow \exists C(x,E), \{x,y \mid x,y \in R\} \tag{9.1}$$

In order to minimize the wastewater treatment, the variables pair uses energy and flow rate as its components as shown in Figure 9.1b. The X axis is accumulative stream flow rates and Y axis is energy consumption over cost factor. The requirement diagram presenting the streams can be changed easily. The slopes of the requirement diagram representing contaminant flow rate that should be removed are used for calculating the flow of the water. Accumulation of the contaminant water needs can be plotted to Y axis. The X axis of the variables pair diagram is calculated from the stream of contaminant.

The energy represents cost of the system for specific flow rates. This variables pair directly shows cost represented by energy need and the stream to handle at the same time. The energy is directly proportional to the contaminant flow rate at composite curve. The stream is additional feature that shows the input of the system. Minimum of the system can be found trough accumulating the stream and its required energy. This number becomes the limit of the system. The gradient shows capacity of the treatment to remove the contaminant. The higher is the gradient, the more its ability to remove the contaminant.

Minimization procedure can be done by selecting probable sequence of the streams and its energy requirement. The strategy of the minimizing is applied for reducing the flow rate as much as possible to minimize the over capacity of the removal contaminant. Combination of some streams can be done as long as the combination on specific streams should be less than the gradient of the maximum targeted. The maximum stream should also be considered.

Adjustment of the variables should be done for different case. Accumulative water flow rate can be changed to be accumulative water usage. The accumulative energy for the system can be transformed to be accumulative energy in new system description of a water allocation problem can be done using streams requirement as shown in Table 9.1. The requirement consists of stream number, flow rate, and concentration. The stream number designates the streams of the problems. The flow-rate indicates amount of each stream. The concentration shows amount of the contaminant over the mass of water at respective inlet stream. The concentration of the contaminant released to the environment was 30 ppm (Kuo and Smith, 1997).

9.3.2 SUTH Energy and Water System

Suranaree University of Technology Hospital (SUTH) main building is the center of the SUTH activities. It has 11 stories plus 1 ground level. This building is functioned for clinics, wards, emergency, operation rooms, office and support system. It becomes the center for employees and visitors. The building is equipped by centralized HVAC with 3×250 TR chillers, 2×1.25 MW electricity system substations, and 1.10 MW back up power generator and 30 minutes batteries. The building has tap water system operating 2×30 kW pump, and provides water heaters with 234 kW total power electricity power need.

Energy and water usage of the SUTH main building was recorded daily for maintenance. The data consisted of building daily water and electricity consumption as the only energy type of the building. The electricity energy usage was measured by a meter at the electricity control cubicle on the ground floor. The water meter for the building was located before ground water tank supplying the system the tap water for the system.

To calculate energy of water usage, estimation of water usage of the building activities was conducted. The activities of the building involving water usage are sanitary, medical activities, cafeteria and HVAC. Gardening and food preparation are excluded from the counting as they were hold by other building and had its own meter. Sanitary system water usage was estimated by combining proportion of employees and patients. The water usage of medical activities was estimated from some medical treatments and its patients. The HVAC water usage was estimated from simulation of the centralized HVAC system of SUTH main building. The cafeteria usage was assumed as the rest of water usage of the building.

Energy intensity of the water was calculated from the ideal condition that becomes the benchmark (named: *benchmark*), current condition operation (named: *current*) and 2 options as enhancement (named: *option 1* and *option 2*). The ideal condition (*benchmark*) takes place when every system uses water without any regeneration or reuse in minimum energy processing. The *current* was the operation condition as the data taken. It used single water tap tank on the rooftop. The *option 1* is proposed condition when there were 2 tap water tanks. They were the current water tap tank for supplying floor 5^{th} – 11^{th} and additional water tap tank in floor 8^{th} for supplying the ground floor until floor 4^{th}. The *option 2* is proposed retrofit through installing system to collect condensed water from HVAC.

As the building is multistory one, the heights of the level determine ideal potential energy of water. Additional energy intensity was added as specific quality of water needed. The HVAC needed soften water for chiller water and medical activities needed RO water. Domestic hot water was excluded as limited number of inpatients who were the main hot water consumers.

9.3.2.1 HVAC Water

HVAC water usage was determined from the make-up water needed for centralized HVAC of SUTH main building with temperature setting 24 ^{o}C and relative humidity 50% using simulation in TRNSYS as shown in previous work. The temperature setting was chosen as it provided reasonable result compared to sampled data condition in 2017. The simulation also reported that HVAC system consumed 1.8 GWh of electricity in a year. The result represents 56% of electricity consumption of the building in the same year. Total evaporated make-up water for the HVAC in a year was 8,506 m^3 that is equal to 23.3 m^3 water per day in average.

Water usage of the HVAC consists of make-up water and blowdown water. The make-up water is defined as amount of water compensating evaporated water at cooling tower. Therefore, the make-up water keeps the condenser water being always equal. Amount of make-up water is equal to amount of evaporated water for cooling. In addition keeping equal amount of water, the cooling tower also needs to maintain the mineral concentration of water is acceptable. Assuming that soften water and hard water have the conductivity 50 µS/cm and 300 µS/cm respectively, the blowdown water can be calculated as Equation (9.2). Therefore, the HVAC water usage is presented in Equation (9.3). It shows that the water of HVAC is function of the water evaporated at simulation.

$$V_{bw} = \frac{V_m}{5}.V_{cdw} \tag{9.2}$$

$$V_w = V_m + V_{bw} \approx \frac{6}{5} V_m \tag{9.3}$$

9.3.2.2 Sanitary Water

Sanitary water consists of water for flushing, water for showering and water for hand washing. According to type of water contacts with human, it is clear that water of flushing does not have contact with human. The water for showering and hand washing is considered to have indirect contact with human because it does not go directly into human body system. The water for flushing can be relatively low quality in term of medical requirement. The water for showering and hand washing can be tap water quality with bacteria colony less than 150 fcu/cm^3(Angelbeck, 2006).

Sanitary water for flushing was determined from number of inhabitants and their times staying at hospital in a day. The inhabitants of the hospitals are employees, outpatients and inpatients. The employees were assumed to stay in hospital for 8 hours. The outpatient stays at hospital in average of 2 hours. The inpatient category lived 24 hours in hospitals. The flushing water equation is shown at Equation (9.4).

$$W_f = \sum C_i N_i t_i \tag{9.4}$$

In similar way, water for hand washing and showering was calculated using Equation (9.4). The difference was the coefficients. The coefficients for flushing water, hand washing, and showering were 50.4 l/day, 29.8 l/day, and 69.6 l/day respectively (BIS and Cranfield University, 2009). The number of daily inhabitants is provided at Table 9.2.

9.3.2.3 Medical Activities Water

Medical activities water is the water used for medical activities such as lubricating at the dentistry clinic, operation and hemodialysis. The other water types were neglected due to minimum amount. Medical activities water is determined by a coefficient of water usage and patient number assumed as activities .The equation of the medical activities water is presented in Equation (9.5).

$$W_m = \sum C_m N_m \tag{9.5}$$

There were some clinics which had significant water usage per patients. They were operation room, delivery room, dentals clinics, and hemodialysis unit. The coefficients of those clinics were 100 l/patient, 100 l/patient, 2 l/patient, and 200 l/patient in respective sequence for the preceding units. The water of hemodialysis and dental clinics was distilled water. While the other clinics used tap water mostly for the hand washing.

9.3.3 Energy of Water Usage

The energy of water usage is depended on the type of the water usage and clinic position. The clinic position implies minimum energy need for pumping. The types of water usage determine the energy intensity of water processing. The energy of tap water usage was assumed to consists of water distribution only which was depended on story. Soften water was assumed to have single phase RO water processing. The intensity of this activity is 0.36 kWh/m^3 (Wakeel et al., 2016). The RO water was assumed as double stage RO water processing which has 0.47 kWh/m^3 (Wakeel et al., 2016) of energy intensity. The hot water is assumed to be proportional to the number of patient, and became part of water showering or hand washing. The hot water of consumption per patient per day was assumed to be 11 liters. The energy needed for the hot water was assumed to heat to 65 ^{o}C from 25 ^{o}C as the average of the water temperature with 4.2 kJ/kg-^{o}C heat capacity. Therefore the energy of the water according the type can be calculated according Equation (9.6).

$$E_{wt} = \sum C_t W_t \tag{9.6}$$

The water usage can be broken down into story water requirement. Every story has different function and water usage. Some stories only need tap water, other stories might need all types of water. The stories also have different levels that determined the energy of tap water. Therefore, water usage of stories can be calculated by Equation (9.7).

$$W_s = W_{fs} + W_{ds} + W_{ms} \tag{9.7}$$

The energy of the water at a story was composed of energy for distribution that was proportional to the amount of story tap water consumption, and energy according to the function. Therefore, energy for water at every story could be calculated by Equation (9.8).

$$E_{ws} = C_s W_s + C_{ms} W_{ms} + C_{hs} W_{hs} \tag{9.8}$$

The HVAC water was calculated as additional water. It was settled at the rooftop, therefore the energy of the HVAC was assumed as much as the tap water energy for the 11th story. The processing of the HVAC water was in accordance with Equation (9.6) with energy intensity as single step RO. Energy for HVAC was calculated as energy for evaporated make-up water and the blowdown. It was calculated following Equation (9.9).

$$E_{HVAC} = \left(C_{11} + C_{SO}\right)\left(V_m + V_{bw}\right) \tag{9.9}$$

After usage, the water was sent to the wastewater treatment before going to the environment. The intensity of water treatment at the building is 0.344 kWh/m^3.

Except the water evaporated at cooling tower, the water from the hospital was treated at the facility. Then the water treatment needed energy as shown in Equation (9.10).

$$E_{WT} = C_T\left(W - V_m\right) \tag{9.10}$$

Energy of the water was calculated as accumulation of energy of water processing for water, energy for distribution and energy for wastewater treatment. Accordingly, energy necessity of the water at the building was calculated using Equation (9.11).

$$E_W = \sum E_{ws} + E_{HVAC} + E_{WT} \tag{9.11}$$

9.3.4 Energy and Water Cost

Energy usage and water amount can be presented as variables pair because there were energy and water at the same time in every process cycles. Amount of water in specific time (could be assumed as flow rate) was projected into x axis. The y axis projection was used for energy usage of the water. The ordered pair variables can be done in every step of the system. The cumulative becomes the system water and energy variables pair.

The variables pair can be transformed for other variables such as cost or CO_2 emission. The cost of energy and water can be calculated as dot product of energy water paired variables and the respective cost prices. The total cost of energy and water can considered as summation of the water cost and energy cost. Equation (9.12) shows cost of energy and water.

$$C_{EW} = \begin{bmatrix} f_{WC} & f_{EC} \end{bmatrix} \begin{bmatrix} W_s \\ E_W \end{bmatrix} \tag{9.12}$$

9.4 Results and Discussion

Comparison of the proposed method and the composite curve on the problem of wastewater treatment (Wang and Smith, 1994) provided a similar result. The composite curve gave 35 t/h contaminant removed capacity with 437.5 ppm contaminant rate at the water as the optimum condition in a single water treatment system with an unspecific removal factor. The new method in the other hand mentioned that the energy needed for removing the contaminant should be at least 35F, with F is the conversion factor connecting removed contaminant and the cost. The rate of contaminant removal shows cost of the system (Wang and Smith, 1994). Accordingly, F is a function that shows energy necessity for removing every ton contaminant. Assuming energy as the basic cost of the removal, the new method also easily shows the condition to reach that.

Specified remove factor of wastewater treatment means that the constraint depends on the structure. Basically, the established method and the proposed one can be applied in similar way. The established method minimizes the area on the left of the graph. The x axis shows the capacity which is related to cost of the system. The present method minimizes the area under the graph with energy as the main factor. Comparison of the methods can be seen in Figure 9.1.

The hospital water usage of the SUTH main building was composed of tap water, RO water in exchange of distilled water. The RO choice was based on assuming practical process. The water cannot be kept for long time in order to avoid contamination. This water composition, basically represents quality of the water which also shows the energy necessity of water processing. In addition to the quality, as the building is multi story, division of the water into floors requirements is also presented. Table 9.3 shows the story and its water requirement. Outpatients were assumed to stay 2 hours in hospital during their visit. The employees were assumed to stay for 8 hours per day for 1 shift work.

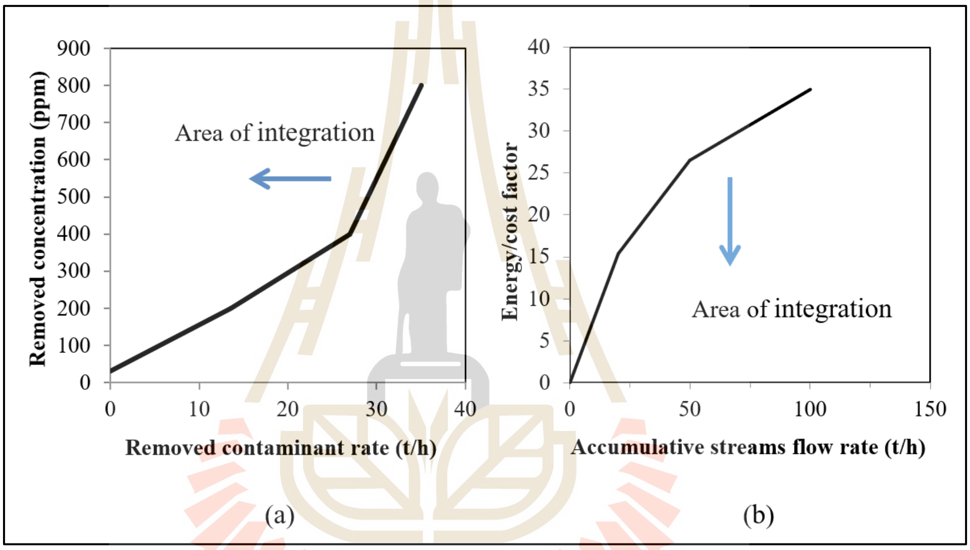


Figure 9.1 a) The composite curve of Kuo and Smith problem (Kuo and Smith, 1997), minimization can be considered as integration to the y axis.

b) The ordered pair variables of the same problem, the minimization process has area of integration to x axis.

Accumulation of the energy for the water processing as the minimum without any reuse or regeneration can be shown in Figure 9.2. This condition represented the ideal condition as there is not any water reuse or regeneration and the water resource. At this condition, the energy for distribution of the water is considered as minimum.

The final water usage of this condition was 82.9 m^3/day consuming 21.2 kWh/day of electricity.

Table 9.2 The daily building inhabitants (in person) and water usage (m^3) of the building.

Floor	Inhabitants			Tap Water	Flush	RO
	OP	IP	Staff			
Ground			53	14.53	0.89	
1	356.4		77	8.24	2.79	
2	141.2		34	3.76	1.16	0.32
3	126.6		38	3.88	1.17	0.25
4			20	0.99	0.34	
5	91.4		16	2.27	0.65	
6	0.5		16	0.96	0.27	
7			43	2.13	0.72	
8	62.5	7.6	13	7.55	0.86	3
9	4.0	18	21	3.77	1.28	
10	1.3	21.8	21	4.30	1.46	
11		13.6	11	2.57	0.87	
HVAC						27.96

Energy of water processing consisted of energy for tap water distribution, water processing to be RO or softening. The minimum pressure of the floor was 20 psi as compensation of the network pressure loss. Therefore floors 8t^{h}, 9th, 10th and 11th needed booster pumps. The additional energy for those floors had to be provided.

Table 9.2 shows the distribution of energy coefficient for floor, and energy usage for water in every floor.

Table 9.3 The coefficients of energy water processing and energy necessity for the main building usage.

Floor	Ct (Tap)	Ct (RO)	Tap (kWh/d)	RO` (kWh/d)	Booster (kWh/d)
Ground	0.013		0.191		
1	0.026		0.217		
2	0.040	0.47	0.137	0.164	
3	0.053	0.47	0.180	0.133	
4	0.067		0.066		
5	0.080		0.182		
6	0.094		0.090		
7	0.107		0.229		
8	0.121	0.47	0.187	1.772	0.030
9	0.134		0.566		0.058
10	0.148		0.636		0.116
11	0.161		0.414		0.098
HVAC	0.173	0.36	5.705	10.044	

The current operation condition (*current*) has energy necessity higher than the ideal condition without regeneration (*benchmark*). The *benchmark* assuming the energy distribution is different for every story, while the *current* need single energy distribution as much as the eleventh story. The single water tower at rooftop is the reason because all of the tap water is distributed from rooftop tank. The current operation (*current*) has variables pair as (82.9 m^3, 26.3 kWh/d). The *option 1* of proposing a new water tower at the 8^{th} floor to supply the ground until 4^{th} floors needs less energy intensity for equal volume of water. Regeneration strategy by collecting condensate water from the HVAC and use it can decrease the necessity for water by 8.6% and the energy for water usage by 39%. The variables pairs of the *option 1* and *option 2* are (82.9 m^3/day, 24.4 kWh/day) and (77.3 m^3/d, 16.3 kWh/d), respectively. The reduction of energy comes from the collected condensate water from HVAC operation, which can be used for flushing.

This final water usage and energy necessity can be depicted into vector like of energy and water ordered pair variables as shown in Figure 9.3. The x axis is water amount withdrawn or water usage and y axis is energy usage. The Figure 9.3 shows that water *option 1* has less water energy intensities than the current operation condition but higher energy intensity than *benchmark*. It also mentions that *option 2* has less water and water energy intensity compared with *current* and *benchmark*. The *option 2* is more preferable for conserving energy and water.

Cost of the water and energy can be calculated using Equation (9.12). As long as the price function of the water and energy is linear or exponentially progressive, cost of energy and water is proportional to the daily water usage and energy consumption. It can be inferred easily that the *option 2* is the best. At the current prices, the daily energy and water consumption concerning water in SUTH main building can be seen at Table 9.4.

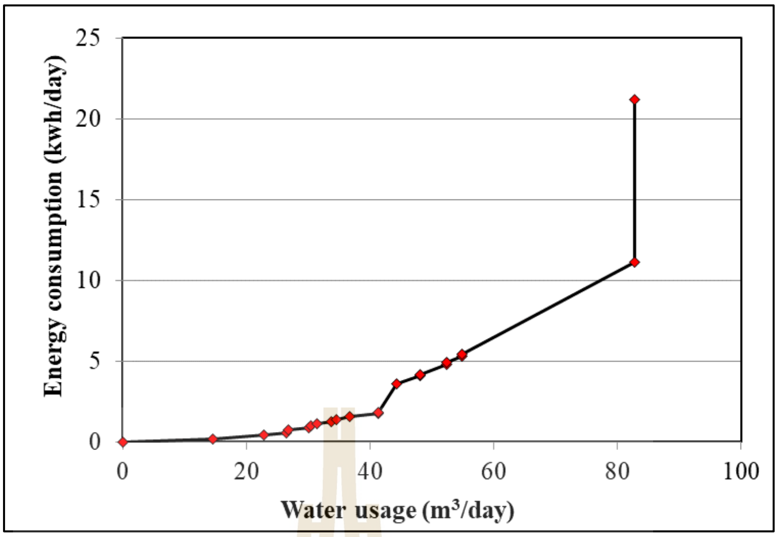


Figure 9.2 The accumulation of water usage and its energy for providing are presented in variables pair approach.

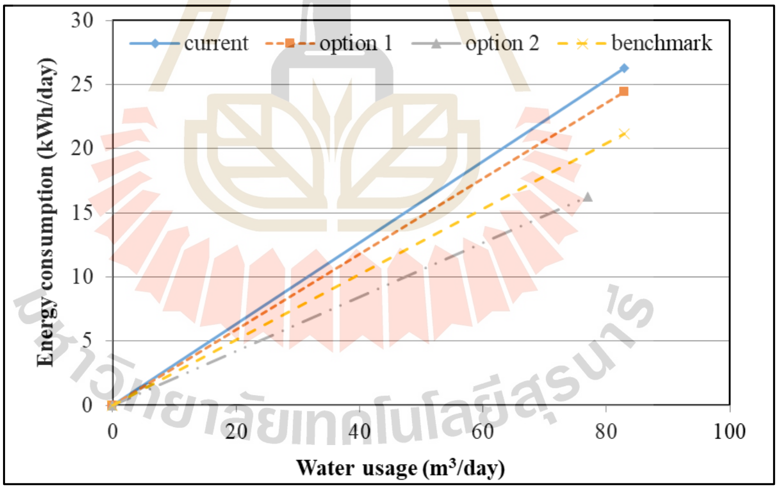


Figure 9.3 Vector like representation of ordered pair variables that consist of water usage and energy consumption. The method also shows the energy intensity of the water as the gradient.

Table 9.4. Comparison of daily electricity and water cost (in Baht).

	Cost of electricity	Cost of water	Total cost
Current	829	118	947
Option 1	829	110	939
Option 2	770	73	844
Benchmark	829	95	924

9.5 Conclusion

Managing water system in SUTH main building can be used for conserving water and energy at the same time. Proposed option 1st, where the additional water tank should be built for supplying the ground until 4th floor, could reduce energy of water by 7.1% without water usage reduction. The second proposed option that includes regeneration of the water from HVAC, could reduce the water usage by 7.1%. It also reduced the energy for water reduction by 38.2%. The total cost reduction of the option 2 was 11%. Similar pattern takes place for water and electricity for water cost.

The variables pair can be used for minimizing the energy and water of the water usage at the SUTH main building. It shows the compatibility with composite curve method in water allocation problem and provides two variables that can easily connected to the cost as the main variable for conservation.

CHAPTER X

AN ANALYSIS OF EXERGY, AVAILABILITY AND ACCESSIBILITY OF WATER USAGE IN HOSPITAL

10.1 Abstract

Chapter IX evaluates the water system of the SUTH main building in term of cost and energy consumption. It is found that option of collecting water from condensate and using it can reduce the cost of energy and water for the water system. It also shows the interrelation of energy and water in consumption process of the building. The following chapter evaluates the energy and water linkage at the building by considering the water requirement of the building.

A study of water and energy conservation at the Suranaree University of Technology Hospital (SUTH) was conducted. Analyses of exergy, energy consumption, availability and accessibility of water were proposed to be tools in this study. Exergy analysis showed effectiveness of energy usage, while combination of availability and accessibility showed the effectiveness of water usage of the system. The tap water system included conventional water and potential alternative water resources. The quality of the water was determined from the energy requirement of the water processing aggregation. According to the study, the current exergy efficiency was 56.39% and the energy consumption was 18.46 kWh/day. The water availability and accessibility were 2.84 and 1, respectively. An adjustment of brine usage for flush in some stories and condensate water for substitution of the ground floor usage was

examined in the study as an alternative. It is found that the water availability and accessibility became 1.47 and 1. Energy consumption in this operation condition was 14.6 kWh/day. It shows that the alternative system conserves more water and energy with fulfilled required function. These results indicate that the proposed method can describe the conservation water and energy of the building.

10.2 Introduction

Exergy analysis is considered as fairer method to evaluate the performance of a system than energy analysis method (Dincer and Rosen, 2007). The exergy analysis can provide thorough information of the performance quality as the method includes irreversibility which limits performance of a system. On the other hand, energy performance indicator such as energy efficiency neglects irreversibility that naturally takes place according the nature law. Therefore, energy analysis can mislead to a conclusion where the possibility does not exist. On the other hand, an exergy analysis has capability to point out the weak component of the system that can be applied for retrofit consideration or new design.

Adequacy as the main part of security implies two important factors. The first is amount which shows level of sufficiency for the need. Amount is important as main factor in comparison to the consumer as per capita or intensity (Sovacool, 2013). The second is the quality fitness onto the necessity. Acceptable quality of resources should be applied for specific usage in order effectivity of the resources.

The problem of energy security can be categorized to be technical infrastructure, diversity and mixture of the supply, impact, and policy (Sovacool et al., 2011; Yao et al., 2018). The technical infrastructure discusses about technology to provide adequate resources. Most of engineering issues are in this part. The diversity and mixture show the vulnerability against the change of supply condition. The impact considers the relation of the resources with other aspect such as economy and environment. The policy regards managing resources to fit the requirement of which are frequently in trade-off condition. The policy also pays attention to the problem of providing strategy among multi stakeholder interests.

Indicators are important in every aspect of the discussion field. It is used for exposing level of the condition and quality of the evaluated field. Amount of water per capita is used to indicate sufficiency water amount of an area (Assessment, 2012). It is also performed to show the ability of an area to provide water amount for its inhabitant. Primary energy consumption is applied for evaluating country or region energy sustainability. It also shows the country level of wealth.

Generally, an indicator can be categorized to be output base or process base type. An output base type indicator portrays the output quality of the system evaluated. Discussion about adequacy is part of this indicator. Impact and effect are the main measurement of the indicator. Meanwhile, a process type indicator depicts the process quality of a system. Such indicator focuses more on the process of the system than the level of output. It shows the quality of the system. Efficiency is a kind of this type. It also portrays level of resource conservation. An output base indicator is useful for assessing the product fitness into the requirement. A process-based indicator is applicable in evaluating the system process for innovation. Combination of both indicators is usually applied to show fitness and usefulness of the system.

Indicator complexity is determined by the process complexity and the evaluated function. A good complex indicator can portray in detail the problem of the system.

Unfortunately, such indicator needs adequate analysis to show its meaning. The simple indicator, on the other hand, can provide easy and handy result with the drawback of limited meaning. The models proposed in Refs (Hawkins et al., 2007; Shi and Zhan, 2015) and (Yang and Chen, 2016) are some methods providing good indicator but need to be interpreted in specific way. The complexity of the indicator increases as the problem complexity increases. A nexus problem of energy and water belongs to this problem.

Energy and water nexus indicators mostly are separated into water indicators and energy indicators. Intensities of consumption and usage are the common indicators. Interconnection of energy and water indicators is not determined inherently except for Network Environment Analysis (NEA) (Lu and Chen, 2016) which adopts biological relationships such as mutualism, commensalism and parasitism. It implies that another study should be conducted to analyze the relation of such indicators.

In order to provide indicator of energy and water inherently interrelated, this work was conducted. Indicator of energy and water quality and processes are provided in 4 parameters. They are exergy efficiency, energy consumption, water availability, and water accessibility. The first exergy efficiency shows the process quality of the system. The water availability shows ratio of provided water and the requirement. The accessibility indicates the fitness of the water quality. A combination of the exergy efficiency and the water accessibility is used for determining nexus state which is called energy water effectiveness (EWeff).

The article is presented in 4 parts. The first part is about the background of the system that showing the gap of the research about indicator of energy and water nexus. The second exposes method which provides the basic indicators derivation and the tap water system of Suranaree University of Technology Hospital (SUTH) as the domain. The third part is results and discussion that shows the indicators of the energy water nexus at SUTH and its interpretation. The final part is about the conclusion of the work.

10.3 Methods

Object, procedure, and the variation operation condition of analysis are the main parts composing this section. The 1st part of this section provides description of the SUTH tap water which becomes the object of the study. The second part offers the concept of the proposed indicators and the way to calculated them. The 3rd part is about the option of the operation condition. They are the current operation condition, and application of alternative water resources.

10.3.1 The Tap Water System of Main Building

Suranaree University of Technology Hospital (SUTH) is a hospital unit affiliated to Faculty of Medicine of Suranaree University of Technology (SUT). It is dedicated for University Hospital and public services. The hospital was operated by 558 staffs and had 5 building for 120 beds capacity in 2017, when the data were collected. These wards are located in main building named Rattanajevapatt with area of 19,000 m^2 in 11 stories. The daily average OPD (Off Patient Department) at that time was 784 visitors. There was averagely 68 inpatients staying on the wards in the same year.

Table 10.1 The water usage of the building according to functions based on the quality of water.

St	Usage (liters/day)					
	B	F	S_h	RO	S_{ft}	O
UG	527.1	890.4	1211.1			11900.0
1	1651.9	2790.6	3795.6			
2	689.2	1164.2	1583.4	321.6		
3	692.7	1170.2	1591.7	253.2		
4	198.9	336.0	457.0			
5	386.5	652.9	888.0	330.0		
6	160.3	270.8	368.0	160.0		
7	427.6	722.4	982.6			
8	511.4	863.5	1175.0	5000.0		
9	755.8	1276.9	1736.7			
10	862.6	1457.1	1981.9			
11	515.2	870.2	1183.6		27960.0	

S_t : story, B: Basin, F : flush, S_h : shower, RO : reverse osmosis, S_{ft} : soften water, O : other

The main building consumed most of the water usage among the hospital buildings. It used 82.7 m^3/day of water in average for all the function of the building. This number was 63% of the daily total water used by the hospital. The water usage of the building is presented in Table 10.1 following water quality according to contact with patient or person in hospital (Jakobsen and Nielsen, 2016). The basin, shower, and other use tap water or better-quality water as it may contact directly to patient, but it does not go inside of the patient body. The flushing water can use secondary water as it has indirect contact with the patient.

The water function in SUTH main building can be categorized into four types. The first type of the function is medical usage. The medical usage includes water for treating patient in every clinics and water for medical laboratory. The second function is water of sanitary usage which consists of water for showering, handwashing, and flushing. The third and the fourth functions are water of domestic usage, and water of HVAC (Heating Ventilating Air Conditioning) usage, respectively. The domestic usage includes water for washing, cleaning, cooking, and dish washing. The HVAC function includes water for condenser water, make-up and chilled water.

The tap water system in SUTH main building provides water for all aforementioned functions. For medical function, the water needs RO processing. For sanitary function and domestic water, the tap water can be used directly. For HVAC system the water need to be softened to reduce the mineral contain in the water (Yu and Chan, 2010). To fit these function, the tap water has to be transferred, distributed, and treated appropriately.

The tap water system in SUTH main building currently only uses conventional water resource for all functions that it provides. The water is supplied by SUT water system. Accordingly, alternative water resources can be applied with additional investment. They are collected condensate water from HVAC system and brine usage for specific function. The boundary of evaluated system is presented in Figure 10.1.

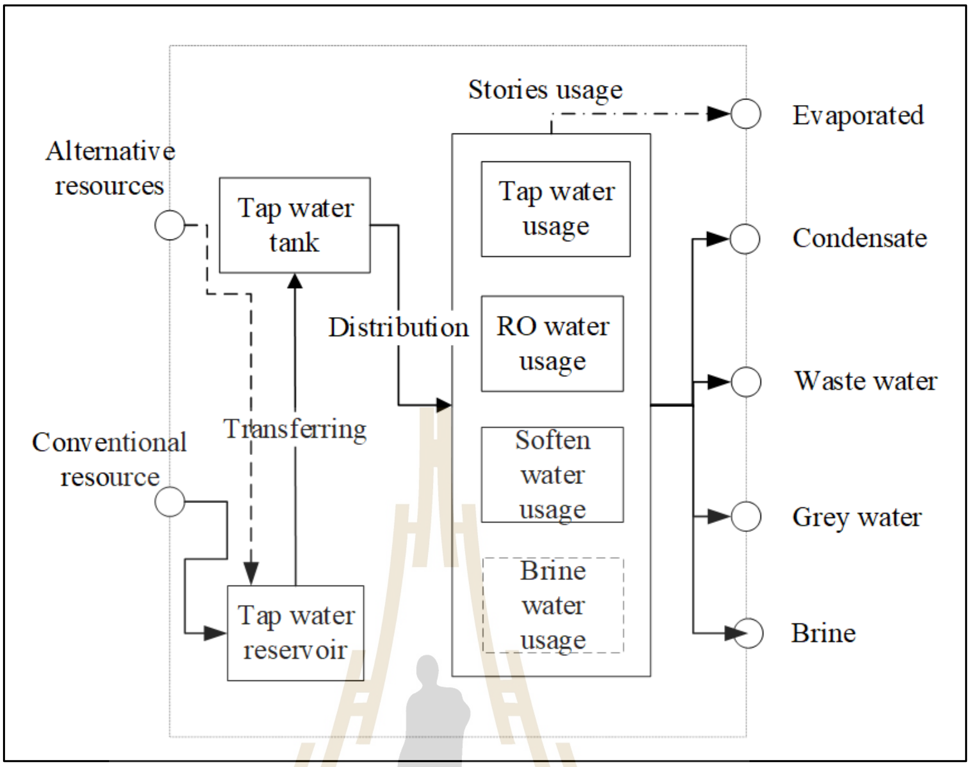


Figure 10.1 The evaluated system and its boundary. The dashed line and dashed box show the alternative additional system. The dashed dotted line is by product in the form of vapor. The lines for output present by products in the form of water.

Figure 10.1 also shows output of the system in the term of material. They are vapor, wastewater, grey water, brine, and condensate water. The vapor is the output of cooling tower and some application such as cleaning in minute amount. The wastewater is the collected used water which is processed to wastewater treatment. The grey water is the water that is simply treated for cafeteria usage. Brine is the water with high mineral contain. It is the released blowdown of the cooling tower or rejected water from reverse osmosis (RO) process. The condensate water is water that can be collected from the condensation process in FCU/AHU (Fan Coil Unit / Air Handling

Unit). Currently, the condensate water is not collected. Additional investment is needed for this process.

In 2017, averagely 82.7 m^3/day of water was supplied from SUT water system. It was transferred and distributed to the usages in stories following Table 10.1. The HVAC usage process released 23.3 m^3/day of water as vapor. It also released 4.7 m^3/day of brine from the blowdown. There was 11.9 m^3/day water used in cafeteria and treated simply as the grey water. The wastewater of the building treated at the wastewater treatment facility was 47.5 m^3/day.

10.3.2 Indicators

This second part discusses about the proposed indicators of the nexus. Because the considered nexus consists of two materials, energy and water, then the indicators of energy and water are provided. The exergy efficiency is proposed for energy indicator including energy consumption of the tap water system. The water accessibility is intended for water indicator. Water availability is also offered to extend the perspective. The nexus is the product of exergy efficiency and water accessibility, called energy water effectiveness.

10.3.2.1 Exergy Efficiency

Exergy is defined as the useable energy. It shows that exergy is amount of maximum work that can be harnessed in specific context. The idea of exergy as useable energy is derived from the existence of irreversibility in every process. The irreversibility happens as the consequence of the spontaneous direction of the flow. The general notion of this flow direction can be connected to tendency of the nature to be in equilibrium. The concept also indicates the impossibility to build a system which is totally isolated from the environment. It implies that the environment factor is important in analyzing a system performance.

To analyze exergy of a system, a control volume of a system is proposed and the exergy balance equation as shown in Equation (10.1) is applied to the control volume.

$$\sum \dot{X}_{in} - \sum \dot{X}_{out} - \sum \dot{X}_{dest} = \frac{dX}{dt} \tag{10.1}$$

$\dot{X}_{in}$, $\dot{X}_{out}$, and $\dot{X}_{dest}$ are defined as exergy rates entering the control volume, exergy rates leaving the control volume and exergy destruction rate, respectively. If the system is considered steady, the right side of Equation (10.1) is zero. It implies that exergy destruction is equal to the difference of total exergy entering the control volume and leaving it.

The exergy in a thermal system consists of exergy of heat transfer, work and mass flow. The exergy of heat transfer is defined as Equation (10.2) with temperatures in absolute.

$$\dot{X}_{ht} \equiv \dot{Q}\left(1 - \frac{T_0}{T_b}\right) \tag{10.2}$$

T_0 is the temperature of reference or dead state. T_b is the temperature of boundary where the heat transfer takes place. $\dot{Q}$ is the heat transferred crossing the boundary. The exergy of mass flowing through the boundary of the control volume is defined as in Equation (10.3). The symbol x is exergy specific of a flowing mass. The suffix *f* stands for the flow.

$$\dot{X}_m \equiv \dot{m}\left(x_{in,f} - x_{out,f}\right) \tag{10.3}$$

The exergy of work is determined by Equation (10.4). W_{in}, and W_{out} are input and output work, respectively.

$$\dot{X}_W \equiv W_{in} - W_{out} + P_0 \frac{dV}{dt} \tag{10.4}$$

This equation shows that the exergy of work is total work difference and the volume change rate of the system at the environment pressure. Accordingly, the exergy destruction is considered as proportional to entropy generation, and determined by Equation (10.5).

$$\dot{X}_{dest} = T_0 \dot{S}_{gen} \tag{10.5}$$

Combination of Equations (10.2), (10.4), and (10.5) compose exergy of the thermal system. A more general exergy in physical system that includes mechanical system is advanced by exergy of kinetic and potential as mentioned in Equation (10.6). $\dot{X}_{ph}$, $\dot{X}_{ht}$, $\dot{X}_{ch}$, $\dot{X}_{pot}$, $\dot{X}_{kin}$, and $\dot{X}_{dest}$ are rate of exergy of physical, heat transfer, chemical, potential, kinetic, and destruction, respectively.

$$\dot{X}_{ph} \equiv \dot{X}_{ht} + \dot{X}_{ch} + \dot{X}_{pot} + \dot{X}_{kin} - \dot{X}_{dest} \tag{10.6}$$

The energy kinetic and energy potential are applied for kinetic and potential exergy, respectively. A work of shaft follows the kinetic and potential exergy.

Exergy efficiency of the water system is determined by Equation (10.7), with $\dot{X}_{in}$ is exergy of the supplied electricity.

$$\eta_{\mathrm{II}} = 1 - \frac{\dot{X}_{dest}}{\dot{X}_{in}} \tag{10.7}$$

10.3.2.2 Water Availability

Water availability is determined as available water amount for doing any function. The amount of the water is determined as accumulation of conventional water provision, alternative water provision, regeneration and reuse water provision. The conventional water provision indicates the water coming from watershed or ground water source. The alternative water source shows that the water is provided by alternative method, such as condensation of the vapor at HVAC system and mining extraction. The regeneration water means that the water is formerly used in a function. Then, it is processed to fit the requirement of another function. The reuse water is water used in a function. Then it is used in another function without any treatment.

Availability is calculated as ratio of the amount of available water and amount of requirement in a specific area. Availability of water is presented in Equation (10.8). $W_{a,j}$ is amount of available water in specific area or function on floor j-th. $W_{r,j}$ is amount of required water in specific area or function on floor j-th.

$$W_{av,j} = \frac{W_{a,j}}{W_{r,j}} \tag{10.8}$$

Aggregation of water availability is calculated as the product of water availabilities of the constituent components. Equation (10.9) shows the aggregated water availability of a system that is composed of more than one sub-system. The suffix j is used for indicating floor as the sub-system in the problem context.

$$W_{av} = \prod_{j}^{n} W_{av,j} \tag{10.9}$$

10.3.2.3 Water Accessibility

Water accessibility is applied to show the fitness of available water onto the requirement. The accessibility also shows the quality of the availability. The fitness is based on energy consumption of water cycles. Coefficient of water transferring and distribution is performed to determine the energy consumption of tap water. In case of the evaluated building, the number is 0.223 kWh/m^3. The number is calculated from average energy consumption for tap water provision. Additional processing implies additional coefficient of the water. The respective coefficients for soften and RO water are 0.36 kWh/m^3 and 0.47 kWh/m^3 (Wakeel et al., 2016).

The water accessibility is calculated from capped water availability as shown in Equation (10.10). The capped function ceils the maximum to be 1. Then, accessibility of water is determined by Equation (10.11). W_{ac}, $\hat{W}_{av,i}$, and C_i are the water accessibility, the capped water availability of specific function i, and the energy for water processing at specific function *i*, respectively. Equation (10.11) shows provision and the water quality in specific area or function. Suffix *i* shows type water in term of quality, while the *j* suffix represents floor.

$$\hat{W}_{av} = \begin{cases} 1 & , 1 < \dfrac{W_a}{W_r} \\ a = \dfrac{W_a}{W_r} & , 1 > \dfrac{W_a}{W_r} \end{cases} \tag{10.10}$$

$$W_{ac,j} = \frac{\sum_{i=1}^{n} C_i \hat{W}_{av,i}}{\sum_{i=1}^{n} C_i} \tag{10.11}$$

Similar to the water availability, the aggregation of water accessibility of a system is determined as the product of the water accessibility of its components. Equation (10.12) shows relation of water accessibility of the component and its aggregation. $W_{ac,j}$ is the water accessibility of the j-th component or floor.

$$W_{ac} = \prod_{j}^{n} W_{ac,j} \tag{10.12}$$

10.3.2.4 Energy Water Effectiveness

Energy and Water nexus is described by energy water effectiveness of the water system. The effectiveness of energy and water is product of exergy efficiency and water accessibility as shown in Equation (10.13). The energy and water effectiveness shows part of exergy for fulfilling the water requirement of the system. Its value ranges 0 until 1. The closer a value to 1 is, the energy water effectiveness is better.

$$EW_{eff} = \eta_{II} W_{ac} \tag{10.13}$$

10.3.3 The System Model and Its Operation Variation

Exergy efficiency of the tap water system was calculated from exergy destruction of transferring and exergy destruction of distribution. The exergy destruction of transferring took place during the pumping process from the reservoir to the tank. The exergy destruction of distribution happened during process of distribution from the tank to the fixture. The calculation of exergy destruction for water transferring and water distribution were conducted from pressure loss and velocity loss. The Darcy-Weissbach equation was applied for the pressure loss. The pressure loss and velocity loss represented potential and kinetic energy loss, respectively.

The exergy destruction of the usage was assumed to be destructing exergy as equal as the energy need for wastewater treatment. The wastewater treatment coefficient of the SUTH main building was 0.344 kWh/m^3 as the average electricity usage for processing wastewater.

Exergy destruction of the system was calculated as aggregation of the exergy destruction in every component. Therefore, exergy destruction of the water cycles at the SUTH could be described by Equation (10.14). $\dot{X}_{desttrf}$, $\dot{X}_{destdist}$, and $\dot{X}_{destuse}$ are the exergy destruction rate of water transferring, exergy destruction of distribution, and exergy destruction of water usage, respectively.

$$\dot{X}_{dest} \equiv \dot{X}_{desttrf} + \dot{X}_{destdist} + \dot{X}_{destuse} \tag{14}$$

The exergy input of the system was calculated as the exergy of water input and electricity supply. With assumption of water input exergy to be based and counted as zero, the exergy input became exergy of electricity only. Therefore, efficiency of the exergy was calculated formula as shown in Equation (10.7) with exergy destruction as function of Equation (10.14).

The water accessibility of the system was calculated using Equation (10.12). The components of the system were tap water usage, RO water usage and soften water usage. Coefficient of tap water usage was combination of the exergy coefficient of the water for distribution and transferring. Therefore, every story had its own value. These values depended on the flow rate of the story and floor number. The flowrate was calculated in the former work (Prasetyadi and Koonsrisuk, 2019).

A variation of the system with reducing water provision and substituting it with alternative water was proposed as comparison to current operational condition. Complete water resources distribution is provided in Table 10.2. The brine and condensate water were proposed to be used for substitution of tap water system for flushing. Brine was proposed to be used in 9^{th} – 11^{th} floors. The HVAC water was assumed to be collected on the ground floor. The brine water was assumed to be collected on the top floor as the cooling tower was located on the rooftop. Condensate HVAC water was assumed to be RO water quality. The brine from the blowdown was assumed to be equal to tap water quality in term of energy processing.

Table 10.2 Distribution of water resources for the current operation condition and its alternative.

St	Current				Alternative			
	B	**F**	**S**	**M**	**B**	**F**	**S**	**M**
UG	C	C	C	C	H	H	H	H
1	C	C	C	C	C	C	C	C
2	C	C	C	C	C	C	C	C
3	C	C	C	C	C	C	C	C
4	C	C	C	C	C	C	C	C
5	C	C	C	C	C	C	C	C
6	C	C	C	C	C	C	C	C
7	C	C	C	C	C	C	C	C
8	C	C	C	C	C	C	C	C
9	C	C	C	C	C	B	C	C
10	C	C	C	C	C	B	C	C
11	C	C	C	C	C	B	C	C

St : Story, B : Basin, F : Flush, S : Shower, M : Medical and Other, C : conventional resource, H : HVAC condensate, B : Brine

10.4 Results and Discussion

Exergy destruction of the transferring process took place at the pump and piping friction losses. As the flow rate of the pump at the current work condition was 11 liters/s, it implied 513,647 Pa pressure drops. Because of the elevation difference, there was potential rising proportional to 510,120 Pa. This pressure difference gave 38.8-watt power of loss at pumping. The kinetic energy difference rate was 5,832 watt.

The pump at current condition had efficiency of 66%. Therefore, the electricity consumption of the transferring process was 8.36 kW. To fit the water requirement of 82.7 m^3/day, the pump had to work for 7,520 seconds. Therefore, the energy for pumping was 18.46 kWh/day. This electricity consumption gave energy intensity for transferring water was 0.223 kWh/m^3. The number also became the exergy destruction rate of the transferring.

Applying pressure loss calculation to the flow rate of the fixture determined by former work (Prasetyadi and Koonsrisuk, 2019), gave the exergy destruction rate of the story during distribution as shown in Table 10.3. This table shows that higher head difference makes pressure loss exergy destruction more dominant than the exergy destruction because of velocity difference (kinetic). Valve controlling principally creates pressure control as the other obstruction method. Total exergy destruction rate of the distribution was 590.7 W.

The exergy destruction rate of the water tap system was calculated according to Equation (10.14). The exergy destruction rate without considering the usage was 3.26 kW. The defined exergy destruction of the usage was very small in comparison to the number of the other exergy destruction rate. This exergy destruction created efficiency of exergy as much as 56.39% of the electricity consumption.

Table 10.3 The exergy destruction rate (in watt) of the tap water distribution according to story.

Story	Exergy destruction rate of distribution (W)	
	By pressure loss	By velocity difference
UG	149.24	0.55
1	67.66	6.41
2	28.19	9.25
3	24.67	11.88
4	5.71	12.75
5	11.43	14.55
6	4.07	15.41
7	7.06	17.22
8	20.90	24.87
9	6.32	29.65
10	3.70	34.85
11	2.17	82.17

The water availability of the system was higher than 1 and the accessibility of the system was 1. The numbers show that water of the system was fulfilled in term of amount and quality. The complete availability and accessibility of the stories can be seen in Table 10.4. The water availability of ground floor and 11th floor were 2.47 and 1.15, respectively. The other floors had water availability of 1. All of floors had the water accessibility of 1. Aggregation of the water availability and accessibility of the system were 2.84 and 1, respectively. The number shows that the available water amount at the current operation was higher than the necessity. The daily water need was 82.7 m^3 and there was 106.7 m^3/day water that consisted of conventional water and alternative water. Table 10.4 also shows stories where the available water was higher than the need of the story.

Table 10.4 indicates that the water availability more than 1 happened at the ground and 11th floors. At the ground floor, it happened because the condensate water was assumed to be collected at the ground floor. It came from all the stories and collected at the lowest part of the building. The rooftop was the place where the blowdown from the cooling tower was released. Assuming that the water could be collected in situ, the amount of the water at the story became more than sufficient.

A variation with applying the alternative water resources to reduce water availability was conducted. Total additional water of alternative resources at the evaluated condition was 25.96 m^3 which was composed of 21.3 m^3 condensate water and 4.66 m^3 of brine. Because the brine only can be used for flush or gardening (Jakobsen and Nielsen, 2016), the brine could be distributed for flush use only. It needed minute additional energy. As the total amount of flush of the building was 12.46 m^3, it still needed additional tap water. Therefore, the brine was assumed to be used only for flushing at floor 9th – 11th. Those floors spent 3.6 m^3 for flushing. The rest of the brine was assumed to be released to wastewater treatment. Similarly, assuming that the condensate water was used at the ground floor only in order to minimize energy for pumping, there was pumped water reduction of 14.5 m^3/day. This reduction implied less energy consumption as shown in Table 10.4.

Table 10.4 The water availability, accessibility of the story, electricity consumption, exergy efficiency, and energy water effectiveness (EW_{eff}). Current represents the current operation in 2017. Alternative is the proposed alternative method.

Story	Current		Alternative	
	W_{av}	W_{ac}	W_{av}	W_{ac}
UG	2.47	1	1.47	1
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1
6	1	1	1	1
7	1	1	1	1
8	1	1	1	1
9	1	1	1	1
10	1	1	1	1
11	1.15	1	1.01	1
Aggr	2.84	1	1.47	1
El_{cons}	18.5 kWh		14.6 kWh	
η_{II}	56.39%		56.39%	
EWeff	0.56		0.56	

Aggr : aggregated , El_{cons} : electricity consumption

The composition of the water availability and accessibility of the alternative condition can be seen at Table 10.4. The total availability and accessibility were 1.474

and 1, respectively. This less water availability in comparison to the current condition indicated that less amount of water was provided in proposed alternative system. While the accessibility is still 1, it means that the water provision could fit the requirement of the system. Generally, the alternative system could provide equal water accessibility with less water availability.

Energy water effectiveness (EW_{eff}) was defined as the product of exergy efficiency and water accessibility. The exergy efficiency represents ratio of the energy transformed into work to its maximum. The water accessibility showed the fitness of the water to the necessity. The current operation had energy water effectiveness of 0.56. The number is composed of 56% and 1 of exergy efficiency and water accessibility, respectively. The number shows the fulfillment of the water necessity and ratio energy which is transformed to be work to its maximum. Less number means more energy rate needed for fulfilling the water requirement. It is always expected that the energy water effectiveness as close as 1.

Energy consumption of the alternative system is less than current operation. It only consumes electricity of 14.6 kWh/day, while the current condition spends 18.5 kWh/day. At the same time, the energy water effectiveness (EW_{eff}) of the alternative system was equal to the current. It shows that the alternative could work with similar efficiency and less energy consumption. The current system and the alternative do not have difference in capacity of the system. Therefore, it is only time operation of the alternative system that generates less energy consumption. The results indicate that the alternative system more conserves energy and water than the current condition.

10.5 Conclusion

A nexus indicator consists of exergy efficiency and water availability and accessibility was proposed to show the condition of energy and water nexus of the building. The current condition had exergy efficiency of 56.39%. The water availability and accessibility were 2.84 and 1, respectively. Therefore, the energy water effectiveness (EW_{eff}) of the current operation was 0.56. This condition shows that some stories had water more than it was needed. It also indicates some exergy destruction of the process. And adjustment of brine usage for flushing and condensate water from HVAC could reduce the water availability with consistent accessibility indicating adequacy of the quality. They were 1.47 and 1 for water availability and accessibility, respectively. The number significantly reduces water provision. The work also shows that the combination of exergy efficiency, water availability and water accessibility can portray the conservation of energy and water in the evaluated system.

CHAPTER XI

INDEXING CONSERVATION OF ENERGY AND WATER INTERRELATION AT SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL MAIN BUILDING

11.1 Abstract

Previous chapter explores possibility of applying metric for energy and water linkage in consumption process of the building. The water availability and water accessibility are proposed to show the water condition in comparison to water requirement of the building. Combining with exergy efficiency, the water accessibility creates energy water effectiveness. These analyses still need two metrics to show the water portray. Therefore, a modification of the method by proposing energy water conservation level as the index is proposed in this chapter.

Indexing nexus to show nexus performance of a system is proposed. The effort to show the conservation of energy and water as the performance of the nexus of Suranaree University of Technology Hospital main building was applied. Combination of exergy efficiency and water quality efficiency was conducted in the systems consuming energy and water. The HVAC, water system, and wastewater treatment of the main building were evaluated using exergy analysis and the advancement of water accessibility. The HVAC, tap water and the water system nexus index are 0.61, 0.36, and 0.07, respectively. The overall index of the system is 0.44 which is multiplication of exergy efficiency of 0.68 and water quality efficiency of 0.65. The exergy efficiency

shows percentage of exergy converted to work and the water quality efficiency points out the energy of water processing used for the system.

11.2 Introduction

Energy and water are considered in intertwined relation. Energy is important in every water cycles and water is important in providing energy. Meanwhile, energy is needed from water extraction until wastewater treatment before releasing it to the environment. Raw water resources, geography and landscape, quality, and law determine intensity of energy consumption of water (Wakeel et al., 2016). In energy provision, water consumption is determined by type of primary energy, method of conveyance and final energy usage (Macknick et al., 2012; Spang et al., 2014). Moreover, the downstream phase of energy provision still needs water.

The relation of energy and water has become the subject of study for many years. Peter Gleick (Gleick, 1994) started to discuss energy and water in 1994. Water usage of energy provision and energy consumption of water provision were discussed with the background of uneven distribution of water and primary energy. Deeper discussion of water consumption of energy production was developed by many researches. A wide range study of water footprint in agriculture was conducted by Hoekstra (Gerbens-Leenes et al., 2008; Gerbens-Leenes et al., 2009; Mekonnen and Hoekstra, 2011). Life cycle analysis as method for calculating thoroughly water consumption of energy production was applied at coal (Ali, 2017), gas (Ali and Kumar, 2016), and renewable energy (Ali and Kumar, 2017). Comparison of water consumption for energy was conducted to find geographical effect of water on energy consumption (DeNooyer et al., 2016; Scanlon et al., 2013; Tidwell and Moreland, 2016). IO (Input Output) method was applied to study impact of water consumption to energy system and vice versa (Zhang and Anadon, 2014; Marsh, 2008). NEA (Network Environment Analysis) was performed to show direct and indirect impact of water of energy or material flow among components (Yang and Chen, 2016; Fang et al., 2014). Water consumption model of water at energy production became the subject of electricity generation (Martin, 2012; Rutberg et al., 2011; Rutberg, 2012).

The interrelation of both materials appeared in many levels of system and area. Geographical context of energy and water interrelation are studied in city level (Fang and Chen, 2017), basin (Lawford et al., 2013), country (Okadera et al., 2014), regional (Tidwell and Moreland, 2016) and global (Spang et al., 2014; Glassman et al., 2011). Policy context of water and energy became the study in order to optimize both resources (Scott et al., 2011). Facilities level was also context of energy and water problems (Yang and Chen, 2016; Younos et all, n.d.). Most of the study was applied at the power generation facilities, its components, or its super structure.

Although there were abundant studies of energy and water, the interrelation of energy and water in building was far from complete discussion. Even collections of energy and water consumption data (https://www.eia.gov) of buildings are still conducted, but it does not include energy and water interrelation. Energy efficiency is the main subject of building study in addition to water efficiency. Both are projected to cost economically and environmentally. Economical cost was conducted to investigate minimum investment, operational, or retrofit requirement. The environment cost includes the CO_2 equivalent emission.

The pattern of interrelation is still not thoroughly defined for the technological design perspective. As the study of interrelation is not complete yet, there is still lack of meaning, description, measure and interpretation of the relation between energy and water, and its implication to design process. Systematic relation of energy and water as the main character of nexus (Whitehead, 1966) is still far from defined. Therefore, the usefulness of interrelation is limited.

Unfinished work of portraying pattern of energy and water interrelation at the building can be interpreted that the development of energy and water study of a building is still lack of concept (Kenway et al., 2011). Imported concept of biology such as mutualism, commensalism, and parasitism were applied in some works. But these concepts weren't used for describing relation of energy and water availability. The concepts indicate that relation among component of the system (Yang and Chen, 2016). Impacts of a variable change to the system were conducted to show the interrelation at IO methods (Shi and Zhan, 2015; Zhang and Anadon, 2014). But, what the nexus is as the interrelation of energy and water is far from solid concept.

A former work of the authors about conservation index using exergy, availability and accessibility of water still has drawback. The exergy destruction characterized the energy quality abatement on the processes. But the combination of availability and accessibility don't show the abatement of the water at the process. Availability only shows sufficiency of water in term of amount. Accessibility on the other hand shows the sufficiency in the term of water quality. Energy water effectiveness as the final index for the conservation does not show the consistent character of the resources.

In order to conceptualize interrelation of energy and water at a building, its measure, and exploring the pattern, the article shows the interrelationship of energy and water in Suranaree University of Technology Hospital using exergy analysis, water availability and accessibility, and variable pair. Two main systems of SUTH main building conveying energy and water, they are HVAC system and water system were evaluated. The interrelationship of energy and water is examined to find its scale.

This article has four parts to present the energy and water nexus in SUTH main building. The introduction as the first part shows the gap of the building nexus conceptualization. The second part is methodology which presents the concept of energy and water interrelation and the way of elaboration. The results and discussion as the third part shows the interpretation of the nexus. The conclusion closes the article with the finding and implication of the work.

11.3 Methodology

The methodology of works consists of four parts. The first part comprises effort in determining the concept of interrelation between energy and water or energy and water nexus in hospital building. The second part is presenting variable pair for describing the interrelation which is called as energy and water nexus. The following part as the third will focus on HVAC system of SUTH. The HVAC system of SUTH was evaluated according to exergy and water flux. The water system evaluation becomes the fourth part.

11.3.1 Nexus Concept of the Suranaree University of Technology Hospital (SUTH) Main Building: Interrelation in Consumption Process

Energy and water nexus in a building needs to be defined. So far, study of energy and water nexus was still far from clear determination of energy and water interrelation in a building. Energy and water nexus was still determined as water use of energy system and energy use of water cycles (Nair et al., 2014). Context of the system for energy and water interrelation is very various. The water of energy production (Copeland, 2014; Rio Carrillo and Frei, 2009), energy of water provision (Liu et al., 2016), energy and water system strategy (Kenway et al., 2011) for area are some examples of the context. Therefore, the definition of interrelation of energy and water are still a blur area. It implies the non-existence of nexus level measurement.

Basically, building consumes energy and water. Therefore, interrelation of energy and water takes place in the process of consuming. The nexus of energy and water at the building are different from the energy and water interrelation at power generation system. The energy and water interrelation at power generation clearly shows the trade-off between energy and water especially in cooling process and emission (Martin, 2012). Increasing energy efficiency by increasing cooling effectiveness implies on aggradation of water availability (Al-Hadban et al., 2018). The water provision mostly affects the power generation during the drought (DeNooyer et al., 2016). Lack of water implied on decreasing power generation or system shut down. The energy for water provision at power generation has impact on the price of the product or lessening the profit of the system.

SUTH main building consumes electricity as the single primary energy. The electricity is used for all of the equipment and for the operation of all system at the building. These systems can be classified as HVAC, lighting, medical equipment, IT, mechanical (lift), tap water system, and wastewater treatment. According to data, 3.2 GWh of electricity was consumed in a year. It was equal to averagely of 9 MWh of electricity consumption in a day. The building does not consume other form of energy to run the functions regularly. A minute of diesel fuel was prepared for emergency.

Water was distributed, consumed, and processed on some system of the building. HVAC was reported as the main water consumer (Prasetyadi and Koonsrisuk, 2019a). The tap water system supplies water for sanitary system (showering, handwashing, and flushing). The tap water system also provides water for medical equipment usage with RO processing. Wastewater system has a treatment for refining the wastewater to be fit into environment requirement. The other system of the building does not consume water or consume in very minute amount.

The systems map shows that some system use energy and water at the same time. They are HVAC, water systems, wastewater system, and medical equipment (Prasetyadi and Koonsrisuk, 2018). The HVAC uses most of the energy and significant amount of water at the same time. The water system takes part in water distribution and processing, but it consumes insignificant energy. The medical equipment is pool of many equipment of the hospital for treating and caring the patient. This equipment is distributed in many parts of the building. The single equipment that consumes energy and water significantly is MRI. In SUTH, MRI and other radiology instrument are located in specific building apart from main building. Therefore, the system discussion of interrelation of energy and water are limited at the HVAC, water system and wastewater.

A consumption process is defined as action of using resources. The definition implies that during the process of consuming, an input resource is degraded in term of amount or quality. Product of the process and the input are not always directly comparable. Services, process productions are some examples of the process. In such process, an output having same type of the input is a kind of by product. Water released by an industry is by product of the process production. This process implies that efficiency is not a kind of measurement of this situation. Projection into another unit is commonly applied such as economical unit (Xu et al., 2019) or energy unit (Younos et al., n.d.). These efficiencies do not describe the process of resource directly. The efficiency shows the need of the resource for the product, instead of the resource change in the process to show its conservation condition.

Nexus of energy and water interrelation in consumption process measurement should indicate conservation level of both materials during the process. Without conservation level indication ability, the metric does not provide valuable information about the process. In addition, the metric of the nexus should be easily interpreted and indicate the relation between the output and input which will be very useful to evaluate the system for comparing vis a vis among the systems.

Regarding the function and the context, the nexus or energy and water interrelation in consumption process is proposed to be defined as conservation level of both resources in specific configuration of a system in order to fulfill the requirement. This definition implies two main features. They are fulfillment of the requirement level and the level of conservation. Therefore, the metric for nexus of energy and water in the consumption process has to fit both features.

11.3.2 Nexus Concept of the SUTH Main Building: Exergy for Indicating the Energy Effectiveness

Exergy is defined as maximum available work that can be harnessed in a system due to the second law of thermodynamic. It shows that the exergy includes environment reference as the parameter. Therefore, the exergy is not conserved in non-reversible system. Exergy is also represented by the energy unit. The exergy analysis has character of portraying the resource degradation during a process (Dincer and

Rosen, 2015). It means that the exergy represents the quality of a substance, or energy system.

The energy consumption efficiency can be measured in term of exergy efficiency assuming that exergy efficiency shows maximum available work that can be harnessed. The exergy efficiency is determined from exergy destruction or exergy consumption (Dincer and Rosen, 2015). In this term, exergy destruction shows the potential work loss at the system. According to Dincer work, the exergy is determined as Equation (11.1). The definition implies that chemical composition of the materials is assumed to be constant.

$$Ex_{non-flow} = Ex_{ph} + Ex_{kin} + Ex_{pot} \quad (11.1)$$

$Ex_{non-flow}$ is exergy of system without material flow. Ex_{ph}, Ex_{kin}, and Ex_{pot} are physical exergy, kinetic exergy, and potential exergy respectively. The kinetic exergy and potential exergy are equal to energy kinetic and energy potential of the system. The physical exergy is determined as exergy thermodynamic of an open system which consists of internal energy, potential work at environment pressure, and entropy difference to the environment. The physical exergy is calculated by Equation (11.2).

$$Ex_{ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \quad (11.2)$$

For the flow material, the exergy equation becomes (11.3). This equation shows the effect of pressure difference driving flow.

$$Ex_{flow} = Ex_{non-flow} + (P - P_o)V \quad (11.3)$$

The exergy destruction is used to determine the efficiency of exergy as shown in Equation (11.4). It is also the ratio of effective exergy to input exergy. The exergy destruction indicates waste exergy dissipation to environment and resource degradation (Dincer and Rosen, 2015). The exergy destruction is calculated from exergy balance at appropriate system.

$$\eta_{\text{II}} = 1 - \frac{Ex_{dest}}{Ex_{in}} \tag{11.4}$$

11.3.3 Nexus Concept of the SUTH Main Building: Water Accessibility

Availability and accessibility are two metric describing state of material according to thermoeconomic found in Georgescu-Roegen (1975). Instead of resembling amount of water which is reachable and useable for mankind as Georgescu-Roegen proposed, the availability represents magnitude ratio to the necessity and the accessibility shows the fitness for usage (Prasetyadi and Koonsrisuk, 2020). Some available resources are not accessible due to unfitness of quality or capacity to use it. For example, amount of water from watershed such as lake, river could be enough for water need of a city, but it is not accessible when there is not sufficient water system infrastructure. The rejected water of RO processing is accessible for gardening, but it is not accessible for drinking water. The mineral contain of the water is not safe for human consumption without any treatment.

The water availability is determined from the concept of available water amount for doing function in general term. Amount of available water is determined as accumulation of conventional water provision, alternative water provision, regeneration water provision, and reuse water provision. The conventional water provision indicates the water earned through conventional process cycles. They are extracted from watershed or groundwater, transferring, distribution, and processing before its usage. The alternative water provision is water from alternative sources such as vapor condensation, and mining process extraction. The regeneration is water that is earned from wastewater treatment after another process usage before. The reuse water comes from direct usage released from another process usage without any processing. To simplify the process, different quality of the water is not considered. It is assumed that the most important point is its availability in the term of amount. Investment cost of the system to provide alternative source.

Availability is calculated as the ratio of amount of available and amount of requirement. The amount of requirement is determined from the function of the system. Therefore, the availability is calculated using Equation (11.5). W_{av} is water availability. W_a and W_r are amount of available water and amount of required water as determined in Ref (Prasetyadi and Koonsrisuk, 2020), respectively.

$$W_{av} = \frac{W_a}{W_r} \tag{11.5}$$

Amount of water could be less than its need, equal, or more. As amount of available water is more than amount of requirement, some of them will be released without usage. When it happens, the availability will be count as 1. It is named as capped availability as the amount of water provision which is used. The capped availability can be calculated by Equation (11.6). Aggregation of the system is calculated in every system and shown as product of the availability.

$$\hat{W}_{av} = \begin{cases} 1 & ,1 \le \dfrac{W_a}{W_r} \\ a = \dfrac{W_a}{W_r} & ,1 > \dfrac{W_a}{W_r} \end{cases} \tag{11.6}$$

Accessibility is fitness quality of water that can be used for the requirement. The fitness quality was based on water energy consumption for processing the water. It includes energy for transferring and distributing, and energy for processing specific water such as RO and soften water. Coefficients of water transferring are used to determine the energy consumption of tap water processing. For the case of SUTH main building, the number is 0.223 kWh/m^3. The other coefficients of processing are added to fit the requirement. Soften water and RO water require additional coefficients of 0.36 kWh/m^3 and 0.47 kWh/m^3 (Wakeel et al., 2016), respectively. Minus coefficient can be applied for the condition of processing needed. Accessibility can be calculated as composition of water amount and coefficient of the water as shown in Equation (11.7).

$$W_{ac} = \frac{\sum_{i}^{n} C_i \hat{W}_{avi}}{\sum_{i}^{n} C_i} \tag{11.7}$$

The $\hat{W}_{avi}$ is calculated following Equation (11.6) for a specific function using W_{ai} and W_{ri} as available water amount for specific function and required water amount of specific function, respectively. As W_{avi} ranges 0 – 1, therefore W_{ac} is also in range of 0 - 1. The 1 condition shows that all requirements in specific function can be fulfilled.

The cumulative of water accessibility is applied to show the system accessible water. As the exergy efficiency function, the cumulative water accessibility is calculated in similar way. The formula calculating cumulative accessibility is shown in Equation (11.8). The j-th index is also for component or subsystem.

$$W_{acc} = \prod_{j=1}^{n} W_{acj} \tag{11.8}$$

11.3.4 Nexus Concept of the SUTH Main Building: Energy Water Effectiveness and Energy Water Conservation Level

Energy water effectiveness was proposed by Prasetyadi and Koonsrisuk (2020) for showing conservation level of a system. The number shows energy degradation for water fulfilling of a system. The energy and water effectiveness is product of exergy efficiency and water accessibility. The exergy efficiency as ratio conserved exergy during the process to supply exergy was used to show the energy conservation in the system. The water accessibility was applied to show the conservation in addition to energy. The energy water effectiveness was calculated by Equation (11.9).

$$EW_{eff} = \eta_{\mathrm{II}} W_{ac} \tag{11.9}$$

The definition of energy and water relation as formulated by Equation (11.9) implies that the water provision does not count on the degradation of water quality during the process. The water provision focused on the fulfillment of the requirement in specific quality. Scale of water quality fulfillment and exergy efficiency can be interpreted as the scale of energy conservation during the water provision. But it does not show the scale of energy and water conservation during the process.

To show both material conservations during the process, a new variable composed of exergy efficiency and modified water accessibility is proposed. The modified water accessibility shows the efficiency of water quality. The efficiency of water quality is determined by Equation (11.10). The W_{ef} is amount of water released by the system as the effluent. The $\hat{W}_{ef}$ is minimum amount of the water as the effluent released in current operation. The nominator shows amount of ideal utilized water. The denominator mentions current utilized water. Index of k mentions type of water. The energy water effectiveness is calculated by Equation (11.11).

$$\psi_j = \frac{\sum_i^n C_i \hat{W}_{avi} - \sum_k^m C_k W_{efk}}{\sum_i^n C_i W_{avi} - \sum_k^m C_k \hat{W}_{efk}} \tag{11.10}$$

$$EW_{eff}^* = \eta_{\text{II}} \psi \tag{11.11}$$

11.3.5 Variable Pair for a System

A variable pair is a method to represent a system as two parameters. For the nexus of energy and water, the parameters of the system describe energy and water state of the system. Exergy efficiency is proposed to show energy conservation of a system or a component in a system. The water quality efficiency indicates water conservation with energy consumption for its processing as the weighting factor. With known parameter of water requirement and energy supply to the system stated intrinsically, the other parameters of energy and water of the system can be predicted.

Therefore, a variable pair can be used to explore the system condition which is described by intrinsic parameters. A model of a system is presented in Figure 11.1.

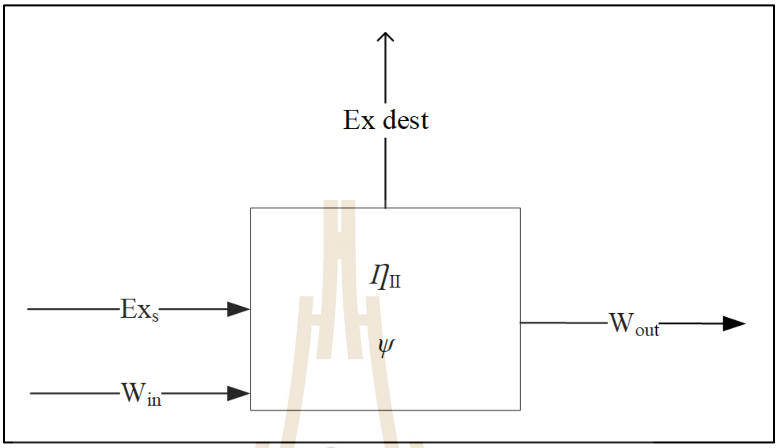


Figure 11.1 Model component of a system.

Figure 11.1 shows that a component of a system has two parameters, they are exergy efficiency and water quality efficiency. It also has exergy supply, exergy destruction, input water, and output water. These material flows also indicate the existence of input and output exergy flow. Assuming there is not any change in temperature and chemical composition, the exergy of the flow is composed of potential and kinetic energy. According to the definition of exergy efficiency in Equation (11.4), the exergy destruction of the system can be calculated. In similar way, the water state of the input and output can be inferred if the water requirement was known

11.3.6 The System Model

The system evaluated in this work includes HVAC, water system and wastewater system. The basic material flow relation of the system is presented in Figure 11.2. Some types of water indicating the water quality are transferred among the subsystems. The condensate water is available to be transferred to the tap water system when the infrastructure is prepared. Currently, the condensate water is unused. The brine is released from the cooling tower and sent to wastewater treatment.

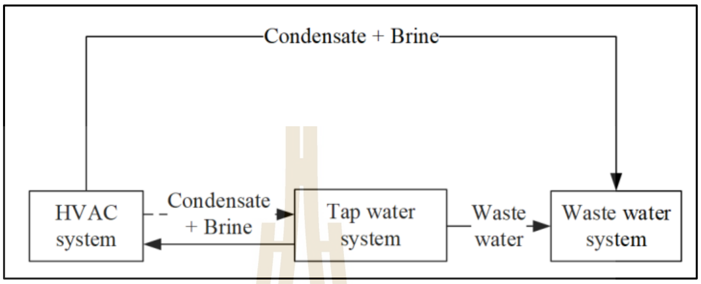


Figure 11.2 Material flow relation of the evaluated system.

The water flows among the subsystem or components are assumed to have constant composition and temperature. The exergy of water flows is assumed to be kinetic and potential energy only. Thermal exergy which depends on temperature is calculated as the high temperature difference exists. Assuming the transfer and distribution process do not change the temperature, the exergy of thermal can be neglected. The mechanical exergy of water as the function of volume change is neglected due to incompressibility of water.

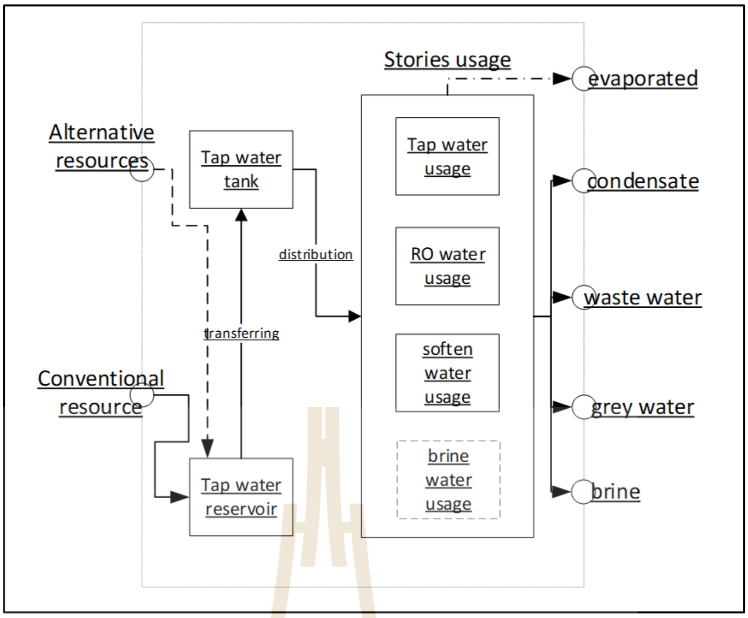


Figure 11.3 The water system and its usage.

The water system has two resources, conventional and alternative ones as shown in Figure 11.3. The conventional water resource is raw water supplied by SUT tap water system. The alternative water resources are the HVAC water origin. They are condensate water which is the condensed vapor at cooled room and the brine as the blow down of the cooling tower. Wastewater and grey water are not included at this work as the resource. The evaporated water at the cooling tower is also considered as the out flow of the water system.

11.3.7 The HVAC System

The HVAC system consists of FCU/AHU (Fan Coil Unit/Air Handling Unit), Chilled water pumps, chillers, condenser water pumps and cooling tower. Elaboration of exergy analysis on centralized HVAC system was provided in former work (Prasetyadi & Koonsrisuk). An aggregated model in the form of Figure 11.1 gives Equations (11.12-11.15). The Equations (11.12) and (11.13) show the exergy supply which is the electricity supply of the system and exergy destruction of the system. The Equations (11.14) and (11.15) are the material flows at the aggregated system.

$$Ex_s = Ex_{s,fcu} + Ex_{s,chp} + Ex_{s,ch} + Ex_{s,cdp} + Ex_{s,ct} \tag{11.12}$$

$$Ex_{dest} = Ex_{dest,fcu} + Ex_{dest,chp} + Ex_{dest,ch} + Ex_{dest,cdp} + Ex_{dest,ct} \tag{11.13}$$

$$W_{in} = A_{r,in} + A_{at,in} + W_{mu,in} \tag{11.14}$$

$$W_{out} = A_{r,\mathrm{out}} + A_{at,\mathrm{out}} + W_{b,out} + W_{cd,out} \tag{11.15}$$

The exergy equation of the HVAC system regarding model of Figure 11.1, can be written as

$$Ex_s + Ex_{win} + Ex_{wout} - Ex_{dest} = 0 \tag{11.16}$$

with the exergy was analyzed as aggregation of the system. The efficiency exergy of the HVAC was calculated using Equation (11.17).

$$\eta_{\mathrm{II}} = 1 - \frac{Ex_{dest}}{Ex_s + Ex_{win}} \tag{11.17}$$

The water flows of the HVAC system can be considered to follow the following equation without any regeneration usage.

$$\psi = \frac{\dfrac{C_{soft}\hat{W}_{mu} + C_{11th}\hat{W}_{mu}}{\left(C_{soft} + C_{11th}\right)W_{mu,r}} - \dfrac{C_{11th}W_{cond}}{\left(C_{soft} + C_{11th}\right)W_{mu,r}}}{\dfrac{C_{soft}W_{mu} + C_{11th}W_{mu}}{\left(C_{soft} + C_{11th}\right)W_{mu,r}} - \dfrac{C_{11th}\hat{W}_{cond}}{\left(C_{soft} + C_{11th}\right)W_{mu,r}}} \tag{11.18}$$

Equation (11.18) can be simplified to be Equation (11.19).

$$\psi = \frac{C_{soft}\hat{W}_{mu} + C_{11th}\hat{W}_{mu} - C_{11th}W_{cond}}{C_{soft}W_{mu} + C_{11th}W_{mu} - C_{11th}\hat{W}_{cond}} \tag{11.19}$$

If the collected condensate water is used for the make-up water, the equation becomes (11.20)

$$\psi = \frac{C_{soft}\hat{W}_{mu} + C_{11th}\left(\hat{W}_{mu} + \hat{W}_{cond}\right) - C_{11th}W_{cond}}{C_{soft}W_{mu} + C_{11th}\left(W_{mu} + W_{cond}\right) - C_{11th}\hat{W}_{cond}} \tag{11.20}$$

11.3.8 Water System

The water system of the SUTH model was discussed in former work of the authors. The model of the water system is provided in Figure 11.4. The tap water was distributed into stories according the need of the stories. The exergy of the water included kinetic energy, potential energy, and losses of the water system. The water usage exergy was not counted on the fixture basis. To simplify the exergy destruction calculation, the exergy destruction of the water was assumed to be every quality removal and minus of water treatment processing exergy destruction.

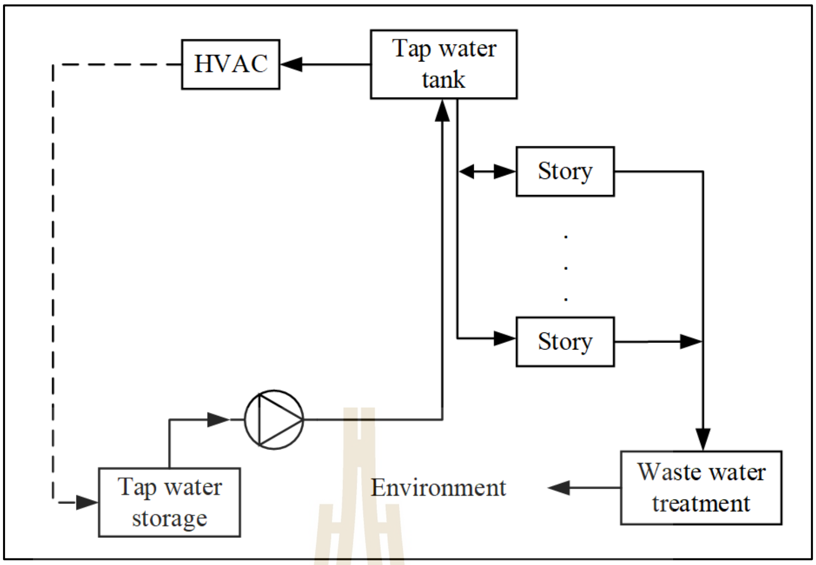


Figure 11.4 The water system of SUTH main building.

The model of Figure 11.1 for the water system can provide the Equations (11.21-11.23), and assuming the relation of $Ex_s = Ex_{s,pump}$. The exergy destruction of the tap water system consists of exergy destruction of pumping, exergy destruction of transferring, exergy destruction of distributing, and exergy destruction of usage as shown in Equation (11.21). The former work of the authors shows that the exergy destruction of the tap water system was very insignificant in comparison to HVAC and wastewater system (Prasetyadi and Koonsrisuk, 2020). $W_{\mathrm{conv},in}$, $W_{\mathrm{bl},in}$, and $W_{cond,in}$ are conventional water resource, brine of the blowdown, and collected condensate water, respectively. The outflow of the water consists of wastewater, brine water, and condensate water. The amount of the water depends on the usage.

$$Ex_{dest} = Ex_{dest,\mathrm{pump}} + Ex_{\mathrm{loss},transf} + Ex_{\mathrm{loss},distr} + Ex_{loss,usage} \tag{11.21}$$

$$W_{in} = W_{\mathrm{conv},in} + W_{\mathrm{bl},in} + W_{cond,in} \tag{11.22}$$

$$W_{out} = W_{waste,out} + W_{br,out} + W_{cond,out} \tag{11.23}$$

Table 11.1 The wastewater system treatment function and capacity.

Function	Power	Capacity (m^3/hr)
CAT (Continuous Aeration Tanks)	4 kW	150
SAT (Sequence Aeration Tanks)	4 kW	150
RSP (Returned Activated Sludge Pumps)	3 kW	150
Decanter		64.8

11.3.9 The wastewater system treatment

Table 11.2 Operation condition options of the water system

Option	Source	Function
Current	Raw water of SUT	All function
Option 1	Raw water of SUT Condensate from HVAC	All function, Except flush Flush
Option 2	Raw water of SUT Condensate from HVAC	All function All function
Option 3	Raw water of SUT Condensate from HVAC Brine	All function, Except UG and flush at 9^{th} to 11^{th} floor All function at UG Flush at 9^{th} to 11^{th} floor

The wastewater processing discussion was conducted in the former work of the authors. It is a kind two steps wastewater treatment and called as activated sludge type. The system comprises pumps that are used to transfer the sludge or to move it. These pumps were operated in 65% efficiency. In term of functions, there are 3 main functions. They are CAT, SAT, and RPS. CAT and SAT were used for aerating and mixing. RPS was the unit for pumping the sludge. The capacity and power of the systems are provided in Table 11.1. The CAT was operated 2 hours per batch, while SAT was set to work 1 hour every batch. The system work 1 times a day as the capacity of the wastewater is higher than the wastewater system of the building. According to model Figure 11.1, the wastewater treatment system provides Equations (11.24-11.26). The system is assumed to process the system without any water losses.

$$Ex_{dest} = Ex_{dest,\mathrm{pump}} + Ex_{\mathrm{loss},CAT} + Ex_{\mathrm{loss},SAT} \tag{11.24}$$

$$W_{in} = W_{waste} \tag{11.25}$$

$$W_{out} = W_{waste} \tag{11.26}$$

11.3.10 Operation Option and Limiting Calculation Model

In addition to the current operational condition, 3 different options are proposed at the water system condition. The current operational condition is determined as the condition when the data was taken. It uses single roof top storage only for distributing all the tap water to the building. The only source of the water is conventional water resource from the Suranaree University of Technology water system. The options are proposed in order to provide the system with minimum retrofitting. The option conditions are shown in Table 11.2. All the options assume that the HVAC condensate water can be collected.

The model of the system is calculated with neglecting detail of stories and subsystems. The detail was discussed on former work. The limitation of function is conducted to clarify the way of water effectiveness calculation and its implication of the indexing.

11.4 Results and Discussion

The operation conditions imply several different options can be selected as shown in Table 11.2. The current option uses only raw water from SUT water system. Potential water resources which consist of the HVAC condensate and blow down, are counted as part of the available water, even it is not utilized yet. So the amount of water available is higher than the amount currently use. Therefore, the water availability of the water system as defined by Equation (11.7) is higher than 1. It means that the amount of water for water system is more than the system needs.

The water quality efficiency of the water system is only 0.39. The number shows that some water is not used efficiently. It is confirmed by the availability of the water system which is 2.84. The number comes from accumulation of availabilities of floors as reported in former work (Prasetyadi and Koonsrisuk, 2020). There is more available water at underground floor and rooftop floor. At underground, the water is accumulated condensate. At the rooftop there is brine.

Table 11.3 shows that HVAC water availability is 1. This indicates that all the water needed for HVAC can be fulfilled as much as the amount it needs in current option. The HVAC system needs 27.96 m^3 make up water and it is supplied by 27.96

m^3 of soften water. It is also can be inferred that the HVAC system worked as it should be because the cooling tower water is sufficient because the cooling tower is the only HVAC equipment consumes water. If the amount of the water were less than the required number, the cooling tower cannot work properly. The cooling tower water works as the final heat removal to the atmosphere.

The water quality efficiency, which is the ratio between the minimum water utilized in specific quality and the utilized water as determined in Equation (11.10). The values of the water quality efficiency are shown in column 6 of Table 11.3. The water quality efficiency of HVAC system which is less than 1 means that in term of quality the provided water is more than the amount that the system needs. The HVAC water quality efficiency is 1. It needs 27.96 m^3 soften water with coefficient of 0.22 and 0.36 kWh/m^3 for transferring and processing. There is also brine as much as 4.66 m^3 with coefficient of transferring only. The brine is on the rooftop as it is released.

Combination water availability of 1 and water quality efficiency of 0.89 indicates that there is alteration of water quality and the existence of by product. There is quality change of the water as the HVAC operating. In the case, the amount of the water supplied for the system is equal, but the cooling process make the quality of the blow down is not as good as the input. The brine needs to be treated for consuming. As the location of the blowdown is on the same floor, the quality of the brine is determined by position only. The unused by product make the second terms of nominator and denominator of Equation (11.10) are different. Therefore, the water quality efficiency is less than 1.

The water quality efficiency shows the equivalent of energy for the water consumption. Some of the water is released as vapor. Some water has alteration as the quality decreasing. At HVAC, the make-up water is supplied as soften water which has 1 phase RO processing. It needs 0.36 kWh/m^3 water. The blow-down released by cooling tower is kind of brine which is assumed to loss its processing quality. Therefore, energy equivalent of the utilized water is determined by amount of the water, input type and output type. The ideal condition is determined with assumption that there is not any change of the quality of the blowdown. At the current option, the difference of 4.46 m^3 blowdown is 1.6 kWh.

The exergy efficiency of the HVAC system as indicated in Table 11.3 is 69%. According to the calculation, it requires 538.6 kW of electricity to run the HVAC system. This electricity becomes the exergy supplied to the system. During the processes, 167.5 kW exergy was destructed as shown in Table 11.3. In an HVAC system, the work consists of cooling process and transfer process. The exergy destruction rate of the system was 31% indicating amount of supplied exergy released to environment or dissipated during the process.

The nexus index of the HVAC is 0.61. It indicates that 61% of the water and energy as a nexus is conserved at the process. Because the number comes from exergy efficiency of 69% and 89% of water quality efficiency, it shows that only 69% of exergy transformed to be work. At the same time 89% of the water is still conserved in term of quality amount. The HVAC also shows that water is more conserved in the process rather than the exergy.

Exergy destruction of water provision is determined by the flow rate of the water at stories and the pumping in transferring process. As the amount of water distributed is equal regardless alternative water is applied. Therefore, exergy destruction of the tap water is still. It means that the exergy destruction does not change as the assumption of other operational condition kept still.

The exergy water processing was 93%. It points out that only few part of the exergy was destructed during the water processing. At the same time, quality water efficiency of the water system was 39% indicating some of the water was not used efficiently. It was affirmed by the water availability of the tap water system scoring higher than 2.8. In the term of water amount there was more than two-fold of water usage. At the same time, with water effectiveness 66.1%, the system was indicated have to use the water inefficiently. A lot of possibility can be applied for saving.

The current option has overall exergy efficiency of 68% and water quality efficiency of 65%. The number created nexus index of 0.44. The exergy destruction rate of the system is 179 kW from the electricity average power of 558.3 kW. The water availability of overall system is equal to water availability of the water system. It tells that the water system is the input of the water system. The different water quality efficiency happens due to different output. The tap water system has output wastewater sent to wastewater treatment. The overall system has output of released water from wastewater treatment. The output of the wastewater treatment has coefficient of 0. While the coefficient of tap water system is -0.343 kWh/m^3. The overall nexus shows that 44% of the energy and water resource are effectively used (transformed) to be work and kept conserved as the water with specific quality.

Table 11.3 The parameters of the system at current option.

System	Equipment	Exergy destruction	Exergy efficiency	Water availability	Water Quality efficiency	Index of Nexus
HVAC	Coil Fans	19.48	0.69	1	0.89	0.61
	CH Pumps	18.12				
	CD Pumps	8.92				
	Chiller	120.98				
	Cooling Tower	0.03				
Tap water	Distribution	3.26	0.93	2.84	0.39	0.36
	Transferring	0.59				
Wastewater	CAT	2.79	0.31	0.22	0.22	0.07
	SAT	2.79				
	Transferring pumps	2.04				
Overall		179	0.68	2.84	0.65	0.44

The water quality efficiency according to options as proposed in Table 11.2 is presented in Figure 11.4. It seems that option 2 which applies the condensate water for alternative source had the best condition in current operational setting temperature. The graph shows that the option 2 is the best in 24 °C and 22 °C setting temperatures. At 26 °C setting temperature, option 3 is considered the best, even it only had slightly different with the 24 °C setting temperature. At 26 °C, the condensate water is relatively equal to the amount of make-up water.

Exergy efficiency of the system was constant for water tap system in every option. It only depends on the amount of the processed water. The operational option did not change the amount of the water to be processed. Therefore, the exergy efficiency of the water system can be represented by Figure 11.6. The graph shows that the difference of exergy efficiency of tap water system was very small for different setting temperature of HVAC.

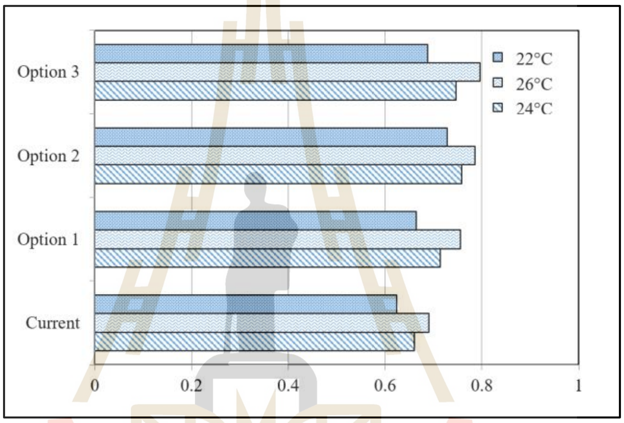


Figure 11.5 Water effectiveness of the operational options of HVAC setting temperature.

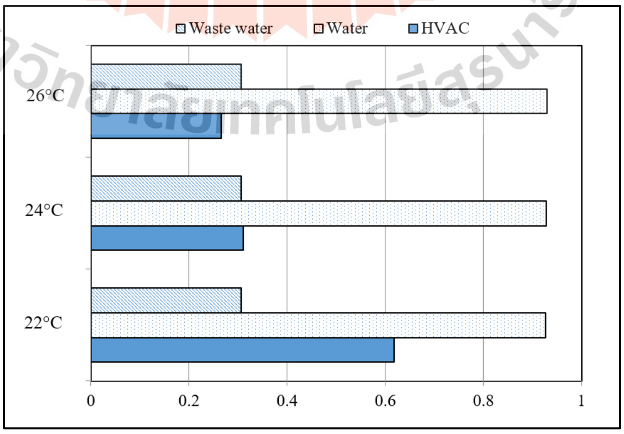


Figure 11.6 Exergy efficiency of the system in various setting temperature of HVAC system.

The wastewater does not have any difference in exergy destruction rate as the amount of the water processed was less than its maximum capacity. It was set to work in accordance with its maximum capacity. While the amount of the wastewater is less than its capacity, the system works as it is in maximum condition. The capacity of the wastewater is 220 m^3.

HVAC system tends to have different exergy efficiency according to the setting temperature. The higher setting temperatures are, the exergy efficiency are less. It is acceptable as the exergy depends on the temperature difference between the working fluid and environment. To work with less setting temperature, the working fluid temperature should have less temperature as well. However, energy consumption of the HVAC was significantly affected by setting temperature. The less the temperature is, the more energy consumption of the HVAC.

11.5 Conclusion

The indexing for nexus of consumption system can be conducted using combination of exergy and water quality efficiency. The exergy shows how the exergy was transformed to be work during the process. The water quality efficiency points out how water is conserved in a system in term of amount and quality. If the water availability is higher than 1, the water quality efficiency is less than 1 as the amount of water is more than its need. When the availability is 1, but the water quality efficiency is less than 1, it indicates that the output water still can be used for another function. It shows inefficiency of processing.

CHAPTER XII

CONCLUSION AND RECOMMENDATION

12.1 Introduction

Suranaree University of Technology Hospital is a kind of Hospital dedicated for learning and support the community nearby. It is addressed in Nakhon Ratchasima, Thailand and has capacity of 120 inpatient wards. The hospital is affiliated with the Institute of Medicine of Suranaree University of Technology. SUTH is a kind of multi speciality hospital with some specialist clinics and general clinic.

Energy and water of Suranaree University of Technology Hospital was studied to understand both resources interrelation. The domain is limited to be the main building, named Rattanajevapat and functioned as the clinics, wards, offices, and some support system. The building has 12 floors including the underground with total area of 19,000 m^2. It has $2\times1{,}250$ kVA transformer for electricity supply, 220 m^3 wastewater treatment and 3×250 TR chiller system.

It is reported that the building consume 9 MWh/day electricity in average. The number approximates 3.3 GWh of electricity consumption per year. The building electricity consumption is 70% of the hospital electricity consumption. HVAC is the dominant electricity consumer of the building. The HVAC consumes 54% of the building consumption. The water usage of the building is reported as much as 82.7 m^3/day in average. This water consumption is 69% of the hospital water usage.

The HVAC of the building uses 33% of building water. It means that HVAC almost uses 50% of the building water.

12.2 Conclusion

The work consists of qualitative and quantitative approaches to understand the interrelation of energy and water in hospital. The qualitative approach is conducted by mapping the system by architectural framework and determining the quality of the flows. The quantitative approaches is applied through simulating the HVAC system, conducting energy and exergy analysis over the system comprise energy and water flow. The following are the conclusion of the works

1) The architectural framework shows that HVAC and the water system which includes tap water, wastewater and hot water, are the place where most of energy and water is consumed. The electricity is the only energy form that is used by the building. For the reasons of safety, the centralized hot water is not operated. Some main equipment, such as radiology instruments, boiler and autoclaves, are not in the main building. This condition limits parts using energy and water simultaneously where energy and water can be interrelated as limited by the scope. It also takes place toward the lighting.

Water type and quality is described by map of water quality flows. There are five types of water that can be consumed. They are tap water, hot water, RO water, soften water, and recycled water. As the hot water system is out of function, there are only four type of water to be consumed. The released water of the system is wastewater, brine and distilled water namely condensate water.

2) Second law analysis of HVAC system provides two indicators namely ratio of exergy destruction to electricity power (XER) and ratio of exergy destruction to cooling load (XLR). The first indicator shows the conservation of exergy and the second indicator shows impact of cooling load to exergy destruction of the system. The XER shows that coil fans are places where destructed most of its energy, most exergy destruction takes place in chiller. It is also mentioned that cooling load affect exergy destruction positively. The XER of the HVAC at 24 °C setting temperature are 57.1%, 41.0%, 36.7%, 21.6%, and 0.2% at chiller, fcu/ahu, chp, cdp, and cooling tower, respectively. The XLR of the system is at 24 °C setting temperature is 0.078. The total cooling load and average exergy destruction are 2139 kW and 167.5 kW. Electricity consumption of the HVAC at 24 °C setting temperature is 3.05 MWh/day with 1.88 MWh/day, 0.43 MWh/day, 0.36 MWh/day, 0.38 MWh/day being consumed by chiller, FCU, CHP, and CDP, respectively.

The exergy analysis of the HVAC system shows that setting temperature of the HVAC affect energy and water conservation. Exergy destruction ratio to electricity input is minimum when the setting temperature of the centralized HVAC 24 °C. Harvesting the condensate water and combining with the brine of the blowdown, significantly reduce the water withdrawal of the HVAC. Energy intensity of the water for HVAC operation also decreases through this method to be less than 0.1 kWh/m^3.

Multistory building provides challenge of distribution the chiller water. Different requirement of the story need different flow rate of the chiller water. The common installation of multi control valves is applied, but it gives pressure and power loss which is linear to the flow rate. The study finds that application of multi small pumps in every story for replacing single powerful pump can reduce the exergy destruction as the resistance of the story depends on the flow rate.

3) The energy for water transferring from the underground storage to rooftop tank was 0.22 kWh/m^2. Wastewater energy intensity was 0.34 kWh/m^2. In average, from 82.7 m^2 water used in SUTH main building, only 47.7 m^2 of the water was released to the environment from 2 phase wastewater treatment of the building. 23.3 m^2 of the water was evaporated at the cooling tower in average. There is 21.3 m^2 of condensate water and 4.7 m^2 of brine that can be harnessed as alternative water source.

Exergy analysis is applied to water of multi-story SUTH main building based on flow rate. The water usage is transformed to be flow rate of every story by probability approach. The water system includes tap water system, HVAC, and wastewater treatment. It is found that the exergy destruction in distribution water is more significant than water transferring. It is also noted that HVAC is the place where most of the exergy destruction happens. Application of multi-tanks for water distribution can reduce the exergy destruction.

Increasing setting temperature of the HVAC reduces energy usage of the HVAC and its exergy destruction rate. At the same time, it also reduces the potential alternative water source harnessing. Increasing temperature setting to be 26 °C, reduces electricity usage 2.1 million Baht a year. At the same time, it increases water cost by 4,000 Baht in a year. Reducing temperature setting to be 22 °C, electricity consumption increases by 2.2 million Baht per year. But it only reduces water cost by 4,000 Baht. It is clear that energy cost is more dominant. This condition implies that 24 °C setting temperature is the best condition of the system.

The study of proposing method for evaluating energy of water system using variable pair is conducted. The method is applied in case of the water streams in SUTH main building. The water usage of HVAC, sanitary and medical are included. Three options in addition to the current operational strategy are tested. The result shows that the current operation strategy can be improved. Even, ideal condition by distributing water tank without regeneration still has less energy intensity than the current condition. Improvement of alternative water resources can reduce cost of electricity and cost of water by 12%. A presentation of vector like graph can easily shows cost different of every proposed options.

4) Indexing as a strategy to show the interrelation of energy and water in SUTH main building is conducted. Exergy efficiency is proposed to show the energy conservation. Availability as the amount of water for use and accessibility as the quality condition of the water are proposed. The current operation condition has exergy efficiency, water availability, and water accessibility of 56.39%, 2.84, and 1, respectively. It shows the adequacy of water and exergy conservation during the operation.

Advancement of the method toward single number indexing is proposed. Modification of the water indexing to be energy water effectiveness that shows the degradation of water quality is applied. The final index of nexus is extracted as combination of exergy efficiency and energy water effectiveness. The results show that the current operation condition has nexus index of 0.44, with exergy efficiency of 0.65 and water quality efficiency of 0.68. Each number shows the conservation of energy and water, energy, and water at the consumption process of the building, respectively.

12.3 Recommendation

Development and assessment of energy and water nexus in SUTH main building is conducted. Process consumption of energy and water shows the degradation of energy and water quality through the process. Indexing of nexus as a method to show the conservation of energy and water in the process has been proposed. The method can provide score in range of 0 and 1. The character of exergy and energy water efficiency can show the process in both resources. The building is reported to run at 0.44 nexus index where only 0.68 of exergy is conserved and 0.65 of water is conserved. Improvement of the system can be conducted through adjustment of water system resources and temperature setting of the HVAC system.

Some improvements that the SUTH can do are

1. Collecting condensate water for alternative resource. The condensate water can reduce raw water 23.3 m^3 in average a day.

2. Collecting brine for water alternative resource is also an alternative to reduce water raw. The brine can be used for some usage such as watering and flushing.

3. Applying multiple water tank storage is also applicable for new multistory building design. The crossing point of pressure loss and velocity loss is the place where the water tank should be built. In case of SUTH, the 6^{th} floor is the best area for dividing water tank.

4. Applying multi pumps for chilled water pump can reduce the exergy destruction of the CHP system. It implies more efficient system can be achieved. The detailed should be studied considering story usage and beyond the current study.

5. Recalculating the cooling load is important in designing a new hospital building. As the system shows that exergy efficiency of the system in average less than

half, it means that all the system is considered overdesign. The lag of cooling capacity in some condition can be affected by imbalance system.

6. If it is possible, do not locate cooling tower on the rooftop. The experience shows that CDP energy need is higher than CHP as the cooling towers are located at the rooftop.

7. Separation functional building as SUTH designed limits the probability of integrating energy and water. Waste heat of autoclaves and boilers are useful to be used for combination of power and heating or tri-generation.

8. Calculating nexus index is important in designing a facility. Nexus indexing shows how the building can conserve the energy and water. A real measurement can be applied in order to support the conservation of energy and water.

REFERENCES

Ackerman, F. and Fisher, J. (2013). Is there a water-energy nexus in electricity generation? Long-term scenarios for the western United States. **Energy Policy**. 59: 235-241.

Adewumi, O. O., Bello-Ochende, T. and Meyer, J. P. (2013). Constructal design of combined microchannel and micro pin fins for electronic cooling. **Int. J. Heat Mass Transf**. 66: 315-323.

Alexis, G. K., & Liakos, P. (2013). A case study of a cogeneration system for a hospital in Greece . Economic and environmental impacts. **Appl. Therm. Eng.** 54(2), 488-496.

Al-Hadban, Y., Sreekanth, K. J., Al-Taqi, H. and Alasseri, R. (2018). Implementation of Energy Efficiency Strategies in Cooling Towers - A Techno-Economic Analysis. **J. Energy Resour. Technol.** 140: 1-11.

Al-Karaghouli, A. and Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. **Renew. Sustain. Energy Rev.** 24: 343-356.

Al Fry. (2006). Facts and Trends: Water. World Business Council for Sustainable Developement.

Ali, B. (2017). Development of life cycle water-demand coefficients for coal-based power generation technologies. **Energy Convers. Manag.** 90: 247-260.

Ali, B. and Kumar, A. (2016). Development of life cycle water footprints for gas-fired power generation technologies. **Energy Convers. Manag.** 110: 386-396.

Ali, B. and Kumar, A. (2017). Development of water demand coefficients for power generation from renewable energy technologies. **Energy Convers. Manag.** 143, 470-481.

Allan, J. A. (1998). Virtual Water: A Strategic Resource Global Solutions to Regional Deficits. **Ground Water**. 4(36): 545-546.

Angelbeck, J. A. (2006). Hospital Water. **Manag. Infect. Control**. 44.

Ataei, A., Panjeshi, M. H. and Karbassian, S. (2009). Simultaneous Energy and Water Minimization. **Res. J. Environ. Sci.** 1-15.

Alperovits, E. and Shamir, U. (1977). Design of optimal water distribution systems. **Water Resour. Res.** 13(6): 885-900.

Alvarez, A., Cabeza, O., Muñiz, M. C. and Varela, L. M. (2010). Experimental and numerical investigation of a flat-plate solar collector. **Energy**. 35(9): 3707-3716.

Alves, O., Monteiro, E., Brito, P. and Romano, P. (2016). Measurement and classification of energy efficiency in HVAC systems. **Energy Build.** 130: 408-419.

Aprea, C., Maiorino, A. and Mastrullo, R. (2014). Exergy analysis of a cooling system: Experimental investigation on the consequences of the retrofit of R22 with R422D. **Int. J. Low-Carbon Technol.** 9(1): 71-79.

Ascione, F., Bianco, N., De Stasio, C., Maria, G. and Peter, G. (2016). Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: A new approach to assess. **Appl. Energy**. 174: 37-68.

Bakaimis, B. and Papanikolaou, I. (2017). Electrical Energy Saving Policies, Initiatives, Results, Challenges and Lessons Learned for the Grevena Hospital. **Procedia Environ. Sci.** (38): 882-889.

Bagnasco, A., Fresi, F., Saviozzi, M., Silvestro, F. and Vinci, A. (2015). Electrical consumption forecasting in hospital facilities : An application case. **Energy Build.** 103: 261-270.

Balaras, C. A., Dascalaki, E. and Gaglia, A. (2007). HVAC and indoor thermal conditions in hospital operating rooms. **Energy Build.** 39(4): 454-470.

Baniassadi, A., Momen, M., Amidpour, M. and Pourali, O. (2018). Modeling and design of solar heat integration in process industries with heat storage. **J. Clean. Prod.** 170: 522-534.

Baños, R., Reca, J., Martínez, J., Gil, C. and Márquez, A. L. (2011). Resilience Indexes for Water Distribution Network Design: A Performance Analysis Under Demand Uncertainty. **Water Resour. Manag.** 25(10): 2351-2366.

Bejan, A. and Lorente, S. (2006). Design with Constructal Theory. **Int. J. Eng. Educ.** 22(1): 140-147.

Bejan, A., & Lorente, S. (2011). The constructal law and the evolution of design in nature. **Physics of Life Reviews,** *8*(3), 209-240.

Bertone, E., Sahin, O., Stewart, R. A., Zou, P., Alam, M. and Blair, E. (2016). State-of-the-art review revealing a roadmap for public building water and energy efficiency retrofit projects. **Int. J. Sustain. Built Environ.** 5(2): 526-548.

Bertone, E., Stewart, R. A., Sahin, O., Alam, M., Zou, P. X. W., Buntine, C. and Marshall, C. (2018). Guidelines, barriers and strategies for energy and water retrofits of public buildings. **J. Clean. Prod.** 174, 1064-1078.

BIS (Bio Intelligence Service) and Cranfield University. (2009). **Study on water performance of buildings**, 33(June): 14-53.

Bonnema, E., Pless, S., and Doebber, I. (2010). Advanced Energy Design Guide for Small Hospitals and Healthcare Facilities. **J. Healthc. Eng.** 1(2), 277-296.

Bonnema, E., Studer, D., Parker, A., Pless, S. and Torcellini, P. (2010). **Large Hospital 50 % Energy Savings : Technical Support Document.** National Renewable Energy Laboratory.

Bottero, M. C., Buffoli, M., Capolongo, S., Cavagliato, E., di Noia, M., Gola, M., and Volpatti, L. (2015). Improving Sustainability During Hospital Design and Operation. in: **Green Energy and Technology** Vol. 218. Capolongo, S., Bottero, M. C., M. Buffoli, and Lettieri, E. (Eds). New York: Springer.

Bonnema, E., Studer, D., Parker, A., Pless, S. and Torcellini, P. (2010). **Large Hospital 50% Energy Savings: Technical Support Document.** National Renewable Energy Laboratory.

Bottero, M. C., Buffoli, M., Capolongo, S., Cavagliato, E., di Noia, M., Gola, M. and Volpatti, L. (2015). Improving Sustainability During Hospital Design and Operation. **Green Energy and Technology** (218). Springer, Springer Cham Heidelberg.

Bujak, J. (2010). Heat consumption for preparing domestic hot water in hospitals. **Energy Build.** 42(7): 1047-1055.

Buratti, C., Ricciardi, P., and Vergoni, M. (2013). HVAC systems testing and check: A simplified model to predict thermal comfort conditions in moderate environments. **Appl. Energy**. 104: 117-127.

Buonomano, A., Calise, F., Ferruzzi, G. and Palombo, A. (2014). Dynamic energy performance analysis : Case study for energy efficiency retrofits of hospital buildings. **Energy**. 78: 555-572.

Buchberger, S., Omaghomi, T., Wolfe, T., Hewitt, J. and Cole, D. (2015). Peak Water Demand Study: Probability Estimates for Efficient Fixtures in Single and Multi-family Residential Buildings. **Under Rev.** 68.

Carravetta, A., Del Giudice, G., Fecarotta, O. and Ramos, H. M. (2012). Energy Production in Water Distribution Networks: A PAT Design Strategy. **Water Resour. Manag.** 26(13): 3947-3959.

Chirarattananon, S., Chaiwiwatworakul, P., Hien, V. D., Rakkwamsuk, P. and Kubaha, K. (2010). Assessment of energy savings from the revised building energy code of Thailand. **Energy**. 35(4): 1741-1753.

Chirarattananon, S., Chaiwiwatworakul, P., Hien, V. D., Rugkwamsuk, P. and Kubaha, K. (2007). Revised Building Energy Code of Thailand-Potential Energy and Power Demand Savings. In **Proceedings of the Joint International Conference on Sustainable Energy and Environment 2**: 1-10. Retrieved from http://e-nett.sut.ac.th

Christiansen, N., Kaltschmitt, M. and Dzukowski, F. (2016). Electrical energy consumption and utilization time analysis of hospital departments and large-scale medical equipment. **Energy Build**. 131: 172-183.

Chirarattananon, S., Chaiwiwatworakul, P., Hien, V. D., Rakkwamsuk, P., and Kubaha, K. (2010). Assessment of energy savings from the revised building energy code of Thailand. **Energy**. *35*(4): 1741-1753.

Choi, W., Ooka, R. and Shukuya, M. (2018). Exergy analysis for unsteady-state heat conduction. **Int. J. Heat Mass Transf.** 116: 1124-1142.

Christiansen, N., Kaltschmitt, M., Dzukowski, F. and Isensee, F. (2015). Electricity consumption of medical plug loads in hospital laboratories: Identification, evaluation, prediction and verification. **Energy Build**. 107: 392-406.

Chow, T. T., Tiwari, G. N., and Menezo, C. (2012). Hybrid solar: A review on photovoltaic and thermal power integration. **Int. J. Photoenergy**.

Collett, S., Samarin, I., Bhalchandra, R., Soundaranayagam, J., Garai, S., Chandy, M., and Bhattacharya, S. (2016). Water usage in a multi-speciality hospital and its effective management. **J. Acad. Clin. Microbiol.**

Congradac, V., Prebiracevic, B., Jorgovanovi, N., & Stanisic, D. (2012). Assessing the energy consumption for heating and cooling in hospitals. **Energy Build.** 48: 146-154.

Congradac, V. (2014). Methods for assessing energy savings in hospitals using various control techniques. **Energy Build**. 69: 85-92.

Copeland, C. (2014). Energy-Water Nexus: The Water Sector's Energy Use. **Congressional Research Service.** 13. Retrieved from http://www.eenews.net.

CSE (Center for Science and Envoronment). (2010). **Water Audit For Centre for Science and Environment (CSE)**. Center of Excellence - Sustainable Water Management, Ministry of Urban development, Government of India. 1-39.

Da Conceição Cunha, M. and Sousa, J. (1999). Water distribution network design optimization: Simulated annealing approach. **J. Water Resour. Plan. Manag.**

Dandy, G. C., Simpson, A. R. and Murphy, L. J. (1996). An Improved An improved genetic algorithm for pipe network optimization. **Water Resour. Res.** 32: 449-458.

Delgado, A., Rodriguez, D. and Sohns, A. (2015). **Thirsty Energy : Understanding the Linkages between Energy and Water**. Live wire knowledge notes series; no.2015/41.Washington, DC:World Bank Group. Retrieved from http://documents.worldbank.org.

Dincer, I. and Rosen, M. A. (2007). **EXERGY, Energy, Environment and Sustainable Development** (1st ed.). Oxford: Elsevier Ltd.

Dincer, I. and Rosen, M. A. (2015). **Exergy Analysis of Heating, Refrigerating and Air Conditioning: Methods and Applications**. Oxford: Elsevier Ltd.

Dincer, I. and Rosen, M. A. (2007). **EXERGY, Energy, Environment and Sustainable Development**. (1st ed.). Oxford: Elsevier Ltd.

Dubreuil, A., Assoumou, E., Bouckaert, S., Selosse, S. and Maïzi, N. (2013). Water modeling in an energy optimization framework - The water-scarce middle east context. **Appl. Energy.** 101: 268-279.

EIA (2012). Commercial Buildings Energy Consumption Survey: Consumption and Expenditures Tables. Retrieved February 20, 2018, from https://www.eia.gov

El-nashar, W. Y. and Elyamany, A. H. (2018). Managing risks of the Grand Ethiopian Renaissance Dam on Egypt. **Ain Shams Eng. J.** 9(4): 2383-2388.

Eltawil, M. A., Zhengming, Z. and Yuan, L. (2009). A review of renewable energy technologies integrated with desalination systems. **Renew. Sustain. Energy Rev.** 13(9): 2245-2262.

EPPO. (2016). **Thailand 20-Year Energy Efficiency Development Plan (2011 - 2030)**. Retrieved on February 20th 2018 from http://www.eppo.go.th.

Fang, D., Fath, B. D., Chen, B., and Scharler, U. M. (2014). Network environ analysis for socio-economic water system. **Ecol. Indic.** 47: 80-88.

Frisvold, G. B., and Marquez, T. (2013). Water requirements for large-scale solar energy projects in the West. **J. Contemp. Water Res. Educ.** 151(1): 106-116.

Gao, Z., Li, Y., and Ning, Y. (2017). The survey and analysis on the energy consumption of hospital buildings in Shandong province. **Procedia Eng.** 205: 2485-2492.

Gerbens-Leenes, P. W., Hoekstra, A. Y. and van der Meer, T. H. (2008). Water footprint of bio-energy and other primary energy carriers. **Value.** 29(29): 44.

Gerbens-Leenes, W., Hoekstra, A. Y., and Meer, T. Van Der. (2007). The Water Footprint of Energy Carriers. Retrieved on 23rd March 2020 from https://www.iwra.org.

Ghaffour, N., Missimer, T. M. and Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. **Desalination.** 309(2013): 197-207.

Ghodoossi, L. and Eğrican, N. (2004). Conductive cooling of triangular shaped electronics using constructal theory. **Energy Convers. Manag.** 45(6): 811-828.

Gimelli, A. and Muccillo, M. (2013). Optimization criteria for cogeneration systems : Multi-objective approach and application in an hospital facility. **Appl. Energy**. 104: 910-923.

Glassman, D., Wucker, M., Isaacman, T. and Champilou, C. (2011). The water-energy nexus: adding water to the energy agenda a world policy paper. **World Policy Institute** (45).

Gleick, P. H. (1994). Water and Energy. **Annu. Rev. Environ. Resour.** 19: 267-299.

Gimelli, A. and Muccillo, M. (2013). Optimization criteria for cogeneration systems : Multi-objective approach and application in an hospital facility. **Appl. Energy.** 104: 910-923.

Gold, G., and Webber, M. (2015). The Energy-Water Nexus: An Analysis and Comparison of Various Configurations Integrating Desalination with Renewable Power. **Resources.** 4(2): 227-276.

González, A. G., García-Sanz-Calcedo, J., Salgado, D. R. and Mena, A. (2016). A Quantitative Analysis of Cold Water for Human Consumption in Hospitals in Spain. **J. Healthc. Eng.** (2016): 1-10.

González, Alfonso González, García-Sanz-Calcedo, J. and Salgado, D. R. (2018). A quantitative analysis of final energy consumption in hospitals in Spain. **Sustain. Cities Soc.** (36): 169-175.

Grumman. (2019). Fossil Fuel Energy Consumption (BTU/SF/YR). **Year 2018 G/BA Hospital Energy and Water Benchmarking Survey For 2017,** Grumman/Butkus Associates. Retrieved from https://grummanbutkus.com 23rd March 2020.

Hawkins, T., Hendrickson, C., Higgins, C. and Matthews, H. S. (2007). A Mixed-Unit Input-Output Model for Environmental Life-Cycle Assessment and Material Flow Analysis. **Environ. Sci. Technol.** 41(3), 1024-1031.

Hassiba, R. J., & Linke, P. (2017). On the simultaneous integration of heat and carbon dioxide in industrial parks. **Appl. Therm. Eng.** 127: 81-94.

Hoekstra, A. Y. (2003). Virtual Water Trade.in **International Expert Meeting on Virtual Water Trade** 12(12), 1-244. Retrieved on March 20th 2018 from http://www.waterfootprint.org.

Holland, R. A., Scott, K. A., Flörke, M., Brown, G., Ewers, R. M., Farmer, E., … Eigenbrod, F. (2015). Global impacts of energy demand on the freshwater resources of nations. **Proc. Natl. Acad. Sci.** 112(48), E6707-E6716.

Hospital Energy Alliance. (2011). **Hospitals Save Costs with Water Efficiency**. US Department of Energy. 4 p.

Intelligent Community Assessment (2012). **Global Water Security**.

Isaka, M. (2012). **Water Desalination Using Renewable Energy**. Irena - Iea-Etsap. Retrieved on 20th March 2018 from http://www.irena.org .

Jain, N. and Alleyne, A. (2014). Transient Exergy Destruction Analysis of a Vapor Compression System. in **International Refrigeration and Air Conditioning Conference (2011)**. Retrieved from http://docs.lib.purdue.edu.

Jawad, H., Jaber, M. Y. and Nuwayhid, R. Y. (2018). Improving supply chain sustainability using exergy analysis. **Eur. J. Oper. Res.** 269(1): 258-271.

Jakobsen, A. M. and Nielsen, U. (2016). Water efficient hospitals, (August), 1-5.

Kalbasi, R. and Salimpour, M. R. (2015). Constructal design of phase change material enclosures used for cooling electronic devices. **Appl. Therm. Eng.** 84: 339-349.

Kalogirou, S. A., Karellas, S., Braimakis, K., Stanciu, C. and Badescu, V. (2016). Exergy analysis of solar thermal collectors and processes. **Prog. Energy Combust. Sci.** 56: 106-137.

Kargarsharifabad, H., Behshad Shafii, M., Taeibi Rahni, M. and Abbaspour, M. (2014). Exergy Analysis of a Flat Plate Solar Collector in Combination with Heat Pipe. **Int. J. Environ. Res.** 8(1): 39-48. Retrieved from http://www.ijer.ir.

Kassai, M. (2017). Prediction of the HVAC Energy Demand and Consumption of a Single Family House with Different Calculation Methods. **Energy Procedia** 112: 585-594.

Kenway, S. J., Lant, P. A., Priestley, A. and Daniels, P. (2011). The connection between water and energy in cities: A review. **Water Sci. Technol.** 63(9): 1983-1990.

Kittikhoun, A., and Michèle, D. (2018). Water diplomacy and conflict management in the Mekong : From rivalries to cooperation. **J. Hydrol.** 567: 654-667.

Kuo, W. C. J. and Smith, R. (1997). Effluent treatment system design. **Chem. Eng. Sci.** 52(23): 4273-4290.

Larson, D., Lee, C., Tellinghuisen, S. and Keller, A. (2007). California's Energy-Water Nexus : Water Use in Electricity Generation, **Southwest Hydrol**. 20-22.

Lee, K. P. and Cheng, T. A. (2012). A simulation-optimization approach for energy efficiency of chilled water system. **Energy Build.** 54:290-296.

Lele, U., Klousia-Marquis, M. and Goswami, S. (2013). Good Governance for Food, Water and Energy Security. **Aquat. Procedia** 1: 44-63.

Li, X., Feng, K., Siu, Y. L. and Hubacek, K. (2012). Energy-water nexus of wind power in China: The balancing act between CO 2 emissions and water consumption. **Energy Policy** 45: 440-448.

Liu, F., Ma, J., Feng, X. and Wang, Y. (2018). Simultaneous integrated design for heat exchanger network and cooling water system. **Appl. Therm. Eng.** 128: 1510-1519.

Liu, Y., Hejazi, M., Kyle, P., Kim, S. H., Davies, E., Miralles, D. G., … Niyogi, D. (2016). Global and Regional Evaluation of Energy for Water. **Environ. Sci. Technol**. 50(17), 9736-9745.

Lorente, S., Koonsrisuk, A. and Bejan, A. (2010). Constructal distribution of solar chimney power plants: Few large and many small. **Int. J. Green Energy**. 7(6): 577-592.

Lubega, W. N. and Farid, A. M. (2014a). Quantitative engineering systems modeling and analysis of the energy-water nexus. **Appl. Energy**. 135: 142-157.

Lubega, W. N. and Farid, A. M. (2014b). A Reference System Architecture for the Energy-Water Nexus. **IEEE Syst. J.** 10(99): 106-115.

Lubega, W. N. and Farid, A. M. (2013a). A Meta-System Architecture for the Energy-Water Nexus. In **8th annual IEEE Systems of Systems Conference** (pp. 1–6).

Lubega, W. N. and Farid, A. M. (2013b). An engineering systems model for the quantitative analysis of the energy-water nexus. **Complex Syst. Des. Manag.** 219–231. Retrieved from http://link.springer.com.

Lu, Y. and Chen, B. (2016). Energy-water nexus in urban industrial system. **Energy Procedia.** 88: 212-217.

Macknick, J., Newmark, R., Heath, G. and Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. **Environ. Res. Lett.** 7(4): 045802.

Ma, J., Wang, Y. and Feng, X. (2017). Simultaneous optimization of pump and cooler networks in a cooling water system. **Appl. Therm. Eng.** 125:377-385.

Marsh, D. M., and Sharma, D. (2007). Energy-water nexus: An integrated modeling approach. **Int. Energy J.** 8(4): 235-242.

Martin, A. D. (2012). Water Footprint of Electric Power Generation : Modeling its use and analyzing options for a water-scarce future. in **International Congress on Advances in Nuclear Power Plants**.

Mekonnen, M. M. and Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. **Hydrol. Earth Syst. Sci.** 15(5): 1577-1600.

Mekonnen, M. M. and Hoekstra, A. Y. (2012). The blue water footprint of electricity from hydropower. **Hydrol. Earth Syst. Sci.** 16(1): 179-187.

Michigan Department of Licensing & Regulatory Affairs (LARA). (1978). **Hospital Water Supply Requirements**.

Miguel, A. F. (2008). Constructal design of solar energy-based systems for buildings. **Energy Build.** 40(6): 1020-1030.

Mohammadi, A., Ahmadi, M. H., Bidi, M., Joda, F., Valero, A., and Uson, S. (2017). Exergy analysis of a Combined Cooling, Heating and Power system integrated with wind turbine and compressed air energy storage system. **Energy Convers. Manag.** 131: 69-78.

Montesinos, P., Garcia-Guzman, A. and Ayuso, J. L. (1999). Water distribution network optimzation using a modified genetic algorithm. **Water Resour. Res.** 35(11): 3467-3473.

Nag, P. K. and Gupta, A. V. S. S. K. S. (1998). Exergy analysis of the Kalina cycle. **Appl. Therm. Eng. 18**(6): 427-439.

Owen, S. M. (2003). **HVAC Design Manual for Hospitals and Clinics** 2nd ed. Owen, S.M. (Ed.). ASHRAE. Retrieved from www.ashrae.org.

Pagliarini, G., Corradi, C. and Rainieri, S. (2012). Hospital CHCP system optimization assisted by TRNSYS building energy simulation tool. **Appl. Therm. Eng.** 44: 150-158.

Perez-Lombard, L., Ortiz, J., & Maestre, I. R. (2011). The map of energy flow in HVAC systems. **Appl. Energy**. 88(12): 5020-5031.

Prasetyadi, A. and Koonsrisuk, A. (2018). A Reference System Architecture for Integrated Energy and Water in a Hospital. In **The 32nd Conference of The Mechanical Engineering Network of Thailand.** pp. 1-8.

Prasetyadi, A. and Koonsrisuk, A. (2019). Second law analysis of the centralized HVAC system of Suranaree University of Technology Hospital. In **Proceedings of the 14th Conference on Energy, Heat and Mass Transfer in Thermal Equipments and Processes.**

Prasetyadi, A.and Koonsrisuk, A. (2019). Exergy Analysis of Water Network for Suranaree University of Technology Hospital (SUTH) Main Building. In **CAFEO 37**.

Racoviceanu, A. I., Karney, B. W., Kennedy, C. A. and Colombo, A. F. (2007). Life-Cycle Energy Use and Greenhouse Gas Emissions Inventory for Water Treatment Systems. **J. Infrastruct. Syst.** 13(4): 261-270.

Regent Pump Australia. (2008). **RSV Series Vertical Multistage In Line Pumps**. Braeside, Victoria. Retrieved from www.regentap.com.au.

Rutberg, M. J. (2012). **Modeling water use at thermoelectric power plants** (Thesis). Massachusetts Institute of Technology

Saad, S. G. (2007). Water and sanitation in hospitals integrated environmental management a serious forgotten issue. In **Proc. IWTC11.** 695-701.

Saidur, R., Hasanuzzaman, M., Yogeswaran, S., Mohammed, H. A. and Hossain, M. S. (2010). An end-use energy analysis in a Malaysian public hospital. **Energy** 35(12): 4780-4785.

Sanders, K. T. and Webber, M. E. (2012). Evaluating the energy consumed for water use in the United States. **Environ. Res. Lett.** 7(3): 034034.

Sanders, K. T., Blackhurst, M. F., King, C. W. and Webber, M. E. (2014). The Impact of Water Use Fees on Water Used for Cooling Thermoelectric Power Generators. **Environ. Sci. Technol.** accepted with revisions.

Santo, D. B. de E. (2014). An energy and exergy analysis of a high-efficiency engine trigeneration system for a hospital: A case study methodology based on annual energy demand profiles. **Energy Build.** 76: 185-198.

Semkov, K., Mooney, E., Connolly, M. and Adley, C. (2014). Efficiency improvement through waste heat reduction. **Appl. Therm. Eng.** 70(1): 716-722.

Shi, C. and Zhan, J. (2015). An input-output table based analysis on the virtual water by sectors with the five northwest provinces in China. **Phys. Chem. Earth.** 79-82: 47-53.

Singer, B. C., Mathew, P., Greenberg, S., Tschudi, W., Sartor, D., Strom, S., … Burch, L. (2009). **Hospital Energy Benchmarking Guidance - Version 1 . 0**. Lawrence Berkeley National Laboratory LBNL Report LBNL-2738E.

Singh, K., & Das, R. (2017). Exergy optimization of cooling tower for HGSHP and HVAC applications. **Energy Convers. Manag.** 136: 418-430.

Singh, O. K. and Kaushik, S. C. (2013). Energy and exergy analysis and optimization of Kalina cycle coupled with a coal fired steam power plant. **Appl. Thermal Eng.** 51**(**1-2): 787-800.

Sohns, A. A., Rodriguez, D. J. and Delgado, A. (2016). **Thirsty energy (II): The importance of water for oil and gas extraction.** World Bank Group.

Sovacool, B. K. (2013). An international assessment of energy security performance. **Ecol. Econ.** 88: 148-158.

Sovacool, B. K., Mukherjee, I., Drupady, I. M. and D'Agostino, A. L. (2011). Evaluating energy security performance from 1990 to 2010 for eighteen countries. **Energy.** 36 (10): 5846-5853.

Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H. and Marks, D. H. (2014a). Multiple metrics for quantifying the intensity of water consumption of energy production. **Environ. Res. Lett.** 9(10): 105002.

Srinivasan, A. V. (2008). Health Care in India A Profile and the Future in **Managing a modern hospital, second edition.** Srinivasan, A. V. (ed). New Delhi, Sage Publications India.

Teke, A. and Timur, O. (2014). Assessing the energy efficiency improvement potentials of HVAC systems considering economic and environmental aspects at the hospitals. **Renew. Sustain. Energy Rev.** 33: 224-235.

Thinate, N., Wongsapai, W. and Damrongsak, D. (2017). Energy Performance Study in Thailand Hospital Building. **Energy Procedia**. 141: 255-259.

Tirmizi, S. A., Gandhidasan, P. and Zubair, S. M. (2012). Performance analysis of a chilled water system with various pumping schemes. **Appl. Energy**. 100: 238-248.

Trane. (2012). **Installation, Operation and Maintenance Series R ® Rotary Liquid Chillers Water-Cooled and Compressor-Chillers**. Trane.

United Nations (2015). **Transforming our world: the 2030 agenda for sustainable development**.

UN-Water (2020). **United Nations World Water Development Report 2020: Water and Climate Change**. Paris: UNESCO.

US Department of Energy (2014). **The Water-Energy Nexus: Challenges and Opportunities**.

US Departement of Energy (2009). **Hospitals Save Energy and Money by Optimizing HVAC Performance**. Energy Efficiency & Renewable Energy.

US Department of Energy. (2006). **Energy Demands on Water Resources Report To Congress on the Interdependency of Energy and Water Power**. Retrieved on 23rd February 2018 from http://www.sandia.gov.

Vakilifard, N., Anda, M., A. Bahri, P. and Ho, G. (2017). The role of water-energy nexus in optimising water supply systems-Review of techniques and approaches. **Renew. Sustain. Energy Rev.** :1-9.

Velázquez, E., Madrid, C., & Beltrán, M. J. (2011). Rethinking the Concepts of Virtual Water and Water Footprint in Relation to the Production-Consumption Binomial and the Water-Energy Nexus. **Water Resour. Manag.** 25(2): 743-761.

Venkatesh, G., Chan, A. and Brattebø, H. (2014). Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors. **Energy**. 75 :153-166.

Volpatti, L. (2015). Improving Sustainability During Hospital Design and Operation. in: **Green Energy and Technology** Vol. 218. Capolongo, S., Bottero, M. C., M. Buffoli, and Lettieri, E. (Eds). New York: Springer.

Wakeel, M., Chen, B., Hayat, T., Alsaedi, A., and Ahmad, B. (2016). Energy consumption for water use cycles in different countries: A review. **Appl. Energy**. 178(19): 868-885.

Wang, J., Huang, G., Sun, Y. and Liu, X. (2016). Event-driven optimization of complex HVAC systems. **Energy Build.** 133: 79-87.

Wang, Y. P. and Smith, R. (1994). Design of distributed effluent treatment system. **Chem. Eng. Sci.** 18(1): 3127-3145.

Wang, T., Li, X., Liao, P. C. and Fang, D. (2016). Building energy efficiency for public hospitals and healthcare facilities in China: Barriers and drivers. **Energy** 103: 588-597.

Wang, L. and Li, N. (2011). Exergy transfer and parametric study of counter flow wet cooling towers. **Appl. Therm. Eng.** 31(5): 954-960.

Xia, L., Lorente, S. and Bejan, A. (2011). Constructal design of distributed cooling on the landscape. **Int. J. Energy Res.** 35: 806-812.

Yan, J., Shamim, T., Chou, S. K., Desideri, U. and Li, H. (2017). Clean, efficient and affordable energy for a sustainable future. **Appl. Energy**. 185: 953-962.

Yang, J. and Chen, B. (2016). Energy-water nexus of wind power generation systems. **Appl. Energy**. 169, 1-13.

Yang, M., Feng, X. and Liu, G. (2016). Heat integration of heat pump assisted distillation into the overall process. **Appl. Energy**. 162: 1-10.

Yao, L., Shi, X. and Andrews-Speed, P. (2018). Conceptualization of energy security in resource-poor economies: The role of the nature of economy. **Energy Policy**. 114: 394-402.

Yen, P., Lip, W., Ra, S., Alwi, W., Shiun, J., Abdul, Z. and Sabev, P. (2017). Total Site Heat Integration planning and design for industrial , urban and renewable systems. **Renew. Sustain. Energy Rev.** 68: 964-985.

Yu, F. W. and Chan, K. T. (2010). Economic benefits of optimal control for water-cooled chiller systems serving hotels in a subtropical climate. **Energy Build.** 42(2): 203–209.

Zhang, C. and Anadon, L. D. (2014). A multi-regional input-output analysis of domestic virtual water trade and provincial water footprint in China. **Ecol. Econ.** 100: 159-172.

Zhang, J.C., Zhong, R., Zhao, P., Wang, Y. and Mao, G. Z. (2016). International energy trade impacts on water resources crises: en embodied water flows prospective. **Environ. Res. Lett.** 11: 13 p.

Zheng, J., Zhou, Z., Zhao, J. and Wang, J. (2018). Integrated heat and power dispatch truly utilizing thermal inertia of district heating network for wind power integration. **Appl. Energy**. 211: 865-874.

Ziher, D. and Poredos, A. (2006). Cooling power costs from a trigeneration system in a hospital. **Forschung Im Ingenieurwesen/Engineering Research,** 70(2): 105-113.

APPENDIX A

FLOWCHARTS

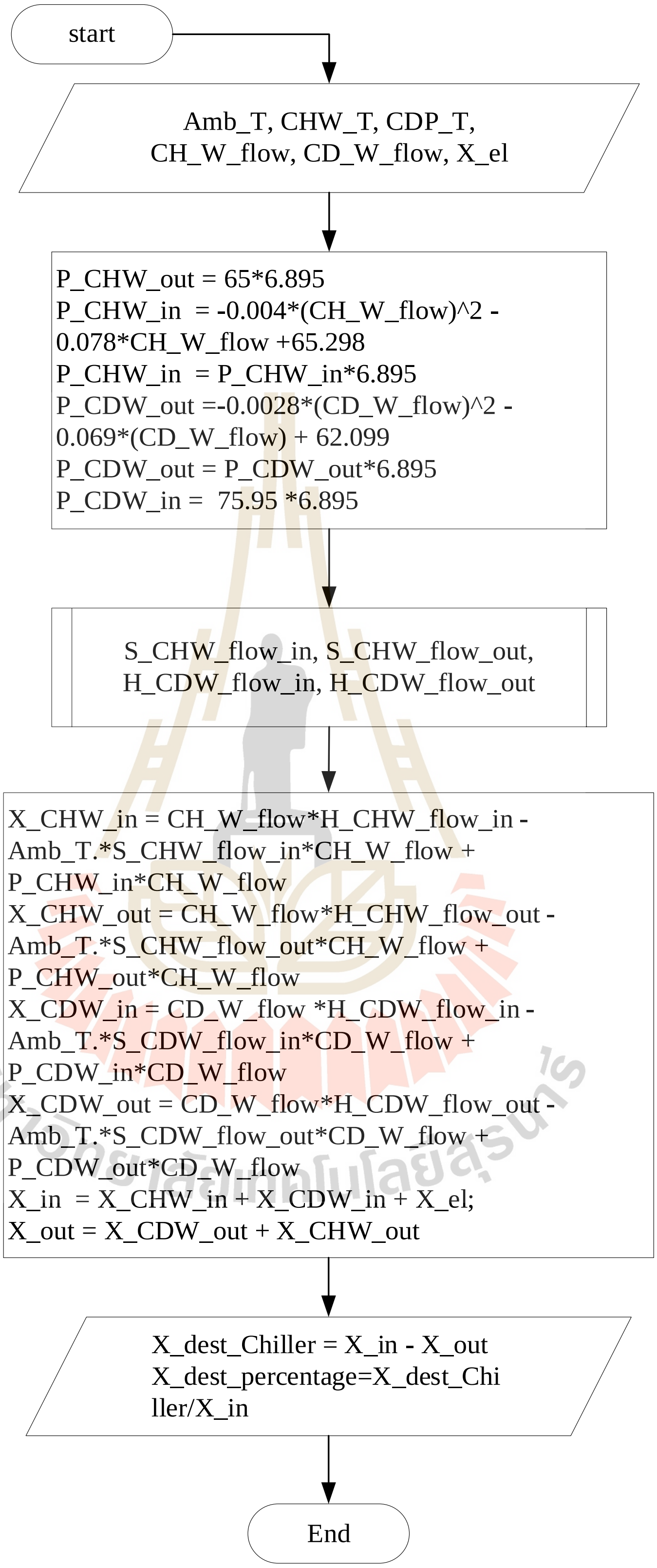


Figure A.1 Flowchart of exergy calculation of the chiller.

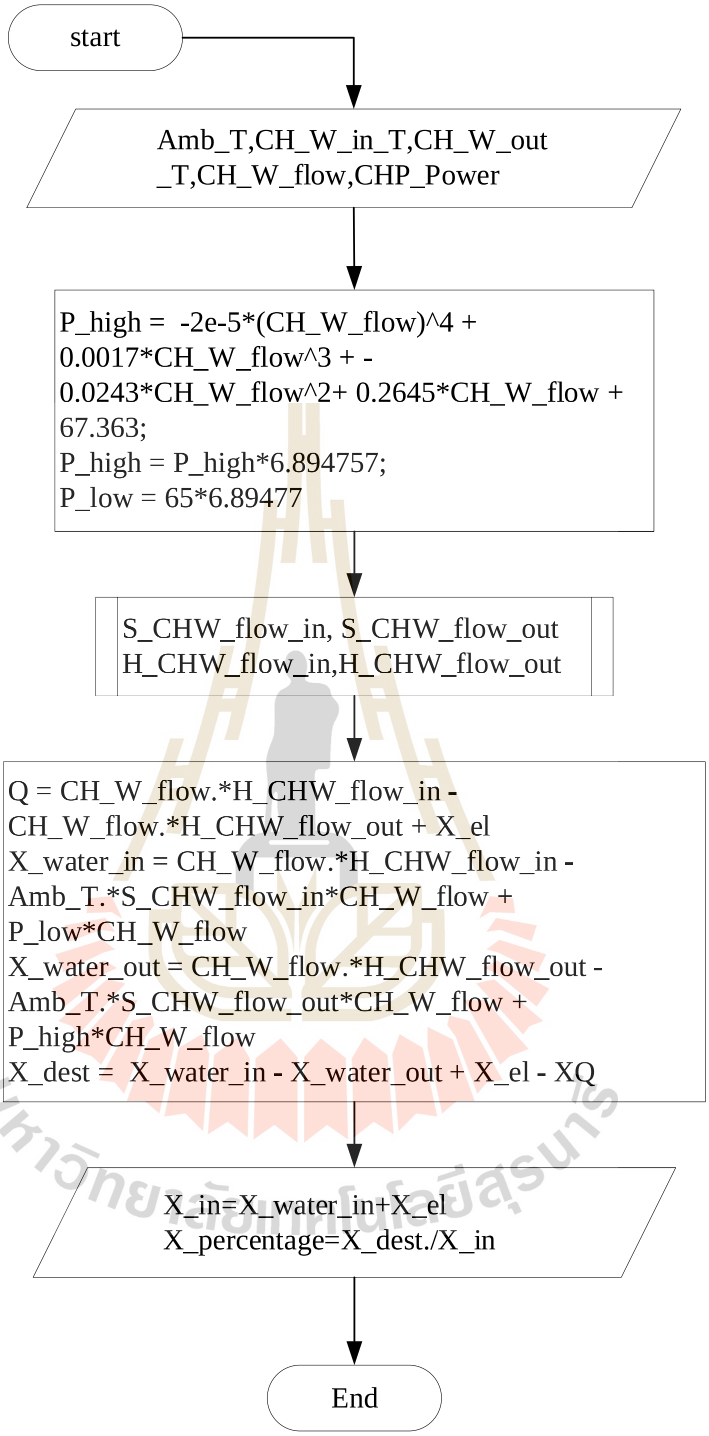


Figure A.2 Flowchart of exergy calculation of the CHP.

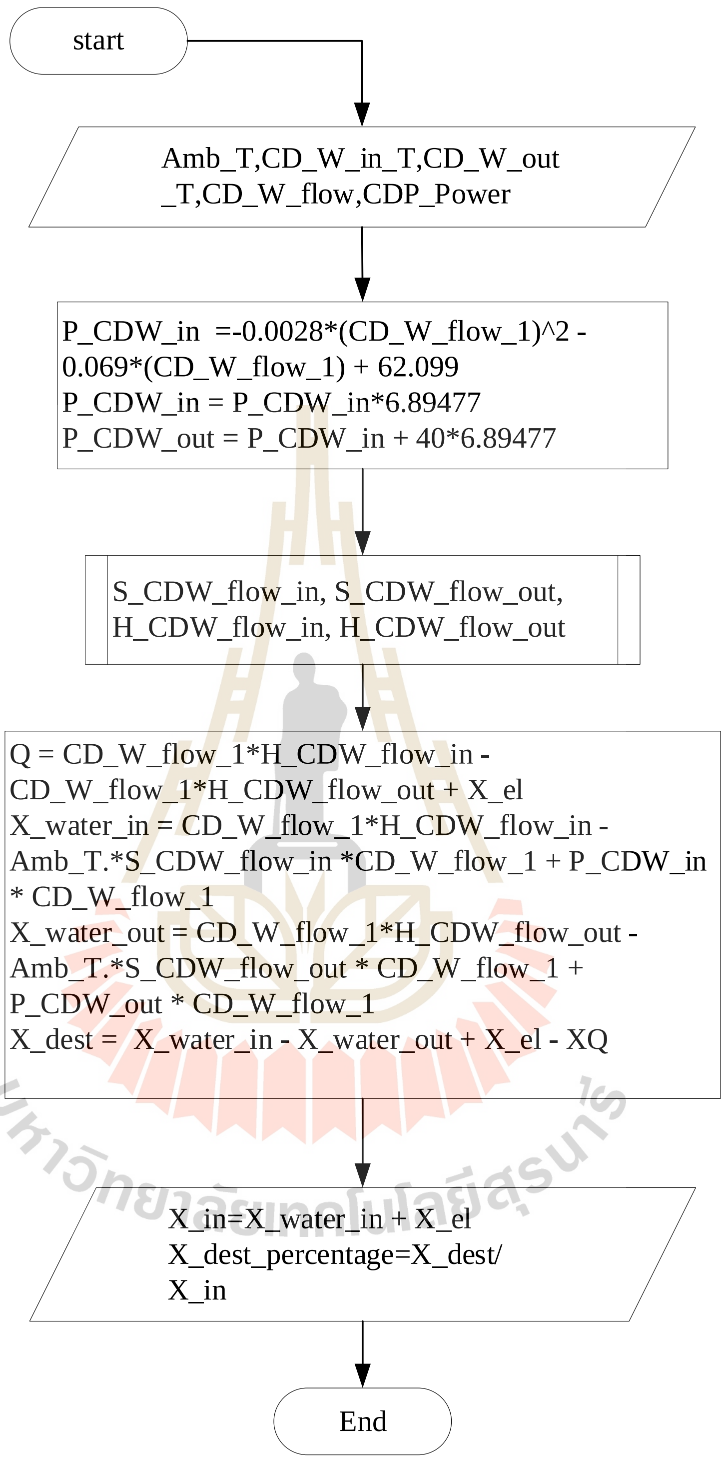


Figure A.3 Flowchart of exergy calculation of the CDP.

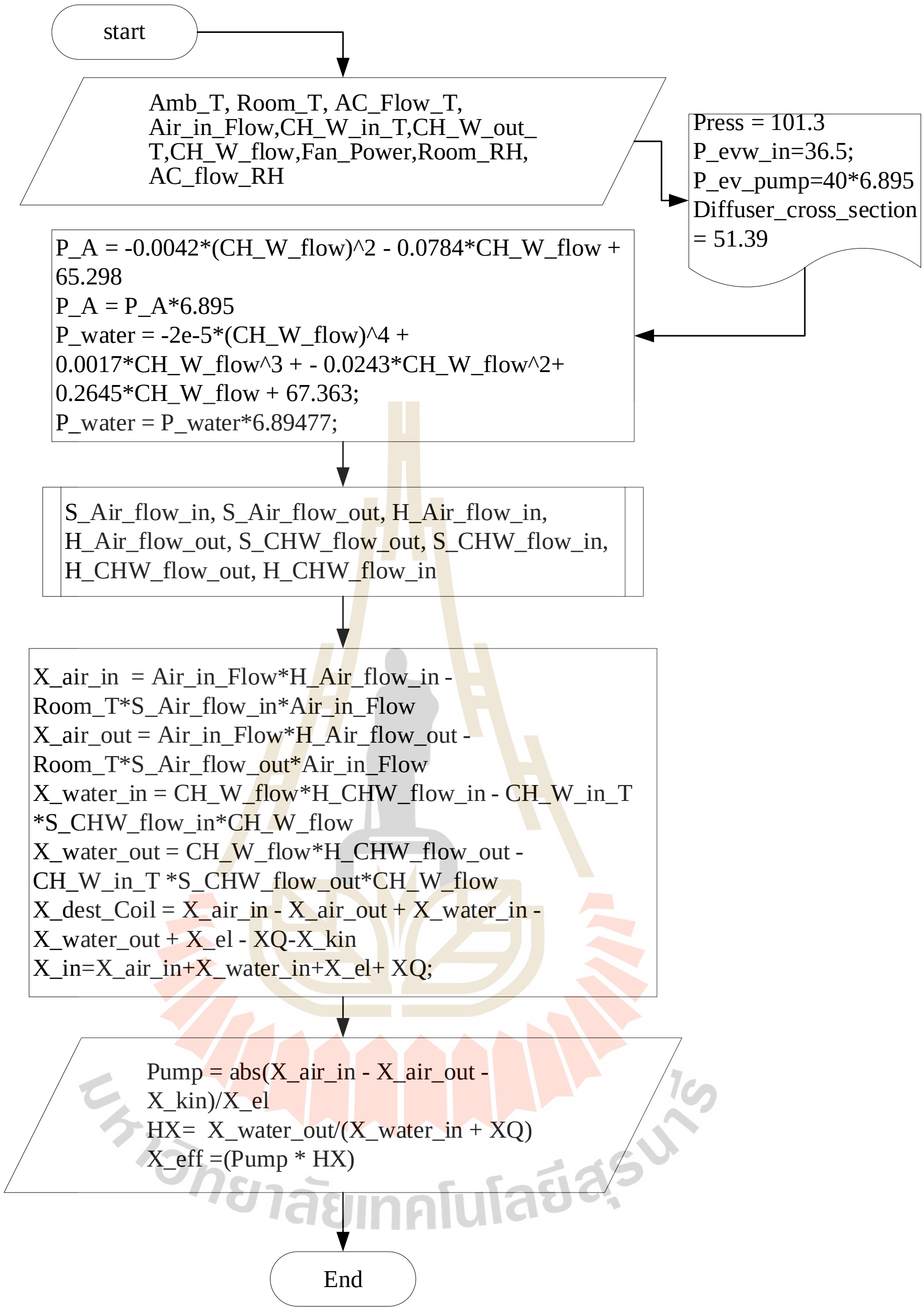


Figure A.4 Flowchart of exergy calculation of the FCU/AHU.

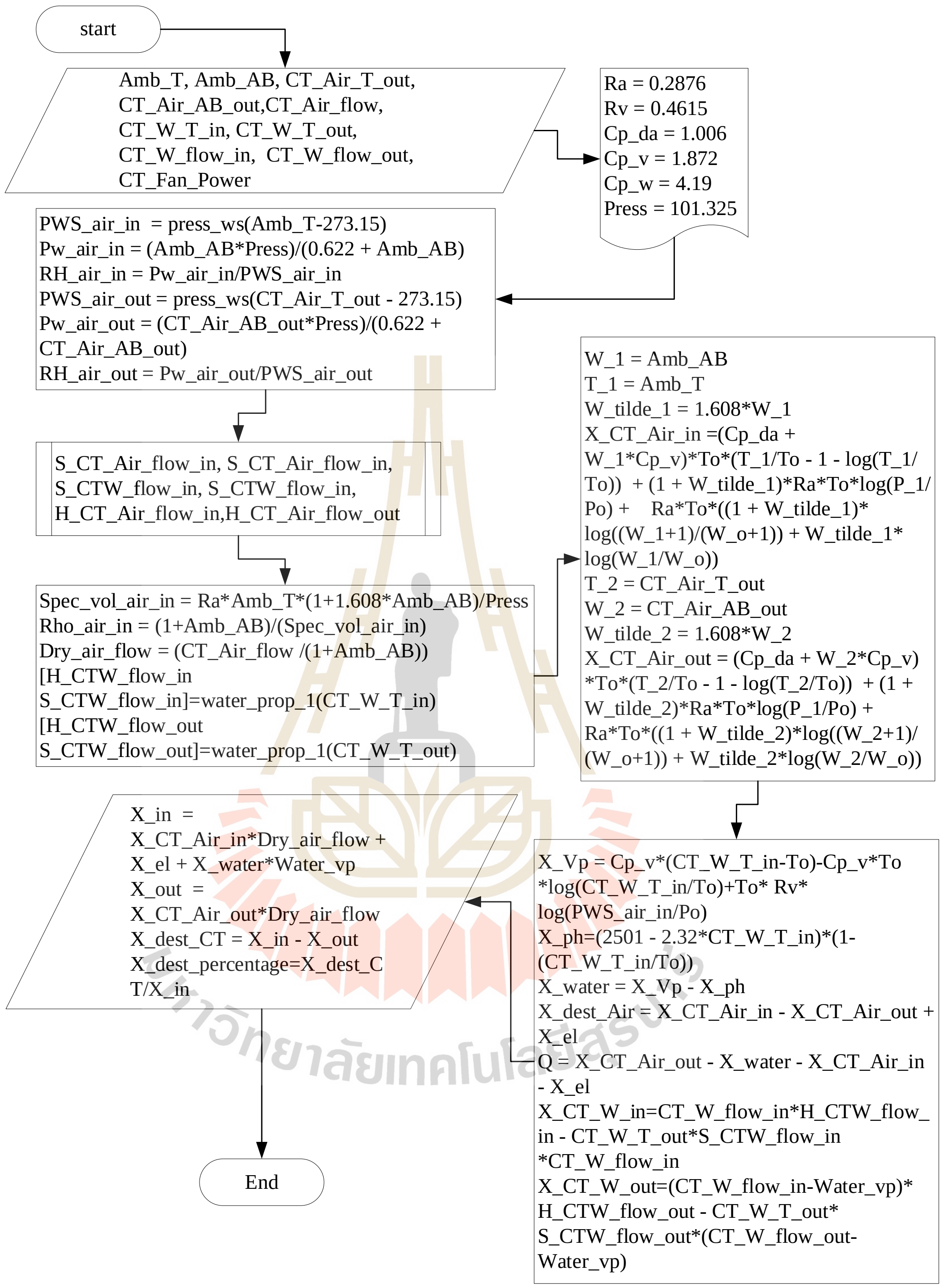


Figure A.5 Flowchart of exergy calculation of the cooling tower.

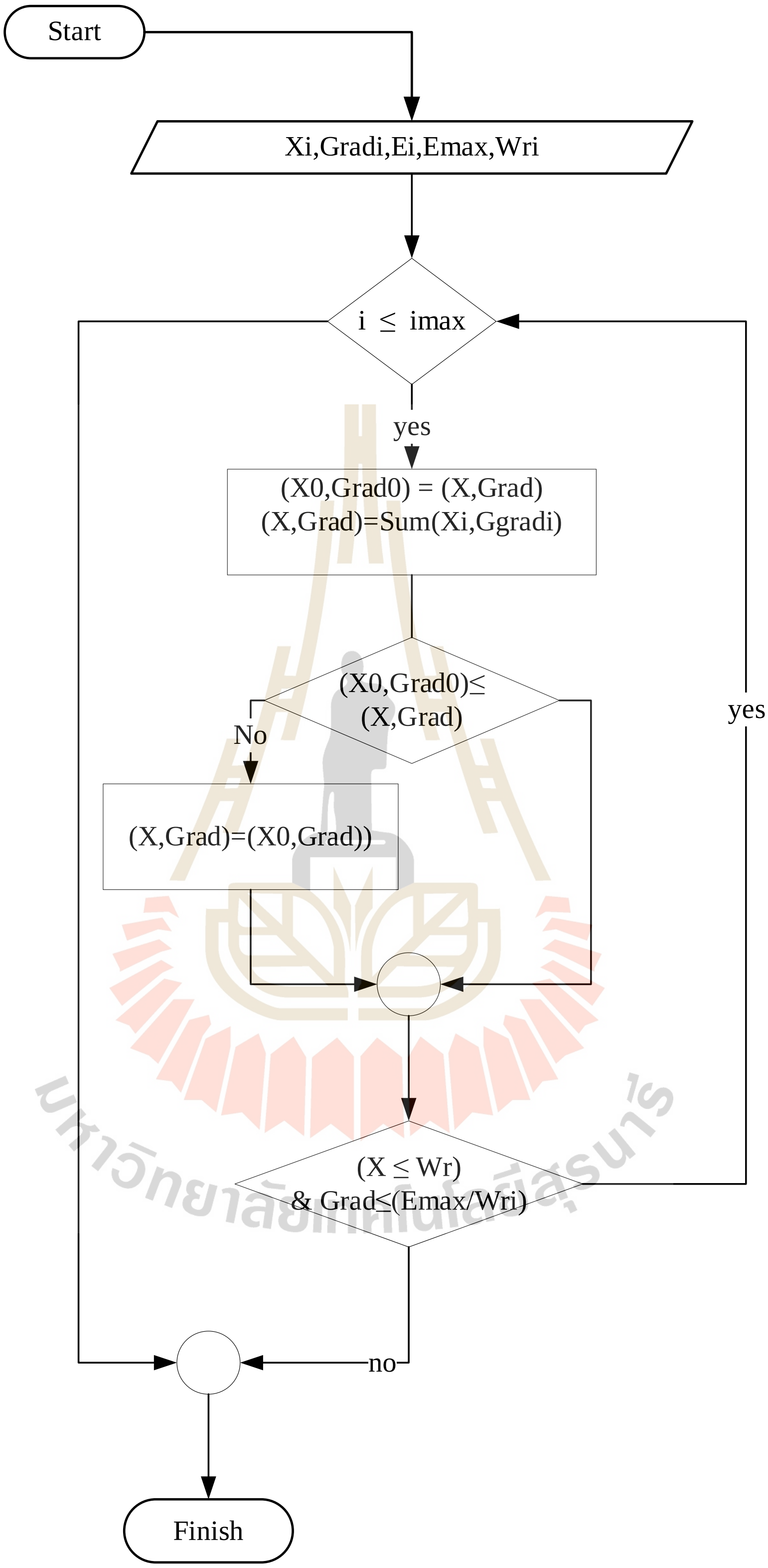
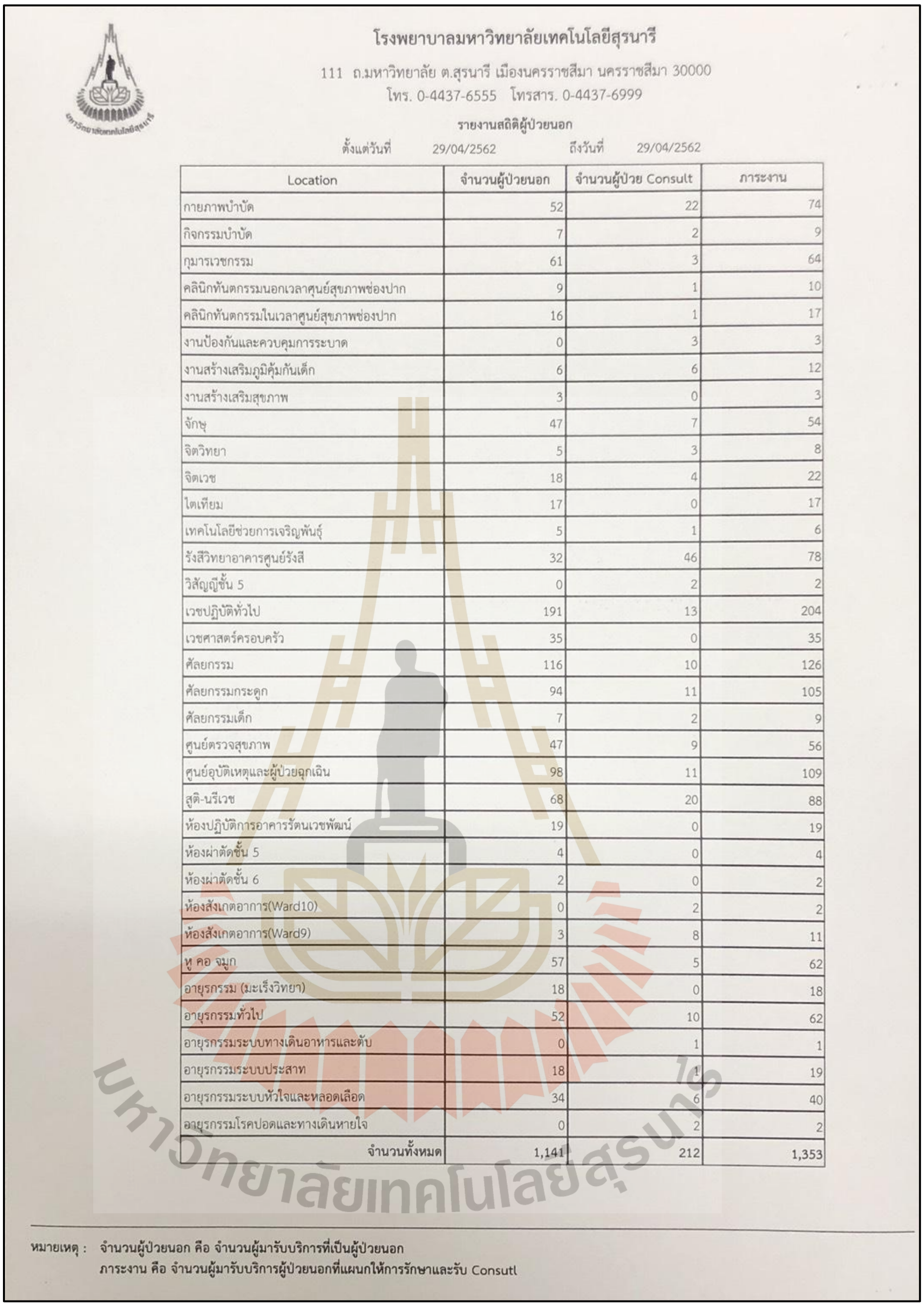


Figure A.6 Flowchart of minimization using variable pair method.

APPENDIX B

SAMPLE OF DATA



โรงพยาบาลมหาวิทยาลัยเทคโนโลยีสุรนารี

111 ถ.มหาวิทยาลัย ต.สุรนารี เมืองนครราชสีมา นครราชสีมา 30000
โทร. 0-4437-6555 โทรสาร. 0-4437-6999

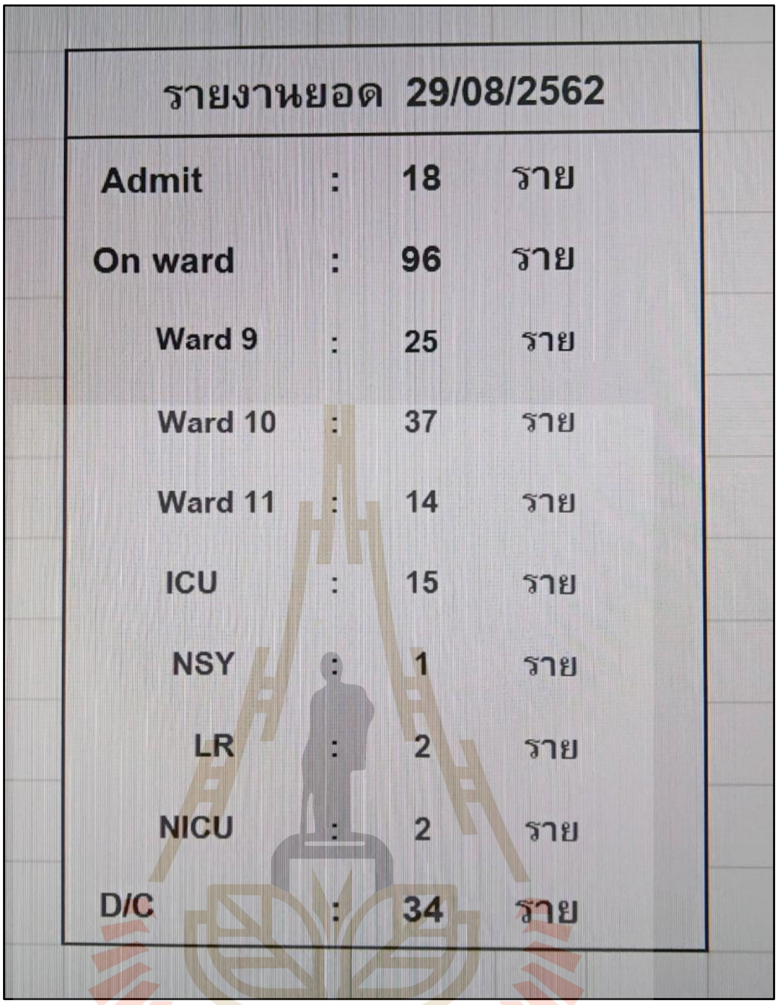
รายงานสถิติผู้ป่วยนอก

ตั้งแต่วันที่ 29/04/2562 ถึงวันที่ 29/04/2562

Location	จำนวนผู้ป่วยนอก	จำนวนผู้ป่วย Consult	ภาระงาน
กายภาพบำบัด	52	22	74
กิจกรรมบำบัด	7	2	9
กุมารเวชกรรม	61	3	64
คลินิกทันตกรรมนอกเวลาศูนย์สุขภาพช่องปาก	9	1	10
คลินิกทันตกรรมในเวลาศูนย์สุขภาพช่องปาก	16	1	17
งานป้องกันและควบคุมการระบาด	0	3	3
งานสร้างเสริมภูมิคุ้มกันเด็ก	6	6	12
งานสร้างเสริมสุขภาพ	3	0	3
จักษุ	47	7	54
จิตวิทยา	5	3	8
จิตเวช	18	4	22
ไตเทียม	17	0	17
เทคโนโลยีช่วยการเจริญพันธุ์	5	1	6
รังสีวิทยาอาคารศูนย์รังสี	32	46	78
วิสัญญีชั้น 5	0	2	2
เวชปฏิบัติทั่วไป	191	13	204
เวชศาสตร์ครอบครัว	35	0	35
ศัลยกรรม	116	10	126
ศัลยกรรมกระดูก	94	11	105
ศัลยกรรมเด็ก	7	2	9
ศูนย์ตรวจสุขภาพ	47	9	56
ศูนย์อุบัติเหตุและผู้ป่วยฉุกเฉิน	98	11	109
สูติ-นรีเวช	68	20	88
ห้องปฏิบัติการอาคารรัตนเวชพัฒน์	19	0	19
ห้องผ่าตัดชั้น 5	4	0	4
ห้องผ่าตัดชั้น 6	2	0	2
ห้องสังเกตอาการ(Ward10)	0	2	2
ห้องสังเกตอาการ(Ward9)	3	8	11
หู คอ จมูก	57	5	62
อายุรกรรม (มะเร็งวิทยา)	18	0	18
อายุรกรรมทั่วไป	52	10	62
อายุรกรรมระบบทางเดินอาหารและตับ	0	1	1
อายุรกรรมระบบประสาท	18	1	19
อายุรกรรมระบบหัวใจและหลอดเลือด	34	6	40
อายุรกรรมโรคปอดและทางเดินหายใจ	0	2	2
จำนวนทั้งหมด	1,141	212	1,353

หมายเหตุ : จำนวนผู้ป่วยนอก คือ จำนวนผู้มารับบริการที่เป็นผู้ป่วยนอก
ภาระงาน คือ จำนวนผู้มารับบริการผู้ป่วยนอกที่แผนกให้การรักษาและรับ Consutl

Figure B.1 Example of patients’ distribution on clinics.



รายงานยอด 29/08/2562			
Admit	:	18	ราย
On ward	:	96	ราย
Ward 9	:	25	ราย
Ward 10	:	37	ราย
Ward 11	:	14	ราย
ICU	:	15	ราย
NSY	:	1	ราย
LR	:	2	ราย
NICU	:	2	ราย
D/C	:	34	ราย

Figure B.2 Example of patients' distribution onwards.

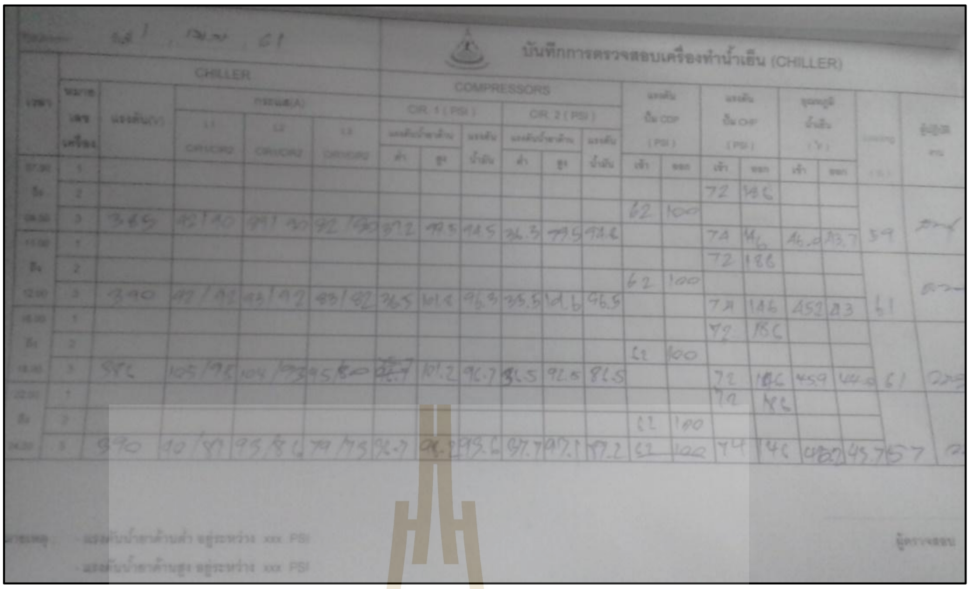


Figure B.3 Example of HVAC daily reports.

Figure B.4 Measuring the air flow rate, temperature and humidity of the cooling tower.

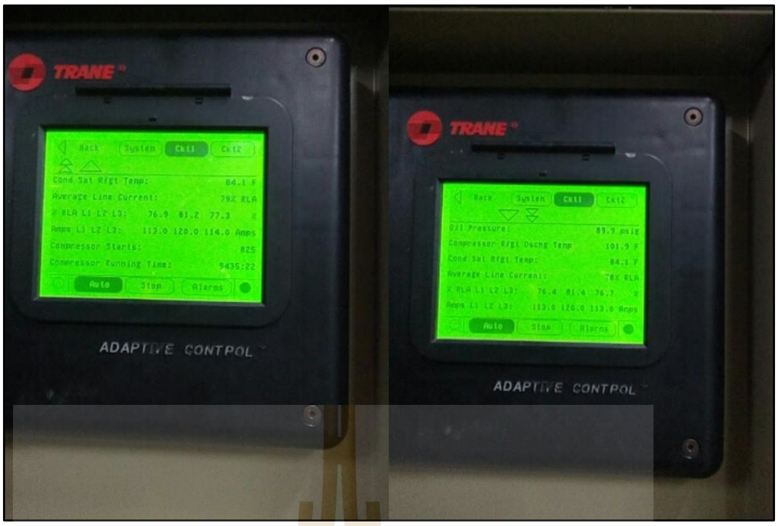


Figure B.5 Control of the chiller showing condenser temperature, lines current, chilled water temperature, chilled water pressure, and percentage of load.

Figure B.6 Control of the chiller showing voltage and current at the chiller, and condenser inlet and outlet water temperature.

Figure B.7 CHP outlet and inlet pump gauges.

Figure B.8 CDP pump gauges.

Figure B.9 Wastewater treatment kWh meter and control panel. The control panel shows operation time of CAT, SAT, and transferring pumps.

APPENDIX C

PUBLICATIONS

LIST OF PUBLICATIONS

Prasetyadi, A., Koonsrisuk, A. (2020). Centralized HVAC System Energy and Water Conservation for Suranaree University of Technology Hospital (SUTH). J. **Suranaree J. Sci. Technol** (Accepted-In press).

Prasetyadi, A. , Koonsrisuk, A. (2020). Evaluation of the Centralized HVAC Chilled Water Pumps of Suranaree University of Technology Hospital Main Building. **IOP Conf. Ser.: Mater. Sci. Eng.**

Prasetyadi, A., Koonsrisuk, A. (2020). An Analysis of Exergy, Availability and Accessibility of Water Usage in Hospital. Proceeding of the **15th Conference on Energy, Heat and Mass Transfer in Thermal Equipment and Processes**, March 12th -13th , 2020, Chantaburi, Thailand, 8 p.

Prasetyadi, A., Koonsrisuk, A. (2019). Minimization of energy and water cost for the main building of Suranaree University of Technology Hospital (SUTH). **The 10th TSME International Conference on Mechanical Engineering**, 10th - 13rd December 2019, Pattaya, Thailand, 13 p.

Prasetyadi, A., Koonsrisuk, A. (2019). Exergy Analysis of Water Network for Suranaree University of Technology Hospital (SUTH) Main Building, in **Conference of Asean Federation of Engineering Organizations CAFEO 37**, 11th-14th September 2019, Jakarta, Indonesia, 6 p.

Prasetyadi, A., Koonsrisuk, A. (2019). Second Law Analysis of the Centralized HVAC System of Suranaree University of Technology Hospital. in Proceeding of **the 14th Conference on Energy, Heat and Mass Transfer in Thermal Equipment and Processes**, February 20th -21st , 2019, Krabi, Thailand, 9 p.

Prasetyadi, A., Koonsrisuk, A. (2018). Type and quality of energy and water in a tropical hospital. **E3S Web of Conferences**.

Prasetyadi, A., Koonsrisuk, A. (2018). Investigation and Modeling of Energy and Water Consumptions for a Centralized Chiller System in Suranaree University of Technology. in **25th Tri University International Joint Seminar and Symposium**, 4th - 8th November 2018, Chiang Mai, Thailand, 5 p.

Prasetyadi, A., Koonsrisuk, A. (2018). A Reference System Architecture for Integrated Energy and Water in a Hospital. in Proceedings of **the 32nd Conference of the Mechanical Engineering Network of Thailand,** 3rd - 6th July 2018, Mukdahan, Thailand, 8 p.

Prasetyadi, A., Koonsrisuk, A. (2017). Energy-Water Nexus: Water of Electricity in Indonesia. in Proceedings of **The 13th Conference on Energy Network of Thailand**, 31st May - 2nd June 2017, Chiang Mai, Thailand, 9 p.

Piriyakulwat, W., Prasetyadi, A., Koonsrisuk, A. (2017). Simple Linear Heat Model for Virtual Water Estimation of Thermal Power Plant with Wet Cooling System. in Proceedings of **the 13th Conference on Energy Network of Thailand**, 31st May - 2nd June 2017, Chiang Mai, Thailand, 8 p.

BIOGRAPHY

Mr. Andreas Prasetyadi was born on the 2nd of July 1974 in Kebumen, Indonesia. He graduated Bachelor of Electronics and Instrumentation from Faculty of Science, Gadjah Mada University (UGM) in 1999. He earned master degree in Physics from Bandung Institute of Technology (ITB) in 2008. In 2016, he obtained the scholarship "*Provision of 2016 Postgraduate Scholarships for Foreign Students*" to presence a Doctor degree at school of Mechanical Engineering, Institute of Engineering, Suranaree University of Technology, under the supervision of Asst. Prof. Dr. Atit Koonsrisuk. He conducted the research in the topic of energy and water nexus.