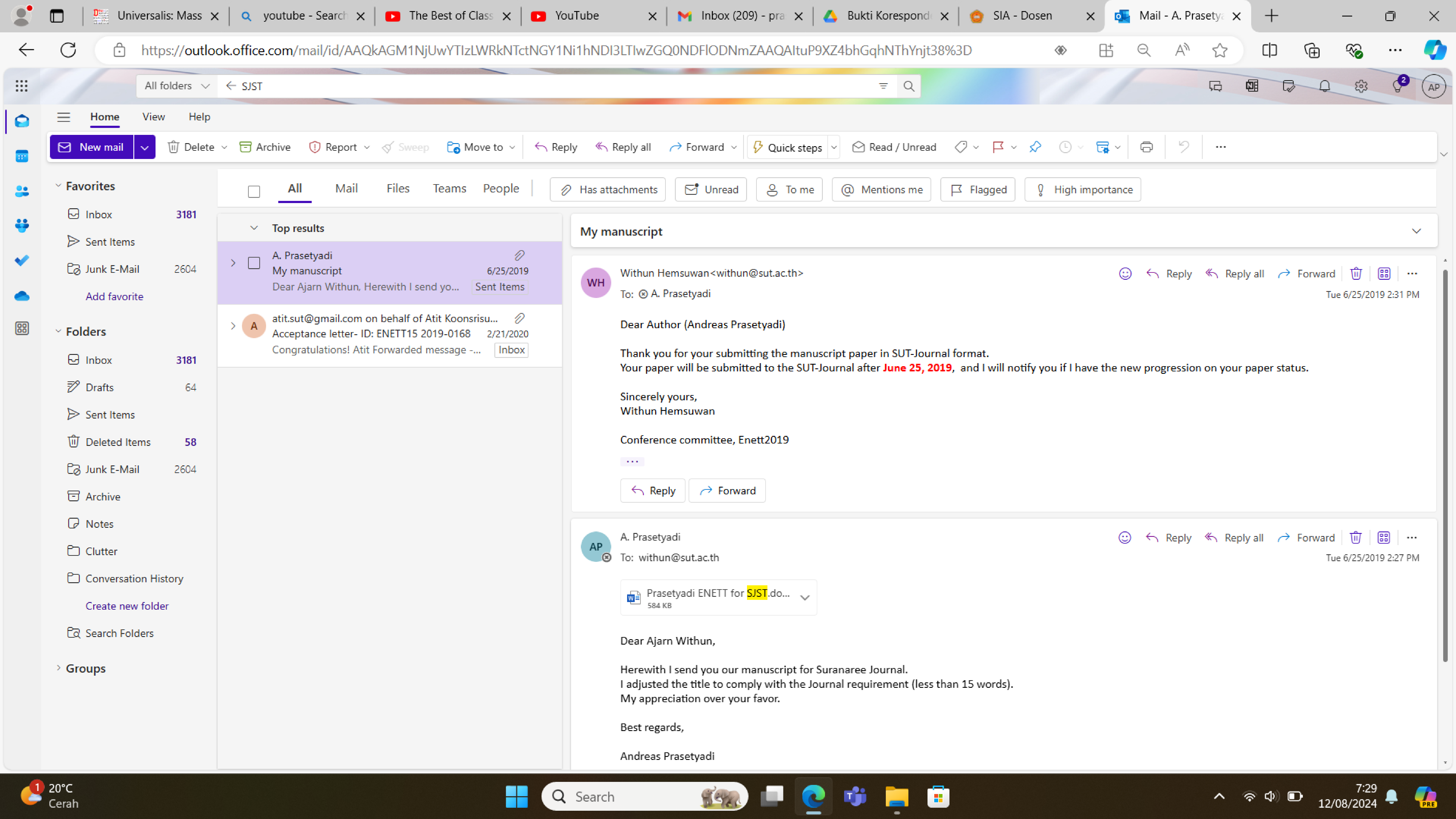
Bukti korespondensi Artikel Centralized HVAC System Energy and Water Conservation for Suranaree University of Technology Hospital (SUTH).

Korespondensi yang saya sertakan merupakan korespondensi setelah artikel dinyatakan terpilih untuk diterbitkan pada Suranaree Jurnal of Science and Technology pasca konferensi ENETT 32.

1. Pernyataann diterima oleh Jurnal tanggal 4 Juni 2019
2. Proof Reading pasca editing tanggal 1 Januari 2021



A. Prasetyadi
My manuscript 6/25/2019
Dear Ajarn Withun, Herewith I send yo... Sent Items

atit.sut@gmail.com on behalf of Atit Koonsrisu...
Acceptance letter- ID: ENETT15 2019-0168 2/21/2020
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**My manuscript**

Withun Hemsuwan<withun@sut.ac.th>
To: A. Prasetyadi
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Dear Author (Andreas Prasetyadi)

Thank you for your submitting the manuscript paper in SUT-Journal format.
Your paper will be submitted to the SUT-Journal after June 25, 2019, and I will notify you if I have the new progression on your paper status.

Sincerely yours,
Withun Hemsuwan

Conference committee, Enett2019

A. Prasetyadi
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Prasetyadi ENETT for SJST.do...
584 KB

Dear Ajarn Withun,

Herewith I send you our manuscript for Suranaree Journal.
I adjusted the title to comply with the Journal requirement (less than 15 words).
My appreciation over your favor.

Best regards,

Andreas Prasetyadi

Ref. No. 7421(3)/c. 6

Suranaree Journal of Science and Technology
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February 14, 2020

Dear Assistant Professor Dr. Atit Koonsrisuk,

I am pleased to confirm that your paper "**Centralized HVAC System Energy and Water Conservation for Suranaree University of Technology Hospital (SUTH)**" has been accepted for publication in Suranaree Journal of Science and Technology since **June 4, 2019**.

This acceptance is subject to the assumption that you meet all the conditions to publish in this journal. In particular, you have not submitted your manuscript to another journal. Please inform me immediately if you cannot meet these conditions.

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Thank you for submitting your paper to Suranaree Journal of Science and Technology.

Sincerely,

Rattikorn Yimnirun

Rattikorn Yimnirun, Ph.D.
Professor
Editor-in-Chief

## Subject: Galley proof for your manuscript [Suranaree J. Sci. Technol.] ID: 200102240

A. Prasetyadi <pras@usd.ac.id>
Sun 1/31/2021 5:00 PM
To:journal@g.sut.ac.th <journal@g.sut.ac.th>
Cc:atit.sut@gmail.com on behalf of Atit Koonsrisuk (atit@sut.ac.th) <atit.sut@gmail.com>

📎 2 attachments (475 KB)
part 5. 200102240-27(4)010020(1-13) for galley proof_prast.pdf; Responses of the comments and the corrections.docx;

Dear Sir,

I would like to **respond some comments on the manuscript of "CENTRALIZED HVAC SYSTEM ENERGY AND WATER CONSERVATION FOR SURANAREE UNIVERSITY OF TECHNOLOGY HOSPITAL (SUTH)" that you have sent us**.
1.
cb 1 (page 6)
It should be added with Vm (upper dot) as the numerator in the previous line.

2.
cb2 (page 7)
The '[10]' should be removed.
The number is calculated with efficiency of the pump 85%. Therefore, the reference is not relevant.

3.
cb3 (page 9)
The 'condensed water' should be 'condenser water' as in original manuscript.

Here are **some corrections**
1.
page 2, 2nd column, line 17
condensed water --> condenser water
2.
page 2, 2nd column, the caption of figure 1 should be
**Energy and water flow at HVAC. Water, energy and heat flows are presented in double line, single line and short dashed line arrow respectively. Potential flows are depicted by round dot and long dashed arrows**
**3.**
page 5, 2nd column, last paragraph , line 42
chilled water and condensed water --> condenser water and chilled water
4.
page 6, 1st column, line 4
condensed water or chilled water --> chilled water or condenser water
5.
page 6, 1st column, line 6
condensed water --> condenser water
6.
page 6, 1st column, line 10
chilled --> chiller
7.
page 6, 1st coulmn, line 11
condensed water --> condenser water
8.
page 6, 1st column, line 19 and 20
condensed water input and condensed water output --> condenser water input and condenser water output

9.
page 6, 1st column, line 32
condenser output exergy rate --> condenser water output exergy rate
10.
page 6, 2nd column, line 28 and 30
condensed water --> condenser water
11.
page 6, 2nd column, line 25
condensed water --> condenser water

12.
page 6, 1st column, line 32
condenser output exergy rate --> condenser water output exergy rate

Herewith I enclosed the notes on the manuscript.
I would like to express my gratitude for your kindness and favor.
I am really happy to discuss about the manuscript to be worthy for publication.

Best regards,

Andreas Prasetyadi

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

**Andreas Prasetyadi and Atit Koonsrisuk***

*Received: May 22, 2019; Revised: August 23, 2019; Accepted: August 27, 2019*

## Abstract

**The heating, ventilation, and air conditioning (HVAC) of hospitals is one of the main consumers of energy and water. Energy and water conservation of the HVAC system at Suranaree University of Technology Hospital 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 temperatures of the HVAC were 22°C, 24°C, and 26°C. To reuse the blow-down water from the cooling tower, treatments by reverse osmosis (RO) filtering, mixing with RO water, and mixing with harnessed condensed water were evaluated. The results show that usage at the 24°C temperature setting provides least exergy destruction, compared with those of the temperature settings at 22°C and 26°C. The percentages of the average exergy destruction at the chiller, fan coil unit/air handling unit, chilled water pump, condenser water pump, 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 consumption and water withdrawal amounts at 22°C, 24°C, and 26°C temperature settings 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 withdrawal. Recycling blow-down water by mixing it with condensed water provides the least energy intensity scoring at 0.1 kWh/m$^3$. Mixing brine with the condensed water reduced the electricity and water cost by 1.6 % of the system's operational cost.**

**Keywords:** **Energy water conservation, HVAC, hospital, TRNSYS**

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* *Corresponding author*

**Suranaree J. Sci. Technol. 27(4):010020(1-13)**

## Introduction

Hospitals are considered to be buildings with high rates of energy and water consumption. Hospitals are comparable with hotels and lodgings in water consumption intensity. On average, a hospital consumes more than double an educational building's energy consumption (Energy Policy and Planning Office, 2016). Among hospital facilities, the heating, ventilation, and air conditioning (HVAC) becomes the main energy (Teke and Timur, 2014; Thinate *et al*., 2017) and water (Hospital Energy Alliance, 2011) consumer. HVAC is the top in the percentage for energy consumption and is in second position for water consumption in hospitals. Managing the HVAC of a hospital can affect the energy (Buonomano *et al*., 2014) and water consumption significantly.

The requirement of 24 hours' operation of the HVAC is the main reason for the high energy consumption of a hospital's HVAC. At the same time, the 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 the cooling load as a function of weather, inhabitants, equipment, and lighting. Ventilation is a source of heat that is related to the outdoor air requirement. For the purposes of minimizing uncontrolled heat gain, enveloping is an important aspect of a building's energy consumption (Ascione *et al*., 2013).

The water consumption of a hospital's HVAC is mainly determined by the cooling tower (CT) operation (Al-Bassam and Alasseri, 2013). A wet CT consumes water in 2 ways; they are the loss of water through evaporation of the water during cooling process and the blow-down water. The make-up water depends mainly on the rejected heat, while the blow-down water replaces the water of the CT system. The water is utilized to keep the water soft enough to prevent mineralization. Therefore, the blow-down water is a function of the amount of process cycle (Rutberg, 2012).

Energy usage of an engineered water system takes place in every step of its cycle. The energy is used at the extracting, conveying, transferring, treating, and consuming stages (Congradac *et al*., 2012). At a hospital, a water system needs energy for transferring, consuming, and treating. The energy is needed to distribute sanitary water for the building. Different qualities of water usage need energy for treatment, and energy is used for heating the water and steaming. The waste water treatment energy consumption has to be acceptable environmentally before the waste water's discharge.

Energy for the water of an HVAC system is determined from its use of the make-up water. It is composed of energy for distribution and treatment. If the quality of raw water does not fit in with the quality of the condensed water, pre-treatment is important. Additional energy for softening is usually needed before the water is used. A diagram presenting the water and energy interrelation in a hospital's HVAC is provided in Figure 1.

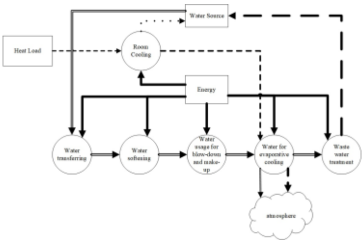


**Figure 1.** **Energy and water flow at HVAC. Water, energy, and heat flows are presented in blue, green, and red, respectively. Potential flows are depicted by dashed arrows**

Figure 1 also shows the possibility of harvesting water from the cooling process. The cooling process implies that less water vapor can exist in the air due to the lower temperature. Lowering the temperature makes the air contain less water vapor at the same relative humidity. The specific relative humidity requirement is that a lower temperature than the ambient and specific outdoor air change in the ventilation can be a source for harvesting water during the cooling process and dehumidification to fit into the HVAC's requirement.

Recycled water as the product of the waste water treatment can be returned to the water source. The amount of energy for recycling water depends on the quality of the water and the targeted product. In the HVAC system, hard water is the waste of a wet CT. This kind of water is not hazardous and is characterized by high calcium and magnesium mineral contents. However, the water can easily form a crust on the surface of the equipment. The treatment for this kind of water can be chemical or physical. Chemical treatment for the water is done with sodium carbonate and calcium reactions followed by filtration. Coagulation can also be an alternative to reduce the hardness of the water. Another popular method is reversed osmosis (RO) which produces tap water and waste water with a higher salt concentration (brine).

The combined evaluation of the energy and water in an HVAC system has been little discussed even when the energy evaluations of HVAC systems were conducted by many researchers. Congradac *et al*. (2012) conducted an assessment of hospital cooling and heating energy including the hot water need, but they did not take into account the water effect. They concentrated on the heat and cooling load of rooms, including the dehumidification to save energy, but the water related to the system was neglected. Alves *et al*. (2016) classified the energy efficiency of HVAC. The energy efficiency ratio, coefficient of performance, seasonal energy efficiency ratio, and coefficient of performance (COP) were applied to evaluate the performance of an HVAC system in the European market. The energy efficiency potentials of a hospital HVAC system were proposed by Teke and Timur (2014). Evaluation of a CT for HVAC and hybrid ground source heat pump was conducted using exergy evaluation by Singh and Das (2017) without evaluation of the water aspect. Pagliarini *et al*. (2012) used the TRNSYS transient simulation program for optimization of the building efficiency with combined heat, cooling, and power. Here again, the water aspect was still not considered.

Evaluation of the energy and water conservation at the centralized Suranaree University of Technology (SUTH) HVAC was the purpose of this study. The amount of water conserved is indicated by the water consumption for 1 year. At the same time, exergy evaluation of the HVAC was conducted as the energy conservation indicator. A combination of the yearly water consumption and exergy evaluation was applied for the final evaluation. A calculation of the price and cost of energy and water for operating the HVAC was performed.

This paper is structured into 4 parts consisting of the introduction, methods, results and discussion, and conclusion. In the introduction, the reason and the main concept for the review are presented. The methods section sets out the steps for evaluating the HVAC. The TRNSYS simulation was applied for yearly data, and a comparison with maintenance data energy consumption was conducted. Indicators of the water and exergy are provided to clarify the strategy in some scenarios. The results of the simulation and a discussion are provided after the methods are set out. The conclusion forms the final part of the paper.

## Methods

There are 4 main steps in the method proposed herein. The first is a simulation of the system to extract data of the water and energy for the SUTH HVAC system. In this part, the specific conditions of the simulation related to the SUTH building's operation are provided. The second step is an evaluation of the energy conservation through exergy analysis of the HVAC. The exergy destruction of the HVAC subsystems is determined. The third part is a water evaluation of the HVAC system. The water usage of the CT is utilized to determine the total water need. The fourth step is an analysis of both the water and energy conservation. A combination of the temperature setting and CT waste water processing methods is applied to find the trends of energy and water conservation patterns across the various settings. A cost and price analysis of the water and energy for the HVAC operation is presented.

## Simulation of the SUTH Main Building Model

The SUTH main building is the 12-storey center building of SUTH and functions as clinics, a laboratory, treatment centers, wards, and offices. Therefore, the building is the center of hospital activities. The average daily number of visitors to the building was 784 out-patients and 65 in-patients in 2017. In the same year, the building consumed 3.2 GWh of electricity and 3.02 $10^4$ $m^3$ of water. Excluding the sterilization system, laundry, radiology instruments, and food preparation, the energy intensity of the building reached 230.4 $kWh/m^2$ for the year.

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

The building model has 15,120 $m^3$ air zone with 2,160 $m^2$ floor space. It has 420 $m^2$ of walls on the north and south sides and 252 $m^2$ of walls on the west and east sides. The walls have an overall heat transfer coefficient of 0.541 $W/m^2K$. The windows areas on the north, east, south, and west sides, in respective sequence, are 63%, 57%, 53%, and 53%. The numbers are in accordance with the actual condition of the building. The overall heat transfer coefficient of the windows is 1.27 $W/m^2K$. These coefficients are fitted into an advanced building envelope as the building was built in 2013 when the new standards for the building were applied (Chirarattananon *et al.*, 2010).

The air conditioning of the zone is determined from the function of the building. The main building of the SUTH has the functions shown in Table 1. The table also provides information about the function percentage areas and the ventilation requirements. The air change per hour describes the amount of air circulated and filtered in volume units. One ACH means that in 1 hour, the air of 1 room volume is circulated through the ventilation system. Ideally, all air in the room is changed. The outdoor air is the amount of air that should be exchanged with air from the ambient air in room volume units. These requirements are for the temperature and humidity of the ventilation system.

**Table 1. Rooms' functions and their ventilation requirements (OA and ACH stand for outdoor air and air change per hour, respectively)**

| 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 |

The heat gain of a room was determined by the numbers of inhabitants, computers, lighting, and medical equipment. The number of inhabitants consists of out-patients, in-patients, and the staff. Out-patients and in-patients are determined monthly from the patient data in 2017. The daily number of out-patient arrivals was assumed to follow the Poisson distribution. The number of staff is set to be 300 people on active days.

The simulation condition of the equipment represents the real condition of the main building's HVAC system. The HVAC of the SUTH main building is centralized with its operating condition as provided in Table 2. However, there are 3 chillers, 3 chilled water pumps (CHPs), 3 condenser water pumps (CDPs), and 3 CTs; only 2 of each item of the equipment are operated at a time. The rest of the equipment is in case of emergency. The specific operation conditions of the equipment are 65 psi of output chilled water pressure, and 40 psi of head loss compensation for the condensed water. The CHP works to circulate chilled water with a pressure loss up to 138 psi.

**Table 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 |
| Chilled water outlet temperature | 44ºF (6.7ºC) |
| Cooling tower type | Cross flow, Single speed |
| Operation Capacity of cooling tower | 2×953,904 kcal/hr |
| Max. chilled 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 difference of the chilled water is provided in Equation (1). The volumetric flow rate is in gallons per minute and the pressure difference of the evaporator input-output is in psi. The specification for the condensed water is presented in Equation (2). The pressure difference is also in psi and the volumetric flow rate is in gallons per minute. For the simulation, the volumetric flow rates are known. The conditions of the previous paragraph are applied for calculating the pressures.

$$\dot{V}_{chw} = -0.0226\Delta p_{ev}^2 + 8.9826\Delta p_{ev} + 136.65 \quad (1)$$

$$\dot{V}_{cdw} = -0.0044\Delta p_{cd}^2 + 12.898\Delta p_{cd} + 161.31 \quad (2)$$

## Exergy of the HVAC System

The HVAC system has 5 main components. They are the fan coil unit/air handling unit (FCU/AHU), chilled water pump (CHP), chiller, condenser water pump (CDP), and CT. The FCU/AHU is utilized for pumping heat from the room with chilled water. The CHP circulates the chilled water and transfers rejected heat to the evaporator of the chiller. The chiller pumps this waste heat from chilled water to condensed water where the CDP transfers it to the CT. The CT conducts evaporative heat transfer from condensed water to the atmosphere where the waste heat is released.

To simplify the processes, the FCU/AHU is assumed to be a combination of a 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 (3). Equation (4) is the equation for calculating the exergy efficiency of the system. $\dot{X}_{rmair,in}$, $\dot{X}_{odair,in}$, $\dot{X}_{air,\text{out}}$, $\dot{X}_{w}$, $\dot{X}_{el}$, and $\dot{X}_{des}$ are the exergy rates of air input from the room, outdoor air input, air output from the coil, condensed water electricity, and exergy destruction, respectively.

$$\dot{X}_{rmair,in} + \dot{X}_{odair,in} - \dot{X}_{air,\text{out}} + \dot{X}_{w} + \dot{X}_{el} + \dot{X}_{des} = 0 \quad (3)$$

$$\eta_{xcf} = \frac{\dot{X}_{air,\text{out}}}{\dot{X}_{rmair,in} + \dot{X}_{odair,in} + \dot{X}_{el}} \cdot \frac{\left(\dot{X}_{chw,\text{out}} - \dot{X}_{chw,\text{in}}\right)}{(\dot{X}_{rmair,in} + \dot{X}_{odair,in} - \dot{X}_{air,\text{out}})} \quad (4)$$

The dehumidifier's existence can be applied in this function. However, because the dehumidifier is applied as separate equipment, the energy consumed by the equipment is applied for calculating the FCU/AHU exergy efficiency function. The exergy of the electricity is a combination of the FCU/AHU and the dehumidifier.

The CDP and CHP are the pumps of the chilled water and condensed water, respectively. Therefore they have similar functions for the exergy. The formulation of the exergy function and its efficiency are presented, respectively, in Equations (5) and (6). The $\eta_{xchp/xcdp}$ is the exergy efficiency of the condensed water or chilled water. The $\dot{X}_{\mathrm{cdw/chw},in}$ and $\dot{X}_{cdw/chw,out}$ are the exergy rates of the condensed water or chilled water input and output, respectively.

$$\dot{X}_{\mathrm{cdw/chw},in} - \dot{X}_{cdw/chw,out} + \dot{X}_{el} + \dot{X}_{des} = 0 \quad (5)$$

$$\eta_{xchp/xcdp} = \frac{\dot{X}_{\mathrm{chw/cdp},out}}{\dot{X}_{\mathrm{chw/cdp,in}} + X_{el}} \quad (6)$$

The chilled function is to exchange heat from chilled water to condensed water. For the real condition of the chiller, where the internal pump is provided in the evaporator only, the combination of pump and heat exchanger to represent the chiller are provided in Equations (7) and (8). The $\dot{X}_{chw,in}$ and $\dot{X}_{chw,out}$ are the exergy rates of chilled water input and chilled water output, respectively. $\dot{X}_{cdw,in}$ and $\dot{X}_{cdw,out}$ are the exergy rates of condensed water input and condensed water output, respectively.

$$\dot{X}_{chw,in} - \dot{X}_{chw,out} + \dot{X}_{cdw,in} - \dot{X}_{cdw,out} + \dot{X}_{el} + \dot{X}_{des} = 0 \quad (7)$$

$$\eta_{xch} = \frac{\dot{X}_{chw,\mathrm{out}}}{\dot{X}_{chw,\mathrm{in}} + X_{el,ch}} \cdot \frac{\left(\dot{X}_{chw,in} - \dot{X}_{chw,\mathrm{out}}\right)}{\left(\dot{X}_{cdw,\mathrm{out}} - \dot{X}_{cdw,\mathrm{in}}\right)} \quad (8)$$

The CT conducts evaporative cooling with condensed water, air input, and electricity as the inputs. The output of the process is air at the outlet. Therefore, the exergy equations formulation for the CT can be provided in Equations (9) and (10). The $\dot{X}_{air,in}$, $\dot{X}_{air,\mathrm{out}}$, $\dot{X}_{w}$, $\dot{X}_{\mathrm{cdw},in}$, and $\dot{X}_{cdw,out}$ are the 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, respectively.

$$\dot{X}_{air,in} - \dot{X}_{air,\mathrm{out}} + \dot{X}_{w} + \dot{X}_{\mathrm{cdw},in} - \dot{X}_{cdw,out} + X_{el} + \dot{X}_{des} = 0 \quad (9)$$

$$\eta_{xct} = \frac{\dot{X}_{air,out}}{\dot{X}_{air,in} + \dot{X}_{W} + X_{el}} \quad (10)$$

Exergy destruction and the electricity ratio are applied for evaluating the energy conservation of the HVAC. Electricity is the only utilized energy of the HVAC system at the SUTH. The ratio of all HVAC components were calculated using Equation (11).

$$XER = \frac{\max(\dot{X}_{dest})}{X_{el}} \quad (11)$$

### Water Evaluation of HVAC System

The water used for the HVAC is composed of water that is consumed and released as vapor and water consumed due to alteration of the water quality. The evaporative make-up water is monitored, but blow-down water is unmonitored. A prediction of the blow-down water can be calculated assuming an equal concentration of the evaporative make-up water and blow-down water.

At every nth cycle of the CT water in which it is assumed that a make-up water addition is n times the volume of the condensed water, the impurities' concentration of the magnesium and calcium particles in the water can be shown in Equation (12). $C_0$ is the impurities concentration of the make-up water which is assumed to be soft water. $m_{cdw}$ is the mass impurities in the condensed water at the beginning and $V_{cdw}^2$ is the square of the condensed water volume.

$$C_n = C_0 + n\left(\frac{m_{cdw}}{V_{cdw}^2}\right)V_{cdw} \quad (12)$$

with the number of cycles $n = \frac{\dot{V}_m}{V_{cdw}}$ and $m_{cdw} = C_0V_{cdw}$, where is the total volume of the evaporative make-up water after the nth cycle. The impurities' concentration can be formulated in Equation (13) as

**Commented [cb1]:** Something missing after “where”.

$$C_n = C_0 + C_0\left(\frac{\dot{V}_m}{V_{cdw}^2}\right)V_{cdw} \tag{13}$$

Therefore, the blow-down water in equal unit time with the evaporative make-up water can be determined, as shown in Equation (14). The $V_m$, $\dot{V}_{m\max}$, and $V_{bw}$ are the volume of recorded evaporative make-up water in a specific time unit, the maximum allowable make-up water before the blow-down, and the volume of the blow-down water in a specific time unit, respectively:

$$V_{bw} = \frac{V_m}{\dot{V}_{m\max}}.V_{cdw} \tag{14}$$

It should be noted that $\dot{V}_{m\max} = \frac{C_{n\max}}{C_0}V_{cdw}$. While the conductivity is the method for determining the water hardness, it can be inferred that $\dot{V}_{m\max} = \frac{\sigma_{hard}}{\sigma_{soft}}V_{cdw} \approx 5V_{cdw}$, then

$$V_{bw} \approx \frac{V_m}{5} \tag{15}$$

It means that the total make-up water usage for the cooling system with a wet CT can be determined, as shown in Equation (16) below:

$$V_w = V_m + V_{bw} \approx \frac{6}{5}V_m \tag{16}$$

**Energy and Water Conservation of the HVAC**

The flow of the water in Equation (16) determines the energy for water transferring and water softening. The make-up water and the blow-down water need to be transferred from the water source to the water tank on the rooftop. They also need to be softened to prevent the crust. On the other hand, the flow of water in Equation (15) determines the waste water processing of the HVAC.

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

$$E_{wt} = V_w\left(C_t + C_s\right) \tag{17}$$

where $C_t$ and $C_s$ are 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 in working condition, in the case $C_t$ = 0.173 kWh/m$^3$ [10]. The total efficiency of the pump is 85%.

There are 2 choices for managing the blow-down water. They are to release it into the environment after treatment or to recycle it. The waste water energy intensity of recycling water is determined in Equation (18). The coefficient of the blow-down waste water treatment can be summarized in Table 3.

$$E_{wwt} = V_{bw}\left(\frac{C_{wwec}}{C_p}\right) \tag{18}$$

**Table 3. Methods for treating blow-down brine and its energy coefficient**

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

**Commented [cb2]:** What is this meant to represent?

The electricity and water cost of the HVAC is determined by the 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 time-of-use (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 (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 subscribed P and OP, respectively, stand for on-peak and off-peak.

$$EC_b = EP_P \times ECon_P + EP_{OP} \times ECon_{OP} \tag{19}$$

The water price for the 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 CT requirement, the raw water should be treated and moved to the tank. The total price of water at the SUTH, neglecting the water price, should include water distribution and treatment. The water cost of the HVAC water is determined in Equation (20). $WC_{HVAC}$, $W_{HVAC}$, $WP$, and $EP$ are the cost of water for the HVAC, water for the HVAC withdrawal, water price per m$^3$, and electricity price, respectively.

$$WC_{HVAC} = W_{HVAC} \times \left(WP + EP\right) \tag{20}$$

The electricity cost of the water recycling is composed of the electricity cost at peak time and off-peak time. The equation of the electricity cost for recycling water is presented in Equation (21), with $EC_{RW}$, $E_{wwtP}$, and $E_{wwtOP}$ being the electricity cost for recycling water, electricity consumption for recycling water at peak time, and electricity consumption for recycling water at off-peak time, respectively.

$$EC_{RW} = E_{wwtP} \times EP_P + E_{wwtOP} \times EP_{OP} \tag{21}$$

The price of the water recycled is used for reducing the energy and water cost of the HVAC. The cost of water is assumed to be static at the current price of 10 Baht per m$^3$. Therefore the energy and water cost for the HVAC operation can be calculated, as presented in Equation (22). $EWC_{HVAC}$ is the electricity and water cost of the HVAC operation, respectively.

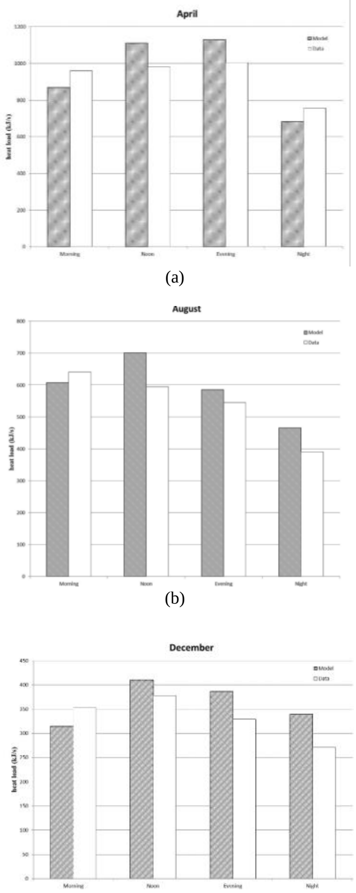
$$EWC_{HVAC} = EC_b + WC_{HVAC} + EC_{RW} - WP_{RW} \tag{22}$$

## Results and Discussion

The simulation produced a reasonable result with the average energy consumption difference to maintenance data of 12%. The differences in April, August, and December are 6%, 14%, and 16%, respectively. Comparison of the model cooling load at the 24ºC temperature setting and its maintenance data are provided in Figure 2. April represents the month with the highest ambient temperature. August shows the pattern of a normal month with high humidity. In 2017, the daily out-patient number in August was 950. It was the highest among the months of that year.

The cooling load differences between the model and the data are varied. In the morning, the model produced less cooling load than the data. At noon and in the evening, the model produced cooling loads higher than the data. In the evening, the data of April was higher, but the other months had lesser cooling loads than the model.

As April is the month with the highest ambient temperature, the effect of the ambient temperature is dominant. The evening load was higher than the noon load. This weather dominance to other loads also appears in the morning data where the difference between the



(a)

(b)

(c)

**Figure 2. Comparison of cooling load of HVAC in (a) April, (b) August, and (c) December**

maintenance data and the model was highest in April. The deficiency of the morning in April was almost 3 times the deficiencies of the other months.

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

Energy consumption for the HVAC system, with the 24°C temperature setting and 50% relative humidity was 1.8 GWh. This number is 56% of electricity consumption for 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 CT consumes a minute amount of electricity recorded at 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 condensed water at the CT was neglected in this system while it belonged to CDP part.

**Commented [cb3]:** I do not understand this.

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

In comparison to the electricity consumption, the exergy destruction of the chiller is the highest. It destroyed 57.1% of the electricity consumption. In second position is the FCU/AHU destroying 41.0% of its electricity input. The CHP, CDP, and CT have exergy destruction in respective sequences at 36.7%, 21.6%, and 0.2%. This trend shows that the chiller has the worst condition for its energy conservation and it also destroyed 72.2% of the total exergy destruction of the HVAC system.

Variation of the temperature setting shows that a temperature less than 24$^{o}$C has more exergy destruction. A significant amount of the additional percentage of exergy destruction takes place at the 22$^{o}$C temperature setting. At the 26$^{o}$C setting, the percentage of exergy destruction of the HVAC system is also higher than the 24$^{o}$C setting. Therefore, setting the temperature to be 24$^{o}$C is considered the best condition, as shown in Table 4.

A relative large amount of water was used for the HVAC. At the 22$^{o}$C, 24$^{o}$C, and 26$^{o}$C temperature settings, the average water consumption for the HVAC was 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 consumption also represents the amounts of water that were evaporated at the respective temperature settings. The water withdrawal as total water used for the HVAC was 38.52 m$^{3}$/day, 27.96 m$^{3}$/day, and 20.88 m$^{3}$/day at the respective 22$^{o}$C, 24$^{o}$C, and 26$^{o}$C temperature settings. The difference between the water withdrawal and water consumption is the blow-down water.

The lower the temperature is, the higher is the possible harnessed water and the water evaporated at the CT. At 26$^{o}$C, 17.4 m$^{3}$/day, water can be harvested from the cooling room. It is also the amount of water lost at the CT during the evaporation process. The 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. An additional one-fifth of the amounts should be added for the blow-down water. It can be inferred that the lower temperature setting consumes more net water for the HVAC system.

Providing the daily water needs an energy intensity of 0.497 kWh/m$^{3}$ for the direct water. The energy is composed of the energy for transferring the water and the energy for softening the water. This number implies that more water needs proportionally more energy. It means a lesser temperature setting needs more energy, but it also releases more brine in the blow-down water. The energy for the water ($E_{wt}$) for the temperature settings 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 of 38.52 m$^{3}$, 27.96 m$^{3}$, and 20.88 m$^{3}$, respectively.

The energy need for waste water treatment of the blow-down brine depends on the scenario of the brine treatment. In the temperature setting range, the energy per m$^{3}$ water product is 0.6 kWh. It still also releases a higher mineral concentration of brine. Mixing the brine with the RO water to produce flushing water has an energy intensity 0.4142 kWh/m$^{3}$. Mixing the blow-down water with condensed water needs a lesser energy intensity.

**Table 4. The exergy destruction percentage: its ratio to electricity, portion percentage of total exergy destruction**

| Temp | Chiller | | FCU/AHU | | CHP | | CDP | | CT | | Total Exergy | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ($^{o}$C) | XER | Portion | XER | Portion | XER | Portion | XER | Portion | XER | Portion | (kJ/h) | XER |
| 26 | 45.6 | 75.8 | 29.9 | 10.3 | 25.5 | 9.2 | 15.3 | 4.6 | 0.2 | 0.02 | 143,479.53 | 26.3 |
| 24 | 57.1 | 72.2 | 41.0 | 11.6 | 36.7 | 10.8 | 21.6 | 5.3 | 0.2 | 0.02 | 167,509.84 | 22.6 |
| 22 | 96.9 | 71.9 | 67.7 | 10.9 | 68.5 | 11.8 | 37.8 | 5.4 | 0.3 | 0.01 | 332,904.21 | 35.4 |

**Table 5. Energy intensity and daily average of water production of the blow-down water treatment**

| Temp. | 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$^{o}$C | 0.6 | 3.85 | 0.41 | 38.52 | 0.099 | 35.52 |
| 24$^{o}$C | 0.6 | 2.80 | 0.41 | 27.96 | 0.098 | 25.96 |
| 26$^{o}$C | 0.6 | 2.09 | 0.41 | 20.88 | 0.091 | 20.88 |

The intensities are 0.091 kWh/m$^3$, 0.098 kWh/m$^3$, and 0.099 kWh/m$^3$ for 26°C, 24°C, and 22°C, respectively. Table 5 shows the relationship of the temperature setting and the energy intensity for recycled water.

Mixing the blow-down water with the RO needs additional water from the source. At the 24°C 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$^3$ of condensed water is uncollected and unused. But this method provides a final waste water reduction of 4.66 m$^3$ and a reduction of flushing water preparation by the same amount. Unfortunately, the method only has a water energy intensity slightly less than direct water withdrawal from the source.

Mixing with condensed water potentially reduces water withdrawal, waste water, and water energy intensity. Producing flushing water of 25.96 m$^3$ per day as a combination of the blow-down brine and condensed water at the 24°C setting implies a 25.96 m$^3$ reduction of water withdrawal and waste water treatment. Having a flushing water energy intensity of 0.098 kWh/m$^3$, less energy intensity of the water can be reached.

The cost of water and electricity for the HVAC operation can be reduced through mixing the brine water and condensed water. As the water price was very low and flat, the cost reductions of integrating water into the HVAC system are 1.71%, 1.62%, and 1.78% at the temperature settings 22°C, 24°C, and 26°C, respectively. The numbers are equal to 126,000, 92,000, and 74,000 Baht at the respective temperature settings. If the price of water increases, more cost benefit can be achieved. These figures show that the cost of energy is more dominant than that of water in this case.

Table 6 also mentions that energy consumption of the HVAC operation is dominant at the on-peak time. This on-peak domination significantly increases the cost of the HVAC electricity consumption. The waste water recycling as treated equally to the HVAC operation was also on-peak dominant. A simple scheduling can easily reduce its cost.

## Conclusions

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

1. TRNSYS could provide a good result model of the 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. A higher temperature setting needs less energy and water consumption. But a lesser temperature setting can produce more potential water that can be harnessed to reduce the water energy intensity consumption through mixing the condensed water with the blow-down water of the CT. However, the ratio of potential harvested water and evaporated water at a lower temperature setting was less than at a higher temperature setting. At the 24°C setting, the electricity need for the system was 1.8 GWh, accounting for 56% of the electricity consumption of the building. Total exergy destruction was 22% of the electricity consumption. The yearly HVAC system's water consumption at the 24°C and 50% humidity setting was 8506 m$^3$. The daily average water that can be harvested at the 24°C temperature setting and 50% humidity was 21.3m$^3$. The evaporated water at the same setting was 23.3 m$^3$. The blow-down water need at the same setting was 4.66 m$^3$. At the

**Table 6. Electricity and water consumption and cost of the HVAC**

| Temp. | $ECon_p$ | $ECon_{op}$ | $W_{HVAC}$ | $E_{wwtP}$ | $E_{wwtOP}$ | $W_R$ | $EC_b$ | $WC_{HVAC}$ | $EC_{RW}$ | $EWC_{HVAC}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | (MWh) | (MWh) | (m$^3$) | (kWh) | (kWh) | (m$^3$) | (1,000 Baht) | (Baht) | (Baht) | (1,000 Baht) |
| 26°C | 812 | 517 | 7,642 | 2,369.98 | 1,428 | 6,356 | 4,143.005 | 88,304 | 2,077 | 4,157 |
| 24°C | 1,150 | 652 | 10,207 | 3,467.191 | 1,606 | 7,778 | 5,657.666 | 118,187 | 2,821 | 5,684 |
| 22°C | 1,601 | 685 | 14,068 | 5,036.783 | 1,955 | 10,617 | 7,295.377 | 163,107 | 3,942 | 7,333 |

26°C temperature setting, the potential harvested water and the evaporated water were nearly equal.

3. The chiller is the equipment where most of the exergy was destroyed at the HVAC system of the SUTH. The chiller at the 24°C setting contributes 72.2% of the exergy destruction. The AHU/FCU, CHP, and CDP have contributions of 11.6%, 10.8%, and 5.3%, respectively. The CT part is only a negligible amount.
4. Mixing the blow-down water with the collected condensed water could significantly reduce water withdrawal and energy water intensity. The electricity intensity of the water result is nearly 0.1 kWh/m$^3$. This is 1/6 of the energy water intensity of operating the HVAC from the current tap water source. The cost of water and electricity of the system reduces by 1.6%-1.8% through mixing the blow-down water with condensed water at the 10 Baht price of water and TOU of electricity.
5. The reduction of the electricity intensity of water for operating the HVAC system and water withdrawal becomes a guideline to consider providing an installation to collect the condensed water from the HVAC system as an alternative water source in a large building. Further study should be conducted for specific conditions.

## Acknowledgments

The authors would like to express gratitude to SUT for providing the Postgraduate Scholarships for Foreign Students to the first author and the support for the conference. The authors also express their sincere thanks to the SUTH director, Dr. Niwatchai Namvichaisirikul, and the staff of the Engineering and Maintenance Department at SUTH, particularly Mr. Watcharin Singtana, Mr. Songkrit Jitpakdeebordin, Mr. Chaleomkiat Kaewkurn, Mr. Prashya Suranachit, and Ms. Naphatthira Decheerawas.

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