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Thermal Energy Storage Optimization in Shopping Center Buildings

Totok R. Biyanto[1*], Akhmad F. Alhikami[1], Gunawan Nugroho[1], Ridho Hantoro[1], Ridho Bayuaji[2], Hudiyo Firmanto[3], Joko Waluyo[4] & Agus Imam Sonhaji[5]

[1]Department of Engineering Physics, FTI, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo, Surabaya 60111, Indonesia
[2]Department of Civil Engineering, FTSP, Institut Teknologi Sepuluh Nopember, Kampus ITS Manyar, Surabaya 60118, , Indonesia
[3]Department of Mechanical Engineering, FT, Universitas Surabaya, Jl. Raya Kalirungkut, Tenggilis, Surabaya 60293, , Indonesia
[4]Department of Mechanical Engineering, FT, Universitas Gajah Mada, Bulaksumur Yogyakarta 55281, , Indonesia
[5]Badan Perencanaan Pembangunan Kota Surabaya, Jalan Pacar No. 8, Surabaya 60272, Indonesia
*Email: trb@ep.its.ac.id

Abstract. In this research, cooling system optimization using thermal energy storage (TES) in shopping center buildings was investigated. Cooling systems in commercial buildings account for up to 50% of their total energy consumption. This incurs high electricity costs related to the tariffs determined by the Indonesian government with the price during peak hours up to twice higher than during off-peak hours. Considering the problem, shifting the use of electrical load away from peak hours is desirable. This may be achieved by using a cooling system with TES. In a TES system, a chiller produces cold water to provide the required cooling load and saves it to a storage tank. Heat loss in the storage tank has to be considered because greater heat loss requires additional chiller capacity and investment costs. Optimization of the cooling system was done by minimizing the combination of chiller capacity, cooling load and heat loss using simplex linear programming. The results showed that up to 20% electricity cost savings can be achieved for a standalone shopping center building.

Keywords: *chiller; energy saving; optimization; shopping center building; thermal energy storage.*

1 Introduction

The total energy consumption of the commercial sector in Indonesia is dominated by electricity usage, reaching up to 70% in 2010, having three times increased compared to the year 2000 [1]. This high increase was due to newly built government offices, shopping centers, and hotels [2]. Figure 1 shows that the most significant energy savings in commercial buildings can potentially be achieved in air conditioning systems. Considering the problem, more suitable

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technologies are needed to reduce the energy consumption of the commercial sector.

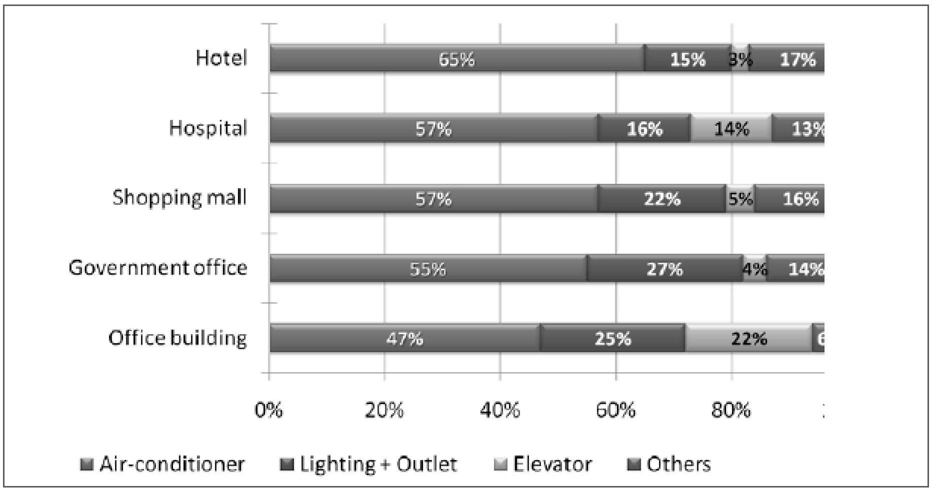

Figure 1 Electricity usage distribution in commercial sector.

In Indonesia, the distribution and management of electrical energy is regulated by the Ministry of Energy and Mineral Resources through PT Perusahaan Listrik Negara (State Electricity Company). Surveys and audits from 2012 on the intensity and usage distribution of electrical energy in commercial buildings concluded that the highest amount of energy is consumed by air conditioning systems, i.e. 65% for hotels, 57% for hospitals, 57% for shopping centers, 55% for government offices, and 47% for office buildings [2]. In addition, it should be noted that the electricity tariffs differ during peakhours (17:00-22:00) and off-peakhours (23:00-16:00) with a considerably lower price for the latter. Consumption of electricity during peak hours costs are higher than during off-peak hours by a factor (k) of 1.4 to 2 [3]. The audit results also revealed that commercial buildings such as hotels, shopping centers, hospitals, government and office buildings have different electrical load profiles. In most commercial buildings, the operating hours for cooling systems are from 07:00 to 22:00. Electrical energy costs may be reduced significantly with a thermal energy storage (TES) system.

The utilization of TES is meant to shift the building cooling load from peak hours to off-peak hours. During the storage process (charging period), the chiller produces cooled water and stores it in the TES tank. Hasnain, *et al.* [4] conducted an analysis of electrical energy savings in office buildings using TES in Saudi Arabia. Their conclusion was that TES can reduce cooling loads by about 30-40% and the electrical load about 10-20%. The TES system can take over the chiller's duty to cover the cooling load, specifically during high-tariff periods [5-8]. The design of the chiller and the capacity of the TES system should be matched to different profiles of cooling loads.

It is important to note that the TES system influences the chiller's capacity. The TES system reduces the capacity of the chiller and its operating time during the charging process. However, the presence of heat loss in the TES tank must be considered. The larger the TES tank and the longer the energy is stored in the tank, the more heat loss will occur, leading to an increase in chiller capacity, power consumption and investment costs [9].

Therefore, the optimization of three variables, i.e. chiller capacity, TES tank capacity, and heat loss in the TES tank, must be taken into consideration in order to minimize energy consumption. In this study, heat loss in the rest of the TES system was ignored. Optimization was carried out using simplex linear programming. This generates an optimum solution that provides minimum difference between chiller capacity and cooling load, minimum heat loss, minimum power consumption, minimum payback period, maximum savings, and maximum return on investment [10]. Optimization of the TES system assists the building operator in achieving energy efficiency and reducing costs [11].

2 Thermal Energy Storage (TES)

The concept of TES is simple: cooled water is stored in an isolated tank during off-peak hours and is delivered to the building during high-tariff periods or peak hours using a circulation pump and other related equipment [8,12,13]. A schematic representation of a cooling system with and without TES is shown in Figure 2.

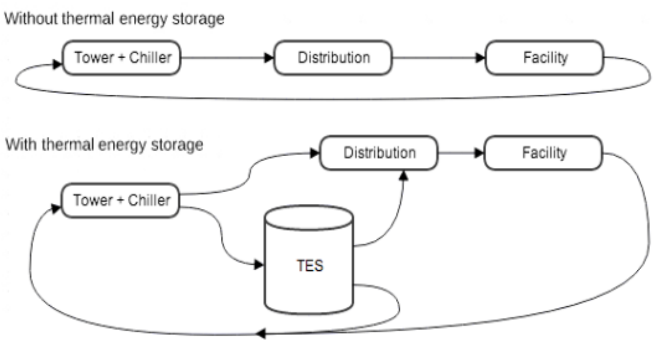

Figure 2 Cooling system with and without thermal energy storage (TES) [14].

The considered system will reduce cost per capita, load shifting, and operational efficiency.

2.1 TES Energy Calculation

The TES system consists of two parts, i.e. the chiller plant and the TES tank. Each has a different energy calculation. Firstly, the chiller plant consists of chillers, chilled water pumps, condenser water pump, and cooling tower. The water pump assists cold-water circulation between the air handling unit (AHU), chiller and TES. The condenser pump or CWP circulates the flow between the cooling tower and chiller from and to the cooling tower. Secondly, the TES tank volume depends on the temperature difference between the water supplied to the AHU and the water returning from the AHU to the TES tank [15].

In this research, the TES tank's capacity is described by,

$$Q = m\, c_p\, (T_m - T_s) \quad (1)$$

where:

Q is the amount of heat absorbed by the chiller with TES water mass.
m is the mass amount of water stored in the TES tank.
c_p is the specific heat of the water.
T_m is the maximum temperature of the chilled water from the air handling unit (AHU).
T_s is the temperature of the chilled water moved from the chiller to the TES tank.

The TES tank's volume is simply given by,

$$V = \frac{m}{\rho} \quad (2)$$

where:

V is the volume of the TES tank (m^3)
m is the amount of water mass (kg)
ρ is water density (kg/m^3)

The CHWP power calculation is,

$$CHWP = \frac{CHWFR\ x\ Pump\ Head}{a\ x\ Pump\ Eff} \tag{3}$$

where:

CHWP	is the chilled water pump power (kW)
CWFR	is the cold water flow rate (GPM)
Pump Head	is maximum high pressure pump (ft)
a	is a constant with value 3960
Pump Eff	is pump efficiency

The CHWFR calculation is,

$$CHWFR = \frac{a\ x\ Q_{tot}}{\Delta T\ Chilled\ Water} \tag{4}$$

where:

a	is a constant with value 24
ΔT	is the temperature difference between the cooled water in the chiller and water from the AHU (°F)

After calculation of the CHWP power, the CWP power can be calculated as follows,

$$CWP = \frac{CWFR\ x\ Pump\ Head}{a\ x\ Pump\ Eff} \tag{5}$$

where:

CWP	is the condenser water pump power (kW)
CWFR	is the condenser water flow rate (GPM)
Pump Head	is maximum head of the high-pressure pump (ft)
a	is a constant with a value 3960
Pump Eff	is pump efficiency

CWFR calculation is done as follows,

$$CWFR = \frac{a\ x\ Q_{tot}}{\Delta T\ Condenser\ Water} \tag{6}$$

where:

a	is a constant with value 30

ΔT is the temperature difference between the water-cooled chiller and water from the cooling tower (°F)

The calculation of the chiller plant energy consumption is described by,

$$Q_{tot}.xt_{op}.x(NPLV + CHWP + CWP + CT) \quad (7)$$

Where:

Q_{tot} is the amount of chilled water produced by the chiller
t_{op} is the time to produce chilled water
CT is the cooling tower water pump power (kW)

The nonstandard part-load value (NPLV) characterizes the cooling system when operated at various cooling capacities. The baseline value of NPLV is determined by ASHRAE [5].

2.2 Investment Cost Calculation

A cost analysis of the TES system was conducted by calculating the investment costs of a conventional cooling system and a TES cooling system. Generally, the investment costs of a conventional cooling system in a commercial building are given by,

$$C_{Conventional} = C_{Chiller} + C_{CHWP} + C_{CWP} + C_{CT} + C_{Operational} \quad (8)$$

where:

$C_{Conventional}$ is the investment cost of the conventional cooling system (IDR)
$C_{Chiller}$ is the investment cost of the chiller (IDR)
C_{CHWP} is the investment cost of the CHWP Pump (IDR)
C_{CWP} is the investment cost of the CWP Pump (IDR)
C_{CT} is the investment cost of the cooling tower (IDR)
$C_{Operationl}$ is the operational cost of the conventional cooling system (IDR)

On the other hand, the cost of a TES cooling system in a commercial building such as shopping center building is given by,

$$C_{TES} = C_{Chiller} + C_{CHWP} + C_{CWP} + C_{TEStank} + C_{CT} + C_{Operational} \quad (9)$$

where:

C_{TES} is investment cost of TES (IDR)
$C_{Chiller}$ is investment cost of the chiller (IDR)

C_{CHWP}	is investment cost of the CHWP Pump (IDR)
C_{CWP}	is investment cost of the CWP pump (IDR)
$C_{TEStank}$	is investment cost of the TES tank (IDR)
C_{CT}	is investment cost of the cooling tower (IDR)
$C_{\text{Operational}}$	is operational cost of TES cooling system (IDR)

In our analysis, the payback period and return on investment (ROI) were calculated. The payback period is the time it takes to save money over the value of the tool, which can be expressed as [16],

$$Payback\ Period = \frac{\text{Investment costs}}{\text{Cost savings}} \tag{10}$$

Return on investment is the ratio between maximum profits of depreciating goods over initial investment. The equation of return on investment (ROI) can be defined as,

$$ROI = \frac{\text{Cost savings}}{\text{Investment costs}} \times 100\% \tag{11}$$

3 Commercial Buildings

The commercial sector is defined as companies that are not involved in the transport or processing or manufacturing industry or other industrial activities such as agriculture, mining or construction. Commercial businesses include hotels, restaurants, large sales such as supermarkets, and retail sales. However, educational institutions, social and health, private offices and government offices, and other public services are also included if operated commercially [2].

The commercial sector can be divided into two sectors, the government and the private sector. The government only covers district government offices and central government, the rest are private offices, schools, hotels, shopping centers and hospitals included in the private sector. The electrical energy required in commercial buildings is used for lighting, air conditioning, elevators, pumps and equipment such as computers and other office equipment.

The total energy consumption of commercial buildings in 2010 in Indonesia was 32,709,000 barrels of oil equivalent (BOE). The total energy consumption of commercial buildings was dominated by electrical energy, i.e. 70% in 2010. When compared with the year 2000, the energy use by electrical appliances in commercial buildings was more than three times higher [1]. The growth in electricity consumption for the period 2000-2010 was 9.6% per year [2].

3.1 Electrical Load Profile of Commercial Building

Referring to the data on the electrical load of commercial buildings in Jakarta published by BPPT and JICA, shopping centers have the highest electrical load, as shown in Figure 3. Shopping centers operate from 09:30 to 22:00 and their major utilities such as air conditioning and lighting systems are started up at 07:00, after which the electrical load keeps rising until 22:00. Second are hospitals, which operate for 24 hours with different operating equipment. The air conditioners, medical and office equipments are operated during working hours from 06:00 to 17:00. However, the equipment in emergency clinics and pharmacies is operated over the entire 24 hours of the day. Hotels also operate for 24 hours daily. The electrical load begins to increase from 07:00 due to hotel operations ranging from reservation and cooling the rooms, which operate for 24 hours. Government and private offices operate for 5 days a week with a duration of 8-9 hours per day. Operations begin at 07:00 and last until 17:00. Meanwhile, private offices have extra work hours, lasting until 22:00.

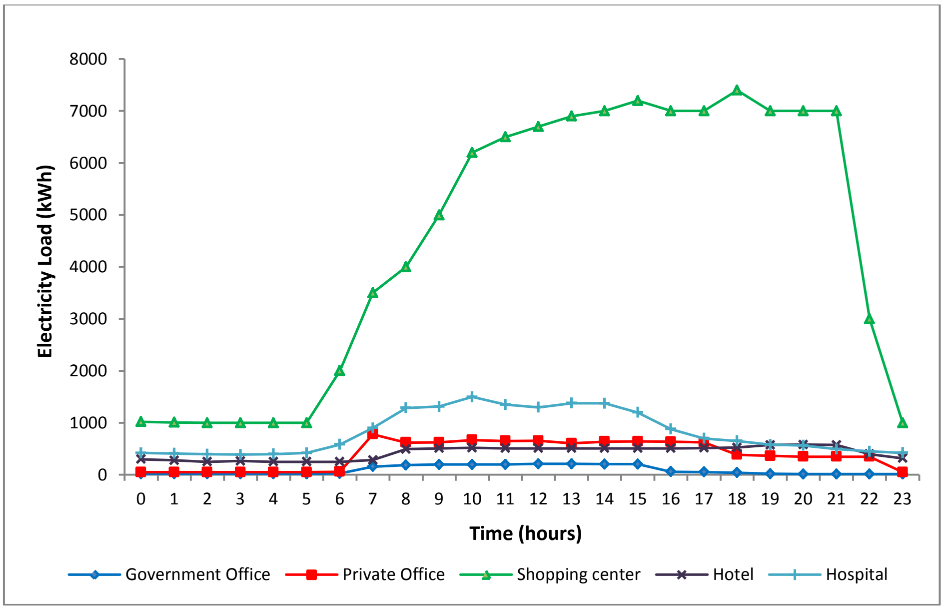

Figure 3 The electrical load profile of commercial buildings in Jakarta, Indonesia.

3.2 Electricity Rates of Commercial Buildings

The electricity tariffs in Indonesia are determined by the Ministry of Energy and Mineral Resources. They are divided in a number of classes [3]:

1. Class of public services

2. Class of households
3. Class of businesses
4. Class of industries
5. Class of government offices and public lighting

According to this categorization, hospitals belong to public services. Hotels, shopping centers and private offices belong to businesses, while government offices are included in the class of government offices and public lighting.

Table 1 Electricity rates.

Group	Building	Period	Value*	Cost/kWh (IDR)
Public service	Hospitals	On-peak	*p* x *k* x 1170	1976
		Off-peak	1170	1170
Business	Privates office	On-peak	*k* x 1020	2040
		Off-peak	1020	1020
	Hotels and shopping centers	On-peak	*k* x 1020	2040
		Off-peak	1020	1020
Government offices and public lighting	Government offices	On-peak	*k* x 947	1894
		Off-peak	947	947

* Multiplier for the value of *k* by 2 and the *p*-value of 1.3

Table 1 shows that the differing cost rates during on-peak and off-peak hours distinguish the building categories. The difference in electricity rate between on-peak and off-peak conditions follows the multiplier k ($1.4 \leq k \leq 2$), whereas the factor p is a multiplier for the general class of commercial services with a value of 1.3. Both values are determined by the Director of the State Electricity Company (PLN) [3].

4 Research Methodology

Calculation of the cooling load in commercial buildings was conducted according to the building profile and the use of air conditioning and operational time. The cooling load affects the capacity of the chiller and the TES tank. The cooling load profile is shown in Figure 4.

Figure 4 shows that shopping centers have the largest expenditure among commercial buildings. The operational time of shopping centers is from 06:00 to 22:00. The peak cooling load of shopping centers is at 18:00 (119 TR). The peak cooling load at hospitals is 10:00 (243 TR). The peak load at hotels occurs at 18:00 (149 TR). The peak cooling load of private offices is at 07:00 (104 TR) and government offices have their peak cooling load at 13:00 (33 TR).

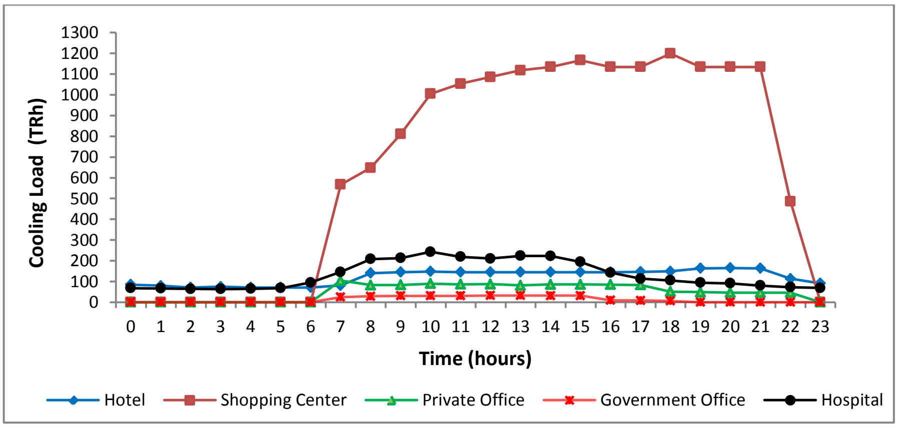

Figure 4 Cooling load profile of commercial buildings.

4.1 Conventional Cooling Systems in Shopping Center Buildings

Conventional cooling systems operate the chiller during working-time operations to supply the cooling load demand. Chilled water is produced and air

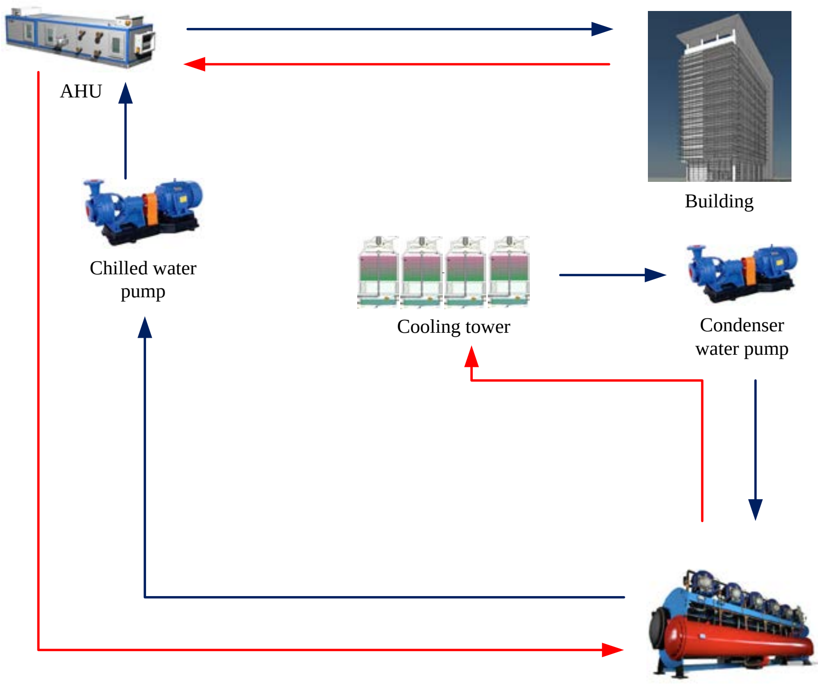

Figure 5 Conventional cooling system.

is distributed by AHU to every room in the building, after which the water is circulated back to the chiller. A conventional cooling system's operational time does not consider the difference in electrical tariff between on- and off-peak periods. A schematic diagram of a conventional cooling system is shown in Figure 5.

4.2 Cooling Systems with the TES in Shopping Center Buildings

Basically, the difference between a cooling system with and without TES is the addition of a TES tank to store the cooling water. A schematic diagram of a TES cooling system is shown in Figure 6. Cooling systems with a TES tank contain insulation to maintain the temperature of the water produced by the chiller. The TES has two processes, i.e. charging and discharging. The charging of the TES tank is performed at a temperature between 4°C and 5°C. The chilled water is returned from the AHU at a temperature between 12°C and 15°C and pumped back into the chiller to be cooled. The charging process is performed during low electricity tariff or off-peak hours.

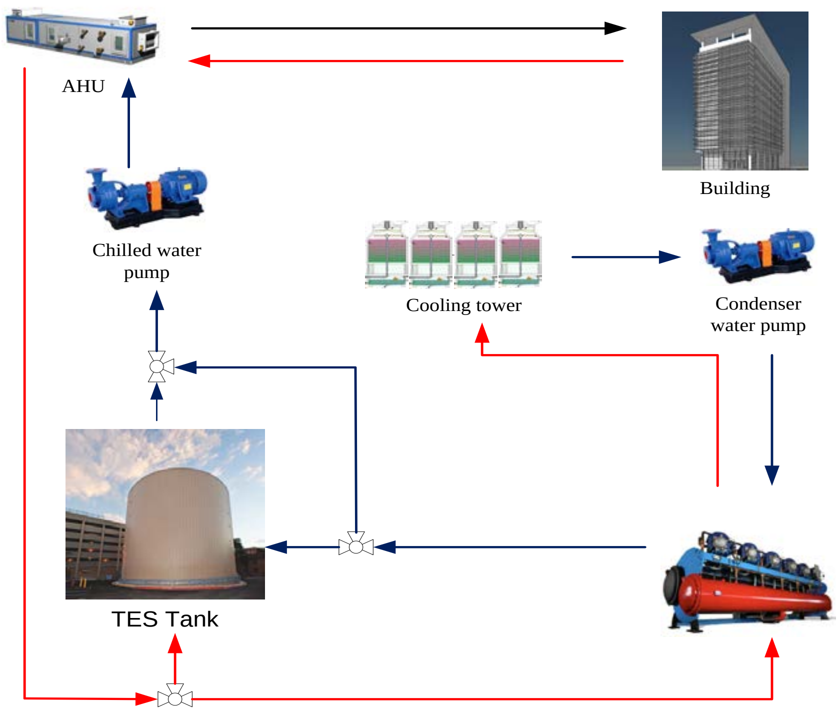

Figure 6 Scheme of TES cooling system.

The discharging from the TES tank toward the AHU is applied at a temperature between 4°C and 5°C. The discharging process is performed during high-tariff electricity period or peak hours.

4.3 Optimization

The TES system helps to reduce chiller capacity and operational time, and therefore it can reduce investment and operational costs. Since a higher TES tank capacity results in higher heat loss in the TES tank, heat loss must be considered in the optimization of TES capacity. The optimization objective function minimizes the energy difference between total chiller capacity and demand consisting of cooling load and TES heat loss for the time frame 1-24 hours, in the unit of ton refrigerant hour (TR h), as given by the following equation,

$$J_{\min} = \sum_{t=1}^{24} ((X(t) - B(t) + y(t)) \tag{12}$$

where, *X(t)* is the chilled water energy (TR h), *B(t)* is the cooling load (TR h), and *y(t)* is the heat loss in the TES tank.

The energy difference between total chiller capacity and demand ($X(t)$ $B(t)$) and heat loss *y(t)* in the TES tank is optimized to be as small as possible, thus improving the efficiency of the chiller and the TES tank. In this study, the TES tank was operated with a small heat loss.

Thermal stratification in the tank degrades due to mixing induced by inlet flow. Meanwhile, heat diffusion is caused by the temperature gradient, wall conduction and natural convective flow via tank walls [9]. Heat loss from the TES tank depends on the environment and the space around the TES tank; the estimated heat loss from the tank is 1-2% of TES tank storage capacity [17]. Through thermal loss, a TES system looses only approximately 1% of its energy during inactive use [6,7]. Therefore, the total estimated heat loss from the TES tank is about of 2% of the storage capacity per hour.

To obtain the optimal value of the objective function, two determined constraint functions are,

1. the constraint function of chiller capacity for t =1,2,3,....24 hours

$$0 \le X(t) \le X_{\max} \tag{13}$$

2. the constraint function of TES capacity for $t = 1, 2..24\, hours$

$$\sum_{t=1}^{17} V\,TES(t) = \sum_{t=17}^{22} B(t) \tag{14}$$

Chiller capacity depends on the building cooling load. X_{max} indicates the amount of chiller capacity in accordance with the needs of the building cooling load by considering the peak load of commercial buildings.

Chilled water is stored in the TES tank, *VTES(t)*, for 16 hours which is determined during off-peak hours from 22:00 to 17:00. The total capacity during charging is the same as the cooling load requirement $B(t)$ during peak hours from 17:00 to 22:00. Simple modeling of the TES tank working at t = 1,2 ... 24 hours is determined by,

$$V_{TES}(t+1) = V_{TES}(t) + X(t) - B(t) \tag{15}$$

Eq. (14) describes the relationship between the cooling load $B(t)$ of the TES tank that will be filled with chilled water and the chilled water $X(t)$ to be issued to meet the cooling load of the building. If $X(t) - B(t)$ is positive then the TES tank is being charged. If $X(t) - B(t)$ is negative then the chilled water is being distributed to the building to meet the cooling load of the building (discharging). This is a linear optimization problem and it can be solved by simplex linear programming.

5 Results and Discussions

5.1 Chiller plant energy consumption

A calculation of energy consumption in the chiller plant was performed in order to determine the electrical energy consumption of the chiller plant. Table 2 shows the energy consumption of the chiller plant in a shopping center building and related constants. The COP of the chiller was calculated from the chiller's full load (6.1).

Table 2 Results of Calculation of Chiller Plant Energy Consumption.

Description	Unit	Value or Constant	Formula
Chilled water flow-out/hour	TR	1,085,869	
Chiller – full load	kW/TR	0.576	ASHRAE
Water cooled chiller – NPLV calculation	kW/TR	0.549	ASHRAE
Primary chiller water pump	kW/TR	0.097	Pump Calc.
Condenser water pump – CWP	kW/TR	0.061	Pump Calc
Cooling tower – CT	kW/TR	0.003	Pump Calc
Total chiller plant	kW/TR	0.71	Total
Chiller plant energy consumption	kW	771.38	Eq. (7)

Description	Unit	Value or Constant	Formula
Chilled Water Pump			
Δ Temperature chilled water	^{o}F	10	ARI
Chilled water flow rate	GPM	2,606,086	Eq. (4)
Pump head	Ft	150	GBCI
Pump efficiency	%	70%	Design
Pump kW	kW	105,625	Eq. (3)
	kW/TR	0.097	
Condenser Water Pump			
Δ Temperature condenser water	^{o}F	10	ARI
Condenser water flow rate	GPM	3,257,607	Eq. (6)
Pump head	Ft	75	GBCI
Pump efficiency	%	70%	Design
Pump kW	kW	66.0159	Eq. (5)
	kW/TR	0.060795	

5.2 Optimization Results

The subject variables for optimization are chiller capacity, TES tank capacity and heat loss in the TES tank per building. In the optimization process, the objective function and the constraint are determined by Eqs. (12), (13) and (14). The result of optimization for shopping center buildings is shown in Figures 7-8.

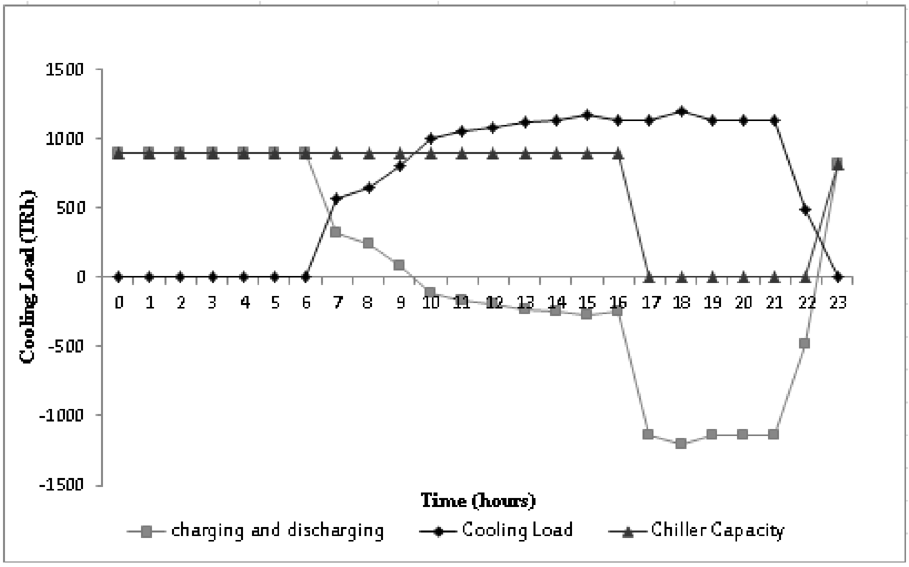

Figure 7 Profiles of building cooling load, chiller capacity, charging, and discharging over time.

Figure 8 describes the charging process, which begins at 23:00 and lasts until 09:00. The chilled water, with a capacity of 890 TR, is stored in the TES tank at 23:00 and at 06:00. The chiller produces chilled water with a capacity of 890 TR until 16:00. The discharging process begins at 10:00 and lasts until 22:00 to meet the cooling load during peak hours. The results show that the chiller capacity in the TES system for shopping center building is 890 TR. This value is lower than the chiller capacity in shopping center buildings without TES system, which is 1300 TR.

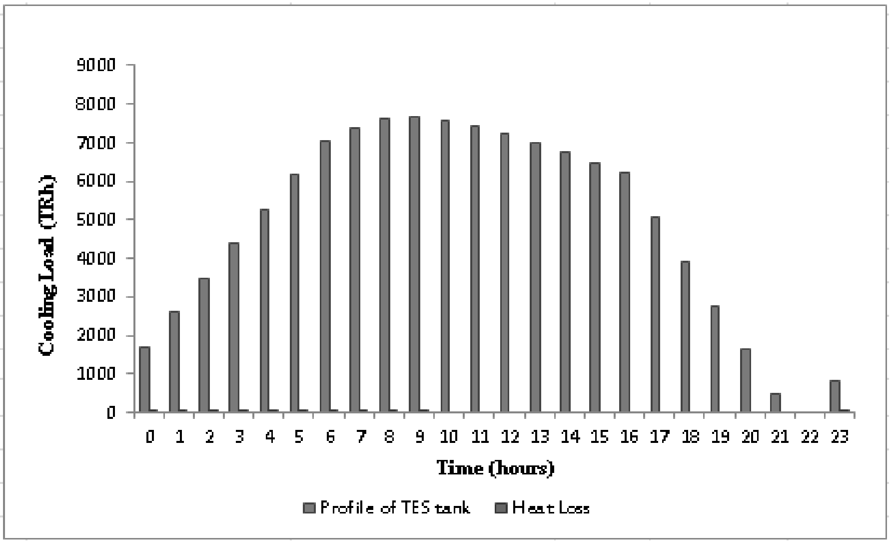

Figure 8 TES tank capacity profile and heat loss in the TES tank over time.

Table 3 and Figure 8 describe the profile of TES tank capacity and the heat loss that occurs during the charging and discharging process. The maximum capacity of the TES tank is 7692 TR and the total TES tank capacity is reduced during the discharging process from 10:00 to 22:00. Heat loss in the TES tank during charging from 23:00 to 09:00 is 154 TR.

Table 3 Results of Optimization at Per Commercial Building.

Building	Charging period (hours)	Chiller capacity (TR)	TES tank capacity (TR)	Volume TES tank (m^3)	Heat loss TES tank (TR)
Shopping center	10	890	7692	2327	154

5.3 Power Cost Savings Analysis

Calculation of the electricity savings was conducted by comparing the electricity consumption of a conventional cooling system and that of a cooling system with TES. Figure 9 describes the electricity cost of shopping center buildings.

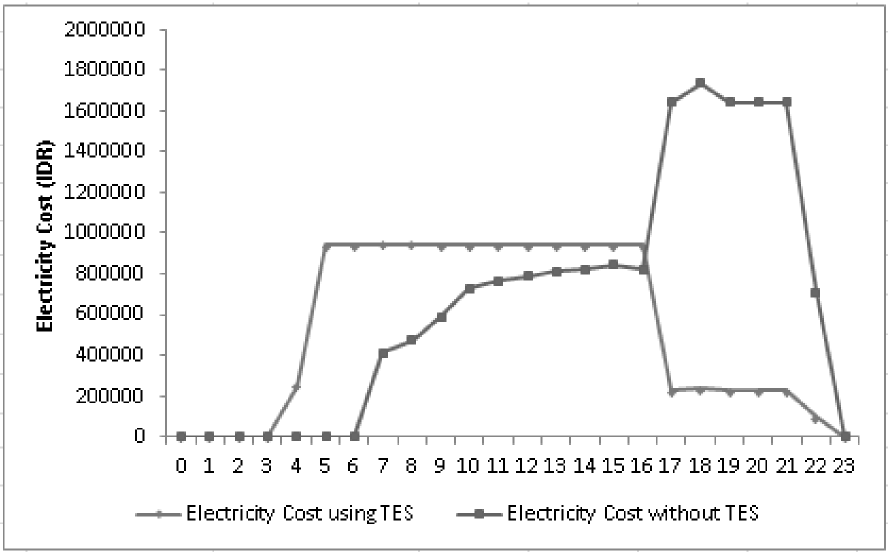

Figure 9 Profile of electricity cost in shopping center building with and without TES over time.

The electricity consumption of a cooling system with TES increases during the charging process, from 04:00 to 16:00. The electricity usage of a cooling system is influenced by the amount of produced chilled water. Electricity cost savings depend on the difference between electricity rates during peak and off-peak hours. M.M. Rahman and M.G. Rasul have conducted an economic feasibility analysis of a TES system applied to school buildings in Australia [18]. They found that the the peak-hour rates were 3 times the off-peak hour rates, so electricity savings could reach up to 61%.

Peak hours in Indonesia are from 17:00 to 22:00 and off-peak hours are from 23:00 to 16:00, each running for 5 hours and 19 hours, respectively. This in contrast to Malaysia and Australia, where peak hours are from 07:00 to 21:00 and off-peak hours from 22:00 to 07:00, each running for 14 hours and 10 hours, respectively [6,7,18]. The longer duration of peak hours increases the potential savings when using TES because the chiller stops operating during high-tariff hours. Applying the above calculation, the obtained cost savings for a shopping center building are shown in Table 4.

Table 4 Savings.

Building	Electricity cost using TES/day (IDR)	Electricity cost without TES/ day (IDR)	Cost savings/ day (IDR)	Savings (%)
Shopping center	12,782,677	16,070,848	3,288,170	20%

5.4 Investment Cost Analysis

In general, the investment costs of a conventional cooling system comprise chiller, chiller plant, TES tank and operational costs, as tabulated in Table 5.

Table 5 Investment Costs Of Conventional Cooling System For Shopping Center Buildings.

Description	Volume	Units	Costs (IDR)
Chiller	1300	TR	6,500,000,000
CHWP	146	kW	467,823,765
CWP	90	kW	288,384,513
Cooling tower	4100	GPM	984,000,000
Operational cost	Year		5,865,859,434
Total			**14,106,067,712**

On the other hand, the costs of a cooling system with TES in accordance with Eq. (9) are as given in Table 6.

Table 6 Investment Costs of Cooling System with TES For Shopping Center Buildings.

Description	Volume	Units	Costs (IDR)
Chiller	890	TR	4,450,000,000
CHWP	172	kW	551,134,846
CWP	54	kW	173,030,708
Cooling Tower	2670	GPM	640,800,000
TES tank	2327	m^3	2,079,005,748
Operational Cost	Year		4,665,677,246
Total			**12,559,648,548**

The price for the chiller and chiller plant equipment follows reference [19], assuming an exchange rate of dollar to IDR of 12,000. The TES tank is built from concrete [8]. The estimated price for the concrete is IDR 3,000,000/m^3 [20]. The ROI and payback period depend on the savings and investment cost. In the application of a TES system, the biggest investment is for the chiller and the TES tank. A larger chiller capacity will result in a faster charging time and smaller heat loss in the TES tank. However, a larger capacity also increases the investment, operational and maintenance costs, so it must be optimized [21].

The result of optimization for shopping center buildings can lead to investment savings of 11% because the total investment in a cooling system with TES is lower than without TES. The detailed investment costs for a shopping center building are shown in Table 7.

Table 7 Investment Cost for Shopping Center Building.

Building	Investment cost savings / year (IDR)	Investment cost (IDR)	Payback period (year)	ROI (%)
Shopping center	1,546,419,164	14,106,067,712	-	-

6 Conclusion

The implementation of a TES system in shopping center buildings was investigated in this research. The method of linear programming was utilized to optimize energy consumption and investment costs. The results showed that the TES system can reduce electricity costs up to 20% and investment costs about 11%.

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