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Optimal Design of Integrated Chiller Capacity with Ice Thermal Storage for Commercial Buildings through Cooling System Cascade Analysis

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Abstract: ***Chilled water air conditioning system is used to supply cooling systems in large capacity for industrial processes and commercial buildings. Air conditioners contribute more than 60 percent of electricity consumption in buildings. District Cooling System (DCS) technology comprises a central chiller plant which provides advantage compared to local air conditioning system. It has higher efficiency, uses less power in system operation, allows more usable space in buildings, and can be operated with minimum manpower while handling same amount of cooling load. The integration of a chiller with ice thermal storage (ITS) offers more operational flexibility while reducing space cooling expenses. This paper presents a systematic framework for design and operation of District Cooling Plant (DCP) comprising an integrated chiller and ice thermal storage system. The Cooling System Cascade Analysis (COSCA) based on pinch analysis is constructed to determine the chiller optimal size and ice thermal storage capacity. The District Cooling System configuration for this study comprises a cooling tower, chiller (centrifugal, variable centrifugal, glycol) and ice thermal storage system. The application of this technique to fulfil 66,284 refrigerant tonne hour (RTH) cooling load demand from commercial buildings reveals the optimal capacity of the chiller is 3068.91 refrigerant tonne (RT), ice tank rating at 989 refrigerant tonne (RT) and ice tank capacity is 9892.75 refrigerant tonne hour (RTH).***

Keywords: ***District cooling system, thermal energy storage, chiller, cooling load, commercial building***

I. INTRODUCTION

The district cooling plant (DCP) or district cooling system (DCS) is a system that can save electricity by optimising the use of an air conditioning system.A DCP consists of glycol chillers and an ice thermal storage (ITS) system, also known as thermal energy storage (TES) that disseminates thermal energy in the form of chilled water. Consumers receive distributed chilled water via pipelines from a central source for the use of space cooling and dehumidification. A common DCScomprises distribution pipelines, chiller plants, pumping stations, heat rejection systems, and user stations [1]. Rapidly appearance of commercial building in Malaysia can be observed as office buildings, hotels, shopping malls physical developments have made KL an urban heat island with the urban heat intensity of 4-6 ° C resulting in the ambient temperature ranges from 23-33 ° C[2]. In terms of air conditioning types, 76.6% of the buildings uses packaged air units, 25.1% used root-top/self-contained units and 16.2% chilled water systems. Only 2.3% of the consumers (22 out of 953) are related the use of TES [3] DCS with TES or ITSis a promising approach to decrease operational costs and electricity bills at peak hours. The application of TES at Universiti Malaysia Sarawak showed a cost saving in the range of 0.08 – 3.13% with respect to the total use of mechanical electrical plants[4]. Another study in Hong Kong showed an annualelectricity cost net saving in the range of 0% to 3% [5]. However, the thermal energy storage system also contributed to an additional capital cost for the heat exchanger and water pumps. It was found that the cost increased by 29% compared to that of an existing system [5]. Nonetheless, the optimisation of the thermal storage could reduce an integrated system's operational cost with consideration of the peak and off peak cooling effect demand. In ITS, water is used as the phase change material to store cool energy due to its low cost and high thermal capacity[1].An optimization analysis on ice thermal energy storage systemincorporated with a water-cooled air-conditioning system was accomplished [6]and the result shows that electricity consumption in ITS system decreased by 11% as opposed to the conventional one. ITS systems were also assessed for commercial buildings in Malaysia [7][8]. [9] SimulatedTES in office and retail buildings in California to assess its cost-effectiveness and demand response (DR) capabilities, and concluded that TES can provide a reliable and fast load shed without interruption in the buildings occupants' comfort.[10] concluded that the main driver for the uptake of TES technology is economic. [11] simulates a medium-sized office building with integrated solar photovoltaic (PV), DR and TES. A recent study to optimally design the thermal energy storage (TES)was carried out [12]. The author presented a methodology based on pinch analysis principles to support the engineer in developing a cost effective and optimal design focusing on different types of TES for batch processes. Similarly, [13]developed a TrigenerationCascade Table (TriGenCT) with energy storage system based on the pinch analysis algebraic technique to simultaneously determinethe minimum target for outsourced power, heating and cooling, amount of excess power, heatingand cooling during the first day and continuous 24 hour operations, and the maximum storage capacity.

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The results showed that the trigeneration system with storage can save energy up to 202 GWh/y and reduce the operational cost to RM31.92 M/d. [14]developed an energy and exergy analysis of thermal storage system in buildings.
Despite the numerous contributions by various authors on designing TES, there are still gaps in the literature with respect to the design, operation and optimisation of an integrated chiller with TES. In this study, a new systematic framework for designing and operating the integration of a chiller and ITS for DCP called the Cooling System Cascade Analysis (COSCA) will be discussed. The COSCA technique is tested using hourly-based cooling load demand from five (5) commercial buildings includes shopping mallsbuilding 1 and building 2, food court, hotel, and cinema. Meanwhile two different types of chillers, glycol chiller (FES) and centrifugal chiller (XR), are considered in this study.

II. CASE STUDY

A District Cooling Plant (DCP) located on the roof top level of The Curve, Mutiara Damansara, Selangor as illustrated in Fig.1 is taken as a case study. The DCP system in this case study generates chilled water to fulfil the cooling load demandsof the nearby customers for the purpose of space cooling. The district

Fig. 1 Location of the area for case study in Malaysia

cooling system consists of three separators which are Plant 1 (DCP1), Plant 2 (DCP2), and the Client Side, Customer 1 (C1), Customer 2(C2), Customer 3 (C3), Customer 4 (C4), and Customer 5 (C5).

DCP 1 consists of two units of centrifugal chillers (XR), three units of glycol chillers (FES), three units of ITS tanks, four units of distribution pumps, and six units of cooling towers. The centrifugal chillers produce 850 RT of cooling loads while the FES chillers can produce up to 991 RT of cooling loads. The FES chillers are used to produce ice for the ITS when the cooling loads exceeds the cooling demands. The thermal storage capacity can store the cooling energy in the form of ice at up to 8000 RT per hour.

DCP 2 consists of two units of centrifugal chillers (XR) which can produce 850 RT each. It is also equipped with a unit of variable speed drive centrifugal chiller (XRV) which can produce up to 500RT. A variable speed drive centrifugal chiller enables the service provider to control the compressing speed for the coolant at an optimal compression. DCP 2 also consists of two units of distribution pumps to supply the cooling demands to the users, and five units of cooling towers to release the heat from the coolant. The client side for the district cooling system consists of five customers that buy the cooling loads from the service provider. The customers' details are as follows:

A. Customer 1 (C1): Shopping Mall 1
B. Customer 2 (C2): Food Court
C. Customer 3 (C3): Hotel
D. Customer 4 (C4): Shopping Mall 2
E. Customer 5 (C5): Cinema

Hotel, Shopping Mall 2, and Cinema each hasits own heat exchanger (HEX) for the heat transfer medium of chilled water supply, whereby the HEX separates the chilled water loop for theDCP and the chilled water loop for the building. This allows the practicality ofa maintenance or repair job during an emergency period because theDCP and building is not on the same chilled water loop.The other two customers, Shopping Mall 1 and Food Court, are not equipped with HEX, hence bypassing the HEX. The cooling energy demandbreakdowns for all the customers are as follows; Customer 1 consumes 38%, Customer 2 consumes 30%, Customer 3 consumes 5%, Customer 4 consumes 21% and Customer 5 consumes 6% respectively. The district cooling system plant consists of three closed loops running on different types of fluid; cooling water, chilled water, and glycol. The system also includes ice tanks which consist of a combination of chilled water and solid ice. The overall DCP process is illustrated in Fig. 2. The cooling water circulates from the condenser tank in the chillers to the cooling tower and vice versa. The function of the cooling water is to reduce the refrigerant temperature coming from the client side. The cooling water flows through the condenser pipe and exchanges heat with the refrigerant in the condenser tank. The inlet temperature of the cooling water to the condenser pipe is 29 ºC and the outlet temperature is hotter than the inlet temperature at 34 ºC. The hot cooling water flowing out of the condenser pipe goes to the cooling tower where the cooling water exchanges heat with the ambient air. The cold cooling water is then recirculates to the chillers and the process is repeated. The overview of the cooling water loop is shown in Fig. 3.

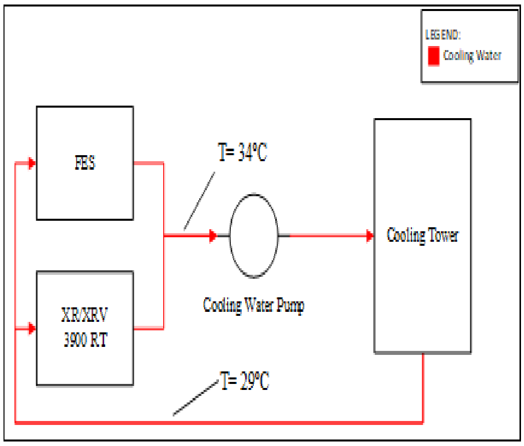

Fig. 2 Overall Process of a District Cooling Plant

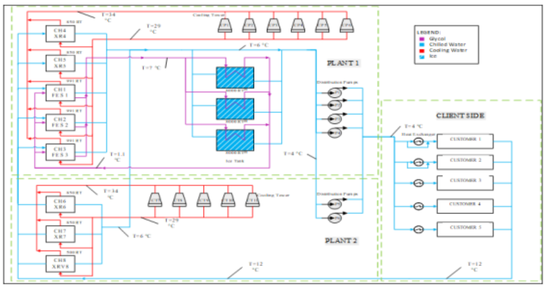

Fig. 3Cooling Water Loop

In this study, it is found that the chillers generated chilled water at the temperature of 6°C. Therefore, to further cool the chilled water from 6°C to 4°C as required by the users, the chilled water is passed through the ice thermal storage. The cooled chilled water at 4°C is pumped to the users' heat exchangers and returned to the chillers at 12°C. The overview of the chilled water loop is shown in Fig. 4.

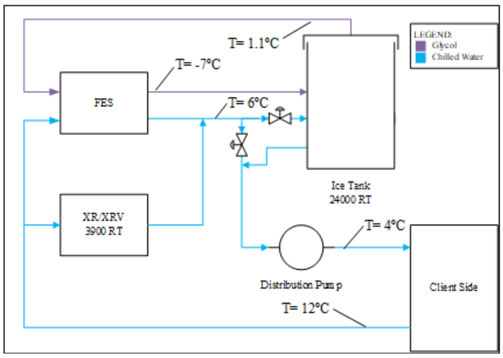

Fig.4 Chilled Water and Glycol Loop

Glycol is the refrigerant used by the chillers to cool the chilled water and to generate ice in the thermal storage tank. Glycol at a temperature of -7 °C is generated by the FES chillers from Plant 1 and flows to the thermal storage tank. The cool glycol flows through a coil pipe which is submerged inside the tank. The water exchanges heat with the cool glycol and ice is formed on the outside of the coil pipe. The glycol coming out of the storage tank is at a temperature of 1.1 °C and is returned to the FES chillers. An overview of the glycol loop is shown in Fig. 4.

III. METHODOLOGY

ADCP comprises a chiller and ITS offers more operational flexibility, while reducing cooling demand expenses.COSCA is a systematic framework to simultaneously design the chiller and the ice storage system (including the ice thermal tank storage capacity, ice tank rated and initial content of ice tank) for a District Cooling Plant (DCP) system. COSCA also aims to design a system with minimal cooling energy generated by
the chiller (cooling energy generation mainly due to the demand by the clients) and the technique includes the chiller efficiency (FES chiller - glycol) and also the ITS tank charging and discharging proficiency in the study. This method will be able to ensure that every discharge happening in the ITS is able to melt solid ice until it becomes chilled water to ensure the cooling demand (RTH) is filled. The assumptions for designing an optimal DCP are listed below:

i. Hourly cooling demand data is obtained from one of the commercial buildings in Malaysia for year 2017.

A. The district cooling system consists of glycol chiller integrated with ITS.
B. The cooling demand is assumed to follow the same trend over the year.
C. The maximum cooling demand in the daily cooling demand profile will be taken as the initial value for the chiller size.
D. The duration analysis in this study is assumed for 24 hours operation in which the chiller must be completely dispersed to upsurge its volume factor and efficiency and maintained at constant generation.
E. Stored cooling energy (chilled water) at the beginning of the analysis when time, t = 0 must be equal to the stored power at the end of the analysis (In this study t = 24 h) to prevent an accumulation of cooling energy in the ITS tank system. Excess cooling supply can be reduced by reducing the amount of 2nd discharging ice to zero.

3.1 COSCA Overall Methodology

The overall methodology for COSCA has been adopted from ECSA [12][15] and extended for determining an optimal sizing of integrated chiller and TES as illustrated in Fig. 5.

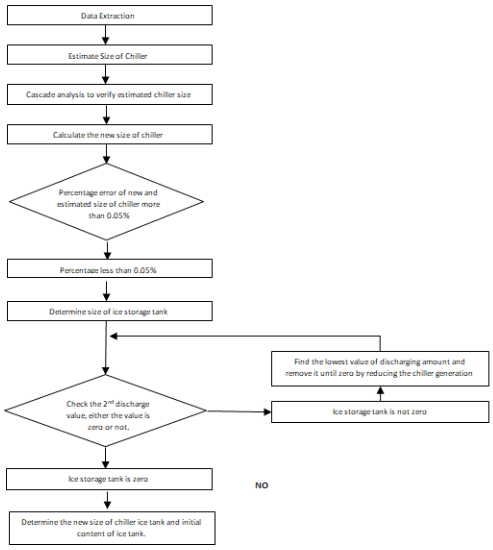

Fig. 5 COSCA overall methodologies

Step 1: Data Extraction

The first step in COSCA is to extract relevant data and construct the cascade table for the district cooling system. The data required for the analysis are listed below:

i. Cooling load demand analysis period can be based on daily or monthly or yearly.
ii. Hourly cooling demand for a 24 hour time horizon.
iii. System configuration comprising of cooling tower, different chiller types (centrifugal, variable centrifugal, glycol) and ice thermal storage system.
iv. Chiller efficiency.
v. Ice tank charging and discharging efficiency.
vi. Depth of discharge (DoD) of ice thermal storage tank.

Step 2: Chiller Size Estimation

DCP efficiency values are estimated via the following equations:

ITS efficiency for charging/discharging,

$$F_c / F_D \qquad (1)$$

Where:

Fc:Ice tank charging efficiency

F_D:Ice tank discharging efficiency

F1 : Glycol chiller efficiency

Ch : Initial glycol chiller capacity

The value for this step is shown in Table 2.

Step 3: Construct the Cooling System Cascade Analysis (COSCA) Table

The table for the cooling system cascade analysis can be constructed based on the following guidelines:

i. Time period is arranged in ascending order in column 1. The analysis is conducted for the time interval of 1 hour for this illustration

ii. Arrange hourly cooling demand, L_t accordingly in column 2.

iii. Arrange the glycol generation, CH_t from the chiller in column 3.

iv. Net cooling demand, N_t is calculated and the results are arranged accordingly in column 4. Equation (2) shows the general mathematical formula for N_t calculation.

$$Nt = CH_t - L_t \tag{2}$$

v. Analyse the system's chilled water surpluses and deficits by referring to the net cooling demand, N_t, chilled water surpluses are recorded in column 5, while chilled water deficits are recorded in column 6.

vi. Chilled water surpluses show excess chilled water (to be charged into ITS), while chilled water deficits show inadequate cooled glycol produced to meet the load, thus an added basis of energy is required from the ITS tank system (discharged from ITS tank). The storage charging, C_t is calculated via the following equation and arranged accordingly in column 5 as storage charging:

$$C_t = N_t F_c F1 \tag{3}$$

Where:

F_c: Ice tank charging efficiency

F1: Chiller efficiency

1) Analyse the cooling load deficit. The cooling load deficit indicates insufficient cooling supply; thus the thermal energy storage needs to be discharged. The cooling deficit is calculated via the following equation and arranged in column 6 as storage discharging:

$$D_t = N_t / (F_D F1) \tag{4}$$

Where:

F_D: Ice tank discharging efficiency

F1:Chiller efficiency

2) Compute the cumulative cooling supply (chilled water) in the storage, Et. The results are arranged in column 7. The cumulative cooling supply in the storage can be calculated via (5).

$$E_t+1 = E_t + C_t + D_t \tag{5}$$

3) Analyse and find the biggest negative value in column 7. The required amount of additional energy is specified by the highest negative value in column 7. The new cumulative energy, E_t (new), is recalculated and arranged in column 8 accordingly. No alteration is required if there is no negative value in column 7.

The detailed cooling system cascade analysis table that follow the step by step guideline is shown as in Table 1.

Step 4: Calculate the New Size of Chillers

The new chiller load$CH_{t\,NEW}$ is calculated using the following equation:

$$CH_{tNEW} = CH_t - \frac{E_{tFINAL} - E_{tINITIAL}}{t} \tag{6}$$

Where:

$E_{t\,FINAL}$:The value in the last row in column 8

$E_{t\,INITIAL}$:The value in the first row in column 8

Step 5: Calculate the percentage change of new and previous chiller loads

The percentage change of the chiller load is then calculated using the following equation:

$$P = \left|\frac{CH_{tNEW} - CH_t}{Gc_t}\right| \times 100 \tag{7}$$

If the percentage change of the chiller load exceeds 0.05%, repeat step 4 by using the new chiller load value in column 3 until the value of percentage change is below 0.05%.

Step 6: Calculate the Capacity of the Thermal Storage Tank

Once the analysis is completed, the capacity of the thermal storage tank can be determined from the final analysis table. The capacity of the thermal storage tank is the largest positive value in column 8.

Step 7: Check whether the 2nd Discharge Value is Zero

To ensure that the ice tank can fulfil the demand effectively, the chilled water in the ice tank must be fully discharged for every discharge period. If the 2nd discharge value is not zero, the following step must be performed.

Step 7.1: Identify the Lowest Value of Discharging Amount and Reduce the Chiller Generation Capacity

Calculate the amount of the generation that needs to be reduced without considering the chiller efficiency, and ice tank charging and discharging efficiency. The calculation is given in (8).

$$Z = \frac{X}{Y} \tag{8}$$

Where:

X:Lowest value of discharging in column 8

Y :Hours of charging after the first discharge

Next, calculate the amount of generation that needs to be reduced with the consideration of chiller efficiency, and ice tank charging and discharging efficiency. The calculation is given in (9).

$$A = \frac{Z}{F_D F1} \tag{9}$$

The new chiller generation which considers the reduced amount of the thermal energy storage content is then calculated by (10) and substitute in column 3 for the number of hours of charging period, Y before the second discharging process.

If the 2nd discharge value is equal to zero, proceed to the next step.

$$B = CHt - A \qquad (10)$$

1	2	3	4	5	6	7	
Time (Hour) t	Cooling Demand (RTH) L_t	Chiller Generation, (RTH) CH_t	Net Cooling Demand (RTH) N_t	Storage Charging (RTG) C_t	Storage Discharging (RTH) D_t	Cumulative Cooling Supply (RTH) E_t	New Cumulative Cooling Supply (RTH) $E_{t\ NEW}$
0	0	0	0	0	0	0	E_{11}
1	L_1	CH_1	N_1	C_1	D_1	E_1	$E_{1\ NEW}$
2	L_2	CH_2	N_2	C_2	D_2	E_2	$E_{2\ NEW}$
3	L_3	CH_3	N_3	C_3	D_3	E_3	$E_{3\ NEW}$
4	L_4	CH_4	N_4	C_4	D_4	E_4	$E_{4\ NEW}$
5	L_5	CH_5	N_5	C_5	D_5	E_5	$E_{5\ NEW}$
6	L_6	CH_6	N_6	C_6	D_6	E_6	$E_{6\ NEW}$
7	L_7	CH_7	N_7	C_7	D_7	E_7	$E_{7\ NEW}$
8	L_8	CH_8	N_8	C_8	D_8	E_8	$E_{8\ NEW}$
9	L_9	CH_9	N_9	C_9	D_9	E_9	$E_{9\ NEW}$
10	L_{10}	CH_{10}	N_{10}	C_{10}	D_{10}	E_{10}	$E_{10\ NEW}$
11	L_{11}	CH_{11}	N_{11}	C_{11}	D_{11}	**Highest –ve value**	$E_{11\ NEW}$
12	L_{12}	CH_{12}	N_{12}	C_{12}	D_{12}	E_{12}	$E_{12\ NEW}$
13	L_{13}	CH_{13}	N_{13}	C_{13}	D_{13}	E_{13}	$E_{13\ NEW}$
14	L_{14}	CH_{14}	N_{14}	C_{14}	D_{14}	E_{14}	$E_{14\ NEW}$
15	L_{15}	CH_{15}	N_{15}	C_{15}	D_{15}	E_{15}	$E_{15\ NEW}$
16	L_{16}	CH_{16}	N_{16}	C_{16}	D_{16}	E_{16}	$E_{16\ NEW}$
17	L_{17}	CH_{17}	N_{17}	C_{17}	D_{17}	E_{17}	$E_{17\ NEW}$
18	L_{18}	CH_{18}	N_{18}	C_{18}	D_{18}	E_{18}	$E_{18\ NEW}$
19	L_{19}	CH_{19}	N_{19}	C_{19}	D_{19}	E_{19}	$E_{19\ NEW}$
20	L_{20}	CH_{20}	N_{20}	C_{20}	D_{20}	E_{20}	$E_{20\ NEW}$
21	L_{21}	CH_{21}	N_{21}	C_{21}	D_{21}	E_{21}	$E_{21\ NEW}$
22	L_{22}	CH_{22}	N_{22}	C_{22}	D_{22}	E_{22}	$E_{22\ NEW}$
23	L_{23}	CH_{23}	N_{23}	C_{23}	D_{23}	E_{23}	$E_{23\ NEW}$
24	L_{24}	CH_{24}	N_{24}	C_{24}	D_{24}	E_{24}	$E_{24\ NEW}$

Table – I : Cooling System Cascade Analysis(COsCA) for District Cooling Plant (DCP)

Step 8: Determine the New Chiller Size, Ice Tank Size and Initial Content of Ice Tank

The final charging phase and the initial charging phase is first ensured to be equal to confirm the feasibility of the system. Some adjustment needs to be done on the final charging phase if it is not equal to the initial charging phase in column 8. The adjustment is made using the following guidelines:

1) Calculate the value of adjustment to be made in column 8, C using (11) where

$$C = \text{final storage - initial content} \qquad (11)$$

2) Include the chiller efficiency and the ice tank charging and discharging efficiency in the adjustment value, C. using (12)

$$D = \frac{C}{F_D F1} \qquad (12)$$

3) Calculate the amount of chiller generation to be added to the current chiller generation capacity, F using (13).

$$F = \frac{D}{E} \qquad (13)$$

Step 9: Determine the New Chiller Size, Ice Tank Size and Initial Content of Ice Tank

The final charging phase and the initial charging phase is first ensured to be equal to confirm the feasibility of the system. Some adjustment needs to be done on the final charging phase if it is not equal to the initial charging phase in column 8. The adjustment is made using the following guidelines:

4) Calculate the value of adjustment to be made in column 8, C using (11)
5) Include the chiller efficiency and the ice tank charging and discharging efficiency in the adjustment value, C. using (12)
6) Calculate the amount of chiller generation to be added to the current chiller generation capacity, F using (13)where E represents hours of charging after second discharge.
7) Calculate the new size of chiller, G, using (14).

$$G = \text{existing value of } CH_t + F \qquad (14)$$

8) Substitute G in column 3 for the period of E, hours of charging after the second discharge.

The chiller size, ice tank size and the initial content of the ice tank will then be determined after the equalisation process of the initial and the final content of the ice tank. The above parameters are determined using the following heuristics:

a. The largest value in column 3 is taken as the chiller capacity.
b. The most negative value in column 6 is taken as the ice tank rating.

c. The ice tank capacity is calculated via (15).

$$\text{Ice tank capacity} = 40\%\ \text{solid ice} + 60\%\ \text{chilled water} \tag{15}$$

d. Where 40% solid ice is indicated as the largest value in column 8.

i. The top value in column 8 is taken as the initial content of the ice tank.

ii. The discharging value of ice is calculated via (16).

$$\text{Discharging value of ice} = \frac{\text{ice tank rated}}{\text{discharging hour}} \tag{16}$$

3.2 Data Collection

In this analysis, data has been taken in terms of period of analysis, system configuration, hourly cooling energy demand, chiller efficiency, ice tank charging and discharging efficiency, and the depth of discharge of the ice thermal storage tank as shown in Table – II. Fig. 6 indicates an hourly cooling load demand starting at 6 a.m. for a period of 24 hours.

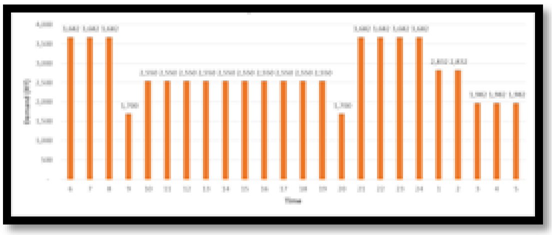

Fig. 6 Hourly Cooling Load Profile for the DCP case study

Table – II : Operational Data for District Cooling Plant [16].

Parameters	Value Assumptions
Glycol chiller efficiency (%)	90
Ice tank charging and discharging efficiency (%)	88.3
Depth of discharge of the ice tank	1
Initial glycol chiller capacity (RT)	3000

IV. RESULTS AND DISCUSSION

The hourly cooling demand profile extracted from Fig. 6 have been arranged in the first 2 columns in Table – II. Further calculation and analysis of COSCA follow the step by step guideline in step 3 as elaborated in the methodology section. It was found that the optimal volume of the ITS tank is 9894 RTH. The optimal volume of the storage tank system is calculated in the Cascade Table after Final Storage Value Adjustment and has been determined via (15).

New chiller generation, $CH_{tNEW}$and the percentagechangeof chiller generation, P is calculated via (6) and (7) and it is found that 2902 RTH is needed with 3.23% change of chiller generation different (1st iteration). Therefore, the 2nd, 3rd, and 4th iterations are repeated until a percentage change of less than 0.05% is obtained. The minimum target of 0.05% is set as a tolerance value to ensure the accuracy of the results. For this case study, the calculation is stopped at the 4th iteration since the percentage change obtained is 0%.

Table – III : Cascade Analysis Table Based on Demand in Fig. 6

Time	Demand (RTH) Lt	Chiller generation (RTH) CHt	Net energy demand (RTH) Nt	Charging (RTH) Ct	Discharging (RTH) Dt	Cumulative energy in ES (RTH) Et	New Cumulative energy in ES (RTH)
						0.00	2574.56
6 am	3682	3000	-682		858	-858.19	1716.37
7 am	3682	3000	-682		858	-1716.37	858.19
8 am	3682	3000	-682		858	-2574.56	0.00
9 am	1700	3000	1300	1033.11		-1541.45	1033.11
10 am	2550	3000	450	357.62		-1183.83	1390.73
11 am	2550	3000	450	357.62		-826.22	1748.34

Highest -ve

12 pm	2550	3000	450	357.62		-468.60	2105.96
1 pm	2550	3000	450	357.62		-110.99	2463.57
2 pm	2550	3000	450	357.62		246.63	2821.19
3 pm	2550	3000	450	357.62		604.24	3178.80
4 pm	2550	3000	450	357.62		961.86	3536.42
5 pm	2550	3000	450	357.62		1319.47	3894.03
6 pm	2550	3000	450	357.62		1677.09	4251.65
7 pm	2550	3000	450	357.62		2034.70	4609.26
8 pm	1700	3000	1300	1033.11		3067.81	5642.37
9 pm	3682	3000	-682		858	2209.63	4784.18
10 pm	3682	3000	-682		858	1351.44	3926.00
11 pm	3682	3000	-682		858	493.26	3067.81
12 am	3682	3000	-682		858	-364.93	2209.63
1 am	2832	3000	168	133.51		-231.42	2343.14
2 am	2832	3000	168	133.51		-97.91	2476.65
3 am	1982	3000	1018	809.00		711.10	3285.65
4 am	1982	3000	1018	809.00		1520.10	4094.66
5 am	1982	3000	1018	809.00		2329.10	4903.66

Table – IV: Cascade Table for 4th Iteration

Time	Demand (RTH) Lt	Chiller generation (RTH) CHt	Net energy demand (RTH) Nt	Charging (RTH) Ct	Discharging (RTH) Dt	Cumulative energy in ES (RTH) Et	New Cumulative energy in ES (RTH)
						0.00	2968.38
6 am	3682	2895.68	-786.32		989	-989.46	1978.92
7 am	3682	2895.68	-786.32		989	-1978.92	989.46
8 am	3682	2895.68	-786.32		989	-2968.38	0.00
9 am	1700	2895.68	1195.68	950.20		-2018.17	950.20
10 am	2550	2895.68	345.68	274.71		-1743.46	1224.91
11 am	2550	2895.68	345.68	274.71		-1468.75	1499.62
12 am	2550	2895.68	345.68	274.71		-1194.04	1774.33
1 am	2550	2895.68	345.68	274.71		-919.33	2049.04
2 am	2550	2895.68	345.68	274.71		-644.62	2323.75
3 am	2550	2895.68	345.68	274.71		-369.91	2598.46
4 am	2550	2895.68	345.68	274.71		-95.20	2873.17
5 pm	2550	2895.68	345.68	274.71		179.51	3147.88
6 pm	2550	2895.68	345.68	274.71		454.22	3422.59
7 pm	2550	2895.68	345.68	274.71		728.93	3697.30
8 pm	1700	2895.68	1195.68	950.20		1679.13	4647.51
9 pm	3682	2895.68	-786.32		989	689.67	3658.05
10 pm	3682	2895.68	-786.32		989	-299.79	2668.59

11 pm	3682	2895.68	-786.32		989	-1289.25	1679.13
12 pm	3682	2895.68	-786.32		989	-2278.70	689.67
1 pm	2832	2895.68	63.68	50.60		-2228.10	740.28
2 pm	2832	2895.68	63.68	50.60		-2177.50	790.88
3 pm	1982	2895.68	913.68	726.10		-1451.40	1516.98
4 pm	1982	2895.68	913.68	726.10		-725.30	2243.08
5 am	1982	2895.68	913.68	726.10		0.80	2969.18

To ensure that the ice tank can fulfil the cooling load demand effectively, the chilled water in the ice tank must be fully discharged for every discharge period. It can be seen that the second discharge value (boxed number) in Column 8 from Table 5is not zero, thus some steps needed to be taken to get the value to zero. The amount of the generation that needs to be reduced without considering the chiller efficiency, and ice tank charging and discharging efficiency, is calculated via (8) with Z = 57.47, while the amount of generation that needs to be reduced with the consideration of chiller efficiency, and ice tank charging and discharging efficiency, is calculated
via (9). The values for FD and F1 are as indicated in Table – IV with A are equal to 72.32.

The new chiller generation which considers the reduced amount of the thermal energy storage content is calculated via (10), B and is found to be 2823.32. The new chiller generation is substituted in column 3 (boxed number) for the number of hours of the charging period, Y before the second discharging process. The new cascade table is as shown in Table IV. The purpose of zeroing the second discharge value is to ensure the fully charged ice capacity is discharged to zero (0) to avoid the ice from unmelt and affecting the ice tank volume ratio (portion of solid ice and chilled water).

An adjustment to the final charging phase and the initial charging phase is made to ensure the feasibility of the system. The adjustment value without consideration of charging and discharging efficiency, and chillers efficiency is calculated via (11), with C equal to 689.18 while the amount of adjustment with consideration of the chillers efficiency, and ice tank charging and discharging efficiency, is calculated via (12). The values for FD and F1 are as in Table –I and D value is 867.23.

Table – V: Cascade Table after Zeroing Second Discharge Value

Time	Demand (RTH) Lt	Chiller generation (RTH) CHt	Net energy demand (RTH) Nt	Charging (RTH) Ct	Discharging (RTH) Dt	Cumulative energy in ES (RTH) Et	New Cumulative energy in ES (RTH)
						0.00	2968.69
6 am	3682	2895.68	-786.32		989	-989.46	1979.24
7 am	3682	2895.68	-786.32		989	-1978.92	989.78
8 am	3682	2895.68	-786.32		989	-2968.38	0.32
9 am	1700	2823.32	1123.32	892.71		-2075.67	893.02
10 am	2550	2823.32	273.32	217.21		-1858.46	1110.23
11 am	2550	2823.32	273.32	217.21		-1641.25	1327.45
12 am	2550	2823.32	273.32	217.21		-1424.04	1544.66
1 am	2550	2823.32	273.32	217.21		-1206.83	1761.87
2 am	2550	2823.32	273.32	217.21		-989.62	1979.08
3 am	2550	2823.32	273.32	217.21		-772.41	2196.29
4 am	2550	2823.32	273.32	217.21		-555.20	2413.50
5 pm	2550	2823.32	273.32	217.21		-337.99	2630.71
6 pm	2550	2823.32	273.32	217.21		-120.78	2847.92
7 pm	2550	2823.32	273.32	217.21		96.43	3065.13
8 pm	1700	2823.32	1123.32	892.71		989.14	3957.83
9 pm	3682	2895.68	-786.32		989	-0.32	2968.38

10 pm	3682	2895.68	-786.32		989	-989.78	1978.92
11 pm	3682	2895.68	-786.32		989	-1979.24	989.46
12 pm	3682	2895.68	-786.32		989	-2968.69	0.00
1 pm	2832	2895.68	63.68	50.60		-2918.09	50.60
2 pm	2832	2895.68	63.68	50.60		-2867.49	101.21
3 pm	1982	2895.68	913.68	726.10		-2141.39	827.31
4 pm	1982	2895.68	913.68	726.10		-1415.29	1553.41
5 am	1982	2895.68	913.68	726.10		-689.19	2279.51

Table –VI : Cascade Table after Final Storage Value Adjustment

Time	Demand (RTH) Lt	Chiller generation (RTH) CHt	Net energy demand (RTH) Nt	Charging (RTH) Ct	Discharging (RTH) Dt	Cumulative energy in ES (RTH) Et	New Cumulative energy in ES (RTH)
						0.00	2968.69
6 am	3682	2895.68	-786.32		989	-989.46	1979.24
7 am	3682	2895.68	-786.32		989	-1978.92	989.78
8 am	3682	2895.68	-786.32		989	-2968.38	0.32
9 am	1700	2823.32	1123.32	892.71		-2075.67	893.02
10 am	2550	2823.32	273.32	217.21		-1858.46	1110.23
11 am	2550	2823.32	273.32	217.21		-1641.25	1327.45
12 am	2550	2823.32	273.32	217.21		-1424.04	1544.66
1 am	2550	2823.32	273.32	217.21		-1206.83	1761.87
2 am	2550	2823.32	273.32	217.21		-989.62	1979.08
3 am	2550	2823.32	273.32	217.21		-772.41	2196.29
4 am	2550	2823.32	273.32	217.21		-555.20	2413.50
5 pm	2550	2823.32	273.32	217.21		-337.99	2630.71
6 pm	2550	2823.32	273.32	217.21		-120.78	2847.92
7 pm	2550	2823.32	273.32	217.21		96.43	3065.13
8 pm	1700	2823.32	1123.32	892.71		989.14	3957.83
9 pm	3682	2895.68	-786.32		989	-0.32	2968.38
10 pm	3682	2895.68	-786.32		989	-989.78	1978.92
11 pm	3682	2895.68	-786.32		989	-1979.24	989.46
12 pm	3682	2895.68	-786.32		989	-2968.69	0.00
1 pm	2832	3069.09	237.09	188.42		-2780.28	188.42
2 pm	2832	3069.09	237.09	188.42		-2591.86	376.83
3 pm	1982	3069.09	1087.09	863.91		-1727.95	1240.74
4 pm	1982	3069.09	1087.09	863.91		-864.04	2104.65
5 am	1982	3069.09	1087.09	863.91		-0.13	2968.56

The amount of chiller generation to be added to the current chiller generation capacity, F is calculated using (13) with the value equal to 173.45, while chiller generation is calculated using(14) and it was found to be 3069.09 RTH. The new chiller generation is substituted in column 3 (boxed number) for the number of hours of charging after the second discharge, ***E***. The new cascade table is as shown in Table – V.

The ice tank capacity is calculated via (15), hence ice tank capacity is equal to 9894.59 RTH. As discussed in the methodology, the highest obtained value in column 8 is the value of solid ice capacity. Considering the ice tank volume in real situation, the ratio of solid ice and chilled water is 40:60. Therefore, in this case study, it is considered that the largest value in column 8 represents 40% of solid ice from the total of the ice tank size. Thus, another 60% of chilled water shall be added to get the total volume or overall capacity of the ice tank. The largest value in column 6 is taken as the ice tank rating where its value is 989RT. The discharging value is calculated via (16), hence discharging value of ice is equal to 82 RTH.

The optimal design parameter for the district cooling system is then obtained from the final cascade analysis table and shown in Table – VI .

Table – VII : Result of DCP optimal design and sizing using COSCA technique

Descriptions	Units	Result
Chiller capacity	RT	3,069
	kJ/s	10,793
Ice tank rating	RT	989
	kJ/s	3,478
Ice tank capacity	RTH	9,894
	MJ	125,258
Hourly ice discharging value	RTH	82
	MJ	1,038
Initial content of ice tank	RTH	2,969
	MJ	37,588

The COSCA method can be extended to determine the optimal value of chiller capacity, ITS rating, ITS capacity and initial content of ice tank with the factor of chiller efficiency and ice tank efficiency charging and discharging as well as DoD of the ice tank, to ensure the value of 2nd discharge is zero (0).The recommendation to ensure the 2ndDischarge be zero (0)is to ensure the water capacity of the chilled water (ratio of 60% chilled water and 40% solid ice) in the thermal storage is enough to meet the demand. Referring to Fig. 3, total of chiller capacity on site is 6873RT and ice tank 24000RTH. Total calculation of the load profile shown in Fig. 6, using COSCA technique can reduce the desired 55% chiller capacity which is 3069RT where the capital expenditure cost is reduced to RM7.6 million and 59% for Ice Tank which is 9894RTH which reduced cost to RM4.8 million. However, the shown saving results are not considered as extra equipment needed for standby unit in the DCS if there experience any breakdown of the duty equipment during the operation.

V. CONCLUSION

This paper presents a major contribution in the field of designing a district cooling system with thermal energy storage system. The new framework called COSCA is useful to design chiller generation capacity, ice tank rating, and ice tank storage size to meet hourly cooling load demand. With this framework, the proposed future plan is to use the storage usage sequencing design parameter to conduct an analysis of electricity tariffs. The storage usage sequencing introduced in the methodology enables the user to take advantage of the lower electricity tariff during the off-peak period at nightwhich is RM0.219/kWh, instead of peak period during day time RM0.355/kWh [16]. The optimal design system is maximised for storage charging during the night and discharged during the day resulting in a huge electricity purchase cost saving. This is beneficial for developers, electrical and power engineers, energy managers and decision makers, in planning to develop DCP systems. COSCA allows its user to have anenhanced understanding of the design and sizing of the system due to the simplicity of the technique. Furthermore, with predictable sizing, users are able to perform a simple cost benefit analysis for DCP systems at thepreliminary design. However, the COSCA technique also has its limitations. This technique assumes that the design ofthe electrical compression driven chiller is integrated with ice thermal storage (ITS) tanks only, without consideringother sources. It is applicable if the system consists of ITS, FES and centrifugal chillers. Therefore, presently, COSCA is not applicable for designing systems with other energy sources such as a combination of an absorption chiller system using heat energy source.

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