Analysis the Energy Saving of Chiller Plant (CHIP) Daily Operation by Using Optimal Projected Capacity of Ice Thermal Energy Storage (ITES)

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Abstract. High total cooling load (COLA) relatively during peak and mid-peak as compared to off-peak hour’s period requires more operating equipment of chiller plant (CHIP) to be operated during that period. The more operating equipment working, the more energy consumed is required to provide cooling thermal for COLA. High energy consumption of CHIP operation during peak and mid-peak hour lead higher energy cost due to higher energy charge charged by utility for every per kWh energy consumed by a CHIP operation. Therefore, this study aims to determine potential energy saving of CHIP operation by using optimal charging of ice thermal energy storage (ITES), then provide cooling thermal (COMA) for total COLA through discharging operation. Cooling thermal of ITES was charged based on maximum required COLA during peak and mid-peak hour. In this study, an optimization technique of linear programming was used to charge ITES optimally during off-peak hour. Analysis was conducted to compare the energy consumption of CHIP operation by using ITES discharging operation with the current practice of CHIP operation. This analysis showed that, the potential energy saving based on this strategy by using optimization technique is 27.89%.

Keywords. Cooling Load, Peak hour, Mid-peak hour, Off-peak hour and Cooling Thermal
1. Introduction

The required cooling load (COLA) during peak and mid-peak hour is relatively high as compared to off-peak hour. Therefore, the more operating equipment of a chiller plant (CHIP) with higher cooling capacity (COPA) are required to provide sufficient cooling thermal (COMA) for COLA. The regular loading and scheduling the operating equipment of CHIP in Malaysia Nuclear Agency have suggested that the two (2) out of three (3) set chiller operating equipment are used to charge ITES tank capacity during off-peak hour. While the required cooling thermal for COLA during peak and mid-peak hour is provided also by two (2) out of three (3) set chiller operating equipment with ITES discharging operation. More or less, loading and scheduling of CHIP operation during peak and mid-peak hour supported by ITES discharging operation could benefit demand side on energy saving of daily CHIP operation. This because of reducing number the set chiller operating equipment working during peak and mid-peak hour. Less number the set chiller operating equipment working lead the less cooling capacity is used to provide cooling thermal (COMA) for cooling load (COLA). Then, the less required energy consumption of CHIP operation during peak and mid-peak hour. Therefore electricity cost of daily CHIP operating getting lower as well. This because lower energy consumption was charged by utility even at high energy charge. This study focus to compare energy consumption and electricity cost based on two (2) conditional cases. These cases are to investigate energy consumption based loading and scheduling of daily CHIP operation through:

1. Charging ITES at actual tank capacity and without using optimization technique.
2. Charging ITES optimally at projected tank capacity equal to the total required cooling load during peak and mid-peak hour.

Optimization technique used for this study is linear programming. This technique could determine optimal operating period each of set chiller operating equipment for ITES charging operation. Other previous study, various effort were implemented by using thermal energy storage to provide cooling thermal (COMA) for cooling load (COLA) technically and economically feasible with tariff scheme. Since the thermal energy storage (TES) systems are mainly intended to enhance the performance of the cooling in terms of storing and releasing heat energy on short-term and seasonal basis, depending on the thermal load requirements experienced in buildings [1]. Therefore, this could improve the working condition of the Distric Cooling System and chillers through shifting more energy consumption of chiller operation for thermal energy storage charging operation during off-peak hours [2]. Potential of using TES in minimizing energy consumption and electricity cost attracted other scholars to study potential strategy could be applied for TES and implement to various application [3]. High temperature of tropical climate country and summer season lead intensive use of cooling system. Employing TES to provide cooling thermal for COLA resulting significant energy saving. A case study in University Teknologi Malaysia, Johor reported that the potential cost saving about 68.5 % saving per year [4]. This potential saving because of TES charging operation could be managed during lower off-peak tariff even vary significantly from a location to other location [5]. Other than that, significant cost saving of chiller plant (CHIP) operation when the charged TES is scheduled their TES discharging operation during peak hour. The set operating operating for TES discharging operation only storage latent heat pump (SLTP).

Enhanced time of use (EToU) tariff scheme may benefit consumers when energy consumption could be shifted from peak to mid-peak or off-peak hours [6]. Therefore, by using TES high energy consumption during peak hour could be potentially shifted to off-peak hour through TES charging operation during off-peak hour and discharging operation during peak and mid-peak hour for demand side economic benefit. Then the consumers could experience more flexibility to rearrange their own energy consumption profile, so that the demand side will experience significant reduction of electricity cost in the future when taking opportunity to employ EToU tariff scheme for load shifting especially on loading and scheduling of chiller plant (CHIP) using TES [7].
2. Research Methodology

Since lower energy charge during off-peak hour as compared to peak and mid-peak hour, minimizing energy consumption during peak and mid-peak hour lead reducing electricity cost of chiller plant (CHIP) operation. Therefore, this study analyze potential energy saving of chiller plant (CHIP) operation using ice thermal energy storage (ITES) that is charge during off-peak hour, then provides cooling thermal (COMA) for total cooling load (COLA) during peak and mid-peak hour. Electricity cost could be reduced because minimal energy is consumed during peak and mid-peak hour through ITES discharging operation to provide COMA for COLA. Only storage latent heat pump (SLTP) and distribution pump (DP) are used during this operation. As to meet total COLA during peak and mid-peak hour, ITES would be charged during off-peak hour optimally by using optimization technique of linear programming. In determine energy saving when employ ITES in CHIP operation, the steps should be followed are as detail.

2.1. Determine the required cooling thermal (COMA) during daytime period.

![Cooling Load Profile of Daytime Period](image)

Figure 1: Cooling Load Profile of Daytime Period

The required cooling thermal (COMA) could be find from calculation area under graph of cooling load profile based on Figure 1. This figure is generated by using MATLAB. Trapezoidal rule is used to calculate the area under graph. This rule evaluates area under a curve by splitting the total area into small trapezoids rather than rectangles [10]. Calculation from MATLAB showed that the required cooling thermal (COMA) is 9960.50RTh.

2.2. Determine energy consumption of chiller plant (CHIP) operation without using ITES-optimization technique. Power consumption the operating equipment of CHIP operation and their operating period for this conditional cases as shown in Table 1.
Table 1: Power Consumption and Operating Period of CHIP’s Operating Equipment [8]

| No. | Operating Equipment       | Operating Period (Hour) | Power Consumption (kW) |
|-----|---------------------------|-------------------------|------------------------|
|     |                           | Day | Night | Day | Night |
| 1   | Chiller 1                 | 0   | 8     | 225.2 | 225.2 |
| 2   | Chiller 2                 | 10  | 8     | 219.2 | 218.2 |
| 3   | Chiller 3                 | 10  | 0     | 179.4 | 179.4 |
| 4   | Chilled Water Pump (CHWP) | 10  | 8     | 45.1  | 70.9  |
| 5   | Storage of Latent Heat Pump (STLP) | 10  | 0     | 16.1  | 16.1  |
| 6   | Distribution Pump (DP)    | 10  | 0     | 63.3  | 63.3  |
| 7   | Condensed Water Pump (CWP) | 10  | 8     | 36    | 31.2  |
| 8   | Cooling Tower Fan (CTF)   | 10  | 8     | 26.7  | 29.5  |

2.3. Characterize the Optimal ITES Charging

2.3.1. Tabulate data from minimum to maximum possible of cooling thermal (COMA) to be charge into ITES tank. COMA is independent variable for experimental process using optimization algorithm to determine optimal energy consumption of CHIP operation.

2.3.2. Organize the rated value of cooling capacity (COPA) and power consumption each of operating equipment sets that would be used to charge ITES tank capacity as stated in Table 1. Operating equipment consists of chiller chiller, chilled water pump (CHWP), condenser water pump (CWP) and cooling tower fan (CTF).

Table 2. Rated Value of Cooling Efficiency Parameter [8], [9]

| No | Equipment Group          | Cooling Capacity, RT (Ton) | Power Consumption, P (kW) |
|----|--------------------------|----------------------------|---------------------------|
|    |                          | Chiller | CHWP | CWP | CTF |
| 1  | Operating Equipment 1    | 374     | 225.2 | 23.63 | 10.40 | 9.83 |
| 2  | Operating Equipment 2    | 374     | 218.2 | 23.63 | 10.40 | 9.83 |
| 3  | Operating Equipment 3    | 340     | 179.4 | 23.63 | 10.40 | 9.83 |

By using all these data in Table 1, this could be synthesized to determine collective cooling efficiency each of operating equipment 1, 2 and 3. This efficiency is shown in Table 2.

Table 3. Collective Cooling Efficiency of Chiller Plant’s Operating Equipment

| No | Equipment Group          | Cooling Efficiency, $\eta$ (kW per Ton) |
|----|--------------------------|----------------------------------------|
| 1  | Operating Equipment 1    | 0.7194                                 |
| 2  | Operating Equipment 2    | 0.7007                                 |
| 3  | Operating Equipment 3    | 0.6567                                 |

This cooling efficiency represents full load condition each of operating equipment. This would be used as a constant in optimization algorithm to determine energy consumption the loading and scheduling of chiller plant (CHIP) for ITES charging operation during off-peak period.
2.3.3. Finding the optimal energy consumption of chiller plant (CHIP) operation based on required cooling thermal (RTh) to charge into ITES tank during off-peak hour by using optimization technique, linear programming in MATLAB as shown in Figure 2. Their mathematically expression to develop algorithm for optimal ITES charging as the follows:

Objective function;

\[ \min E(t) = \min \sum_{i=3}^{n} RT_i \eta_i t \]

Subject to equality constraint;

\[ \sum_{i=3}^{n} RT_i t = RTh_i \]

With lower and upper bound constraint;

\[ 0 \leq t \leq 8 \]

Where;

- \( E \) (kWh): Energy Consumption of Chiller Plant (CHIP) operation
- \( RT(T) \): Cooling Capacity each of Chiller
- \( RTh_i \): Cooling thermal capacity of ITES tank
- \( \eta_i \): Cooling Efficiency of Operating Equipment
- \( t \): Operating period each of Operating Equipment

In this algorithm, operating period of operating equipment, \( t \) is variable. Linear programming will find and determine the optimal operating period within the lower and upper bound constraint as to minimize energy consumption of the ITES charging operation as well.
Minimize Energy Consumption, E(kWh) of CHIP Operation for ITES charging during off-peak hour: Constant Partial Load Ratio (PLR), Variable period, T(h)

Objective Function to minimize energy consumption of chiller loading and scheduling for collective hours period during off-peak hours

Constant PLR at minimum kW per Ton for all chillers in CHIP operation

Set operating period of CHIP’s operating equipment as variable

Determine optimal operating period each of CHIP’s operating equipment

Operate each of operating equipment of CHIP based on optimal operating period to charge ITES optimally

Figure 2: Optimization Algorithm for ITES Charging

This optimization algorithm is applied for each of tabulated cooling thermal (COMA) data in order to determine optimal energy consumption CHIP for ITES charging operation.

2.3.4. Plotting the graph and linear regression analysis to determine coefficient and intercept of relationship between these two (2) variables, energy consumption and cooling thermal. This would be used to determine the optimal function the energy consumption of chiller plant for charging operation.

2.4. Determine the optimal energy consumption for the optimal projected capacity of ITES by using optimal function consumption of chiller plant for ITES charging operation. In this study, the optimal projected capacity of ITES tank is equal to the required cooling thermal (COMA) during daytime. This because that COMA is benchmarking for upgrading the ITES tank capacity.
3. Result & Analysis

Result of energy consumption of chiller plant (CHIP) operation by using ITES-optimization technique and without using ITES-optimization technique are compared to ensure effectiveness the optimal projected ITES capacity for daily CHIP operation.

3.1. Energy Consumption of Chiller Plant Operation without ITES-Optimization Technique

Total energy consumption of CHIP operation without using ITES-optimization technique is 10,458 kWh as shown in Table 4. This derived from energy consumption for each of operating equipment in CHIP operation during nighttime and daytime period.

Table 4: Energy Consumption of Chiller Plant Operation without ITES-Optimization Technique

| No. | Operating Equipment               | Energy Consumption (kWh) Day | Energy Consumption (kWh) Night | Total Energy Consumption (kWh) |
|-----|----------------------------------|------------------------------|-------------------------------|-------------------------------|
| 1   | Chiller 1                         | 0                            | 1801.6                        | 1801.6                        |
| 2   | Chiller 2                         | 2192                         | 1745.6                        | 3937.6                        |
| 3   | Chiller 3                         | 1794                         | 0                             | 1794                          |
| 4   | Chilled Water Pump (CHWP)         | 451                          | 567.2                         | 1018.2                        |
| 5   | Storage of Latent Heat Pump (STLP)| 161                          | 0                             | 161                           |
| 6   | Distribution Pump (DP)            | 633                          | 0                             | 633                           |
| 7   | Condensed Water Pump (CWP)        | 360                          | 249.6                         | 609.6                         |
| 8   | Cooling Tower Fan (CTF)           | 267                          | 236                           | 503                           |
|     | **Total Energy Consumption (kWh)**| 5858                         | 4600                          | 10458                         |
3.2. Optimal Energy Consumption of Chiller Plant

While Table 5 shows optimal energy consumption of chiller plant (CHIP) operation for ITES charging using optimization technique for each of ITES tank cooling thermal capacity, RTh. This data would be used to determine optimal function the energy consumption of Chiller Plant.

Table 5: Optimal Energy Consumption of Chiller Plant for Each of Cooling Thermal Capacity

| Cooling thermal capacity, RTh | Operating Period, t (h) | Optimal Energy Consumption, kWh |
|------------------------------|-------------------------|---------------------------------|
|                              | Operating Equipment 1    | Operating Equipment 2    | Operating Equipment 3    |
| 0                            | 0.0000                  | 0.0000                  | 0.0000                  |
| 340                          | 0.0000                  | 0.0000                  | 1.0000                  | 223.28 |
| 500                          | 0.0000                  | 0.4278                  | 1.0000                  | 335.39 |
| 1000                         | 0.0000                  | 0.8556                  | 2.0000                  | 670.78 |
| 1500                         | 0.0000                  | 0.3743                  | 4.0000                  | 991.21 |
| 2000                         | 0.0000                  | 0.8021                  | 5.0000                  | 1326.60 |
| 2500                         | 0.0000                  | 0.3209                  | 7.0000                  | 1647.00 |
| 3000                         | 0.0000                  | 0.7487                  | 8.0000                  | 1982.40 |
| 3500                         | 0.0000                  | 2.0856                  | 8.0000                  | 2332.80 |
| 4000                         | 0.0000                  | 3.4225                  | 8.0000                  | 2683.10 |
| 4500                         | 0.0000                  | 4.7594                  | 8.0000                  | 3033.50 |
| 5000                         | 0.0000                  | 6.0963                  | 8.0000                  | 3383.80 |
| 5500                         | 0.0000                  | 7.4332                  | 8.0000                  | 3734.20 |
| 6000                         | 0.7701                  | 8.0000                  | 8.0000                  | 4089.90 |

3.3. Optimal Function the Energy Consumption of Chiller Plant

![Figure 3: Optimal Function the Energy Consumption of Chiller Plant for ITES Charging Operation](image-url)
This optimal function of energy consumption chiller plant is just for ITES charging operation during nighttime. This is not representing all energy consumption for daily chiller plant (CHIP) operation during both daytime and nighttime. For daytime CHIP operation, ITES discharging operation also acquire storage of latent heat pump (SLTP) and distribution pump (DP). Power consumption for both pumps are 16.1kW and 63.3kW respective. This pumps have operated all daytime, \( t_{\text{day}} \) along for 10 hours.

Therefore, **optimal function the energy consumption of chiller plant (CHIP) daily operation** could be determined as follows:

\[
y = 0.6795x - 21.386 + (P_{\text{SLTP}} + P_{\text{DP}})t_{\text{day}}
\]

where;

\( y: \text{Optimal energy Consumption of daily chiller plant operation (kWh)} \)
\( x: \text{Variable of cooling thermal } R\text{Th} \)
\( P_{\text{SLTP}}: \text{Power consumption of Storage Latent Heat Pump (SLTP)} \)
\( P_{\text{DP}}: \text{Power Consumption of Distribution Pump (DP)} \)
\( t_{\text{day}}: \text{Period for daytime chiller plant operation on daily basis} \)

Since;
\[
\begin{align*}
P_{\text{SLTP}} & : 16.1kW \\
P_{\text{DP}} & : 63.3kW \\
t_{\text{day}} & : 10 \text{ hours}
\end{align*}
\]

**Daytime required cooling thermal (C0MA):** 9960.50\text{RTh}

Therefore, by using the optimal function, the energy consumption of chiller plant (CHIP) operation for ITES discharging operation is;

\[
E_{\text{disch}} = 7540.77\text{kWh}
\]

Then, this finding could be further compare with energy consumption of chiller plant (CHIP) operation without using ITES-Optimization technique.

### 3.4. Comparative Analysis Chiller Plant (CHIP) Daily Operation

Table 6 shows that energy consumption of chiller plant (CHIP) daily operation based on two (2) conditional cases of using ITES-optimization technique and without using ITES optimization technique.

| Performance Output                              | Result          |
|------------------------------------------------|-----------------|
| Energy Consumption without using ITES-Optimization Technique (kWh) | 10,458.00 kWh   |
| Potential Energy Consumption ITES-Optimization Technique          | 7,540.77 kWh    |
| Potential Saving on Energy Consumption (kWh)                      | 2917.23 kWh     |
| Percentage of Potential Saving on Energy Consumption (%)          | 27.89%          |
This results shows that significant potential energy saving when chiller plant (CHIP) operation using ITES-optimization technique. Lower potential energy consumption is required as compared to CHIP operation without using ITES optimization technique. This because by using optimization technique, minimal operating period was found for loading and scheduling the CHIP’s operating equipment to charge ITES optimally.

4. Conclusion & Future Work

Providing from the previous study, employing ice thermal energy storage (ITES) could minimize energy consumption of chiller plant (CHIP) daily operation. This opportunity could offer more potential energy saving by using optimization technique of linear programming to optimize the operating period the operating equipment of chiller plant (CHIP) to charge ITES tank at required daytime cooling thermal (COMA). This study on ITES-optimization technique for chiller plant (CHIP) could potentially be extended further for looking of how save electricity cost of chiller plant (CHIP) operation when engage with a tariff scheme such as time of use (ToU) and enhanced time of use (EToU) tariff scheme.

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