ECONOMIC ANALYSIS OF THERMAL ENERGY STORAGE IN AN EDUCATIONAL BUILDING BASED ON BUILDING LOAD PROFILE

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ABSTRACT

Thermal energy storage (TES) system is recognized as one of the possible solution to reduce the building cooling cost by shifting the cooling load to the off peak hours. In Malaysia, the utilization of the TES technology is still immature due to the high system capital cost and lack of experience. However, the encouragement from the utility company has untapped the potential of the TES by offering attractive tariff package to the customers. In 1 January 2014, [1] introduced a new tariff package for TES consumers. In this paper, a mathematical model is constructed to simulate the potential cooling cost saving performance by the system. This study intends to provide reliable and low-cost evaluation on the implementation of ice-based thermal energy storage system in educational building of School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia (USM). The TES operation is simulated according to the building load profile, ambient temperature of the investigated building, tariff package and peak/off peak periods. The cooling cost saving performance of the designed TES system is studied under different operating strategies and storage media. Among the alternatives, water storage media under partial load operating strategy shows the best cooling cost saving performance of over RM40,000 annually with the payback period of eight years. In conclusion, under the latest tariff package offered by TNB, an attractive return is expected from the investment on the ice-based TES system in the investigated building.

Keywords: Building load profile, cooling, economic analysis, and thermal energy storage.

INTRODUCTION

The tropical climate of Malaysia is warm and humid with the average day time temperature of 35 °C throughout the year. Since it is like summer all year round, there is a high cooling demand for the buildings. Cooling of buildings in Malaysia is a major contributor to the peak electrical load. It is estimated that building cooling contributes up to 45 percent of the total electrical demand [2]. One possible solution to the problems of reducing building cooling cost and energy demand savings is the installation of ice-based Thermal Energy Storage (TES) for space cooling. By implementing TES system, the energy demand is shifted from peak hour to off peak hour. As shown in Figure 1, the ice is generated by a chiller during the off peak hours, particular at night, and stored to provide cooling during the day time. The systems allow electrical driven and power-hungry cooling equipment to be operated at off peak hours when the utility rates are lower. In addition, nighttime chiller operation has higher efficiency due to lower ambient temperature. Thus, less energy is required to reject the heat from the system. Furthermore, TES system allows chiller downsizing which reduce the capital cost significantly in the initial construction stage. However, a number of issues have hindered the commercialization of thermal energy storage device in Malaysia. Firstly, an effective TES cooling system required a well-organized operating strategy to obtain the best possible cost saving. This issue is enhanced by the high capital costs typically associated with energy storage technologies and the lack of experience for many participants involved including investors, transmissions system operators (TSOs), and market designers [3].

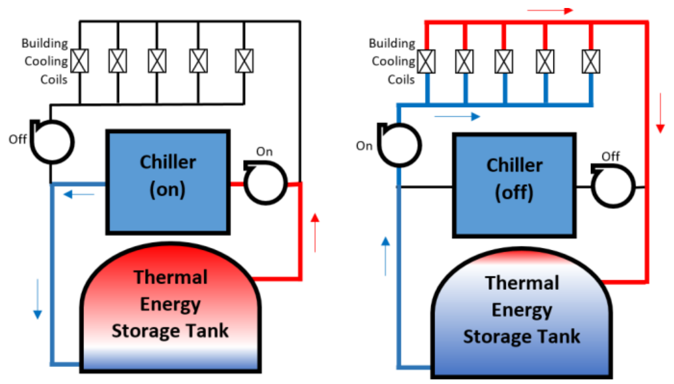

Figure 1 Off peak cooling mode (left) and peak rate cooling mode (right)

In 2006, [4] studied the performance of the TES system implemented in Kompleks Sains & Teknologi, Universiti Teknologi MARA, 2002. The objective of this paper was investigating the actual operating condition of a centralized air-conditioning plant integrated with ice thermal energy storage. The actual operation conditions and building load profile were observed and simulations were carried out to measure its energy consumption. The plant utilized partial load operating strategies which shown in Figure 5. In the research, Integrated Part-Load Value (IPLV) was calculated to estimate the average chiller efficiency. IPLV may be good for comparison among different individual equipment part-load performance under consistent test conditions but would not be a good yardstick for evaluating energy consumption or operating, and could be misleading if it is being specified in energy standard [5]. Moreover, the imposed energy demand charge on the consumers was neglected in the research that might lead to the misleading result. In actual operating condition, the system was able to store 6,000 RTh in the ice charging process. Study showed that by running the chiller at optimum hours and higher efficiency, 10800 RTh can be stored. In 2011, University Tun Huseein Onn Malaysia (UTHM), [6] conducted an economical analysis to investigate the possible energy saving by the implementation of TES system. This paper presented the return of initial investment by implementing a centralized air-conditioning plant integrated with thermal energy storage with partially operation strategies. Building load profile was constructed hourly according to building specification and building usage trend. TES operation conditions were designed according to building load demand profile, storage capacity, tariff packages and peak/off peak period. The Payback Period analysis method was used to evaluate economic analysis.

In this study, the economic analysis was performed to investigate and estimate the cost saving performance offered by TES. The system analysed was water cooled packaged units (WCPU) air-conditioning system. The building load profile was constructed and a mathematical model of the TES system was developed to assist in the calculation of the saving performance. The study was limited to two types of most common materials which were water and brine. In addition, the effect of ambient temperature on the saving performance of TES system was considered.

METHODOLOGY

Cooling load is the main factor in outlining the design of a cooling system. The fact is that the air-conditioning process is meant to meet the demand of the cooling requirement, which varies from time to time in a particular day. A chart that represents the cooling requirement in a day is called building load profile. In this study, the building load of the educational building of School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia (USM) is investigated.

The developed model (in Microsoft Excel) included the sizing of cooling storage capacity, efficiency of the cooling system due to ambient temperature, and dynamic electrical utility rate to simulate the system at the best possible accuracy. Next, the effect of manipulated variables (operating strategies and the selection of PCM) on the controlled variables (cost saving performance of the system) is studied. The chosen process variables are varied and controlled to observe the relationship of the variables to the overall performance of the system. Sensitivity analysis is introduced to study the relationship between the input and output variables. The sensitivity study is run independently of the base-case simulation. After obtaining the result, plot the results to easily visualize the relationships between the input and output variables. Possible optimization is conducted to improve the accuracy of the simulation and performance of the system. Lastly, obtained results are analysed to perform economic analysis. Evaluation is performed to identify the best possible use of TES.

WCPU cooling system used in these educational building is expendable to integrate with TES system. In existing air conditioning system, 26°C of return water is first supplied to seventeen units of WCPU via water circuit. Inside the WCPU system, return water is further cooled to provide cool air to the air distribution system. The 31°C of warm water is then leaving the WCPU system heading to the cooling towers. The cooling towers discharge the heat and cool the water to 26°C. Three units of condenser water pumps distribute the return water to the WCPU in each floor. Table 1 shows the details of the building.

Table 1 Educational Building Description

Floor Area	11200m^2
Configuration	4 Storey
Maximum Occupancy	650
Lighting/Equipment	32W/m^2 of floor area
Glazing	Single Pane 10% of the exterior wall
Roof	U= 0.522 W/m^2°C
Wall	U=2.43 W/m^2°C
Equipment	Water Cooled Packaged Unit System
System Operation	8:00hour to 17:00hour

To make a meaningful comparison, it is assumed that both the existing HVAC system and modelled TES system experience the same cooling load profile and daily temperature profile. Additionally, both systems are analysed under standard, one liquid vapour compression cycle and having identical isentropic compressor efficiency. The only different is that the ice-chiller has lower evaporator temperature compared to existing HVAC system. Moreover, it is assumed that there is no energy loss in the heat transfer process between the working fluid and the storage media. In addition, the storage capacity is sized restricted to the 30m^2 storage tank due to the limited available space in the investigated building. Limited space available is the main concern in the integration of the TES to existing HVAC system in the investigated site. Therefore the sizing of storage capacity is based on the available space in the rooftop of the building. The building is able to accommodate a storage tank with the volume of 30m3 (W: H: L=5m: 1m: 6m).

RESULTS AND DISCUSSION

To design a TES system, the cooling load of the educational building was first calculated by using cooling load temperature difference and cooling load factor (CLTD/CLF) calculation methods. Safety margin of 20% was considered to obtain the actual building load profile. Then, the required tonnage of the ice cells and chiller was able to be estimated. The major sources of the heat gain were heat conduction through exterior surfaces of the building, solar radiation through glasses, lighting, human activities and the operation of equipment. A continuous increment of cooling load at 8am due to the rising educational and research activities, increasing occupancy rate and radiant heat from the sun. From 12pm to 2pm, the cooling load goes down as students and staffs left the building for lunch. After 2pm, the cooling load was recovering rapidly as most of the lab activities were scheduled in the evening. The doubled number of students and actively operated machines contribute more heat gain. Not surprisingly, the peak cooling load of 248 RT was recorded at 4pm as most exterior surfaces of the building were facing the setting sun, resulting in the growing cooling load. From 5pm to 8am in the morning, no cooling load was recorded as the occupancy rate was zero. There were no activities scheduled during those hours. In overall, the average cooling load was significantly less than the peak cooling load.

In the proposed design, an additional unit of chiller and storage tank was integrated with the existing WCPU. The storage tank separated the generation of chilled coolant from the water circuit. An extra piping looping with pumps, valves and controller was required to control the system. Basically, the proposed TES system was operated in 3 operating modes; ice building, pre-cooling with ice TES storage, and cooling without TES storage. In ice building mode, the chiller produces ice by circulating the refrigerant (R134a) through the storage tank. Generally, this mode will be launched in off peak hours, typically at night to enjoy cheaper utility rate and high chiller efficiency due to lower ambient temperature. While in pre-cooling with ice TES storage mode, the warm return water was circulated through the storage before entering the water cool packaged units system (WCPU). Heat transfer takes place when the stored ice in the tank absorbs the heat from the return water. By supplying the near to freezing point water to the WCPU, the cooling capacity required was reduced dramatically. This mode was activated during the peak hour where the electrical utility rate was higher and lower WCPU efficiency due to high ambient temperature. In cooling without TES storage, the return water would not be circulated through the ice thermal energy storage. 26°C of return water from the cooling tower was supplied to the WCPU. The cooling load of the building will be met by the WCPU alone.

Nighttime chiller operation takes advantage of lower ambient temperatures. Chiller has higher efficiency as it required less energy to reject heat in the cooler surrounding. Thus cooling cost reduction is expected by operating chiller at cooler ambient, particular at night. The efficiency of WCPU is decreasing steadily as the average ambient temperature of Malaysia is varying from 24°C to 34°C. At 24°C, 0.514kW of electrical power is required to provide 1RT of cooling capacity. While in 34°C, 0.767 kW/RT of system efficiency is expected. The WCPU is operated at the evaporator temperature of -1°C. Ice chiller is operated at the evaporator temperature as low as -24°C to provide sufficient cooling capacity for the phase change material (PCM) to solidify in to ice. Thus ice maker has lower efficiency comparing to the WCPU system. At 24°C, 1.025 kW of electrical power is required to produce a unit of cooling capacity. The more electrical power is consumed by the compressor as the ambient temperature is increasing. Lowest system efficiency of 1.135 kW/RT is achieved at 34°C.

Ice-based storage system was considered in the designed TES due to high density energy storage as limited space was available. Due to the limited building space in the investigated building, the size of the storage tank is limited to 30m^3. Table 2 shows the available storage capacity and required chiller capacity based on the selection of storage media.

Table 2 Physical Properties of Storage Media

Storage Media	Ice	Brine
Melting Point (°C)	0	-2
Heat of Fusion (kJ/kg)	333.6	334.9
Specific Heat (kJ/kg.k)	4.2	4.06
Density (kg/m3)	1000	973.7
Storage Capacity	1056RT	1032RT
Chiller Capacity	88RT	86RT

A well-organized operating strategy is the key to ensure high saving performance from the TES system. In this research, the outcome of the full load and partial load operating strategies are investigated to define the best system configuration. The system is simulated on two different storage media; water and brine.

Ice-based TES System (Water as PCM)

Full Load Operating Strategy

Figure 2 shows the hourly building cooling load profile utilizing water as phase change material and operated under full load strategy. From 1700 hour until 0800 hour, the cooling system is shut down as no occupancy rate during those hours. The ice chiller is then operated during the off peak hour (2100 hour to 0900 hour) as the electrical utility rate is offered at lower cost. Ice TES system charges the ice at the rate of 88RT per hour and the total refrigerant hour for a day is 1056 RTH. Under total load operating strategy, the stored ice is discharged from 1100 hour to 1600 hour where water cool packaged unit (WCPU) system has lowest efficiency. The rest of the cooling load is met by the WCPU system alone. The total cooling load required per day is 1970 RTh. With the total storage capacity of 1056, the 914 RTh of load has to be catered by WCPU system alone.

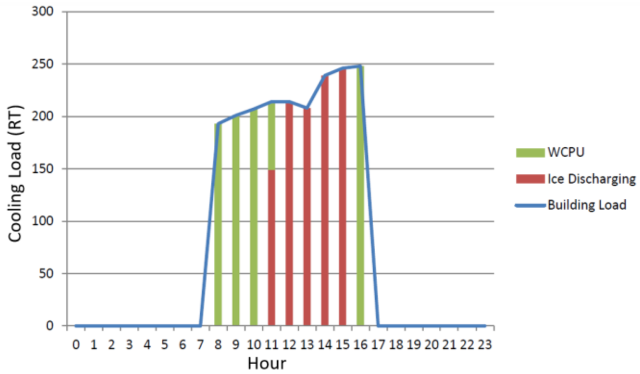

Figure 2 Full load operating strategy of water

Partial Load Operating Strategy

Figure 3 shows the hourly building cooling load profile utilizing water as phase change material and operated under partial load strategy. From 1700 hour until 0800 hour, the cooling system is shut down as no cooling load requirement. The ice chiller is operated during the off peak hour as the cheaper electrical utility rate is offered. Ice TES system charges the ice at the rate of 88 RT per hour and the total refrigerant hour for a day is 1056 RTH. Under partial load operating strategy, the stored ice is discharged at the rate of 117 RT per hour from 0800 hour to 1700 hour. In existing cooling system, 26°C of return water is supplied to the WCPU. By discharging the ice, the return water is cooled to nearly freezing point before entering the WCPU. Thus, less energy is consumed by the compressor of WCPU.

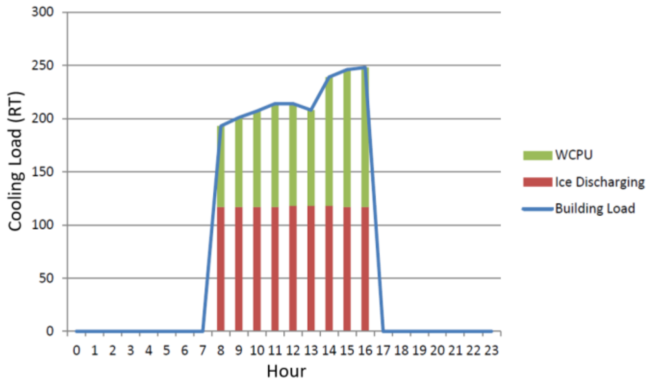

Figure 3 Partial total load strategy for water

Ice-based TES System (Brine as PCM)

Full Load Operating Strategy

Figure 4 shows the hourly building cooling load profile utilizing brine as phase change material and operated under total load strategy. From 1700 hour until 0800 hour, the cooling system is shut down as no cooling load requirement. The ice chiller is operated during the off peak hour (2100 hour to 0900 hour) as the cheaper electrical utility rate is offered. Ice TES system charges the ice at the rate of 86RT per hour and the total refrigerant hour of 1032 RTH is stored in the ice cell. Under full load operating strategy, the stored ice is discharged from 1100 hour to 1600 hour where WCPU has lowest efficiency. The total cooling load required per day is 1970 RTh. With the total storage capacity of 1032 RTh, the excess load has to be catered by WCPU alone.

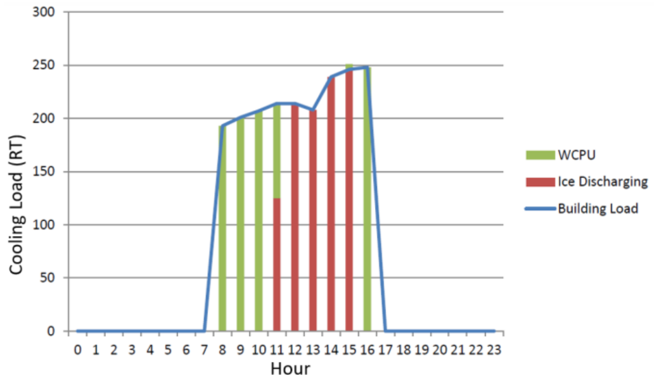

Figure 4 Full load operating strategy of brine

Partial Load Operating Strategy

Figure 5 shows the hourly building cooling load profile utilizing brine as phase change material and operated under partial load strategy. From 1700 hour until 0800 hour, the cooling system is shut down as no cooling load requirement. The ice chiller is operated during the off peak hour as the cheaper electrical utility rate is offered. Ice TES system charges the ice at the rate of 93RT per hour and the total refrigerant hour stored for a day is 930RTH. Under partial load operating strategy, TES system discharges the stored ice at the rate of 103RT per hour from 0800 hour to 1700 hour where higher utility rate is offered. In existing cooling system, 26°C of return water is supplied to the WCPU. By discharging the ice, the return water is cooled to nearly freezing point before entering the WCPU. Thus, less energy is consumed by the compressor of WCPU.

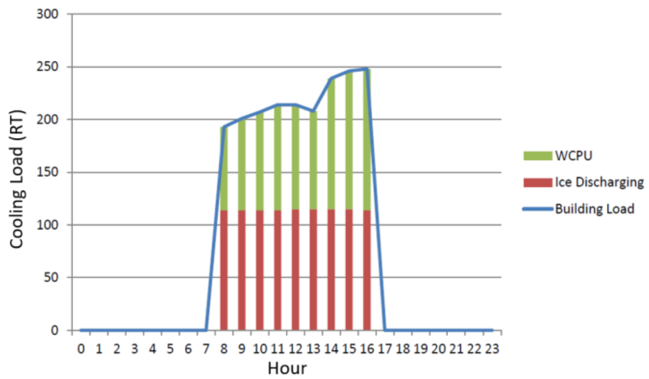

Figure 5 Partial load operating strategy for brine

Cost Saving Performance

Under the tariff package offered by TNB [1], the bill is charged in two criteria. Those are the electric consumption during the peak/off-peak period and the maximum demand (MD) per month during the peak hour. A 20% discount for consumption during the off-peak period for consumers. Table 3 shows the cost saving performance of the designed system. The cooling cost of the existing HVAC system is RM18839.65. By selecting water as storage media, the partial load operating strategy (RM3376.69) provides more saving potential compared to full load operating strategy (RM457.16). In the selection of brine as storage media, partial load operating strategy saves RM3209.20 while full load operating strategy saves RM844.70. This is because the partial load operating strategy reduces the cost due to the maximum demand during the peak period.

In short water storage media operating under partial load has the best cost saving performance. Annual energy savings are expected RM 40520.32 per year. Moreover, the return of investment period (ROI) of the system is 8.22 years which is economically feasible for the investment.

Table 3 Cost Saving Performance of TES System

	Existing System	Water		Brine	
Operating Strategy		Full Load	Partial Load	Full Load	Partial Load
Peak MD (kW)	132.06	169.7	89.64	169.7	91.69
Off Peak MD (kW)	N/A	93.17	93.17	91.06	91.06
Peak MD/Off Peak MD	N/A	1.82	0.96	1.86	1.01
Peak Rate (RM)	0.365	0.365	0.365	0.365	0.365
Off Peak Rate (RM)	N/A	0.1536	0.1536	0.1536	0.1536
RM/kW	30.3	45.1	45.1	45.1	45.1
Monthly Operation Cost (RM)	14838.23	10729.02	11420.19	10341.49	11495.23

Monthly MD Cost (RM)	4001.42	7653.47	4042.76	7653.47	4135.22
Monthly Cost (RM)	18839.65	18382.49	15462.96	17994.96	15630.45
Saving/month	N/A	457.16	3376.69	844.70	3209.20
ROI (Year)	N/A	60.74	8.22	32.26	8.49

CONCLUSION

This study investigated the potential saving performance by implementing the thermal energy storage system to the existing air conditioning plant of School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia (USM). The mathematical model of the system combined the effects of the ambient temperature on the efficiency of the chiller, effect of active thermal energy storage, and dynamic utility structure rate. In order to simulate the TES system, a mathematical model is constructed based on the building load profile, ambient temperature, tariff package, peak/off-peak periods as well as the cost functions.

The mathematical model shows reasonable cost savings with partial load operating strategy. The water TES system under partial load operating strategy is able to provide cooling cost saving over RM40000 annually and the capital cost will be paid in eight years. Saving out of full load operating strategy is not attractive and has high payback period. Under the latest TES tariff offered by TNB, partial load operating strategy is able to offer higher cooling cost saving by reducing the energy charge demand significantly.

REFERENCES

[1] TNB, “Electricity tariff schedule, Tariff Manual, 2014.

[2] Salim.S, & Rosli.M, (1999) “Electric Thermal Energy Storage – Mutual Benefit. Jurutera – Journal Institution of Engineers Malaysia.

[3] Connolly, D. (2010). A Review of Energy Storage Technologies For the integration of fluctuating renewable energy. University of Limerick, Version 4.

[4] Hazran, H., Najmi, W.M.W.A., & Suhairil, M., (2006) “Energy Consumption of TES at UiTM Based on Actual Building Load Profile”. *Universiti Teknologi MARA, Shah Alam.*

[5] Wu Wei-Dong. (2014). Cycle Analyses of Vapor Compression Refrigeration.

[6] Noranai, Z., Md Yusof, M.Z., & Salleh, H., (2011). Energy cost reduction by partially operation of thermal energy storage based on building load profile. *International Conference on Energy and Environment 2011.*