



# Cost-Effectiveness Opportunities for Thermal Energy Storage Systems: A Case Study of School Building in Saudi Arabia

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**Abstract:** Air conditioning in houses, office buildings and schools consume high portion of the generated electricity in Saudi Arabia. This paper presents a study of the economic opportunities afforded by installing an ice storage system to existing air conditioning plants of a school in Jeddah, Saudi Arabia. In this paper, the assumptions are i) fixed interest rate of 10%, ii) a tenure of 10 years and iii) estimated operational tariff structure depending on both the number of operating hours and the ambient temperature. The study examines both full and partial load storage scenarios then calculates the effect of various pricing tariffs on cost optimization. The results show that the current fixed electricity tariff rate of \$0.0267/kWh which is not economically feasible. Combining both the energy storage and an incentive time structured rate shows reasonable daily bill savings. For a base tariff of \$0.07/kWh during daytime operation and \$0.0267/kWh for the off-peak period, savings of \$33/d and \$73.36/d is achievable for full load storage and partial load scenarios, respectively. These savings will increase to \$159/d for full load storage and \$124.06/d for partial load storage after 10 years.

**Keywords:** Ice Storage, Cooling Load, Economic Analysis

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## 1. Introduction

The air conditioning (A/C) systems in Saudi Arabia consume more than 60% of the total electric energy available for buildings. The high consumption rates encourage the authorities to work on both increasing the energy generating rates and reducing the demand. Therefore, shifting the energy consumption from peak to off-peak hours and improving A/C systems performance are necessary for fulfilling the electricity demand reduction. The main purpose of using a thermal storage system (TES) is to shift the electricity peak load associated with buildings' cooling from peak time to off-peak periods. When applying variable tariff policy, TES becomes a good candidate for utilities to enforce demand management for many users. Cold TES technology provides a feasible solution for solving peak load problems (Yau and Rismanchi [1]; Parameshwaran et al [2]; Habeebullah [3]). The TES is suitable for buildings having

discontinuous working hours such as offices, schools (Michael [4]), court-halls, campus buildings (Yau and Rismanchi [1]), subway stations (Keisuke [5]) and many others (Habeebullah [3]).

Applying different tariffs based on the day time of high and low consumption levels creates opportunities for the use of energy storage systems. Ihm *et al* [6] presented a TES simulation model within the EnergyPlus (EnergyPlus [7]) buildings analysis package. Henz *et al* [8] carried out an investigation of the possible savings in the electricity bill for various storage strategies, different combinations of chiller types, building type and weather conditions. Sanaye and Shirazi [9] performed a study on the thermo-economic modeling and optimum design of an ice TES for A/C applications. The same study took into consideration the penalty for CO<sub>2</sub> emission. Sebzali *et al* [10] have studied the implementation of a chilled water thermal system in Kuwait city and have demonstrated that this reduces the peak power demand of A/C systems.

## 2. Cost Function

The total annual cost of the combined chillers and a storage system consists of the annual capital cost of both the chillers  $C_{ch}$  and the energy storage tanks  $C_{st}$  in addition to the annual operational expenses. The annual operational cost which is a function of the operation period  $t_{op}$ , the consumed electrical energy  $E_{el}$ , and energy rate  $C_{el}$  (\$/kWh) is given as

$$C_{total} = a^c [C_{ch} + C_{st}] + \int_0^{t_{op}} C_{el} E_{el} dt \quad (\$/y) \quad (1)$$

where,  $a^c = i_r (1 + i_r)^{ny} / (1 + i_r)^{ny} - 1$  is the capital recovery factor after a period of  $ny$  years. The capital expenses comprise the purchase of the equipment, equipment installation, and maintenance. According to the mechanical equipment index, the chillers' capital cost depends on the cooling capacity  $C_A$ . Therefore, the chillers the cost is  $C_{ch} = \alpha_{ch} C_A$ , where  $\alpha_{ch}$  is a multiplication cost index in \$/kW or \$/ton refrigeration (TR) (Habeebullah [3]). This analysis estimates the maintenance cost as a percentage of the capital cost  $\alpha_m$ ; hence the chillers cost is

$$C_{ch} = (1 + \alpha_m) \alpha_{ch} C_A \quad (2)$$

The capital cost of the ice storage tank depends on the required mass of ice during the ice build-up period. The specified cooling load variation for the corresponding ice buildup process affects size selection as well as the tank internal coils and auxiliaries. If the thermal storage capacity is  $S_{st}$  (kWh), the capital cost of ice storage including installation, piping, accessories and control units is expressed as

$$C_{st} = \alpha_{st} S_{st} \quad (3)$$

where  $\alpha_{st}$  is in \$/kWh, which is furnished by manufactures.

Substituting Eqs. 2 and 3 into Eq. 1 gives

$$C_{total} = a^c [(1 + \alpha_m) \alpha_{ch} C_A + \alpha_{st} S_{st}] + \int_0^{t_{op}} C_{el} E_{el} dt \quad (\$/y) \quad (4)$$

In Eq. 4, the electrical energy consumption  $E_{el}$  (kW) is function of time. It includes the energy consumed by the cooling chillers and/or ice making units during the period  $t_{op}$ . The hourly cooling load determines the needed electric power to drive the air conditioning system. The cooling load varies with the building structure, activities of the occupants in addition to the ambient conditions. Electrical energy cost is also another factor. Electricity cost might follow from one of many accounting method and could have a fixed flat rate or variable tariff rate (e.g. function of time of use).

## 3. Operation Strategies

Cold storage systems usually operate on either full storage or partial storage modes. The storage supplies the total energy needed during peak hours while the chillers operate only at nighttime. Figure 1 shows an illustration for this scenario for a daily cooling load with a peak period between 7:00 AM and 4:00 PM.

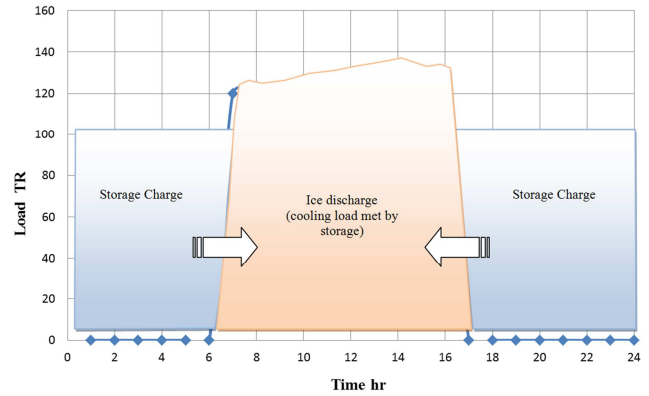
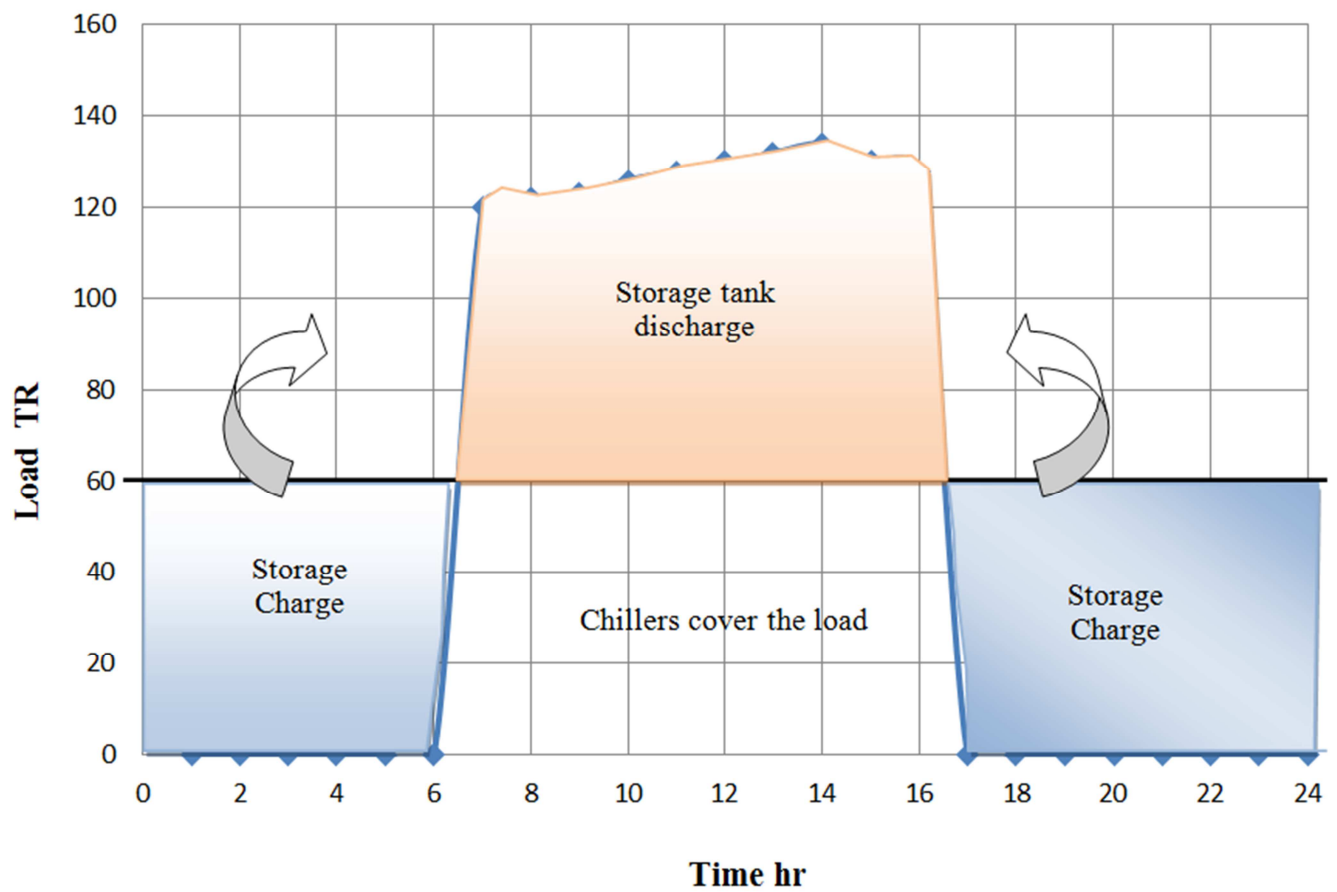


Figure 1. Schematic of full load storage scenario.

For partial storage systems, the peak load covers a small segment of the load while the chillers meet the rest as shown in Fig. 2. The part load scenario is suitable for load leveling or demand limiting. In this scenario, the chillers operate continuously for 24 hours mostly at the rated capacity. During the periods of low demand, the excess energy is stored, which is used later to cover the peak load. In our case study, the chillers operate between 6:00 PM to next 6:00 AM depending on the time required to charge the storage because there is no cooling load during this time.

## 4. Application to the School Air Conditioning Plant

New school buildings in Jeddah are constructed to a standard plan called *Mubassat Modon*. Schools are normally built as a complex of three identical buildings. Each school contains twenty-five classrooms, two offices, two labs, an open area, and a library distributed on three floors. A typical school plan is shown in Figs. 3 and 4. The school is subdivided into a total of five main zones (Table 1) and the running time for the purpose of cooling load is established as between 6:00 AM to 4:00 PM. The cooling loads have been determined from school building simulations using EnergyPlus software (Energyplus<sup>7</sup>). The total area of 24428.91 m<sup>2</sup> exhibits an approximately 1608 GJ peak electrical demand for non-thermal loads. Details of maximum loads are presented in Table 1. The cooling load is estimated around 1273 TR h using EnergyPlus. Fig. 5 clearly shows how the school cooling load changes from 6:00 AM to 5:00 PM, as a result of the outside temperature variation.



*Figure 2. Schematic of partial storage or load leveling scenario.*



*Figure 3. Typical school complex in Jeddah.*

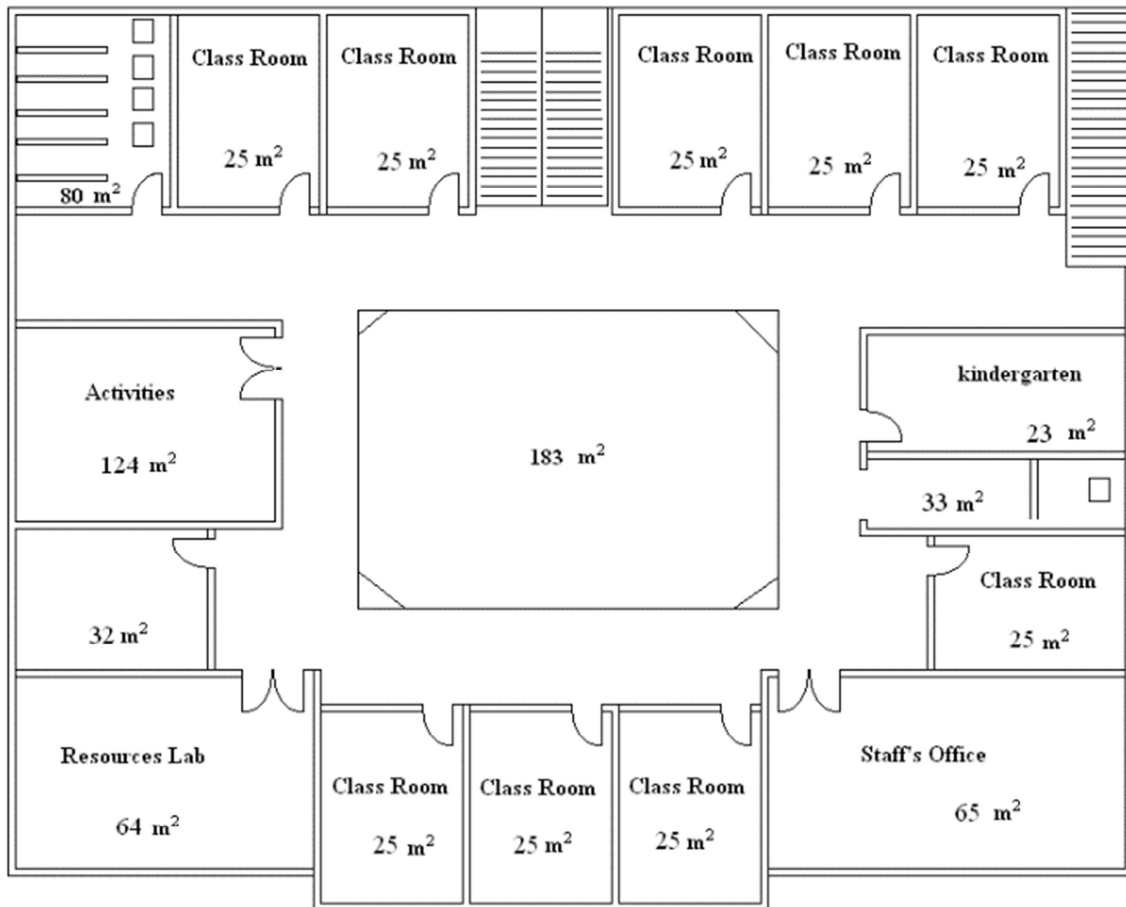
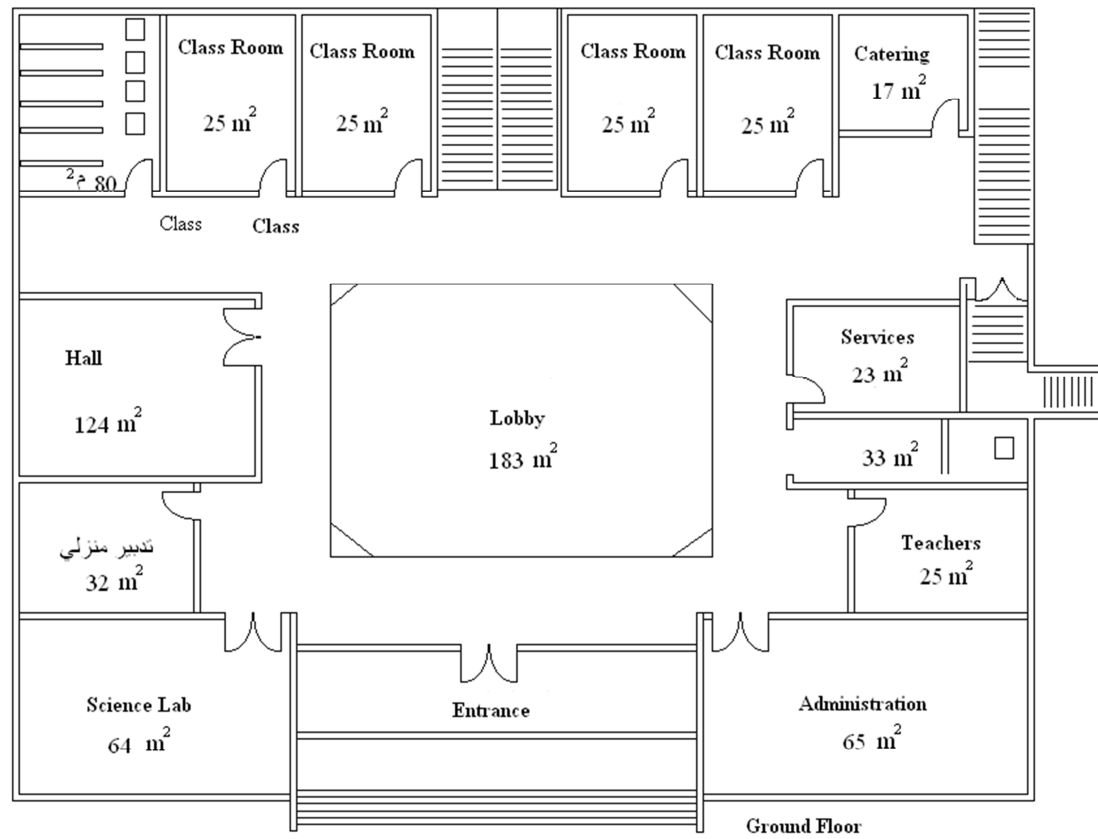


Figure 4. Floor design of a school building in Jeddah.

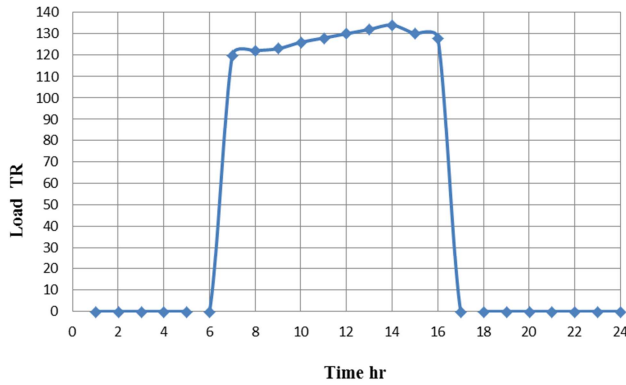


Figure 5. School cooling load curve.

Table 1. Summary of EnergyPlus results.

Zone	Max. Design Load [W]		Electricity [GJ]
1	133830	Cooling	1608
2	150300	Interior lighting	144
3	159271	Interior equipment	124
4	164448	Fans	360
5	97325.7	Pumps	78
Total (W)	705175.9		
Total (TR)	200.89	Total End Uses (GJ)	2314

The data presented in Fig. 5 indicates that two chillers in which each capacity is of 100 TR are sufficient for the cooling load between 6:00 AM and 5:00 PM. One chiller is operating at full load and the other one is partially in operation to cover the peak load. During off-peak operation, the units operate at part load and consequently at a low coefficient of performance (COP) that directly increases the power consumption per kW. For the evaporation temperature of  $-1^{\circ}\text{C}$ , the COP varies daily in terms of the condensing temperature as calculated from the log data sheet and provided by the maintenance department of the school. It can be seen that during the peak load hours and because of the high ambient temperature, the COP drops from 2.46 at dawn to 2.2 at midday. This simply means a decrease in the units' performance and an increase in the energy consumption.

## 5. School Cooling Load Calculations

The analysis in this study uses Energyplus to perform the cooling load calculations for the school's three floors.

### 5.1. Comfort Standards

The conditions that affect the comfort levels of both students and school staff have been considered. Using the recommended indoor air conditions for comfort as published in ASHRAE Standard 55 [11], Thermal Environmental Conditions for Human Occupancy, the ranges of air temperature and relative humidity (RH) are acceptable to at least 80%.

### 5.2. Cooling Load Calculation Procedures

The following step-by-step instructions summarize how to calculate school cooling loads:

1. Select indoor and outdoor design conditions.
2. Use architectural plans (Fig. 4) to measure dimensions of all surfaces through which there will be external heat gains, for each zone.
3. Calculate areas of all these zones.
4. Select heat transfer coefficient U-values for each element from appropriate tables, or calculate them from individual R-values.
5. Determine time of day and month of *peak load* for each zone by calculating external heat gains at times for which they are expected to be a maximum.

Hourly school cooling loads for 24 hours were converted to cooling load temperature difference (CLTD) values by dividing the roof or wall area and the overall heat transfer coefficient so that the school cooling load can be calculated for any wall or roof by the following relation:

$$\dot{Q}_w = A \times U \times CLTD_c \quad (5)$$

where

$\dot{Q}_w$ : the rate of heat transfer in Watts ( $W$ ).

$A$ : the outside surface area of the wall ( $\text{m}^2$ ).

$U$ : the overall coefficient of heat transmission in  $\text{W}/\text{m}^2\cdot\text{K}$ .

$CLTD_c$ : Corrected Cooling Load Temperature Difference

$$CLTD_c = CLTD + LM + (25.5 - t_R) + (t_a - 29.5) \quad (6)$$

$$t_a = t_o - (DR / 2) \quad (7)$$

$DR$ : Daily Range

$LM$ : CLTD correction for Latitude and Month

$t_a$ : indoor temperature ( $^{\circ}\text{C}$ )

$t_o$ : outdoor temperature ( $^{\circ}\text{C}$ )

### 5.3. Class Room Peak Cooling Load

Air conditioning system must be sized to handle peak loads that should be determined based on the estimated cooling load. The external heat gain components vary in intensity with time of day and time of year following the changing in solar radiation caused by the changes of the sun orientation and changes in the outdoor temperature. This results in a change in the total room cooling load. Occasionally, it is immediately apparent by inspecting the tables at what time the peak load occurs, but often calculations are required at a few different times. Some general guidelines can be offered to simplify this task. From the  $CLTD$ ,  $SHGF$ , and  $CLF$  tables (ASHRAE Standard 55 [11]) we can note the following:

1. For west-facing glass, the maximum load is in mid-summer in the afternoon.
2. For east-facing glass, maximum solar load is in early or



mid-summer in the morning.

3. For south-facing glass, maximum solar load is in the fall or winter in early afternoon.

4. For southwest-facing glass, maximum solar load is in the fall in the afternoon.

5. For roofs, maximum load is in the summer in the afternoon or evening.

6. For walls, maximum load is in the summer in the afternoon or evening.

These generalizations can be used to localize approximate times of zone peak loads. For instance, we might expect a south-facing zone with a very large window area to have a peak load in early afternoon in the fall, not in the summer. If the zone had a small glass area, however, the wall and glass heat conduction might dominate and the peak load time would be a summer afternoon. Once the appropriate day and time are established, a few calculations will determine the exact time and value of the peak load.

7. Calculate each zone peak load, using the values for the external heat gains determined above and by calculating and adding the internal heat gains from student/staff, lights, and equipment. If there is infiltration, this must be added to the zone cooling load.

8. Find the time of *school peak cooling load* - see suggestions below.

#### 5.4. School Peak Cooling Load

The school cooling load is the rate at which heat is removed from all air-conditioned zones in the school when the school cooling load is at its peak value. If peak cooling loads for each zone were added, the total would be greater than the peak cooling load required for the whole school due to the fact that these peaks do not occur at the same time. Therefore, the designer must also determine the time of year and time of day at which the school cooling load is at a peak, and then calculate it. A reasoning and investigation similar to that carried out in finding zone peak loads is used. From our experience, the following guidelines emerge:

1. The school buildings have approximately squared shapes in plan with similar construction on all four walls. The peak load is usually in late afternoon in summer. This is because the outside temperature is highest then, and there is no differential influence of solar radiation on one side of a building.
2. For school buildings with a long south or southwest exposure having large glass areas, the peak load may occur in the fall, around mid-day, because radiation is highest then. This case requires careful analysis.
3. For one-storey school buildings with very large roof areas, the peak load usually occurs in the afternoon in summer.

These suggestions must be verified in each case because there are so many variations in the construction and orientation of school buildings. Once the peak load time is determined, the total building heat gains can be calculated. The search for the time and value of peak zone and building

cooling loads is greatly simplified by using Energyplus software. After the necessary data are entered, a complete time profile of loads for many hours can be developed in a few minutes.

4. Calculate the school building load at peak time, adding all external and internal gains and infiltration, if any. Add supply duct heat gain, duct heat leakage, and draw-through supply fan heat gain if significant
5. Find the *cooling coil and refrigeration load* by adding the ventilation load to the school building heat gains; add blow-through fan, return air fan, and pump heat gains, if significant.

#### 5.5. Cooling Coil Load

After the school building cooling load is determined, the cooling coil load is found. The cooling coil load is the rate at which heat must be removed by the air conditioning cooling coil(s). The cooling coil load will be greater than the building load because there are heat gains to the air conditioning system itself. These gains may include:

1. Ventilation (outside air)
2. Heat gains to ducts
3. Heat produced by the air conditioning system fans and pumps
4. Air leakage from ducts

#### 5.6. Refrigeration Load

The refrigeration load is the load on the refrigeration equipment. For central systems with remote chilled water cooling coils, the pump heat is a load on the refrigeration chiller, but not the cooling coil. For a direct expansion system, the refrigeration load and cooling coil load are equal. For chilled water system, the refrigeration load is the cooling coil(s) load plus the chilled water pump heat.

#### 5.7. School Cooling Load Calculations Summary

The HVAC system with storage for the example Building will have the following characteristics:

- The primary chillers and the partial modular or encapsulated ice storage system meet design day cooling load. Thermal storage placement is downstream of chillers.
- The actual capacity of the primary chillers at design ambient condition of 46°C is 200 tons to cover the required school capacity of 1273 TR h.
- Ethylene glycol brine (25%) is the heat transfer fluid in the Primary distribution, chillers and storage loops. Chilled water is the heat transfer in the Secondary networks.
- On-peak period loads are cooled by the combination of primary chillers and storage system. A secondary chiller meets coincident off-peak cooling.
- Variable flow pumps are used for storage, Primary and Secondary loops. Constant volume pumps are used for chiller loop.
- Decoupler line is used for flow balances. No blending

or bypass valves are required.

- In-building heat exchangers to separate the Primary brine and the Secondary chilled water networks. Two-way control valves located at outlets of exchangers and AHU coils control both sides of the heat exchangers. Coincidental cooling loads have the brine pipe connected directly to the AHU coils.
- Charging of the storage system is controlled by Time of Day Programming. Two indicators control storage ice level: tank water level measurement and brine leaving temperature.
- Discharge strategies are Time of Day Programming and BMS selectable discharge. Charging schedule is between 5 pm to 6 am the day after.
- System can operate in six operating modes: chillers only, storage discharge, chiller and storage discharge, storage charge, Charge with coincidental cooling load, and off.
- Operating temperatures of storage;

During charging: at inlet  $T_{isc} = -5^{\circ}\text{C}$  ( $23^{\circ}\text{F}$ ) at outlet  $T_{osc} = -1^{\circ}\text{C}$  ( $30^{\circ}\text{F}$ )

During discharge: at inlet  $T_{isd} = 15.5^{\circ}\text{C}$  ( $60^{\circ}\text{F}$ ) at outlet  $T_{osd} = 5.5^{\circ}\text{C}$  ( $42^{\circ}\text{F}$ )

- Operating temperatures of chillers;

During charging: at inlet  $T_{icc} = -1^{\circ}\text{C}$  ( $30^{\circ}\text{F}$ ) at outlet  $T_{occ} = -5^{\circ}\text{C}$  ( $23^{\circ}\text{F}$ )

During discharge: at inlet  $T_{icd} = 15.5^{\circ}\text{C}$  ( $60^{\circ}\text{F}$ ) at outlet  $T_{ocd} = 5.5^{\circ}\text{C}$  ( $42^{\circ}\text{F}$ )

Set point Control: Chiller Only =  $5.5^{\circ}\text{C}$  ( $42^{\circ}\text{F}$ )

Storage Only =  $17^{\circ}\text{C}$  ( $62^{\circ}\text{F}$ )

Charge =  $-7.7^{\circ}\text{C}$  ( $18^{\circ}\text{F}$ )

- Operating temperatures of building brine-side heat exchangers; at inlet  $T_{ie} = 5.5^{\circ}\text{C}$  ( $42^{\circ}\text{F}$ ) at outlet  $T_{oe} = 15.5^{\circ}\text{C}$  ( $60^{\circ}\text{F}$ )
- Total additional cost of introducing the ice storage system is SR 850,000 for full load and SR 350,000 for partial load.

Based on the school's available data it is of interest to look

for an energy storage option and operation schedule that provide the most economic cost function,  $C_{total}$ .

## 6. Costing Scenarios

For the present case, an ice storing technology is adapted and two scenarios are investigated in the following section.

### Scenario 1

#### 6.1. Full Load Storing Scheme

For full load storing, it is suggested that a substantial amount of ice be produced overnight to handle the entire peak load between 6:00 and 16:00 o'clock. In this proposed operation scenario and because of the cooling load, two chillers with a capacity of 100 TR operate at full load between 7 pm to 5 am as shown in Table 2. No chiller is in operation as water chiller to provide the school with the necessary air conditioning load, where the other chillers charge the storage tank (produce the required amount of ice) this is because there is no load at school between 6 am to 4 pm. The present chiller control is set to provide chilled water at  $5^{\circ}\text{C}$  at evaporator temperature of  $-1^{\circ}\text{C}$ . Using the same chillers to produce ice requires a reduction of the evaporator temperature to  $-10^{\circ}\text{C}$  therefore, the ice making chillers' cooling capacity is reduced to less than 100 TR. The refrigeration cycle is solved for evaporator temperature of  $-10^{\circ}\text{C}$  with R404A and the drop in capacity was found to be 4.95%. Therefore, a correction factor of 0.945 for the evaporating temperature change is used. In addition, storing energy in the form of ice passes through a freezing process where the rate of heat transfer is affected by the ice buildup thickness. A factor of 0.75 is assumed for the ice formation process (Anonymous [12]). This makes an overall conversion factor of 0.7088, which means that the chiller capacity when controlled to make ice reduces from 100 TR to 71 TR.

**Table 2.** Scenario 1 Operation scheme for full load storage (based on Carrier HXC30-100TR).

Scenario 1 Full load storage							
Time Hours	Required load, TR	Water Chiller		Ice Chiller		Storage discharge TR	Total No. of chillers in operation
		No. of Chillers in operation	TR	No. of Chillers in operation	TR		
0	0	off	off	2	141.8*	-	2
1	0	off	off	2	141.8	-	2
2	0	off	off	2	141.8	-	2
3	0	off	off	2	141.8	-	2
4	0	off	off	2	141.8	-	2
5	0	off	off	off	off	-	0
6	0	off	off	off	off	-	0
7	120	off	off	off	off	120	0
8	122	off	off	off	off	122	0
9	123	off	off	off	off	123	0
10	126	off	off	off	off	126	0
11	128	off	off	off	off	128	0
12	130	off	off	off	off	130	0
13	132	off	off	off	off	132	0
14	134	off	off	off	off	134	0

Scenario 1 Full load storage							
Time Hours	Required load, TR	Water Chiller		Ice Chiller		Storage discharge TR	Total No. of chillers in operation
		No. of Chillers in operation	TR	No. of Chillers in operation	TR		
15	130	off	off	off	off	130	0
16	128	off	off	off	off	128	0
17	0	off	off	off	off	-	0
18	0	off	off	off	off	-	0
19	0	off	off	off	off	-	0
20	0	off	off	2	141.8	-	2
21	0	off	off	2	141.8	-	2
22	0	off	off	2	141.8	-	2
23	0	off	off	2	141.8	-	2
Total, TR-h	1273	0	0		1276	1273	

\*The chiller capacity is multiplied by correction factor (0.7088) to convert the water chiller into ice chiller

The total cooling load, which is the integrated area under the cooling curve, amounts to 1273 TR-h as shown in Fig. 6, of which 510 TR-h is the off-peak cooling load and the rest is stored in the ice tanks. Therefore, the plant is operated during nighttime and early morning, only making use of the relatively low ambient temperature and high COP. The operation time schedule is given in Table 2, which indicates that only 1 chiller operating close to full load for only 9 hours is required to handle the entire total daily cooling needs. The main advantage of the suggested scenario is the improved operation of the chillers the entire time (average  $COP_a = 2.2$ ).

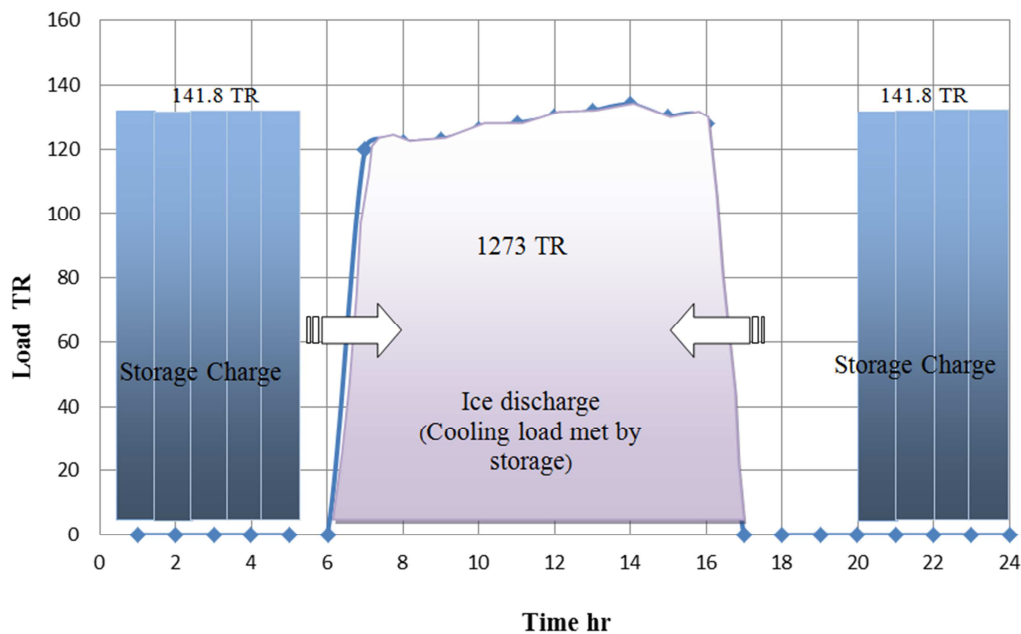


Figure 6. Full load storing scenario (based on Carrier HXC30-100TR).

Let us investigate the economics of the proposed scenario where the chiller operates only for 11 hours at their rated capacity. The electricity tariff as used in Saudi Arabia is shown in Table 3. The daily operational cost (the last term in Eq. 4) for normal operation without ice storage using the tariff rate that shown in Table 3.

Table 3. Saudi Arabia electricity tariff.

0		0
Saturday to Thursday	12 am-8 am	0.1
	8 am-12 pm	0.15
	12 pm-5 pm	0.26
	5 pm-12 am	0.15

$$\begin{aligned}
 \int_0^{24} C_{el} E_{el} dt &= \int_0^{24} (\dot{Q}_{evap} / COP_a) C_{el} dt = \\
 &\left\{ \frac{2 \times 2 \times 100 \times 3.51}{2.2} \right\} \times 0.1 + \left\{ \frac{2 \times 4 \times 100 \times 3.51}{2.2} \right\} \times \\
 &0.15 + \left\{ \frac{2 \times 5 \times 100 \times 3.51}{2.2} \right\} \times 0.26 \\
 &= 670 \text{ SR/d (177 \$ /d)}
 \end{aligned}$$

The daily operation cost of making ice during the 9 hours



nighttime and morning period is calculated in two parts using the data of Tables 1 and 2 to give

$$\left\{ \frac{(2 \times 5 \times 100) \times 3.51}{2.46} \right\} \times 0.1 + \left\{ \frac{(2 \times 4 \times 100) \times 3.51}{2.46} \right\} \times 0.15 = 314 \text{ SR/d (84 \$/d)}$$

The *capital investment* of the ice storage tank is determined by calculating the mass of ice formed during the 9 hours operation period that is necessary to provide 1273 TR-h (4468 kW h). Following the current pricing data for local market cost of 668 SR/ TR h. The capital investment for the storage tanks  $C_{st}$  is then 850,000 SR.

Assuming an interest rate of 10% and 10 years payback period the capital recovery factor  $a^c$  is 0.163. The capital investment annuity,  $A$ , is

$$A = a^c \times C_{st} = 0.163 \times 850,000 = 138,550 \text{ SR (36,947 \$)}$$

Assuming 300 working days per year, the storage capital contributes 126 \$/d (462 SR/d) for the daily total investment repayment.

The total daily effective expenses, including the cost of the water chillers in Eq. 1, is

$$C_{d,n} = a^c [C_{ch} + C_{st}] / n_{day} + \frac{t_{op} \dot{Q}_{evap} C_{el}}{COP_a} = 126 + 84 = \$210 \text{ (788 SR)} \quad (8)$$

The daily cost feasibility, or in other words the daily benefit when introducing ice storage tanks, is the difference between the expenses of the plant without and with the ice storage system as  $177 - 210 = -33$  \$/d (-124 SR/d). The negative sign here indicates that there is no saving and the school AC plant is performing well with the current tariff.

However, after 10 years the capital will be paid off and the saving will be  $177 - 84 = 93$  \$/d (349 SR/d). Additionally, assuming the base tariff structure where the current low rate of 0.1 SR/kWh is fixed as nighttime rate and the daytime rate is maintained at its level of 0.26 SR/kWh, the daily cost of operation will be increased from 177 \$/d to 243\$/d. Thus, the daily saving will be  $243 - 210 = 33$  \$/d (124 SR/d) and after 10 years it will be  $243 - 84 = 159$  \$/d (596 SR/d).

#### Scenario 2

### 6.2. Partial Load Storing Scheme

Inspection of the cooling load shows that the peak load falls between 6 AM to 4 PM, where the load reaches 134 TR. For partial storing the peak load is leveled at 94.5 TR for 8 hour only so that the energy above this load and from 4 pm to 6 pm is supplied from storage tanks (Fig. 7). This arrangement will reduced the capital invested in ice storage at the same time reduced the transformer and cables cost. The operation scenario is one chiller covers the energy required below the selected level of 94.5 TR running at 100% capacity the extra loads are covered from the ice storage tank which charge by running 2 chillers between 1 am-5 am. The advantage of this arrangement is the operation of all chillers with maximum COP and at lowest tariff. The energy stored during this period is 567 TR h while the required energy during the discharge period is 517 TR h. In this case adjusting the control of the chillers to have a shorter ice-charging period is required to correct the difference. In this scenario only 350,000 SR will be invested in ice storage system. Table 4 shows the detailed operation scheme for partial storage scenario.

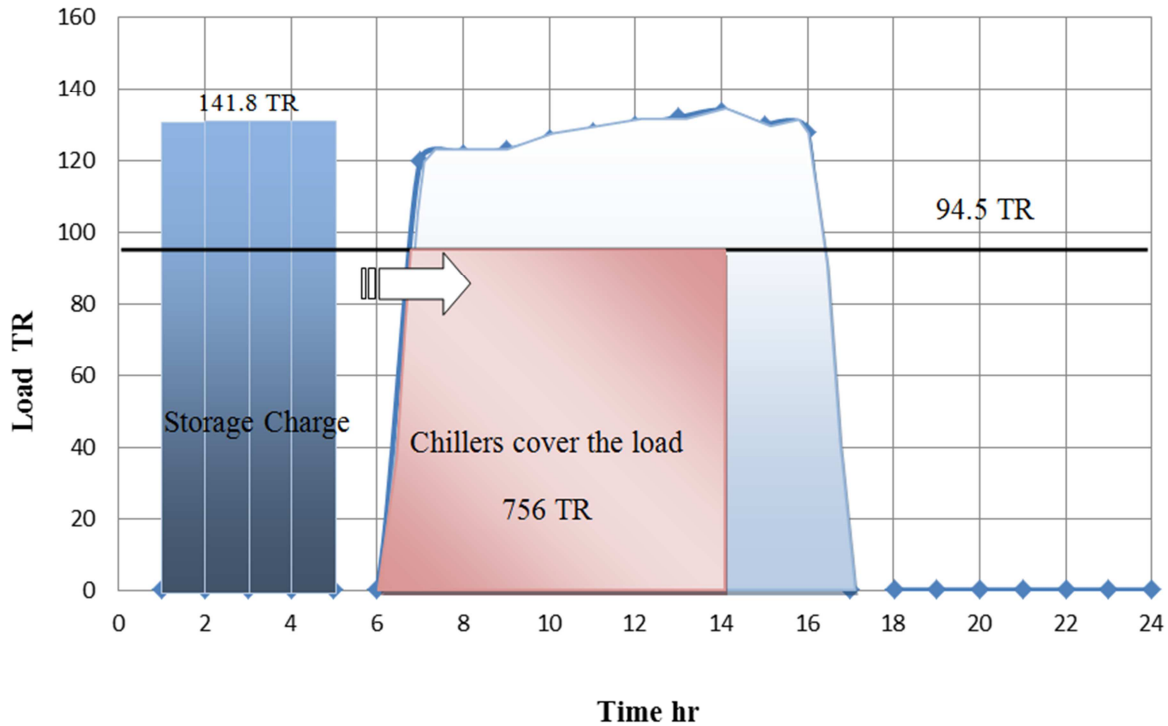


Figure 7. Partial load storing scenario (based on Carrier HXC30-100TR).

Table 4. Scenario 2 of cooling load profile.

Scenario 2 Part load storage								
Time Hours	Required load, TR	Water Chiller		Ice Chiller				Total No. of chillers in operation
		No. of Chillers in operation	TR	Excess	Storage discharge TR	No. of Chillers in operation	TR	
0	0	0		-	-	2		2
1	0	0	-	-	-	2	141.8*	2
2	0	0	-	-	-	2	141.8	2
3	0	0	-	-	-	2	141.8	2
4	0	0	-	-	-	2	141.8	2
5	0	0	-	-	-	2	-	-
6	0	0	-	-	-	off	-	-
7	120	1	94.5	-	25.5	off	-	-
8	122	1	94.5	-	27.5	off	-	-
9	123	1	94.5	-	28.5	off	-	-
10	126	1	94.5	-	31.5	off	-	-
11	128	1	94.5	-	33.5	off	-	-
12	130	1	94.5	-	35.5	off	-	-
13	132	1	94.5	-	37.5	off	-	-
14	134	1	94.5	-	39.5	off	-	-
15	130	0	-	-	130	off	-	-
16	128	0	-	-	128	off	-	-
17	0	0	-	-	-	off	-	-
18	0	0	-	-	-	off	-	-
19	0	0	-	-	-	off	-	-
20	0	0	-	-	-	off	-	-
21	0	0	-	-	-	off	-	-
22	0	0	-	-	-	off	-	-
23	0	0	-	-	-	off	-	-
Total, TR-h	1273		756		517		567	

\* The chiller capacity is multiplied by correction factor (0.7088) to convert the water chiller into ice chiller

Let us investigate the cost for the proposed partial load-storing scenario, where the ice chillers operate only for 4 hours, 1-5 AM, at their rated capacity and average  $COP_a$ . Noting that the average actual  $COP_a$  is 2.46 for the time between 1 am -5 am and 2.2 between 10 am and 1 pm.

Following the same calculation procedure and using the data of Table 4 the cost items are summarized as,

- a Operation cost for the total cooling load, 1273 TR-h 177 \$/d  
 Operation cost for the water chillers 56.16 \$/d producing 756 TR-h =  $\left\{ \frac{1 \times 2 \times 100 \times 3.51}{2.2} \right\} \times 0.1 + \left\{ \frac{1 \times 4 \times 100 \times 3.51}{2.2} \right\} \times 0.15 + \left\{ \frac{1 \times 2 \times 100 \times 3.51}{2.2} \right\} \times 0.2$
- b  $0.15 + \left\{ \frac{1 \times 2 \times 100 \times 3.51}{2.2} \right\} \times 0.2$
- c Operation cost during ice making period  $\left\{ \frac{(2 \times 4 \times 100) \times 3.51}{2.46} \right\} \times 0.1 = 30.44$  \$/d
- d The ice storage capital to form 517 TR-h equivalence of ice in 4 h = 93,333 \$
- e Fixed charges rate for the ice storage capital (300 working days/y and 0.163 fixed charges rate = 50.7 \$/d
- f Total daily cost with ice storage  $C_{d,n} = b + c + e$  137.3 \$/d
- g Net daily benefit (a – f) 39.7 \$/d

Here, it is seen that the positive sign means that there is a little saving with the partial storage scenario. The reason is the electricity tariff rate as charged by the authorities is relatively affordable. However, the annual saving is 11,910 \$ (44,663 SR) and after 10 years it will be  $(90.4 \times 300 = 27,120\$)$  (101,700 SR).

The net daily savings of 39.7 \$/d can be increased to 73.36 \$/d if a base tariff structure is assumed where the current low rate of 0.1 SR/kWh is fixed as nighttime rate and while daytime rate is maintained at its level of 0.26 SR/kWh. Table 5 shows the savings using this scenario where the annual saving increases from 11,910 \$ to 22,008 \$.

Table 5. Daily saving of partial load storing scenario.

Function	Current Tariff Fig. 2	Assumed Tariff SR/kWh nighttime 0.26 SR/kWh daytime
	\$/d	\$/d
a	177	243
b	56.16	88.5
c	30.44	30.44
e	50.7	50.7
f = b + c + e	137.3	169.64
g = a - f	39.7	73.36

## 7. Conclusions

This study investigated the potential savings that result from the installation of a thermal energy storage system to the air conditioning plant of a school building in Saudi Arabia. In the analysis economic outcomes are considered in terms of what effect time-structured tariffs can have, coupled with the role active energy storage systems can play, on the daily electricity utility bill.

The results based on measured cooling load and ambient temperature showed that with the current subsidized electricity rates as shown in Table 3 there is no gain in

introducing ice storage systems for a full load storage scheme. However, there is a daily saving of \$39.7 for partial load storage schemes as shown in Table 6. Combining energy storage and an incentive time structured rate showed reasonable daily bill savings. A base tariff of \$0.07 /kWh during daytime operation and \$0.0267/kWh for the off-peak period, make a total savings of \$33/d and \$73.36/d for full load storage and partial load scenarios, respectively. These savings increases to \$159/d for full load storage and \$124.06/d for partial load storage after 10 years of operation as summarized in Table 6.

**Table 6.** Daily saving for different scenario and tariff.

Full load Saving \$/d				Partial load Saving \$/d			
Current base tariff		Incentive base tariff		Current base tariff		Incentive base tariff	
Present time	After 10 years	Present time	After 10 years	Present time	After 10 years	Present time	After 10 years
0	93	33	159	39.7	90.4	73.6	124.06

**Table 7.** Daily saving for all Jeddah schools.

Full load Saving \$/d				Partial load Saving \$/d			
Current base tariff		Incentive base tariff		Current base tariff		Incentive base tariff	
Present time	After 10 years	Present time	After 10 years	Present time	After 10 years	Present time	After 10 years
0	17,786	6,311	30,409	7,593	17,289	14,076	23,726

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## Notation

$a^c$	capital recovery factor
$C$	unit cost (\$/kWh)
$C_{el}$	unit cost of electrical energy (\$/kWh)
$SHGF$	solar heat gain factor
$CLF$	cooling load factor
$COP$	coefficient of performance
$d$	day
$E_{el}$	consumption of electrical energy (kW) = $\dot{Q}_{evap}/COP_a$
$i_r$	interest rate
$n$	number of operation days per year
$ny$	number of years of repayment
$\dot{Q}_{evap}$	evaporator capacity Ton-Refrigeration
$t_{op}$	period of operation per year (h)
<b>Subscripts</b>	
a	average
ch	chiller
el	electricity
ie	inlet heat exchanger
oe	outlet heat exchanger
icc	inlet chiller during charging
icd	inlet chiller during discharging
occ	outlet chiller during charging

isc	inlet storage during charging
isd	inlet storage during discharging
ocd	outlet chiller during discharging
osc	outlet storage during charging
osd	outlet storage during discharging
s, st	storage GENERAL COMMENTS

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