

Economic feasibility of thermal energy storage systems: Application to Al-Haram Grand Holy Mosque air conditioning plant

B. A. HABEEBULLAH

*Faculty of Engineering, King Abdulaziz University, P. O. Box 80204,
Jeddah 21589, Saudi Arabia*

bhabeeb@kau.edu.sa

ABSTRACT. In hot aired countries with sever weather, cooling and air conditioning of buildings contributes significantly to the electricity peak demand, which normally occurs during noontime period. Shifting the electrical loads to off-peak periods is achieved by introducing time of rate tariff as incentive control on the demand-side and/or using active thermal energy storage technology. This paper investigates the economic feasibility of both building an ice thermal energy storage and a timely based tariff structure for the unique air conditioning plant of the Grand Holy Mosque of Makkah, Saudi Arabia (the largest religious building on earth). The features of the building are unique where the air-conditioned 39300 m² zone is open to the atmosphere and the worshippers fully occupy the building 5 times a day. Hundreds of thousands of worshippers attend the blessed Friday prayer at noontime, which escalates the peak electricity load. For economic analysis, the objective function is the daily electricity bill that includes the operation cost and the capital investment of the ice storage system. The operation cost is a function of the energy imported for operating the plant in which the tariff structure, number of operating hours and the ambient temperature are parameters. The capital recovery factor is calculated for 10% interest rate and payback period of 10 years. Full and partial load storage scenarios are considered.

The results showed that with the current fixed electricity rate (0.07 \$/kWh), there is no gain in introducing ice storage systems neither for full nor for partial storage schemes. Combining energy storage and an incentive time structured rate showed reasonable daily bill savings. For base tariff of 0.07 \$/kWh during daytime operation and 0.016 \$/kWh for off-peak period, savings of 549.4 \$/d was achieved for full load storage scenario. the storage capital cost will be paid in 10 years and afterwards the daily saving in operational cost will be 4011.76 \$/d.

Different tariff structure is discussed and the break-even nighttime rate was determined (varies between 0.008 and 0.03 \$/kWh). Partial load storage scenario showed to be unattractive where the savings for the base structured tariff was insignificant.

KEY WORDS: ice storage; religious building; cooling load; economic analysis.

1. Introduction

In today's fast-paced economy and unstable fuel market, energy conservation is becoming an important issue. Electricity generation authorities focus attention on programs to reduce the demand and/or achieve optimum generation cost. The energy economy can be sufficiently improved by employing techniques to either tame the energy demand and/or effectively utilize the available resources. Air conditioning (A/C) systems are major contributors to buildings' energy consumption, in hot climate locations 60% of the energy is consumed for A/C. Therefore, improving A/C systems performance will not only reduce the demand but also can significantly reduce the future capital investment in building new power plants.

Several methods are currently in use to save energy in buildings, they can be classified into passive and active methods. For the passive techniques heat loads of buildings are reduced by using any of the thermal energy reduction methods, this include shading of facades and fenestrations, use of thermal insulation material, proper orientation of buildings' envelop. Management of the heat loads thorough dynamic tariff strategy, optimum operation scheme and energy storage policy are examples of the active methods. The principal idea in using thermal energy storage (TES) is shifting the electricity peak load associated with buildings' cooling from peak time to off-peak periods. In general, TES is considered by utilities as demand management strategy, which is suitable for specific applications. The concept of thermal energy storage has been employed long ago for solar energy applications; recently with the vast

increase of A/C energy demand, cold TES technology appeared to provide a feasible solution for solving peak load problems [1-3]. In hot climate areas where reliance on air conditioning increases, the maximum cooling loads of buildings occur during midday period. At the same time the performance of generating units, specially gas turbine plants, drops because of the high inlet air temperature to the compressor [4]. Though use of cold storage seems to be a promising technology, its implementation depends on the variation of the daily cooling load. The latter depends on the features of the building and occupants activities. Cold storage systems have been practically used for buildings of different features. Hasnain *et al* [5 and 6] investigated the prospects of using cold thermal storage for office buildings in the hot weather of Saudi Arabia. Successful application to buildings of high cooling loads (above 100000 TR-h capacity) is reported, Baltimore [7]. The TES is quite adequate simple technology for buildings with only daytime working hours and closed during nighttime and weekends. Applications cover a wide range of facility types, but most commonly are offices, schools [8], court-hall [9], campus buildings [10], retail stores [7], subway station [11], hospitals and places of worship [12 -14]. The load profile for religious buildings has been investigated in many countries for churches, synagogues and mosques [14]. In general, religious buildings heat loads whether it is heating or cooling are not very high because of the limited activities of the worshippers and the short occupation periods. Exceptions are the two grand mosques; Al-Haram Grand Holy Mosque in Makkah and the Profits' Mosque at Madina, Saudi Arabia, where the cooling capacities are 13440 TR and 24000 TR, respectively. The air conditioning plant of the Grand Holy Mosque is the subject of the present study where introducing ice storage system is investigated.

There are many studies related to the theoretical modeling, experimental simulation and cost analysis of TES. Most of the studies are based on sole thermo-fluid analysis of TES [15-18] or searching for optimal control strategy to maximize a kind of an objective function. The objective function can be net energy saving, cost, comfort condition or any combination of these. Chen *et al* [15] presented a simulation model based on detailed heat transfer analysis of ice storage for air conditioning systems. In their model, a direct heat transfer evaporator with (R-22)

primary refrigerant was considered for ice formation. They calculated the rate of ice formation on finned tubes and showed that heat transfer efficiency on the flat plates is higher than that on the curved tube sections. Silver, *et al* [16] modeled a refrigeration unit coupled to an ice storage tank for load shaving. The model was based on spatial thermo-fluids analysis of the evaporator coil. Other systems [17-19] use brine or Glycol as the cooling medium for ice formation, for this case an intermediate closed loop is integrated between the refrigeration machine and the ice storage tank. Therefore, the analysis is based on single-phase flow inside pipes with ice formation on the outer surface.

Kawada *et al* [20] conducted an experimental study on large capacity ice storage tanks investigated both static and dynamic modes of energy storage. The objective of that work was mainly devoted to explore different freezing methods, capsulated flakes ice for static testing and super-cooling brine for dynamic experiments. West and Braun [21] presented two models to predict the performance of ice storage tanks with partial charging and discharging scenarios. Saito [22] reviewed advances in the field of energy storage where he compared the different types of energy storage systems.

Successful operation of ice storage systems is not limited to only thermo-fluid analysis (which is important to size out the equipment) but extends to include cost analysis, which is a deterministic factor. Sizing out of ice storage tanks depends technically on the energy to be stored and the operation period. Manufacturers' guidelines and even ASHRAE procedure [23] focus on simplified schemes for shifting the electrical energy from peak to off peak periods. These methods do not provide conclusive information as to the work scheme for maximum possible savings.

Because of the growing concern on energy conservation, many utilities have adopted time of use (TOU) tariff, which opened a wide door for the use of energy storage systems. Therefore, recent studies are direct to search for storage systems suitable for specific type of buildings that maximize the net annual savings [24 - 26]. Installing or retrofitting an energy storage system is becoming an economic problem related to the cooling load and the features of the buildings. Henze and Krarti [27]

defined the cost function as the summation of demand charge, which consists of the electrical energy (kWh) cost and the total peak power consumption cost. A simplified plant model was implemented taking into account the components of a cooling system [28]. This model includes the environment parameters (i.e. load capacity and electrical rate structure). Ihm *et al* [29] extended the previous studies and integrated a TES simulation model within the EnergyPlus buildings analysis package [30] to determine potential cost savings under different control strategies. Henz *et al* [31] carried out an extensive investigation to determine the utility bill savings for different ice storage systems' control strategy, different combinations of chiller types, building type and weather conditions.

The main purpose of this study is to investigate the economic feasibility of retrofitting an ice storage system for the air conditioning plant of the Grand Holy Mosque in Makkah, Saudi Arabia. The A/C plant of the Mosque meets unique building conditions, where the 39300 m² air-conditioned area is open to the surrounding hot weather and occupied by worshippers around the clock. Full and partial load storage scenarios are investigated and the effect of different tariff structures on the objective cost function is determined.

2. Cost function

For a system that includes chillers and a storage system, the total annual cost consists of the *capital* cost for the chillers C_{ch} and energy storage tanks C_{st} in addition to the operational annual expenses. The latter is a function of the operation period t_{op} , the consumed electrical energy E_{el} and energy rate C_{el} (\$/ kWh). The total annual cost can be expressed in a general form 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 is the capital-recovery factor $a^c = \frac{i_r (1 + i_r)^{ny}}{(1 + i_r)^{ny} - 1}$, which when multiplied by the total investment gives the annual repayment necessary to pay back the investment after the period (ny). The capital expenses include purchase, installation and maintenance of the equipment. In the present analysis, maintenance is included in the capital costs C_{ch} and C_{st} . The chillers' capital cost may be estimated from mechanical equipment cost index, where the capital is related to the equipment capacity, C_A . For chillers $C_{ch} = \alpha_{ch} C_A$, where α_{ch} is a multiplication cost index in \$/kW or \$/ton refrigeration (TR). The maintenance cost is expressed as a percentage of the capital cost α_m , therefore 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 size selection as well as the tank internal coils and auxiliaries depend on the cooling load variation for which the ice build up process is specified. 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 α_{st} measured in \$/kWh, which is furnished by manufactures [7].

Substituting equations 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 equation 4 the electrical energy consumption E_{el} (kW) is function of time and includes the energy consumed by the cooling

chillers and/or ice making units during the period t_{op} . For air conditioning systems, the electric load is determined from the hourly cooling load variation, which in turn depends on the type of building, occupants activities and to a great extent on the ambient conditions. In addition, the cost of electrical energy seems to be a deterministic factor, therefore the different electricity tariff rate such as time of use (TOU), flat rate, preference customer's tariffs or any other structured accounting method should be carefully considered.

The operation time of a system with ice storage is another important factor that should be determined on basis of a selected operation strategy. The operation time may split into intervals for the chillers and storage units. However, the cost function gives the relation between the parameters; there is no formal algorithm to determine the best operation scenario because of the continuous changes in the cooling load. Therefore, the search for an operation scenario to minimize the cost function and determine the amount of stored energy as well as the charging and discharging periods depends on a trial search approach and designers' selection of the operation strategy.

3. Operation strategies

Cool storage systems operate on either full storage or partial storage mode. For full load storage, the total energy used during peak hours is supplied by the storage while the chillers operate only at nighttime. Fig. 1 is a schematic of that scenario for a daily cooling load with peak period between 12 and 18 o'clock. During this period, the cold tanks are discharged to supply the load. For the rest of the day the chillers operate to supply the load and charge the cold tanks at the same time.

For partial storage systems, only a segment of the peak load is covered by the storage while the chilling machines, as seen in Fig. 2 meet the rest of the load. This part load scenario can be designed for load

leveling or demand limiting. In this scenario, the refrigeration machines 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.

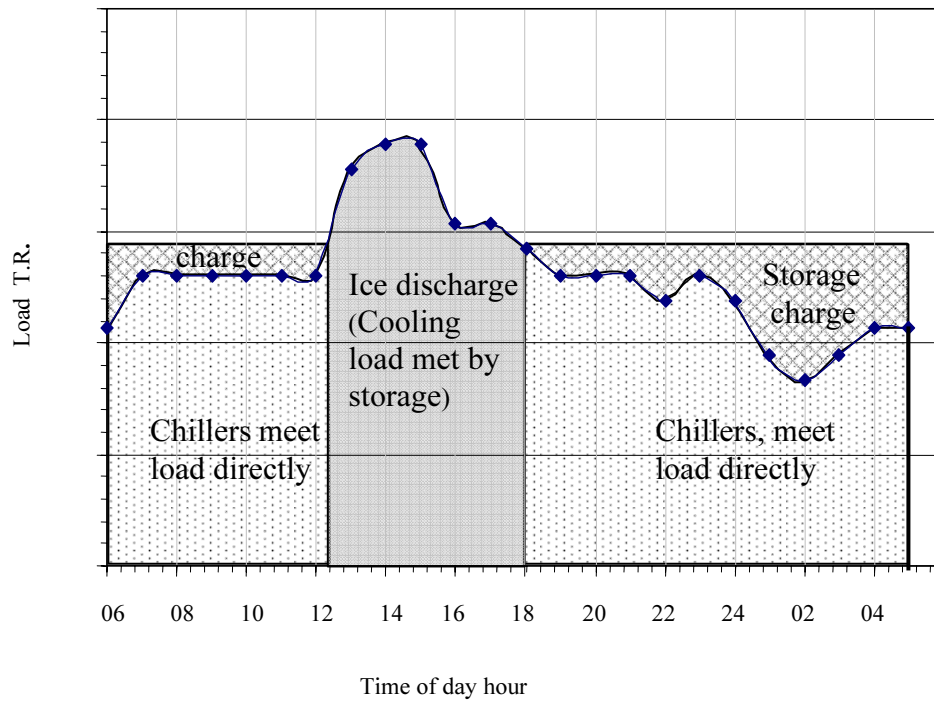


FIG. 1. Schematic of full load storage scenario.

4. Application to the Grand Holy Mosque air conditioning plant

Al-Haram Holy Mosque at Mekkah is the site of the Ka'bah (ancient and supremely holy stone building, which was originally built by Abraham and his son). For Muslims the mosque is the utterly sacred building, which is visited by millions of worshippers. The total area of

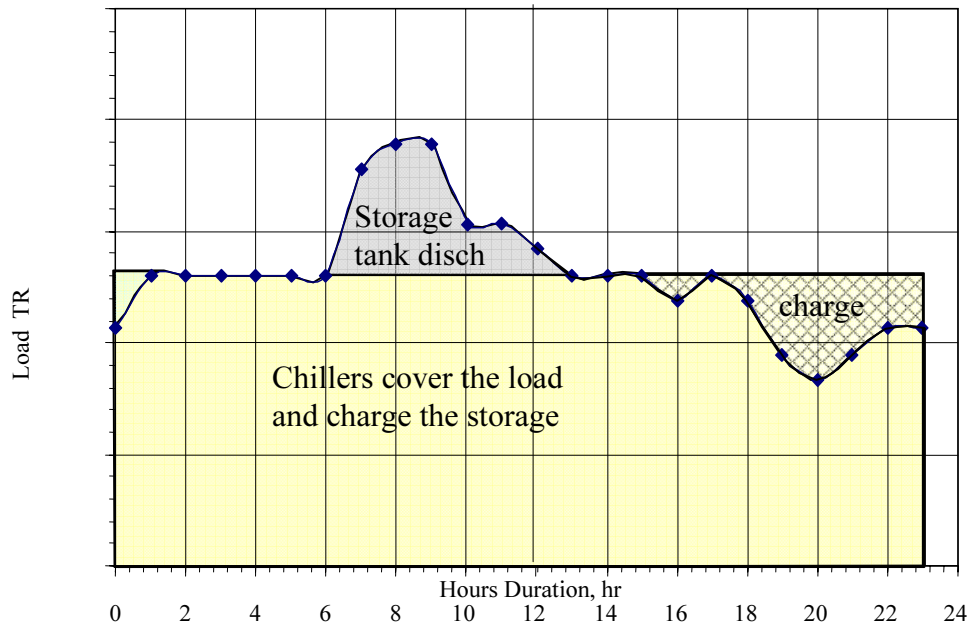


FIG. 2. Schematic of partial storage or load leveling scenario.

the mosque is 328000 m² of which 120000 m² is open area. The Mosque accommodates 730000 worshippers every prayer (5 times daily). The number rises to one million on weekends' prayer (Friday) and during special religion ceremonies. An extension plaza around the Mosque has been made to accommodate for 2 million worshippers during pilgrimage time. Air conditioning of the roof-covered area in the mosque presents a challenging engineering venture. To supply cold air to an area without side walls is a unique problem, where most of the cold air cannot be recirculated. In addition, the large heat load generated by occupants while performing their prayers raises the capacity of the air conditioning machines. The A/C project is the second largest of its kind on earth, where special air manifolds, underground chilled water system extends from a central air conditioning plant 3 km from the site are designed and custom built. At present the capacity of the air conditioning system is 47000 kW (13440 TR). The system uses conventional water chillers, which comprises 32 DX type chillers (420 TR each) and each chiller has 4 York compressors. Fig. 3 shows a plan of the Holy Mosque where the

Kabah is in the center of 27000 m² open to sky, marble paved area. This area is surrounded by an arched open sides roof covered zone of 61000 m² area.

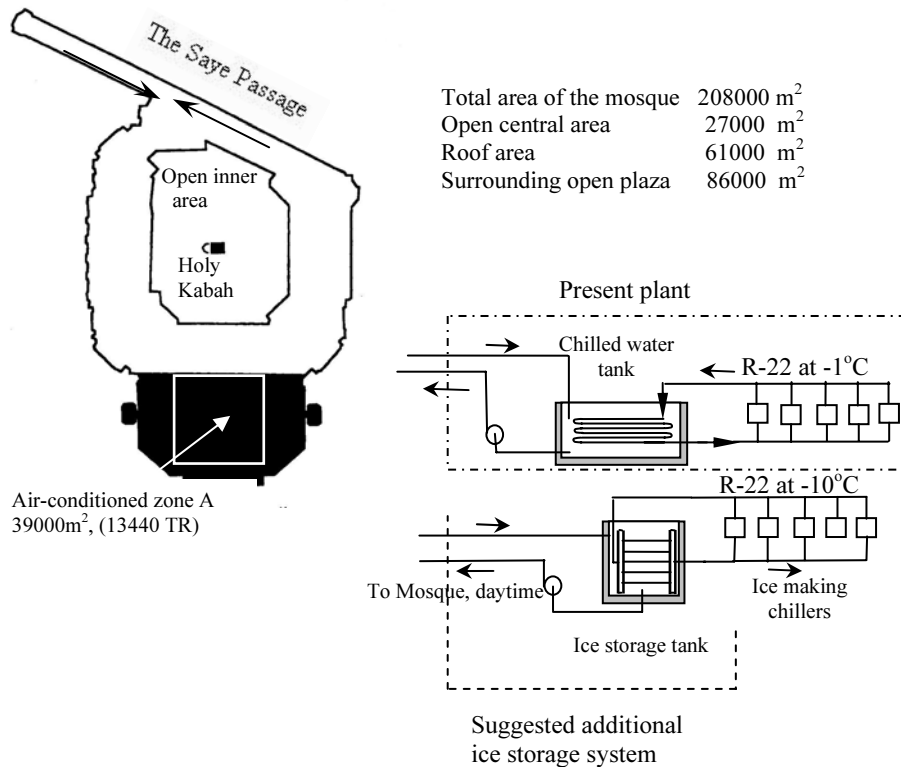


FIG. 3. The Grand Holy Mosque (Al-Haram) with the A/C plant and suggested ice storage system.

The ambient temperature in Makkah (22° N and 39° E) is generally high around the clock, where it varies between 33°C to 43 °C (see Fig. 5). Since the mosque is open for worshippers around the clock and the conditioned area is open to the environment, the cooling load variation follows mainly the climatic conditions. Figure 4 shows the

measured load variation for a section of the plant serving a floor area of 39300 m². For this area, the present capacity is 13440 TR, which gives 0.34 TR/m². This ratio is high, compared to the practical ratio for conventional buildings of 0.1 TR/m². The over designed plant is covering an open area so that it is not a conventional A/C plant for a well-contained space. In addition, the thermal mass of the building is small because of the low number of walls structure. The daily load variation indicates that the load rises between 10 and 13 o'clock. The ratio of the peak load, L_{peak} , to the base load, L_{base} is 2.2, while $L_{\text{peak}} / L_{\text{average}} = 1.3$. The data presented in Fig. 4 indicates that between 11 and 13 o'clock 13 chillers, of which 12 are operating at full load, cover the peak load. During off peak operation the units operate at part load and consequently at low coefficient of performance (COP) that directly increases the power consumption. For the evaporator temperature of -1°C, Fig. 5 shows the COP daily variation with the condensing temperature as calculated from the log data sheet provided by the plant authorities. It is seen that during the peak load hours, because of the high ambient temperature, the COP drops from 4.5 at dawn to 3.75 at midday. This simply means decrease in the units' performance and increase in the energy consumption.

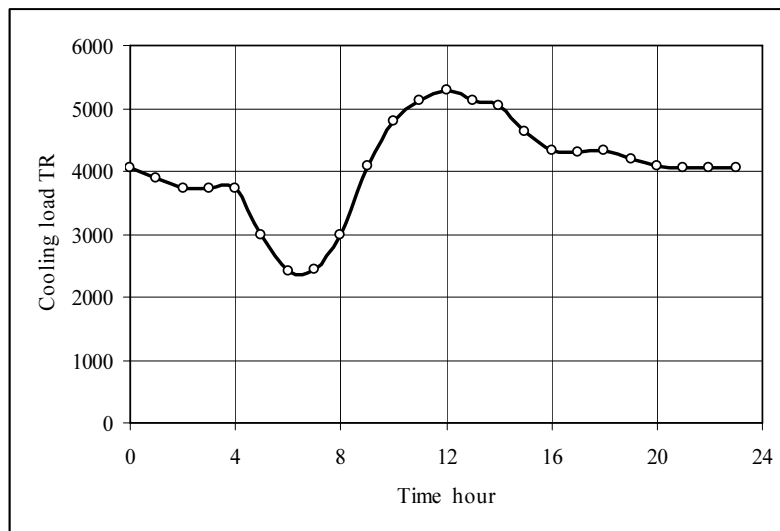


FIG. 4. Measured cooling load variation of zone (A) of Al-Haram Holy Mosque

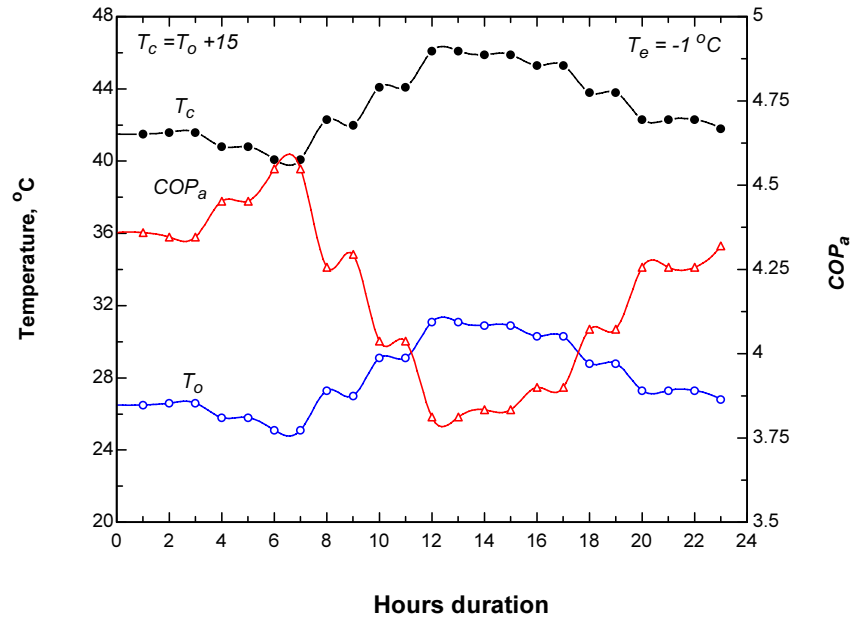


FIG. 5. Hourly variation of COP_a with condensing and ambient temperatures for the DX chillers of Al-Haram plant

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

5. Costing Scenarios

Scenario 1

5.1. Full load scheme

For full load storing, it is suggested to produce substantial amount of ice overnight to handle the entire peak load between 5:00 and 16:00 o'clock. In this proposed operation scenario, 25 chillers operate at

full load between 17 PM to 04 AM and an additional chiller operates for 1 hour at 6 AM as shown in Table 1. Some of these chillers are in operation as water chillers to provide the Holy Mosque with the necessary air conditioning load, where the other chillers charge the storage tanks (produce the required amount of ice) to be discharged between 5 AM and 16 PM. The present chillers control is set to provide chilled water at 5°C at evaporator temperature of -1°C. Using the same chillers to produce ice requires reduction of the evaporator temperature to -10 °C therefore, the ice making chillers' cooling capacity decreases below the 420 TR. The refrigeration cycle is solved for evaporator temperature of -10 °C with R-22 and the drop in capacity was found to be 13.5%. Therefore, a correction factor of 0.865 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 build up thickness. A factor of 0.75 is assumed for the ice formation process [7]. This makes an overall conversion factor of 0.649, which means that the chiller capacity when controlled to make ice reduces from 420 TR to 272.6 TR.

The total cooling load, which is the integrated area under the cooling curve, amounts to 97485TR-h, of which 49940 TR-h is the off-peak cooling load and the rest is stored in the ice tanks. Therefore, the plant is operated during night time only making use of the relatively low ambient temperature and high COP. The operation time schedule is given in Table 1, it indicates that only 25 chillers of the plant operate close to full load for 12 hours a day to handle the entire total cooling needs. The main advantage of the suggested scenario is the improved operation of the chillers all the time (average $COP_a = 4.2$). The average COP is calculated as the mean of the variation shown in Fig. 5.

Let us investigate the economics of the proposed scenario where the chillers operate only for 12 hours at their rated capacity. In Saudi Arabia the electricity tariff is mainly a flat rate at 0.016 \$/kWh (0.06 SR/ kWh) for low-level consumption up to 1000 kWh and increases to 0.07 \$/kWh (0.26 SR/kWh) for higher consumption. The daily *operational* cost (the last term in Eq. 4) for *normal operation without* ice storage assuming the high electricity rate is

$$\int_0^{24} C_{el} E_{el} dt = \int_0^{24} (\dot{Q}_{evap} / COP_a) C_{el} dt = 5702.2 \$/d$$

The daily operation cost of supplying the normal load and making ice during the 12 hours nighttime period is calculated in two parts using the data of Table 1 to give

$$\left\{ \begin{array}{l} \left(\frac{(7 \times 10 \times 420 + 3 \times 9 \times 420 + 2 \times 11 \times 420) \times 3.51}{4.2} \right) + \\ \text{Water chillers} \\ \left(\frac{(8 \times 15 \times 420 + 3 \times 16 \times 420 + 1 \times 14 \times 420) \times 3.51}{4.2} \right) \\ \text{Ice chillers} \end{array} \right\} \times 0.07 = 7325 \$/d \text{ (27469 SR/d)} \quad (5)$$

The *capital investment* of the ice storage tank is determined by calculating the mass of ice formed during the 12 hours operation period that is necessary to provide 49590 TR-h (174,061 kW) (area marked charge in Fig. 6). Following the pricing data of Hasnain [5] for local market cost of 29.3 \$/kWh (110 SR/ kWh, base year 1998) and assuming a 25% inflation rate that makes the installation cost 36.7 \$/kWh (137.5 SR/kWh).

The capital investment for the storage tanks C_{st} is then, \$ 6.38 million (23,933,374 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

$$A = a^c \times C_{st} = 1.039 \text{ Million } \$ \text{ (3,895,157 SR)}$$

Assuming 300 working days per year, the storage capital contributes 3462.36 \$/d (12984 SR/d) for the daily total investment repayment.

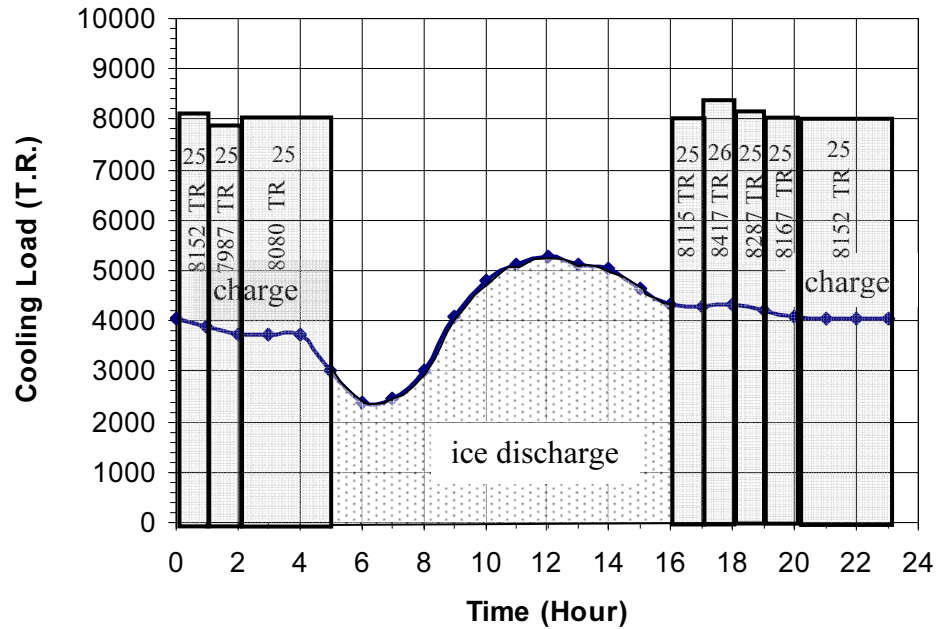


FIG. 6. Full load storing scenario (Al-Haram case)

The problem here is a retrofitting one where the chillers are existing and only some of the chillers are modified to operate at lower evaporator temperature (-10°C). Subsequently the total daily effective expenses, excluding the cost of the chillers in Eq. 1, is

$$C_{d,n} = [C_{total} - \alpha_{ch} C_{ch} / n_{day}] = a^c [C_{st}] / n_{day} + \frac{t_{op} \dot{Q}_{evap} C_{el}}{COP_a} = 10787.5 \text{ \$/d (40453 SR/day)} \quad (6)$$

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 $5702.2 - 10787.5 = -5085 \text{ \$/d (-19069.9 SR/d)}$. The negative sign here indicates that there is no saving and the plant of the Mosque is performing well with the current tariff.

TABLE 1. Scenario 1 Operation scheme for full load storage Al Haram Holy Mosque Plant

| 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 | 4065 | 10 | 4200 | 15 | 4087* | - | 25 |
| 1 | 3900 | 10 | 4200 | 15 | 4087 | - | 25 |
| 2 | 3720 | 9 | 3780 | 16 | 4360 | - | 25 |
| 3 | 3720 | 9 | 3780 | 16 | 4360 | - | 25 |
| 4 | 3720 | 9 | 3780 | 16 | 4360 | - | 25 |
| 5 | 3000 | off | off | off | off | 3000 | 0 |
| 6 | 2400 | off | off | off | off | 2400 | 0 |
| 7 | 2450 | off | off | off | off | 2450 | 0 |
| 8 | 3000 | off | off | off | off | 3000 | 0 |
| 9 | 4070 | off | off | off | off | 4070 | 0 |
| 10 | 4800 | off | off | off | off | 4800 | 0 |
| 11 | 5120 | off | off | off | off | 5120 | 0 |
| 12 | 5290 | off | off | off | off | 5290 | 0 |
| 13 | 5130 | off | off | off | off | 5130 | 0 |
| 14 | 5040 | off | off | off | off | 5040 | 0 |
| 15 | 4625 | off | off | off | off | 4625 | 0 |
| 16 | 4330 | off | off | off | off | 4330 | 0 |
| 17 | 4300 | 11 | 4620 | 14 | 3815 | - | 25 |
| 18 | 4330 | 11 | 4620 | 15 | 4087 | - | 26 |
| 19 | 4200 | 10 | 4200 | 15 | 4087 | - | 25 |
| 20 | 4080 | 10 | 4200 | 15 | 4087 | - | 25 |
| 21 | 4065 | 10 | 4200 | 15 | 4087 | - | 25 |
| 22 | 4065 | 10 | 4200 | 15 | 4087 | - | 25 |
| 23 | 4065 | 10 | 4200 | 15 | 4087 | - | 25 |
| Total, TR-h | 97485 | | 49980 | | 49590 | 49255 | |

* The chiller capacity is multiplied by correction factor (0.649) to convert the water chiller into ice chiller

Adapting a time dependent tariff to encourage savings is investigated. Assume a base tariff structure where the current low rate of 0.016 \$/kWh is fixed as nighttime rate and the daytime rate is maintained

at its level of 0.07 \$/kWh. In this case the daily cost of operation (replace 0.07 by 0.016 \$/kWh in Eq. 5) is 1690.4 \$/d.

The total daily effective cost $C_{d,n}$ as in Eq. 6 becomes 5152.8 \$/d

In this case the daily cost saving including the ice storage is $5702.2 - 5152.8 = 549.4$ \$/d

The above result is based on the suggested full load storage scenario and base tariff structure. In this scenario, the daily saving is 549.4 \$/d, the storage capital cost will be paid in 10 years, afterwards the daily saving in operational cost will be 4011.76 \$/d.

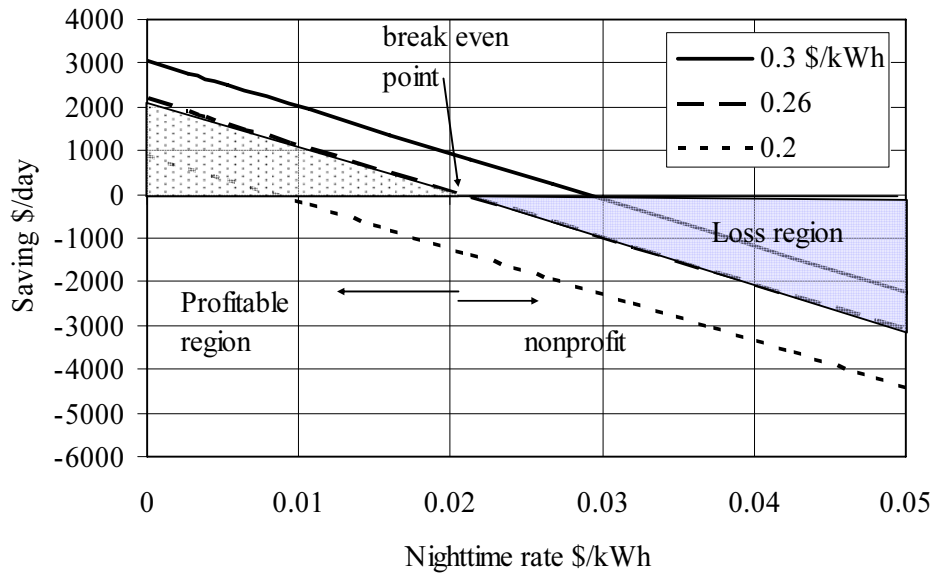


FIG. 7. Dependence of the daily savings on the tariff structure.

Figure 7 shows the saving for different nighttime rates, which indicates that the break-even point is 0.021 \$/kWh (0.077 SR/kWh). As seen in the figure, selecting a daytime rate higher than this value would

not achieve any savings. In addition the break-even point depends on the absolute value of the time rates. In principle, the daily saving is

$$\text{daily saving} = \left(\begin{array}{c} \text{daily operation cost} \\ \text{with flat rate tariff} \end{array} \right) - \left[\left(\begin{array}{c} \text{daily operation cost with} \\ \text{break even point (bep) tariff} \end{array} \right) + \left(\begin{array}{c} \text{daily ice storage tank} \\ \text{contribution} \end{array} \right) \right] \quad (7)$$

The break-even point is determined when the savings in Eq. 7 becomes zero. Changing the off-peak rate between 0.05 and 0.08 \$/kWh changes the break-even point from 0.008 to 0.03 \$/kWh, and consequently changes the saving zone as seen in Fig. 7. To that point, it is of interest to investigate a partial storage scenario and compare to that of the full storage mode.

Scenario 2

5.2. Partial load storing scheme

Inspection of the cooling load (Fig. 4) shows that the peak load falls between 9 AM to 4 PM, where the load reaches 5290 TR. For partial storing the peak load is leveled at 3780 TR so that the energy above this load is supplied from storage tanks. As in the case of full ice storage, some of the chillers operate at their design condition to produce chilled water and others make enough ice to cover the required energy (the shaded area in Fig. 8). The operation schedule of the cold-water chillers starts by operating 9 chillers at full load from 9 PM to 4 AM then shut down one chiller at 4 AM to cover a load of 3000TR. For the next two hours, only 6 chillers cover the 2500 TR load. At 8 AM, an additional chiller is started to raise the load to 2930 TR as shown in Table 2. The operation scenario covers the energy required below the selected level of 3780 TR; the extra loads are covered from the ice storage tank. For example at midnight the required load is 4065, the difference (285 TR) is provided by the ice storage tanks. The advantage of this arrangement is the operation of all water-chilling units at their full load with maximum COP. The ice is built up between 1 AM and 5 AM by operating 11 ice making units for 2 hours then continue for another two hours by 10 units as shown in Table 2 column # 8. The energy stored

during this period is 11448 TR-h while the required energy during the discharge period is 11275 TR-h. Adjusting the control of only one ice-making unit to have a shorter ice-charging period can correct for this difference. Table 2 shows the detailed operation scheme for partial storage scenario.

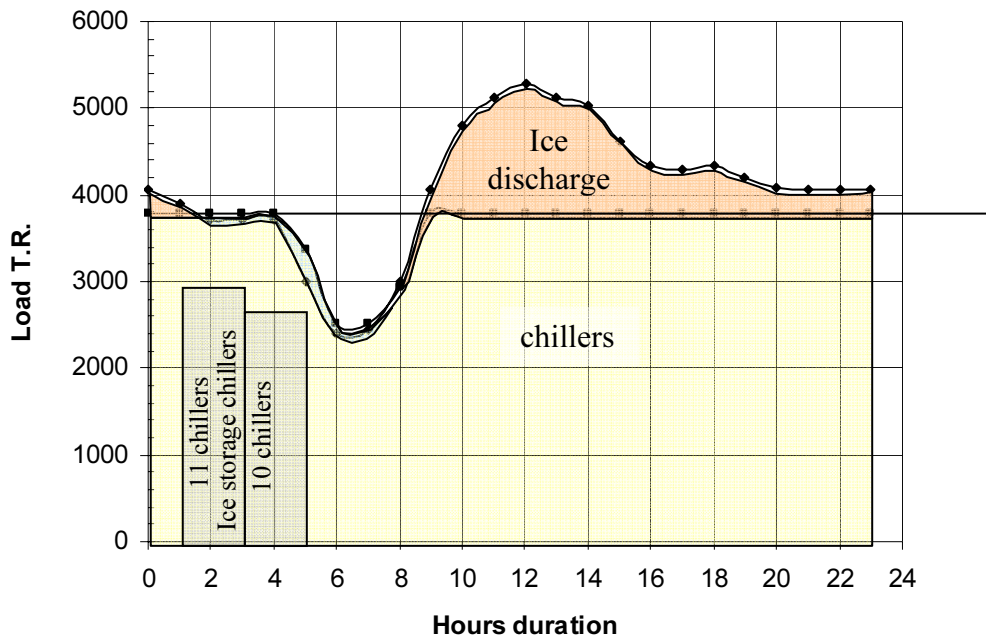


FIG. 8. Partial load storing scenario

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 4.38 for the time between 1 AM-5 AM and 4.01 between 10 AM and 1 PM as estimated from Fig. 5.

TABLE 2. Scenario 2 of cooling load profile in Al Haram Holy Mosque

| 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 TR | Storage discharge TR | No. of Chillers in operation | TR | |
| 0 | 4065 | 9 | 3780 | - | 285 | - | - | 9 |
| 1 | 3900 | 9 | 3780 | - | 120 | - | - | 9 |
| 2 | 3720 | 9 | 3780 | 60 | - | 11 | 2998* | 20 |
| 3 | 3720 | 9 | 3780 | 60 | - | 11 | 2998 | 20 |
| 4 | 3720 | 9 | 3780 | 60 | - | 10 | 2726 | 19 |
| 5 | 3000 | 8 | 3360 | 360 | - | 10 | 2726 | 18 |
| 6 | 2400 | 6 | 2520 | 120 | - | - | - | 6 |
| 7 | 2450 | 6 | 2520 | 70 | - | - | - | 6 |
| 8 | 3000 | 7 | 2940 | - | 60 | - | - | 9 |
| 9 | 4070 | 9 | 3780 | - | 290 | - | - | 9 |
| 10 | 4800 | 9 | 3780 | - | 1020 | - | - | 9 |
| 11 | 5120 | 9 | 3780 | - | 1340 | - | - | 9 |
| 12 | 5290 | 9 | 3780 | - | 1510 | - | - | 9 |
| 13 | 5130 | 9 | 3780 | - | 1350 | - | - | 9 |
| 14 | 5040 | 9 | 3780 | - | 1260 | - | - | 9 |
| 15 | 4625 | 9 | 3780 | - | 845 | - | - | 9 |
| 16 | 4330 | 9 | 3780 | - | 550 | - | - | 9 |
| 17 | 4300 | 9 | 3780 | - | 520 | - | - | 9 |
| 18 | 4330 | 9 | 3780 | - | 550 | - | - | 9 |
| 19 | 4200 | 9 | 3780 | - | 420 | - | - | 9 |
| 20 | 4080 | 9 | 3780 | - | 300 | - | - | 9 |
| 21 | 4065 | 9 | 3780 | - | 285 | - | - | 9 |
| 22 | 4065 | 9 | 3780 | - | 285 | - | - | 9 |
| 23 | 4065 | 9 | 3780 | - | 285 | - | - | 9 |
| Total, TR-h | 97485 | | 86940 | 730 | 11275 | | 11448 | |

* The chiller capacity is multiplied by correction factor (0.649) to convert the water chiller into ice chiller

Following the same calculation procedure and using the data of Table 2 the cost items are summarized as follows,

| | | | |
|-----------|--|---------------|------|
| <i>a-</i> | Operation cost for the total cooling load, 97484 TR-h at a daily average COP of 4.2 and 0.07 \$/kWh | 5702.2 | \$/d |
| <i>b-</i> | Operation cost for the water chillers producing 86940 TR-h at an average COP of 4.2 at 0.07 \$/kWh | 5086 | \$/d |
| <i>c-</i> | Operation cost during ice making period at 0.07 \$/kWh and COP _a of 4.38 (column # 8, Table 2) | 980 | \$/d |
| <i>d-</i> | <i>c</i> Ice storage capital to form 11448 TR-h equivalence of ice in 4 h (10046 kWh storage) at 36.7 \$/kWh | 368,353 | \$ |
| <i>e-</i> | Fixed charges rate for the ice storage capital (300 working days/y and 0.16275 fixed charges rate) | 200 | \$/d |
| <i>f-</i> | Total daily cost with ice storage $C_{d,n} = b + c + e$ | 6266 | \$/d |
| <i>g-</i> | Net daily benefit ($a - f$) | <u>-563.8</u> | \$/d |

Here again, the negative sign means that there is no saving with the partial storage scenario. The reason is the constant electricity rate imposed by the authorities. If the tariff strategy is applied, and an attractive rate of 0.016 \$/kWh is enforced during nighttime (8 AM -8 PM), then the daily ice making cost becomes 226 \$/d instead of 980 \$/d. For this case, the operation cost for the water chillers changes because of the reduced rate at night to become 3187 \$/d. The cost of operation for the chillers without ice storage (item *a* above) drops by benefiting from the low nighttime rate to be 3776.6 \$/d.

- h-* Operation cost for the total cooling load, 97484 TR-h at 0.016 \$/kWh from 8 PM to 8 AM and 0.07 for the day time with daily average COP of 4.2 3776.6 \$/d
- i-* The net daily benefit is then [$h - (226 + 3187 + 200)$] 163 \$/d

As can be seen from the above values, the operating cost of using the ice storage system with base tariff strategy is cheaper than the conventional system. The ice storage investment will be paid back after 10 years, otherwise it is impractical. The saving for the first 10 years is 163 \$/d, while the net daily saving afterwards will be 363 \$/d. Both numbers are not encouraging to implement a partial load storing strategy.

The net daily benefit of applying the partial load storing is much less than that for full load storing, nearly 30%. This indicates that because of the special variation of the cooling load of the Holy Mosque and the abnormal features of the building, the partial load storage is not attractive.

6. Conclusions

This study investigated the potential of installing a thermal energy storage system to the air conditioning plant of a special religious building with unique cooling demand. The Grand Holy Mosque building is the largest religious building on earth and of distinctive features where the large air-conditioned floor area is roof covered and has no walls; it is open to the atmosphere. The worshippers' traffic is in bulk five times daily and demands high cooling load. In addition, hundreds of thousands of worshippers attend the sacred weekend ceremony, which takes place at noontime of maximum ambient temperature. The economic analysis

combines the effects of active energy storage system and a time-structured tariff on the daily utility bill.

The results based on measured cooling load and ambient temperature showed that with the current subsidized electricity rate of 0.07 \$/kWh there is no gain in introducing ice storage system neither for full nor partial load scenarios. Combined utilization of an incentive tariff model and storing technology showed reasonable daily savings for full load storing scheme. Savings out of partial load storing were not attractive even with the structured base tariff (0.016 \$/kWh for night operation and 0.07 \$/kWh for peak period operation). The break even daytime electricity tariff was determined for different conditions.

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Nomenclature

| | |
|------------------|--|
| a^c | capital recovery factor |
| t_{op} | period of operation per year (h) |
| C | unit cost (\$/kWh) |
| C_{el} | unit cost of electrical energy (\$/kWh) |
| COP | coefficient of performance |
| E_{el} | consumption of electrical energy (kW) = \dot{Q}_{evap} / COP_a |
| i_r | interest rate on the capital |
| n | number of operation days per year |
| ny | the period (number of years) of repayment |
| \dot{Q}_{evap} | evaporator capacity Ton-Refrigeration |

Subscripts

| | |
|-----------|-------------|
| <i>a</i> | average |
| <i>ch</i> | chiller |
| <i>el</i> | electricity |
| <i>st</i> | storage |

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الجدوى الاقتصادية لنظم تخزين الطاقة الحرارية: تطبيق على محطة تكييف المسجد الحرام

د. بدر حبيب الله

كلية الهندسة، جامعة الملك عبد العزيز، جدة، المملكة العربية السعودية

تستهلك الدول ذات المناخ الحار كمية كبيرة جدا من الطاقة الكهربائية في أعمال التبريد و التكييف خصوصا في فترة ذروة الاستهلاك اليومي للكهرباء و التي تقع عادة في فترة الظهيرة. و يمكن تحويل الأحمال الكهربائية إلى فترات الاستهلاك المنخفض عن طريق إصدار شرائح زمنية للتعرفة الكهربائية كوسيلة محفزه للتحكم في الاستهلاك أو باستخدام تقنية تخزين الطاقة. تناقش هذه الورقة الجدوى الاقتصادية لكل من بناء نظام خزن حراري و استحداث تعرفه زمنية لاستهلاك الكهرباء لمحطة تكييف الهواء التابعة لبيت الله الحرام في مكة المكرمة (أضخم معبد ديني في العالم). إن خصائص مبنى الحرم فريدة في نوعها حيث أن

المساحة المكيفة من الحرم و التي تقدر بحوالي 39300 م² هي مساحة مفتوحة للجو الخارجي كما أن المصلين يملأون المكان خمس مرات في اليوم. و في يوم الجمعة يحضر مئات الآلاف من المصلين صلاة الجمعة في فترة الظهيرة مما يؤدي إلى زيادة الطلب على الحمل الكهربائي. من أجل التحليل الاقتصادي، فإن فاتورة الاستهلاك اليومي قد استخدمت كدالة أساسية و تتضمن مصاريف التشغيل و رأس المال المستثمر في بناء نظام تخزين ثلجي. تشمل مصاريف التشغيل اليومي الطاقة المستهلكة لتشغيل المحطة و التي يدخل فيها نظام التعرفة و عدد ساعات التشغيل و درجة حرارة الجو كعوامل مؤثرة. تم حساب معامل استرداد رأس المال لنسبة عمولة مقدارها 10% و لفترة استرداد مدتها 10 سنوات. كما تم تطبيق الدراسة على نظام تخزين كامل أو جزئي. أوضحت نتائج الدراسة أنه ليس هناك فائدة اقتصادية من بناء نظام خزن ثلجي سواء لنموذج التخزين الكامل أو الجزئي في ضوء وجود شريحة ثابتة للاستهلاك الكهربائي (0.07\$/كيلووات ساعة). في حالة الجمع بين تخزين الطاقة و إنشاء نظام زمني محفز للتعرفة الكهربائية فإنه يمكن الحصول على توفير معقول في

الفاتورة اليومية. فعلى سبيل المثال فإنه لتعرفة استهلاك الذروة مقدارها 0.07\$/كيلووات ساعة في وقت التشغيل نهارا و 0.016\$/كيلووات ساعة في غير أوقات الذروة فإن توفيراً مقداره 549.4\$/يوم يمكن الحصول عليه لنظام التخزين الكامل. كما أنه يمكن استرداد رأس المال المدفوع في إنشاء نظام التخزين الكامل في فترة 10 سنوات و بعد ذلك يصبح الوفر اليومي في تكلفة التشغيل هو 4011.76\$/يوم.

تم مناقشة تعريفات مختلفة للاستهلاك الكهربائي كما تم حساب تعرفه الاستهلاك الليلي المتعادلة (تتراوح بين 0.008 و 0.03\$/كيلووات ساعة). بالنسبة لنظام التخزين الجزئي فإن الدراسة أوضحت بأنه غير مجدي لهذه الحالة حيث أن قيمة الوفر من هذا النظام غير ذي أهمية.