

# Thermodynamic analysis of an ice slurry thermal energy storage system for decreased size and cost of HVAC systems

## Düşük boyutlu ve düşük maliyetli iklimlendirme sistemleri için bir buz bulamacı ısıl enerji depolama sisteminin termodinamik analizi

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### Abstract

Performance assessment of a cold thermal energy storage (ITES – Ice Thermal Energy Storage) system with ice slurry generation for closed space air conditioning purposes is conducted. A detailed energy and exergy analysis are performed for the baseline system and some parametric studies are also presented for varying environmental conditions. Exergy definition is linked to sustainability and reported with graphical representations. A compressor & condenser unit linked to an ice slurry generator and generated ice is stored at storage tank for specific hours of a day. Stored energy is then discharged to the building through a flat-plate heat exchanger. Thermodynamic analysis results suggest that high capacity cooling can be conducted with low capacity vapor compression refrigeration systems (VCR) by integrating ITES systems, leading to a significantly lower size and lower cost HVAC systems.

**Keywords:** Thermal energy storage, HVAC, Energy, Exergy

### Öz

Bu çalışmada kapalı alanların iklimlendirilmesi için buz bulamacı (ice slurry) üretimi yapan bir buz depolama (ITES-Ice Thermal Energy Storage) sisteminin performans değerlendirmesi yapılmıştır. Temel alınan model için detaylı bir enerji ve ekserji analizi yapılmış, değişen çevre ve sistem koşulları için parametrik çalışmalar rapor edilmiştir. Ekserji konsepti aynı zamanda sürdürülebilirlik ile bağlantılandırılarak grafiksel olarak sunulmuştur. Bir kompresör-kondenser ünitesi buz bulamacı üreteciğine entegre edilmiş ve üretilen buz-glikol bulamacı günün belirli saatlerinde depolanmıştır. Depolanan enerji daha sonra kapalı alana bir düz-plaka ısı değiştiricisi yardımıyla deşarje edilmektedir. Termodinamik analiz sonuçları, ITES yardımıyla düşük kapasiteli buhar sıkıştırma soğutma sistemleri ile yüksek kapasiteli soğutma yapılabileceğini göstermektedir ve bu entegrasyon düşük boyutlu ve düşük maliyetli iklimlendirme sistem kurulumuna öncülük etmektedir.

**Anahtar kelimeler:** : Isıl enerji depolama, İklimlendirme, Enerji, Ekserji

## 1 Introduction

On-peak use of electricity for many purposes brings an additional electricity cost in many countries through the world. Therefore off-peak storage of energy forms to be utilized at on-peak times are of interest in many areas from residential to industrial applications where on-peak power requirement is high [1]. Here, concept of the storage takes the lead with efficient, less complex, and viable design conditions. Cold storage can be made by ice, chilled water, phase change materials (PCM) etc. [2]. Ice thermal energy storage is generally performed using a solution of water and a suitable substance that freezes at lower temperatures than freezing temperature of water, and hence icing process occurs without jeopardizing the evaporator surface to be layered by ice. An ice slurry is generated and stored to be used as a cooling medium at on-peak hours [3].

The CTES technology is simply based on latent heat release or gain through discharging and charging, and this option brings a compact system size compared to that of sensible energy storage. As an example, assuming a 1 °C of energy change of water requires around 79 kg of water in order to provide the same energy content as in melting or freezing of only 1 kg of the same substance [4].

An ice thermal energy storage (ITES) is introduced to an HVAC of large office building integrated with heat recovery and cold air distribution in [5], where projected savings and expected

cost of such integration is reported. The cooling unit of a department store is replaced by an ice storage system to increase the cooling [6]. Cost aspects of ITES (Ice thermal Energy Storage) are discussed in [7] for a Saudi Arabian case, in which integration of such technology is unattractive for flat electricity cost rates, while it is of importance to install ITES technologies when the electricity prices are variable, as expected. A feasibility study for a pre-cooling and TES adapted high school building is conducted in [8], resulting in around 47% annual savings. A difference between the ITES and CTES can be explained with the storage medium. When there is ice in the storage medium, these systems are called as ITES, and called CTES when there is no ice storage, however, the reason for storage is cooling.

This study focuses on the efficiency aspect of an ITES system using a glycol-water solution as the thermal energy storage carrier. Various parameters are taken into consideration for enhanced plant performance and sustainability. An ice slurry generator is adapted with storage for use as the cooling medium at busy hours, while decreasing the size of the HVAC system, significantly.

## 2 System description

In the system, the compressor & condenser unit is linked to an ice slurry generator and generated ice is stored at a storage tank for specific hours of a day. Stored energy is then discharged to the building through a flat-plate heat exchanger.

The considered system is illustrated in Figure 1 with state points and all system components. Vapor compression refrigeration unit (VCR) uses R22 as a working fluid between 40/-12 °C condensing and evaporating temperatures. Energetic COP of the VCR unit is taken to be 2.4 for the baseline model. Evaporator of VCR unit takes the heat of glycol-water mixture and ice slurries are generated. Generated ice is then pumped using a glycol-water pump to the storage tank. Stored ice is then used to cool the air in flat-plate heat exchanger [9]. Following assumptions are made for the VCR system:

- 1-2: Isentropic compression,
- 2-3: Isobaric condensation,
- 3-4: Isenthalpic expansion,
- 4-1: Isobaric evaporation.

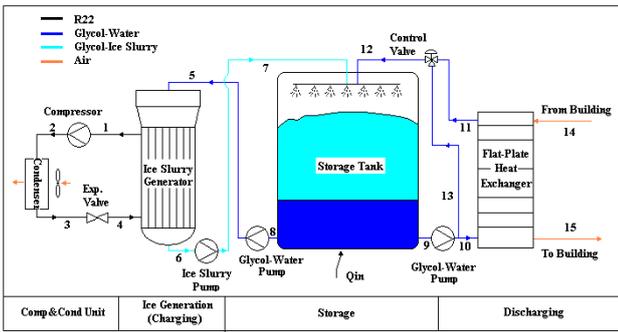


Figure 1: System schematic (Adapted from [9]).

### 3 Analysis and assessment

Since the main target of the study is to perform a thermodynamic assessment for the studied system, many assumptions are made in order to keep the variable system parameters as low as possible resulting in a decreased error through the analysis. Below assumptions are made for the analysis:

- All kinetic and potential effects are neglected,
- All pressure drops during piping is neglected,
- Specific heats of ice, water and glycol does not change by temperature variation,
- Work inputs for pumps and ice slurry generator are assumed to be far too lower than the compressor work, therefore only input to the overall system is assumed to be compressor work,
- VCR system works between 40/-12 °C condensation and evaporation temperatures,
- COP of the system is taken to be 2.4 for the baseline model,
- Other assumed input values required for the system are shown in Table 1.

Cooling capacity profile and obtained data for the building for 24 hour of a day is represented in Figure 2. Charging process is performed during the off-peak hours and additional 2 hours of storage is conducted. Discharging is conducted on the peak hours from 9 am to 18 pm to help decrease the overloads and oversizing of the refrigeration system. This selection decreases the investment cost of the system as well.

Table 1: Property data and range of variation.

Property	Unit	Range
Dead state temperature ( $T_0$ )	K	293-313
Dead State Pressure ( $P_0$ )	kPa	101
Storage temperature ( $T_{st}$ )	K	262
Coefficient of Performance ( $COP$ )	-	2.0-3.0
Evaporator Temperature ( $T_{ch}$ )	K	260-265
Discharge Temperature ( $T_{dis}$ )	K	271-275
Storage Tank Thermal resistance ( $R_T$ )	m <sup>2</sup> K/W	1.98
Latent fusion of water ( $L$ )	kJ/kg	334
Specific heat of water ( $C_w$ )	J/kg °C	4200
Specific heat of ice ( $C_{ice}$ )	J/kg °C	2106
Specific heat of glycol solution ( $C_g$ ) (for 30% concentration)	J/kg °C	3574
Desired building temperature ( $T_b$ )	K	293
Storage area ( $A$ )	m <sup>2</sup>	150

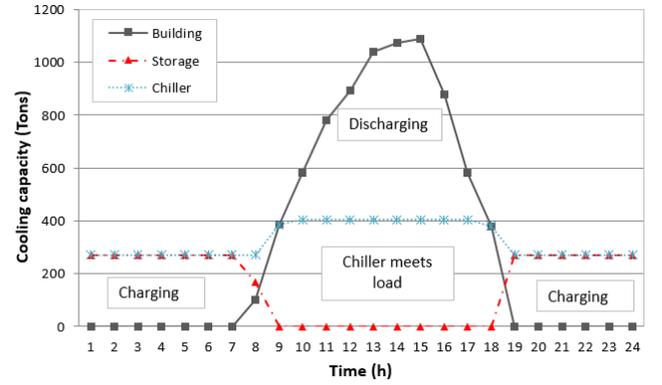


Figure 2: Cooling capacity profile for the building under consideration (partial storage).

Thermodynamic analysis of the system is based on simplified steady-state modeling of all components through mass, energy, entropy, and exergy balances as follows [10]:

$$\sum \dot{m}_i - \sum \dot{m}_o = \Delta \dot{m}_{sys} \quad (1)$$

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{sys} \quad (2)$$

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{des} - \dot{E}x^Q = \Delta \dot{E}x_{sys} \quad (3)$$

$$\dot{S}_{in} - \dot{S}_{out} + \sum (\dot{Q}_r/T_r) + \dot{S}_{gen} = \Delta \dot{S}_{sys} \quad (4)$$

Here, the definition  $Ex$  refers to exergy rate and calculated with its specific form as follows:

$$\dot{E}x = \dot{m} \cdot ex \quad (5)$$

And the specific exergy is the sum of chemical and physical exergy of a substance which are also defined in the flowing equations below, as follows:

$$ex = ex_{ph} + ex_{ch} \quad (6)$$

$$ex_{ph} = (h - h_0) - T_0 \cdot (s - s_0) \quad (7)$$

$$ex_{ch} = \sum x_i \bar{ex}_{ch}^0 - RT_0 \cdot \sum x_i \ln(x_i) \quad (8)$$

The third and fourth components of Eq. (3) refer to exergy destruction and thermal exergy rates as follows:

$$\dot{E}x^Q = \dot{Q} \cdot \left(1 - \frac{T_L}{T_H}\right) \quad (9)$$

$$\dot{E}x_{des} = \dot{I} = T_0 \cdot \dot{S}_{gen} \quad (10)$$

COP of the refrigeration cycle is simply the ratio of heat addition to the evaporator from the glycol-water mixture, and for the exergetic COP, the nominator changes into thermal exergy of added heat while the compressor power remains the same. All components throughout the studied system are individually analyzed using the balance equations given in Eqs. 1 to 4. Given assessment above is for steady state modeling of components. Since air is also used in the system, following definition is used to calculate the entropy change in an ideal gas:

$$\Delta s = c_{avg} \ln\left(\frac{T_f}{T_i}\right) \quad (11)$$

Where,  $c_{avg}$  is the average specific heat of ideal gas. There is also a phase change process from water to ice and vice versa, in which the entropy change is defined as follows [4]:

$$\Delta s = c_{ice} \ln\left(\frac{T_i}{T_f}\right) + \frac{L}{T_{freeze}} + c_w \ln\left(\frac{T_i}{T_f}\right) \quad (12)$$

Where L is the latent fusion of water. Here charging, storage and discharging processes are required to be modeled in a transient manner. Modeling of the overall process needs to be treated non-steadily by considering charging, storage, and discharging processes individually. For the charging process, the energy and entropy balances can be written as follows [4]:

$$m_{g-w}(h_8 - h_7) = m \left( \frac{du}{dt} \right) + \frac{dQ}{dt} \quad (13)$$

$$m_7 h_7 + \frac{m_i s_i}{\Delta t} + \frac{S_{gen}}{\Delta t} = m_f s_f + m_8 h_8 + \frac{Q}{\Delta T} \quad (14)$$

The energy input to the storage tank during storage phase is calculated using the following definition [4]:

$$Q_{in,st} = \frac{A_{st}(T_0 - T_{st})}{R_t} \Delta t \quad (15)$$

Where  $R_t$  and  $A_{st}$  are storage tank thermal resistance and storage area as given in Table 1. The irreversibility occurring through storage is [4]:

$$I = m_w c_{ice} T_0 \ln\left(\frac{T_{st} + \Delta T}{T_{st}}\right) \quad (16)$$

For the discharging process as given in the schematics, following definitions are used to balance the energy and entropy components of this process as follows [4]:

$$m_9 h_9 + \frac{m_i u_i}{\Delta t} = m_{12} h_{12} + \frac{m_f u_f}{\Delta t} \quad (17)$$

$$m_9 h_9 + \frac{m_i s_i}{\Delta t} + \frac{S_{gen}}{\Delta t} = m_{12} s_{12} + \frac{m_f s_f}{\Delta t} \quad (18)$$

Total energy and exergy efficiencies of the Thermal energy storage is calculated as multiplication of efficiencies of charging, storage, and discharging process by the following definitions [1]:

$$\eta_{TES} = \prod_{j=1}^3 \eta_j \quad (19)$$

$$\Psi_{TES} = \prod_{j=1}^3 \Psi_j \quad (20)$$

Energy and exergy efficiencies of all three processes (j=1,2,3), correspond to charging, storage, and discharging, respectively, as given below [1]:

$$\eta_{ch} = \frac{m \Delta u}{E_{in}}, \quad \Psi_{ch} = \frac{m \Delta x_{f-i}}{Ex_8 - Ex_7} \quad (21)$$

$$\eta_{st} = 1 - \frac{Q_{in,st}}{\Delta E_{ch}}, \quad \Psi_{st} = \frac{1 - (ex^Q + I)}{\Delta ex_{ch}} \quad (22)$$

$$\eta_{dis} = \frac{H_{12} - H_9}{\Delta E_{dis}}, \quad \Psi_{dis} = \frac{ex_7 - ex_5}{\Delta ex_{dis}} \quad (23)$$

Finally, overall system energy and exergy efficiencies can be written by considering as the ratio main useful output to the required inputs of energy and exergy contents as follows [1]:

$$\eta_{ov} = \frac{E_{14} - E_{15}}{W_{comp}} \quad (24)$$

$$\Psi_{ov} = \frac{Ex_{14} - Ex_{15}}{W_{comp}} \quad (25)$$

And the sustainability index, which is a connection between the thermodynamic performance of thermal systems with the environmental impacts, is ultimately dependent on the exergy efficiency as follows [1]:

$$SI = \frac{1}{1 - \Psi_{ov}} \quad (26)$$

Given basic thermodynamic model is applied for the system and corresponding results are discussed in detail.

## 4 Results and discussion

Discussion of results and variations of key parameters with the environmental and system parameters are performed in this section. Energy and exergy efficiencies for the baseline model are represented in Figure 3. Energy efficiencies of charging, discharging and storage processes are more than 98%, however, exergy efficiencies of charging and discharging is lower due to losses and irreversibilities by time. For a 150 m<sup>2</sup> of storage area, the size of the system is significantly high, which can be used for medium- to large-size buildings.

Exergy efficiency of charging, discharging, storage and overall ITES are 64%, 98%, 17% and 10.6%, respectively. Irreversibility ratio of each sub unit to overall irreversibility and amounts of irreversibilities are illustrated in Figure 4. Discharging process shows the highest irreversibility ratio and the corresponding irreversibility value due to its relatively higher temperature interaction. 55.7% of total ITES unit irreversibility belongs to discharging, while 43.6% belongs to charging process. Here, storage irreversibility is significantly lower than those of charging and discharging at 0.7%. The main reason of low irreversibility value is the time dependence of the evaluated irreversibility and a short period of storage-only process is considered.

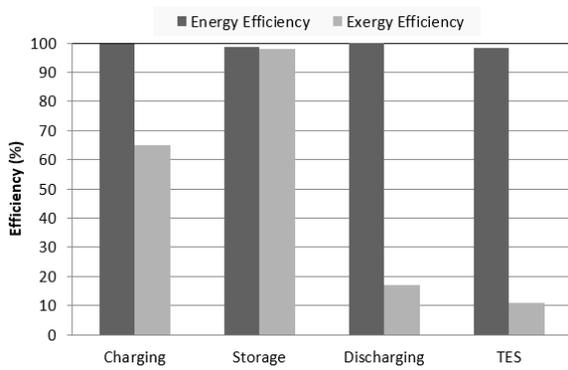


Figure 3: Energy and exergy efficiencies for the baseline model.

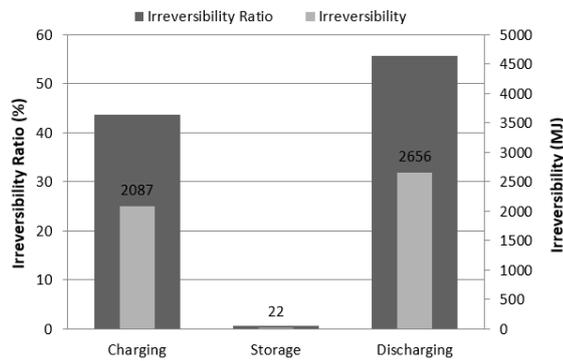


Figure 4: Irreversibility ratio and irreversibilities for charging, storage and discharging process.

COP of the VCR unit is taken to be 2.4 for the baseline model. A system with better COP decreases the power consumption and increases the exergetic COP of the VCR system. Figure 5 illustrates the effect of COP on power consumption and exergetic COP. It is possible and convenient to generate a COP value from the studied VCR unit, however, since the main focus of the study is the overall time-dependent storage process, this assumption is made for analysis simplicity and the COP range at a reasonable span, showing consistency with industrial VCR applications. For the same amount of evaporator cooling load production, higher COP values result in lower power consumption by also significantly increasing the exergy based COP of the VCR system.

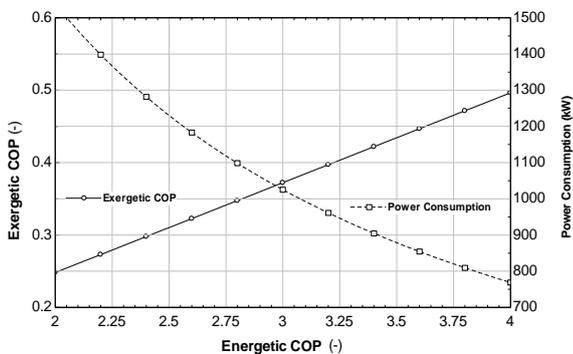


Figure 5: Variation of exergetic COP and power consumption via energetic COP.

Dead state temperature is an influential environmental parameter for evaluation of both energy and exergy efficiencies of all sub units and the overall ITES system since these system are in interaction with environmental conditions. Figure 6 and

7 represents the effect of dead state temperature on energy and exergy efficiencies, respectively. Increasing dead state temperature decreases energy efficiencies of the ITES system but it slightly increases the exergy efficiencies of the ITES system. Heightened ambient temperature provides a better quality ice storage.

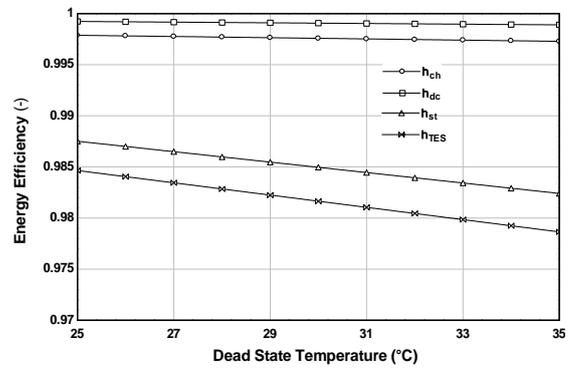


Figure 6: Ambient temperature effect on energy efficiencies of ITES sub-processes.

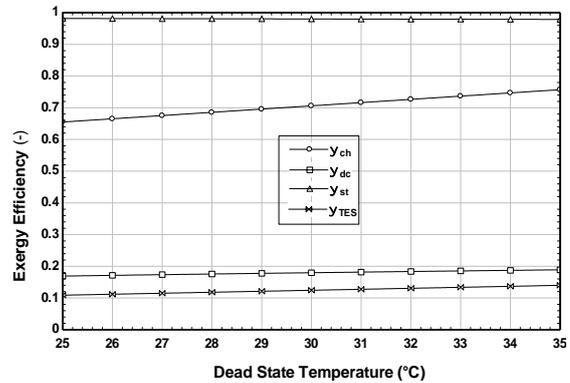


Figure 7: Ambient temperature effect on exergy efficiencies of TES sub processes.

Another way to understand the scope for improvement at the design stage as well as in the existing system is through the sustainability index (SI). Sustainability index is directly related to the exergy efficiency, thus sustainability should be considered together with exergy analysis. Figure 8 illustrates the variation of sustainability index and ITES exergy efficiency by dead state temperature. At higher ambient temperatures both the sustainability index and the overall exergy efficiency increase while the sustainability index shows a higher yield at higher ambient temperatures.

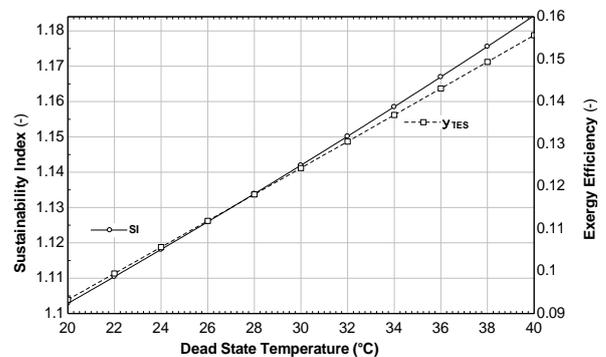


Figure 8: Ambient temperature effect on TES exergy efficiency and sustainability.

## 5 Conclusions

A detailed thermodynamic performance analysis is performed for an ice slurry cold thermal energy storage system and performance parameters are illustrated with parametric studies. Following concluding remarks are extracted from the study:

- Largest irreversibility occurs in discharging process due to losses to environment by time and low efficient heat exchange. Environmental conditions and duration of the process strongly effects the system energy and exergy efficiencies,
- High performance refrigeration system selection decreases the power consumption of such system and increases efficiencies,
- Overall ITES energy and exergy efficiencies are determined to be 98.4%, and 10.9%, respectively,
- Cooling system electricity cost of large buildings can be decreased by installing ITES systems, since these systems are charged at off peak hours while the prices are lower, and especially adaptable in large malls.
- High capacity cooling can be conducted with lower capacity vapor compression refrigeration systems by integrating ITES systems, leading to less capital investment costs.

## 6 Nomenclature

E	: Energy (kJ),
Ex	: Exergy(kj),
L	: Latent heat (kJ),
P	: Pressure (kPa),
Q	: Heat (kJ),
S	: Entropy (kJ/K),
T	: Temperature (C-K),
x	: Concentration (-).

### Greek Letters

$\eta$	: Energy efficiency (-),
$\psi$	: Exergy efficiency (-).

### Subscripts

0	: Ambient,
b	: Building,
ch	: Chemical, Charging,
comp	: Compressor,
dis	: Discharge,
f	: Final,
gen	: Generation,

H	: High,
i	: Initial,
L	: Low,
Ov	: Overall,
Ph	: Physical,
St	: Storage,
sys	: Systems.

### Superscripts

Q	: Heat.
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### Acronyms

COP	: Coefficient of performance,
CTES	: Cold thermal energy storage,
HVAC	: Heating, ventilation, air conditioning,
ITES	: Ice thermal energy storage,
SI	: Sustainability index,
TES	: Thermal energy storage,
VCR	: Vapor compression refrigeration.

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