# Examination of the performance of cooling energy storage system in partial storage mode

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**One strategy to reduce the power consumption in air-conditioning (AC) systems is employing ice thermal energy storage (ITES) systems. ITES facilities are categorized into two groups, full and partial storage modes (FSM and PSM). In this work, initially, an AC integrated with an ITES system is modeled and studied in partial load operating mode. The SEAP2 multi-objective optimization method and multi-objective particle swarm optimization (MOPSO) were applied for computing the optimum amounts of design parameters. Exergy efficiency and total annual cost were considered as two objective functions in multi-objective optimization. The obtained results indicated a difference in the optimum value of the model to the outcomes of the first objective function (exergy efficiency) and the second objective function (total costs). The maximum exergy efficiency for the multi-objective mode in PSM was 39.12%, and the minimum cost was $1152 * 10^5$ US$. Moreover, an assessment of the model displayed that by using ITES, electricity consumption was reduced by 11.83% in PSM. Also, because of heat transfer of cooling load from the peak hours to non-peak hours and reduction of power consumption by 35.12%, there was a reduction in total costs in PSM. The results confirmed that the payback period for the proposed system was 3.43 years. The environmental assessment revealed that this type of system reduces $CO_2$ production. In the end, the influential impacts of using various types of PCMs as the construction have been studied.**

***keywords:*** *Ice thermal energy storage (ITES), air-condition, partial storage mode, energy consumption optimization.*

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## NOMENCLATURE AND SYMBOLS

### Sets

| | |
|---|---|
| $AHU$ | Air handling unit |
| $CESS$ | The cooling energy storage system |
| $Cond$ | Condenser |
| $COP$ | Coefficient of operation |
| $CTES$ | Cool thermal energy storage |
| $D$ | Destruction |
| $e$ | Exit condition |
| $EV$ | Evaporator |
| $F$ | Fuel |
| $GA$ | Genetic algorithm |
| $i$ | Inlet condition |
| $ITES$ | Ice thermal energy storage |
| $K$ | Component |
| $L$ | Loss |
| $P$ | Pressure (bar) |
| $PCM$ | Phase change material |
| $PSM$ | Partial storage mode |
| $PSO$ | Particle swarm optimization |
| $Q$ | Heat (kJ) |
| $R$ | Resistance or gas constant (kJ/kg K) |
| $ST$ | Steam turbine |
| $T$ | Temperature (C or K) |
| $TES$ | Thermal energy storage |
| $Tot$ | Total |
| $\dot{W}$ | Work rate (kW) |
| $\eta$ | Efficiency |

## 1. INTRODUCTION

Introducing innovative facilities for power generation and energy storage are crucial solutions for a promising development[1] –[4]. The basic types of Thermal energy storage (TES) techniques can be described as sensible heat storage (e.g. water and stone) and latent heat storage (e.g. water/ice mixtures and phase change materials (PCMs))[5]. In sensible heat storage, the temperature of the storage material varies with the amount of energy stored in the storage medium (without phase change). In this case, the cost of energy storage media is low. In latent heat storage, energy is stored by changing the phase of energy storage material at a constant temperature (phase change temperature of the material). This kind of energy storage technique provides a high-energy storage density relative to the sensible heat storage method. This means that in the latent heat storage technique, much lower weight and volume of material are needed to store a certain amount of energy[6]. That is why latent TES systems (especially ITES systems and PCMs) were a research subject of interest in the last decade[7]. PCMs can be divided into three major categories: organic, eutectics, and salt hydrates materials. Among these materials, salt hydrates are the most common materials for use in A/C applications. Hydrated salts are specific salts (e.g. potassium fluoride tetrahydrate and calcium chloride hexahydrate that can store cooling energy during their solidification (charging time). When the environment temperature is lower than the PCM solidification temperature, PCMs are in solid-state. On the other hand, they release the stored cooling energy during melting (discharging time) when the environment temperature is greater than their melting temperature[8]. TES systems use all the elements of a non-TES cooling system that is based on chillers. This implies that chillers operating at off-peak times, the minimum (when the consumption is relatively low) leads to ice production or cooling water or fluid, and at on-peak times (when the consumption is high) the storage melts ice or heats water or stored fluid [9]. ITES systems operate in two full and partial operating modes. In full storage mode (FSM), all cooling load required during the on-peak period would be produced by a VCR system of ITES during off-peak hours (charging period), and VCR is off during the on-peak period (discharging period). In partial storage mode (PSM) VCR would operate with nominal load constantly during on and off-peak hours. In partial operation (partial storage), the chiller size is smaller than conventional systems not using TES and operates the whole day continuously. Some studies have been conducted in this regard. Ameri et al.[10] did some studies on two Frame 6 Gas Turbines with an output capacity of 16.6 MW and two Frame 5 Turbines with a capacity of 16.6 MW that supply electricity to Kish Island. Their results showed an increase of MW 5 (about 13.6%) in cooling power output. In a commercial building in Saudi Arabia in 2000, a TES system was used for the building's cooling cycle[11]. In 2002, a combined power-heating system was used in the Netherlands by a variance analysis company[12]. Cool thermal energy storage (CTES) system was established at the main food storage branch in the state of Illinois in America. The results indicated that the annual cost of electricity consumption in this building was 200,000 US$ less than a similar building, 3 km away without a TES system[13].

In PSM, the charging cycle is used to produce ice during low consumption hours and produces 90% of the building's cooling load, and stores it in the storage tank. It has to be noted that the remaining 10% of the required load by the building is provided by the PCMs that have stored the cooling load. Saito studied various types of CTESs and compared their advantages and disadvantages [14]. Dincer and Rosen[15] published a book on conducting energy storage tanks to examine various models of energy storage systems, basic principles, and types of storage tanks. West and Braun[16] proposed two models for examining the performance of a CTES system in PSM. Their modeling only included energy analysis for a partial storage system and a limited demand system. Sanaye et al. [17] showed that an ITES system at PSM has a lower payback period as well as a higher exergy efficiency.

Chen et al. [18] studied and modeled an ITES system and estimated the amount of stored ice and heat transfer rate for charging ITES by a vapor compression refrigeration (VCR) system (with R-22 refrigerant). MacPhee and Dincer[19] evaluated the performance of four major types of ice storage techniques based on energy and exergy analyses in charging and discharging processes. The results showed that energy analysis alone cannot give realistic information of the system behavior, and that is why exergy analysis of the system is essential. Sanaye and Shirazi[20] investigated an ITES system by 3E (energy, exergy, and economic) modeling and analysis. The total cost rate (including investment, operating, maintenance costs as well as the cost of exergy destruction) was the objective function in that study. Energy and exergy analyses of a latent heat storage system with PCM were carried out by Koca et al.[21]; which average net values of energy and exergy efficiencies were obtained from their experimental study.

Hence, this study focuses on the comparison of PSM in optimum ITES design. After analysis, multi-objective optimization of ITES in POM was performed. ITES system included a charging cycle, discharging cycle, and an energy storage tank. Total annual cost (including initial investment costs, maintenance costs, operating costs, and CO2 production penalty costs) was minimized and exergy efficiency was maximized as two objective functions in this study.Therefore, the goals of this study are:

- An ITES system in PSM with all its subsystems and all equipment will be modeled for a similar A/C system and analyzed for exergy, energy, and economic and environmental points of view.
- The optimal values of system design variables have been obtained in PSM with the help of multi-objective optimization using a genetic algorithm (GA). The two objective functions used include the overall cost rate (which is minimized) and the exergy efficiency (which is maximized).
- The performance of the ITES system in PSM will be examined and then compared with a traditional air conditioning system for power consumption and CO2 output.

## 2. METHODOLOGY

In PSM, the charging cycle is used to produce ice during low consumption hours, producing 90% of the building's cooling load that is stored in the storage tank. It has to be noted that the remaining 10% of the required load of the building is provided by the PCMs storing the cooling load. In this model, PCM is considered as a partial supplier of cooling load. At night (charging time), when the ambient temperature is lower than the melting temperature, the cooling load is stored in PCM particles. Bypassing air through the gaps between PCMs, the cooling load is stored in the particles for the subsequent day.

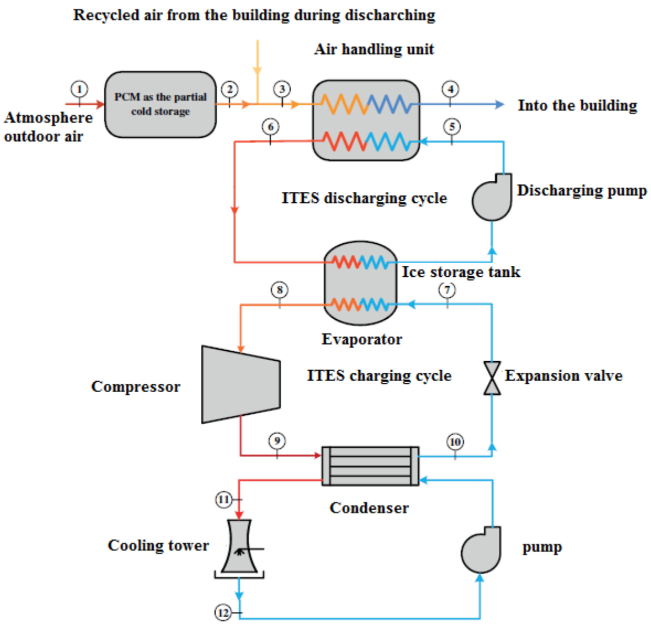

**Fig. 1.** . Modeling an ITES system in partial load mode

The equations used to model this cycle, including air coolant and storage tank as follows. We first examine the characteristics of fluid flow: Reynolds, Prandtl, and Nusselt of the flow are obtained from the following equations[22]:

$$Re_{di} = \frac{4in_{\omega}}{10ud_i\mu_1} \tag{1}$$

$$NU_i = 0.Re_{di}^{0.625}\left(\frac{A_t}{A_b}\right)^{-0.375} Pr_i^{0.333} \tag{2}$$

$$Pr_{\omega} = 11.255exp\left[-0.020IT\right] \tag{3}$$

The cooling load needed for the building (QC) can be obtained as follows:

$$Q_C = \int_{t_{dc}}^{\dot{Q}_c}(t)\,dt \tag{4}$$

Here,$t_{dc}$ is the discharge time. The form of the storage tank is considered cylindrical with equal diameter and height. The reason for this was the studies by Macphee and Dincer[19], showing that such a tank has the lowest heat transfer with the external environment. With these assumptions, the cooling load stored in the tank is obtained from the following equations:

$$Q_{ST} = \frac{Q_C}{\eta_{ST}} \tag{5}$$

$$\eta_{ST} = \frac{Q_{ST} - Q_{l,ch} - Q_{l,dc}}{Q_{ST}} = 1 - \left(\frac{Q_{l,ch} + Q_{l,dc}}{Q_{ST}}\right) \tag{6}$$

The heat leakage from the tank will be a function of the temperature entering the tank, the ambient temperature, the area of heat transfer from the storage tank, as well as the thermal resistance during the charging process, assuming that the constant nature of the temperature distribution inside the tank. If we assume the constant temperature of the tank as TST, then the heat leakage from the storage tank during the charging process($Q_{l,ch}$) can be obtained from the following equation:

$$Q_{l,ch} = A_{ST}\frac{T_{amb} - T_{ST}}{R_{th}}t_{ch} \tag{7}$$

The power consumption of the fan in AHU ($\dot{W}_{fan,AHU}$) can be obtained from the equation provided by Ameri et al.[10] as follows:

$$\dot{W}_{fan,AHU} = \frac{\left(\blacksquare p_0 + \blacksquare p_{fan}\right) \times \dot{V}_a}{\eta_{fan}} \tag{8}$$

In the above equation$\Delta p_0$,$\Delta p_fan$ ,$\dot{V}_a$ and $\dot{V}_a$, respectively, show the decrease in air pressure in AHU, fan pressure drop, air mass flow rate, and isentropic fan efficiency.
For an ITES system with no chemical changes or chemical reactions, exergy only appears as physical changes. Thus, we have the following equation:

$$\dot{E} = \dot{E}^{ph} = \dot{m}\left[(h - h_0) - T_0\left(s - s_0\right)\right] \tag{9}$$

We define the total exergy efficiency (first objective function) for the entire ITES system as follows:

$$\blacksquare_{tot} = \frac{\dot{E}_{out}}{\dot{E}_{in}} = 1 - \left(\frac{\dot{E}_{D,tot}}{\dot{W}_{fan,AHU} + \dot{W}_{pump,dc} + \dot{W}_{cond} + \dot{W}_{pump,cT} + \dot{W}_{fan,cT}}\right) \tag{10}$$

The total cost rate for an ITES system includes the total cost and capital cost for purchasing an ITES system, maintenance costs, operational costs, as well as the penalty costs of producing carbon dioxide in the environment. The total cost (second objective function) can be written as follows[11]:

$$= \dot{Z}_{\mathrm{inv+main}} + \dot{Z}_{\mathrm{op}} + \dot{Z}_{co_2,\mathrm{penalty}} \tag{11}$$

The payback period can be written by the equation presented by Oskunejad as follows because of the addition of new parts in full and partial storage modes[23]:

$$\Delta\left(Z_{op}\right)\left(\frac{(1+i)^p - 1}{i(1+i)^p}\right) + \Delta Z_{sv}\left(\frac{i}{(1+i)^p}\right) = \Delta\left(\sum_k Z_k\right) \tag{12}$$

Here, $\Delta z_s v$ is the salvage cost of an ITES system is in full storage compared to a traditional air conditioning system. The $CO_2$ emitted in an ITES system can be expressed in terms of the equation provided by Wengtal as follows[11]:

$$\begin{aligned} &CO_{2,emission}\left[kg\right] = \mu_{co_2}\left[\mathrm{kg.kwh}^{-1}\right] \times \\ &\mathrm{annual} - -\mathrm{electricity} - \mathrm{consumption} \end{aligned} \tag{13}$$

In the above equation, $\mu CO_2$ is a conversion factor$CO_2$ emitted from the power consumption of the grid, where the value of this parameter is considered 0.968kg $_{\mathrm{kwh}^{-1}}$, according to Wengtal's study[11]. The penalty cost because of $CO_2$ emission is considered US $ 90 per ton $CO_2$ emitted[13]. Thus, the penalty cost for $CO_2$ emitted ($\dot{Z}_{CO_2,\mathrm{penalty}}$ ) can be stated as follows:

$$Z_{CO_2,\mathrm{penalty}} = \frac{\left(\frac{CO_{2,\mathrm{emission}}}{1000}\right) \times CO_{2,\mathrm{emission,penalty}}}{N \times 3600} \tag{14}$$

The list of all design variables for PSM, as well as their correct range, is presented in Table1 [24].

## 3. RESULTS AND DISCUSSIONS

In order to validate our simulations codes, we have used the inputs of Dincer's research [30]. In this case, we have used their data as the input for our codes to estimate the errors. Table2 presents these validations which confirm acceptable accuracy. For the partial operating system, the required cooling load for

**Table 1.** The variables of designing an ITES system in PSM and their correct range[13], [14],[25]

| Variables | Explanations and reasons |
|---|---|
| $3 < T_{in,ST} < 5$ | Nominal data for a compression refrigeration system |
| $11 < T_{out,ST} < 13$ | Nominal data for a compression refrigeration system |
| $-10 < T_{ST} < 0$ | Nominal data for a compression refrigeration system |
| $-30 < T_{EV} < 0$ | Minimum and maximum refrigerant saturation temperature in the evaporator for a wide range of functions and systems |
| $(T_{wb,out}) + 5 < T_{cond} < 60$ | Minimum and maximum refrigerant saturation temperature in the condenser for a wide range of functions |
| $T_{EV} < T_{ST}$ | The necessary condition for heat transfer between the evaporator and the storage tank |
| $T_{FD,Glycol} < T_{ST}$ | The allowable temperature limit for the mixture of water and glycol in the discharge mode |

**Table 2.** The comparison of computed values of system operating parameters with Ref

| Inputs | | Outputs | | |
|---|---|---|---|---|
| Parameters | Values | Parameters | Dincer research [30] | This work |
| $T_{EV}$ (°C) | -20 | $\dot{m}_r$ (kg/s) | 0.2 | 0.2001 |
| $T_{cond}$ (°C) | 40 | $\dot{W}_{comp}$ (kW) | 9 | 9.1043 |
| $\dot{Q}_{EV}$ (kW) | 25.9 | COP | 2.87 | 2.85 |

the building was provided by pumping chilled water through the storage tank. Therefore a smaller storage tank (than that for the full operating mode) was required for supplying the specified cooling load, which means lower investment and maintenance costs for the storage tank for POM state. Furthermore, a smaller VCR system was needed to supply the required cooling load in this operating mode. Moreover, operational costs of the ITES system in partial operating mode include charging and discharging cycle costs. Operational costs in the charging cycle during off-peak hours included costs of electricity consumption for cooling tower pump and fan as well as electricity consumption of VCR compressor. Operational costs during the discharge cycle (for on-peak hours) included all terms mentioned for off-peak hours plus electricity consumption by pumping chilled water to AHU as well as electricity consumption of AHU fans. The optimization technique for the optimal design of an ITES system was studied in an office building in Bushehr. The building is used during office hours from 7 am to 7 pm. The daily load required to supply the cooling section of the building is shown in Figure2.

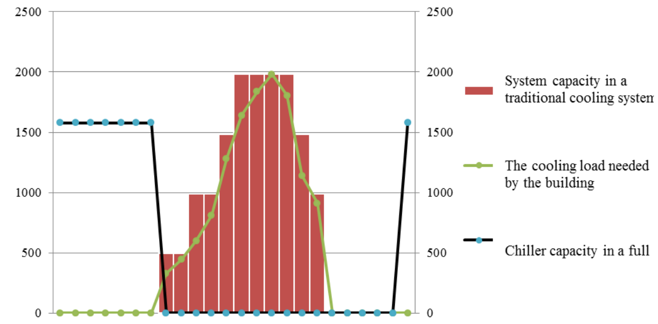

**Fig. 2.** . The nominal load needed by the building at different times of the day, the load produced by the electric chiller system (traditional air conditioning), and the load produced by the partial load storage system

**Table 3.** The cooling load needed by the building and the chiller capacity in the ITES system at PSM (in the case where 10% of the load is provided by PCM =0.1)

| Day hours | Load needed by the building | Chiller capacity and the load stored in the tank at full load mode | Chiller capacity in a traditional air conditioning system |
|---|---|---|---|
| 1 | 0 | 1421 | 0 |
| 2 | 0 | 1421 | 0 |
| 3 | 0 | 1421 | 0 |
| 4 | 0 | 1421 | 0 |
| 5 | 0 | 1421 | 0 |
| 6 | 0 | 1421 | 0 |
| 7 | 0 | 1421 | 0 |
| 8 | 330 | 0 | 495 |
| 9 | 445 | 0 | 495 |
| 10 | 598 | 0 | 990 |
| 11 | 810 | 0 | 990 |
| 12 | 1280 | 0 | 1485 |
| 13 | 1640 | 0 | 1980 |
| 14 | 1836 | 0 | 1980 |
| 15 | 1980 | 0 | 1980 |
| 16 | 1805 | 0 | 1980 |
| 17 | 1140 | 0 | 1980 |
| 18 | 910 | 0 | 990 |
| 19 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 |
| 22 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 |
| 24 | 0 | 1421 | 0 |

**Table 4.** Thermo-physics properties of the PCM material used in the reference[29]$Mn\,(NO_3) - 6H_2O$

| Value | Properties |
|---|---|
| 27 | Melting point ($^oC$) |
| 1890 | Density in solid state ($kg/m^3$) |
| 1480 | Density in liquid state ($kg/m^3$) |
| 1.52 | Specific heat (solid) ($kJ.kg^{-1}.K^{-1}$) |
| 2.22 | Specific heat (liquid) ($kJ.kg^{-1}.K^{-1}$) |
| 194.32 | Latent heat of melting ($kJ.kg^{-1}$) |

Table2 provides a good approximation of the energy stored in the storage tank in PSM for the charge and discharge cycles. The refrigerant used in the compression refrigeration system used in the modeling is considered to be R152a, and its characteristics have been extracted from commercial software. Thermodynamic resistance ($R_{th}$) of the reservoir tank in full and partial storage modes is considered as 1980 $m^2kWh^{-1}$[26]. The optimal temperature for building staff comfort is considered as temperature efficiency from 19 to 22, and relative air humidity in which humans do not feel discomfort is considered from 45% to 55% humidity [27]. Environmental pressure has been considered once in Iran due to the coastal nature of Bushehr, Iran. The price of household electricity at on-peak was $ 0.09 per kilowatt and at off-peak $ 0.060 per kilowatt-hour [20], [28]. The material used in PCM is hexahydrate manganese nitrogen $Mn\,(NO_3) - 6H_2O$, whose melting point is very close to the temperature of human thermodynamic comfort. The thermo-physics properties of the PCM used in this report are shown in Table4. Moreover, to calculate the CRF stated in the first reference report, the annual interest rate, the approximate lifetime of the system, and the maintenance coefficient are 15%, 15 years, and 1.06, respectively, of the total initial investment cost[28]. Revenues from salvage ($\Delta Z_{sv}$)were considered as 10% of the total capital cost for all three systems: complete storage, partial storage, and traditional air conditioning [27],[28]. The charge time in full storage mode for the building was from 12 am to 7 am and discharge from 7 am to 7 pm. Thus, N, which is the annual operating hours between the warm months, from March to December, is 2100 for charging and 3600 for discharging.

The following is the range of design parameters in which optimization is performed using the MOPSO algorithm in their range (Table5). The Pareto-front curve for optimal multi-objective solution for PSM is shown in Figure3. As Fig-

**Table 5.** Designing variables of an ITES system in PSM and their correct range

| Variables | Explanations and reasons |
|---|---|
| $5 < T_{in,ST} < 7$ | Nominal data for a compression refrigeration system |
| $11 < T_{out,ST} < 13$ | Nominal data for a compression refrigeration system |
| $-10 < T_{ST} < 0$ | Nominal data for a compression refrigeration system |
| $-30 < T_{Ev} < 0$ | Minimum and maximum refrigerant saturation temperature in the evaporator for a wide range of functions and systems |
| $(T_{wb,out}) + 5 < T_{Cond} < 60$ | Minimum and maximum refrigerant saturation temperature in the condenser for a wide range of functions |
| $0 < T_{in,ST} < 0.1$ | Due to spatial constraints |
| $T_{Ev} < T_{ST}$ | The necessary condition for heat transfer between the evaporator and the storage tank |
| $T_{FD,Glycol} < T_{ST}$ | The allowable temperature limit for the mixture of water and glycol in the discharge state |

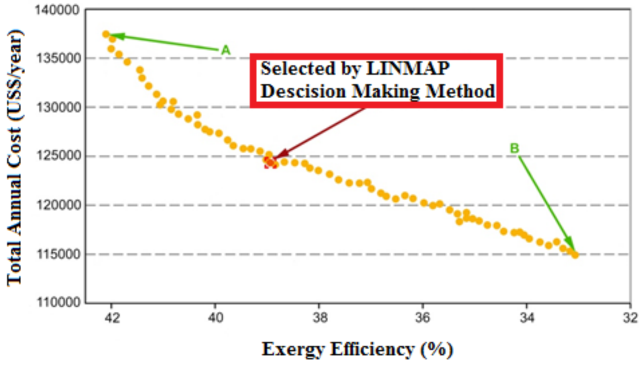

**Fig. 3.** Pareto-front in PSM

**Table 6.** The optimal value of system designing parameters for all three optimization methods in PSM

| Objective functions | LINMAP selection method | TOPSIS selection method |
|---|---|---|
| Exergy efficiency on PSM | 39.12 | 39.63 |
| Total cost on PSM | $1.242 \times 10^5$ *US$* | $1.253 \times 10^5$ *US$* |

ure3 shows, the highest excerpt efficiency belongs to point A (1.377×10+5/year), which corresponds to the highest rate of cost. On the other hand, point B corresponds to the lowest exergy efficiency (33.11%). This point also corresponds to the lowest cost rate ($1.152 \times 10^5$US$ per year); thus, if the exergy efficiency is examined as the only objective function, point A is selected as the optimal value possible, but point B is chosen as the optimal possible value if the lowest value of the cost rate is considered as the only objective function. In this study, after the non-dimensionalization of the objective functions, two conventional methods for selecting the optimal point - LINMAP and TOPSIS - have been studied and evaluated. For PSM of the ideal point, the non-ideal point, the point at the shortest distance from the ideal state (LINMAP) is shown in Figure3. The results in Table (4-6) show that both selection methods for determining the optimal point obtain the excerpt efficiency in an almost identical range (In PSM, 39.12% for LINMAP, and 39.63% for TOPSIS). However, the overall cost in PSM differs about $ 11,000 between the two methods of selecting, LINMAP and TOPSIS, which is a significant value. Given the significant reduction in costs in the LINMAP method for PSM, this method was used for PSM, and only the point selected by the LINMAP method is shown in the figure. Table (7) shows the optimal numerical values with the help of the LINMP selection method in PSM for designing variables in single-objective and multi-objective modes. In this study, the ITES system in PSM (Partial load system means a part of its cooling load is on PCM) is modeled for the same system (A / C). Figure (2-5) shows an outline of this modeling for PSM. Overall, one can state that an ITES system has two main parts:

**Table 7.** Optimal mode value for exergy efficiency and annual total cost for TOPSIS-LINMAP methods of selecting for PSM

| Designing parameter | Single-objective (objective function 1) | Single-objective (objective function 2) | Multi-objective (objective functions 1 and 2) |
|---|---|---|---|
| $T_{in,ST}$ ($^oC$) | 3.86 | 4.93 | 4.49 |
| $T_{out,ST}$ ($^oC$) | 12.71 | 11.02 | 11.75 |
| $T_{ST}$ ($^oC$) | -4.12 | -2.19 | -2.86 |
| $T_{EV}$ ($^oC$) | -6.18 | -4.15 | -5.08 |
| $T_{cond}$ ($^oC$) | 37.83 | 40.18 | 38.54 |

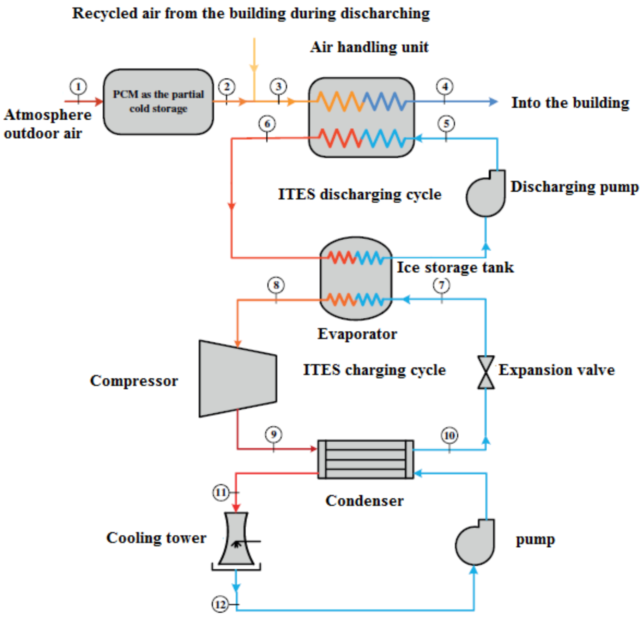

**Fig. 4.** Modeling an ITES system in partial load mode

1- Charging cycle which includes a compressor, condenser, evaporator, cooling tower, expansion valve, and so on.

2. Discharge cycle, which includes air handling unit (AHU), discharge pump, ice storage tank, PCM, and so on In PSM, the charge cycle operates to produce ice during off-peak hours, producing 90% of the building cooling load that is stored in a storage tank. It is worth mentioning that the remaining 10% of the required load of the building is provided by PCMs that have stored cooling loads in them. In this model, PCM is considered as a partial supplier of cooling load. At night (discharge time) when the ambient temperature is lower than the melting temperature, the cooling load is stored in the PCM particles. As air passes through the gaps between the PCMs, the cooling charge in the particles is stored for the next day.

The optimal values of excerpt efficiency in PSM for optimal objective function 1, objective function 2, and multi-objective mode are 33.11%, 41.93%, and 39.12%, respectively (Table8). Moreover, from an economic point of view, the optimal design points for PSM in the single-objective mode as well as multi-objective mode are shown in Table (9). The power consumption in PSM compared to a conventional compression refrigeration system is shown in Figure (5-6). The partial load mode reduces the operating costs by transferring the operating hours of the system to low consumption hours. Moreover, in the case of a partial load, as ten percent ($\alpha$=0.1) of the required load is provided by PCM, the cost is reduced from this perspective in this case. After reimbursing the additional costs of using the ITES system in PSM, the reduced costs are considered the operating cost as the stored costs for the system. Figure6 shows that the power

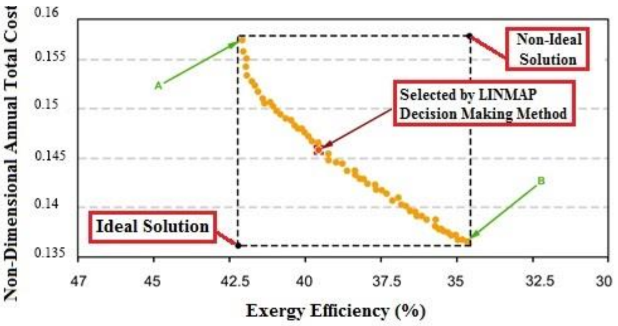

**Fig. 5.** Pareto-front diagram of objective functions in the non-dimensionalized mode for partial load mode

**Table 8.** The results of exergy and energy analysis for all three optimization methods in PSM

| Exergy waste (kW) | Single-objective 1 | Single-objective 2 | Multi-objective |
|---|---|---|---|
| CO2 produced annually | 1960000 | 170000 | 1800000 |
| AHU | 109.49 | 136.21 | 116.38 |
| Storage tank | 63.12 | 84.42 | 70.78 |
| Evaporator | 20.25 | 29.22 | 22.35 |
| Compressor | 27.4 | 39.63 | 30.47 |
| Pressure valve | 64.6 | 72.28 | 66.18 |
| Condenser and cooling tower | 27.25 | 34.58 | 28.43 |
| Exergy efficiency (%) | 41.93 | 33.11 | 39.12 |
| PCM required | 19435 | 2167.1 | 17850 |

**Table 9.** The results of exergy and energy analysis for all three optimization methods in PSM

| The cost of different components | Single-objective 1 | Single-objective 2 | Multi-objective |
|---|---|---|---|
| AHU | 0.2505 | 0.2092 | 0.2144 |
| Storage tank | 0.2152 | 0.1945 | 0.1982 |
| Evaporator | 0.1231 | 0.1025 | 0.1077 |
| Discharge pump | 0.041 | 0.0208 | 0.0229 |
| Cooling tower pump | 0.0385 | 0.0212 | 0.0244 |
| Compensation co2 | 0.1905 | 0.1643 | 0.1699 |
| Condenser and cooling tower | 0.2856 | 0.191 | 0.2153 |
| Heat exchanger | 0.0007869 | 0.0003423 | 0.0004471 |
| Compressor | 0.3008 | 0.2493 | 0.261 |
| Total annual cost | $1.377 \times 10^5$ | $1.152 \times 10^5$ | $1.242 \times 10^5$ |

**Table 10.** Reduction of electricity consumption in ITES systems compared to traditional air conditioning

| System type | The percentage of electricity consumption reduction |
|---|---|
| PSM | 11.83% |

consumption for an ITES system is slightly lower than that of a traditional air conditioning system. This difference is because the cooling produced in the traditional air conditioning mode is much higher than in the ITES mode. However, ITES (partial storage) systems produce the same amount of cooling load (by controlling the amount of pumped cold water). Although the evaporator temperature in ITES mode (Multi-objective solution) is lower than in traditional air conditioning, the fact that in traditional air conditioning is more than the required amount of cooling load makes the overall operating costs of an ITES system less than being a traditional air conditioning system. As stated in the above line, and ITES system consumes less electricity than a traditional air conditioner. This lower power consumption reduces Co2 emission, the results of which are given in Tables (10) and (11).

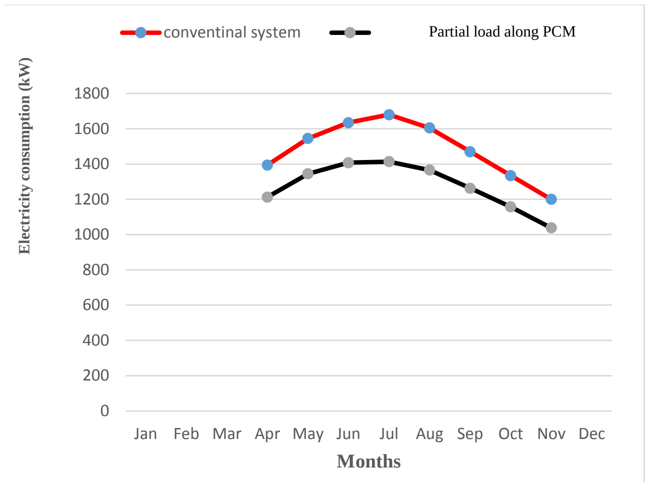

**Fig. 6.** Comparison of power consumption between a system (A / C) in PSM and traditional air conditioning mode

**Table 11.** Reduction of Co2 emissions in ITES systems (compared to the year)

| System type | Co2 reduction in kg |
|---|---|
| PSM | $0.605 \times 10^6$ |

Reducing operational costs because of using ITES will offset the additional investment costs for the ITES system (partial storage). The results are shown in Table (12). Finally, payback period, for an ITES system that has been replaced by a traditional air conditioning system, a partial storage system of about 3.43 years is obtained due to the additional costs of the subsets. This is because, in the partial storage system, a much smaller energy storage tank and a smaller compression refrigeration system are used compared to the full storage mode, which reduces the overall costs and leads to a smaller payback period in PSM. The results of the two objective functions (excerpt efficiency and annual cost rate) for the two objective functions are shown in the SEAP2 optimization algorithm. In Figure (7), objective function 1 is the rate of expenditure in dollars per second, and objective function 2 is efficiency exergy. Table (5-11) shows a comparison between the results obtained by the two algorithms. One of the objectives of this study is to compare different types of materials with phase change capability (PCM) so that a consistent pattern for using PCM materials can be achieved. Overall, PCMs are divided into two general categories, organic and inorganic. Table14 shows the exergy efficiency for the PCMs introduced above. The results show that manganese nitrate hexahydrate has the best performance efficiency in terms of exergy efficiency. It should be noted that inorganic PCMs have cost far less than organic and salt hydrates.

## 4. CONCLUSION

An ITES (including equipment for charging and discharging cycles) for an AC application at partial storage mode was modeled and analyzed by the energy, exergy, economic, and environmental features. The system was then optimized using SEAP2 and

**Table 12.** . Percentage of reduction of operational costs because of using ITES system compared to traditional air conditioning

| System type | Percentage of reduction in operational costs due to changes in peak hours |
|---|---|
| PSM | 35.94% |

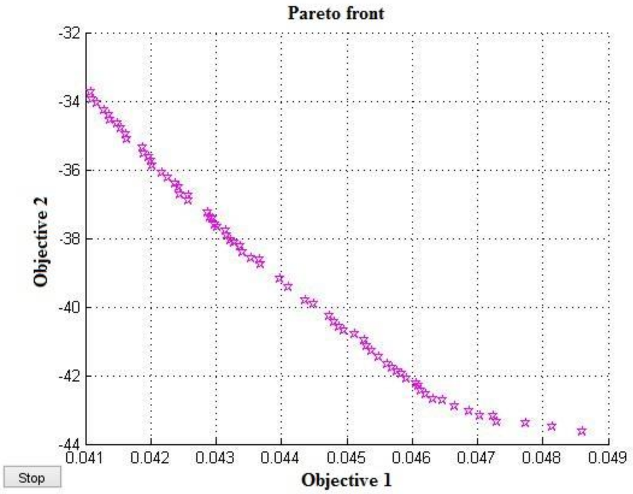

**Fig. 7.** Pareto-front diagram for objective functions obtained by SEAP2 algorithm in partial load mode

**Table 13.** Comparison of the results for objective functions by MOPSO and SEAP2 algorithms

| Objective functions | The results of the MOPSO algorithm | The results of the SEAP2 algorithm |
|---|---|---|
| Exergy efficiency in PSM (%) | 39.12 | 38.49 |
| Total cost in PSM (US$) | $1.242 \times 10^5$ | $1.267 \times 10^5$ |

**Table 14.** Comparison of the results for objective functions by MOPSO and SEAP2 algorithms

| PCM name | Exergy efficiency obtained by MOPSO SEAP2 (%) | Exergy efficiency obtained by MOPSO (%) |
|---|---|---|
| $KF - 4H_2O$<br>Potassiumfluoridetetrahydrate | 34.06 | 34.23 |
| $Mn(NO_3)_2 - 6H_2O$<br>Manganesenitratehexahydrate | 38.88 | 39.12 |
| $CaCl_2 - 6H_2O$<br>Calciumchloridehexahydrate | 37.92 | 38.27 |
| $CH_3(CH_2)_{16}COO(CH_2)_3CH_3$<br>Butylstearate | 34.16 | 34.18 |
| $CH_3(CH_2)_{11}OH$<br>1 − dodecanol | 37.76 | 37.94 |
| $CH_3(CH_2)_8COOH$<br>Capric − lauricacid | 37.45 | 36.89 |
| Cyprylic acid | 31.22 | 31.27 |
| Lactic acid | 35.72 | 35.95 |
| Potassium fluoride tetrahydrate | 31.96 | 32.18 |
| Calcium chloride hexahydrate | 34.55 | 34.72 |
| Lithium nitrate trihydrate | 35.23 | 35.7 |
| Paraffin blend$(n = 16 - 18)$ | 33.10 | 33.57 |

MOPSO methods by defining exergy efficiency and total annual cost (including investment costs, maintenance costs, operational costs, and also penalty costs due to $CO_2$ release for generation of electricity consumption by the system) as objective functions. Objective functions were considered as overall cost rates (including initial capital costs, maintenance costs, operating costs, and compulsory $CO_2$ production charges which should be minimized) and exergy efficiency (which should be maximized). The main results of this research are as follow:

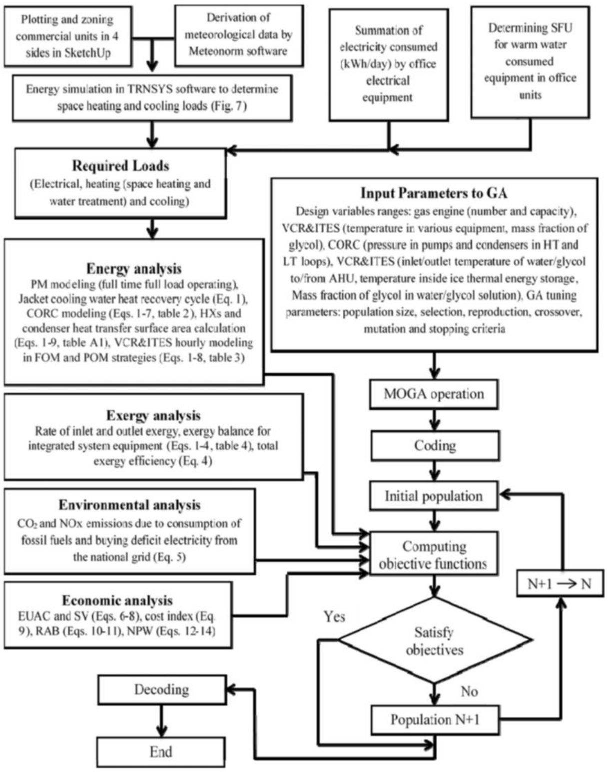

**Fig. 8.** Flowchart of modeling and optimizing the proposed system

- The maximum exergy efficiency for the multi-objective study in the partial storage mode was 39.12%.
- The minimum total cost rates for the multi-objective study in partial storage mode was 1152 $\times 10^5$US$, each
- The assessments of the model of this study showed that due to the use of ITES by 11.83% in partial storage mode, we have a reduction in electricity consumption. which corresponded to a reduction of 3159 US$ (equal to 11.08% of the overall total) annual operating cost in partial storage mode, in comparison with that for the conventional system. Also, operational costs decreased 13.45% (3848 US$), owing to conveying the power consumption for providing cooling load from on-peak hours to off-peak hours.
- Due to the transfer of cooling load from peak hours to low consumption and reduced 35.12% power consumption in partial storage have a reduction in operating costs compared to a traditional air conditioning system. This reduction in costs compared to a conventional air conditioning system compensates for the additional costs of adding ITES to an A/C system.
- In the end, the results showed that the payback period for an ITES system in partial storage mode is 3.43 years.
- The total stored cost of this system after the useful life of the set (15 years) is more than the partial storage mode. As a result, it is up to the consumer to decide whether to opt for a shorter return on investment or to save more after 15 years.

- Additionally, the lower electricity consumption of ITES in comparison with that for a conventional system is equivalent to produce less amount of $CO_2$ for generating electricity. Results showed that the annual decrease of $CO_2$ production for the lower need for electricity consumption by ITES is $0.587 \times 10^6$ kg/year. Ultimately, it has to be noted that using the ITES system reduces $CO_2$ emissions that bring about a reduction in environmental pollution.

Finally, it should be noted that the use of the ITES system reduces $CO_2$ production, which reduces environmental pollution. The results also show that manganese nitrate hexahydrate has the highest exergy efficiency. In this original research paper, we have investigated a wide range of PCMs. The lacks of access to all economic, technical, and environmental information of other types of PCMs were a major obstacle to develop this research to other aspects. More researches on some other specific types such as paraffin wax, polyethylene glycol (PEG), Hygroscopic materials, Heptadecanone, Cyanamide, etc. with applicable additives can be conducted. Moreover, for the proposed cycle, using advanced exergy analysis for further investigations can specify exogenous, endogenous, avoidable, and unavoidable exergy destruction rates for all involved components.

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