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Optimization strategy for system management of cold thermal energy storage (CTES) in conditions of dynamic changes in energy carrier value

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In world of contemporary challenges involving the continual increase in demand for energy resources and corresponding environmental pollution, the necessity has arisen to develop and implement advanced technologies to reduce energy consumption. This calls for enhancing energy utilization efficiency and optimizing energy generation systems, taking into account the utilization of alternative and renewable energy sources. Specifically, thermal energy storage becomes crucial as an effective economic option. Thermal energy storage systems enable meeting heating or cooling needs during optimal periods when it is more energy-efficient. Traditional management methods rarely prove optimal due to fluctuating electricity tariffs, cooling loads, and ambient temperature. This leads to suboptimal achievement of maximum savings in the utilization of thermal energy storage systems. In this work, the advantages of Cold Thermal Energy Storage (CTES) systems based on Ice Thermal Energy Storage (ITES) were analysed alongside existing management strategies implemented in most enterprises and buildings utilizing ITES. A simplified engineering methodology for analysing the thermodynamic efficiency of CTES was proposed. It was determined that cold losses during exergy analysis during storage are caused by both losses through surfaces and internal exergy losses (i.e., exergy consumption due to irreversibility within the reservoir). For modern systems, exergy losses encompass both external and internal components. As an example, if the heat transfer at the external surface temperature of the storage reservoir equals the ambient temperature, external exergy losses would be zero, while total exergy losses would be entirely due to internal consumption. Conversely, if heat transfer occurs at the liquid's temperature for storage, a greater portion of exergy losses will be due to external losses. In all cases, the cumulative exergy losses, comprising internal and external exergy losses, remain constant. The implementation of CTES allows for shifting the use of electrical energy from peak to off-peak hours. During off-peak hours, electrical energy is used to charge the storage to fulfil (fully or partially) the peak demand for refrigeration equipment. Ice-based ITES has the potential to reduce maximum energy consumption, peak demand, and most importantly, the average cost of energy consumed.

Keywords: *Energy resources; Energy consumption; Renewable energy sources; Utilization; Thermal energy storage; Heat transfer*

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1. Introduction

Environmental conservation. Reducing energy consumption in cooling systems through the application of CTES (Cold Thermal Energy Storage) leads to decreased CO_2 emissions, resulting in mitigated global warming. In recent decades, peak demand management for low-grade energy (cooling) has become an active research area. Various strategies for altering energy loads have been developed to reduce overall operational costs without compromising the quality of the cooling supply. As noted in the International Energy Agency report, an annual saving of \$10-15 billion solely in the US municipal cooling market can be achieved through peak demand management for low-potential energy [1].

The benefits of Ice Thermal Energy Storage (ITES) systems are twofold. ITES can address the issue of limited capacity prevalent in many modern cooling systems [2] due to increased demand for improved cooling quality. Through ice storage (ice accumulator), these systems can not only meet high peak demands for cooling during periods of high temperatures but also enhance overall productivity and efficiency [3, 4]. More importantly, by managing the appropriate distribution between periods of storage and release of cold according to the time of use (TOU) electricity cost, overall operational costs for chiller installation and ITES system are significantly reduced [5, 6, 11-13].

Management of ITES systems, commonly applied in most enterprises and buildings, relies on rather simple strategies: either manually controlled or constrained by accumulator capacity and priorities. However, such an approach doesn't leverage the full potential of the available storage and often doesn't yield significant economic benefits [7, 8, 10]. Various models and algorithms, such as the Genetic Algorithm GA [6, 15, 23], Particle Swarm Optimization PSO [9, 24], Mixed-integer Linear Programming MILP [21, 22, 25], and Mixed-Integer Nonlinear Programming MINLP [20, 26], have been extensively utilized in research to address optimization issues. However, all mathematical methods implementing the strategic model only make sense if the optimization problem is reliable, meaning it's based on an objective optimization criterion, clearly formulated dynamic objective functions and closure conditions.

2. Optimal management strategy for ITES system

In developing relevant optimization models, it is crucial to formulate an optimization criterion that objectively evaluates the viability of integrating ITES into the cooling system. Considering recent trends in data collection and analysis, an optimal management strategy can now be devised using real efficiency data. By leveraging this data, it becomes possible to tailor optimal solutions aimed at enhancing its operation and overall efficiency.

Objective function of optimization

For a system comprising chillers and storage units, the total annual cost encompasses the capital expenses of chillers C_{ch} and ice storage C_{st} in addition to the yearly operational costs. The latter is a function of the maximum operating period, consumed electrical energy E_{el} and the cost of electrical energy e_{el}. The overall annual cost can be expressed in a general form as:

$$C_{total} = a^{c}\left(C_{ch} + C_{st}\right) + \int_{0}^{top} e_{el} E_{el}, \tag{1}$$

where a^c – represents the capital return coefficient, defined as $a^c = i^r\,(1 + i^r)\,n_i\,/\,((1 + i^r)\,n_i - 1)$, and when multiplied by the total investment amount, yields the annual repayment required to recover the investments over a specific period (n_i); i^r – denotes the interest rate on capital.

For industrial facilities' cooling systems and air conditioning, the load is determined by the temporal variation of cooling load, which, in turn, depends on the type of load and significantly on environmental conditions. Additionally, the cost of electricity is evidently a deterministic factor, thus necessitating a careful examination of various electricity tariff rates, usage times, fixed electricity costs, consumer tariffs, and any other structured accounting method.

Consequently, the subject of cost minimization should be the variable component in equation (1), namely:

$$\begin{aligned} M &= \min \sum_{i=0}^{23}\left(e_{el_i} \cdot E_{el_i}\right) = \\ &= \min \left[\sum_{9}^{22} \left(e_{el_i} \left(\frac{Q_{ch_i}}{COP_{chiller}} + \frac{Q_{ch_i}}{COP_{pump}} + \frac{Q_{ch_i}}{COP_{ct}} \right) \right) + \right. \\ &\left. + \sum_{9}^{22} \left(e_{el_i} \frac{Q_{st_i}}{COP_{ice}} \right) + \sum_{23}^{8} \left(e_{el_i} E_{chr} \right) \right], \end{aligned} \tag{2}$$

where Q_{ch_i}, Q_{st_i} – represent the chiller and ice storage system loads; $\mathrm{COP}_{chiller}$, COP_{ice} – denote the coefficients of performance for chillers and ice accumulators (the ratio of total cooling load Q_0 to total consumed electrical energy E_{tot}).

$$\mathrm{COP} = \frac{Q_0}{E_{tot}}. \tag{3}$$

COP_{pump}, COP_{ct} – represent the efficiency coefficient of the pumping system and cooling towers; E_{chr} – stands for the electrical energy consumption for charging the ice accumulator.

Efficiency coefficients. This evaluation method holds an advantage in accounting for changes in Coefficient of Performance (COP) under partial loads, stemming from various condenser adjustments while considering air/water temperature variations under consistent chilled water flow conditions.

Refrigeration machine (chiller). The energy efficiency of a refrigeration machine primarily relies on the variation in temperature settings throughout the day and operational periods, along with the level of part load rate (PLR).

In VDMA 24247-2 «Energy efficiency of refrigeration systems – Requirements for the system design and the components», the COP of an actual refrigeration system is compared against the Carnot cycle between the «warm» temperature T_U and the «cold» temperature T_N sources:

$$\eta_{\mathrm{COP}} = \frac{\mathrm{COP}_{real}}{\mathrm{COP}_{reference}} = \frac{\mathrm{COP}_{real}}{\mathrm{COP}_{NUC'}}, \qquad (4)$$

where $\mathrm{COP}_{NUC} = T_N/(T_U - T_N)$.

This coefficient is known as the «energy efficiency level», equivalent to the «total energy efficiency». It mirrors the «exergetics efficiency» of the chiller, representing the «second law efficiency».

The impact of the temperature regime on the cycle. A real chiller cycle between temperatures T_0 and T_c demands more power consumption compared to the Carnot cycle between temperatures T_N and T_U, assuming both processes have equal cooling performance.

Therefore, if $\eta_{\Delta T} \approx$ const, the equation becomes:

$$\mathrm{COP}_{OC} = \eta_{\Delta t} \cdot \mathrm{COP}_{NUC} = \\ = \eta_{\Delta t}\left[\frac{T_N}{T_U - T_N}\right] \approx const\left[\frac{T_N}{T_U - T_N}\right], \qquad (5)$$

where $\eta_{\Delta T}$ – represents the energy efficiency level, COP_{OC} – stands for the efficiency coefficient considering solely the impact of the cycle temperature difference (disregarding the influence of other chiller operation parameters). Thus, equation (5) describes what is termed as a partial or «isolated» system function (partial system function).

If, in the first approximation, it is assumed that $\mathrm{COP}_{OC} = \mathrm{COP}_{OCc}$, where COP_{OC} – is the efficiency coefficient of the reverse Carnot cycle within temperatures T_0 and T_c, then it can be expressed as:

$$\mathrm{COP}_{OC} \approx \frac{T_0}{T_C - T_0} = \eta_{\Delta t}\left[\frac{T_N}{T_U - T_N}\right]. \qquad (6)$$

Therefore, if at a fixed chiller load and certain fixed temperature conditions (T_{0ref}, T_{cref}, T_{Nref}, T_{Uref}) the COP_{ch} had a specific value COP_{chref}, then with a change in temperature conditions, the efficiency coefficient would assume a value:

$$\mathrm{COP}_{ch} \approx \mathrm{COP}_{ch_{ref}}\left(\frac{\mathrm{COP}_{OC}}{\mathrm{COP}_{ch_{ref}}}\right) \approx \mathrm{COP}_{ch_{ref}}\left(\frac{\left[\dfrac{T_0}{T_C - T_0}\right]}{\left[\dfrac{T_{0_{ref}}}{T_{C_{ref}} - T_{0_{ref}}}\right]}\right) \approx \\ \approx \mathrm{COP}_{ch_{ref}}\left(\frac{\left[\dfrac{T_N}{T_U - T_N}\right]}{\left[\dfrac{T_{N_{ref}}}{T_{U_{ref}} - T_{N_{ref}}}\right]}\right). \qquad (7)$$

Comparison of the relative change in COP_{real} when temperatures T_0 and T_c vary, as per (7), with the results of the comprehensive analysis by Raja Kumar Gond et al [27], conducted for R134a, R290, R123, R600, R600a, R717, R152a (T_0 = 248…283K, T_c = 298…323K), demonstrated that the deviation does not exceed ±8%.

Impact of chiller load. Analysis of the refrigeration system's performance modelling conducted by F.W. Yu, K.T. Chan [29, 30] allowed for summarizing the influence of partial load on the chiller's energy efficiency in the form of a linear dependency:

$$\mathrm{COP}_{PLR} = \mathrm{COP}_0 - 0{,}56 \cdot \mathrm{COP}_0\left(1 - PLR\right), \qquad (8)$$

where COP_0 – is the efficiency coefficient at full chiller load, PLR = 1; (correspondence of calculated values according to (8) PLR ± 4%).

Na Luo et al conducted a comprehensive analysis of a water-cooled chiller refrigeration system and obtained an array of experimental data, which they summarized in the form of an equation ($R^2 = 0{,}9066$):

$$\mathrm{COP}_{PLR} = 5{,}715 \cdot PLR^{0{,}7584}. \qquad (9)$$

In equation (8), the experimental data is generalized by a dependency:

$$\mathrm{COP}_{PLR} = 5{,}715 \cdot PLR^{0{,}7584}. \qquad (10)$$

the correspondence of the values calculated by (10) COP_{PLR} is within ± 7%.

According to the findings of Yan Junwei et al study on a powerful refrigeration system with water cooling and turbo compressors, the COP_{PLR} values fall within the range of values calculated by (8), (10).

Therefore, the impact on the coefficient of efficiency due to changes in load and temperature regime can be described by the equation:

$$\mathrm{COP}_{ch} = \left[COP_0 - k \cdot COP_0\left(1 - PLR\right)\right] \cdot \left(\frac{\left[\dfrac{T_0}{T_C - T_0}\right]}{\left[\dfrac{T_{0_{ref}}}{T_{C_{ref}} - T_{0_{ref}}}\right]} \right) \approx$$

$$\approx \left[COP_0 - k \cdot COP_0\left(1 - PLR\right)\right] \cdot \left(\frac{\left[\dfrac{T_N}{T_U - T_N}\right]}{\left[\dfrac{T_{N_{ref}}}{T_{U_{ref}} - T_{N_{ref}}}\right]} \right). \qquad (11)$$

where k – is a coefficient, $k = 0{,}56\ldots0{,}78$.

Pump system and cooling towers. According to [31], the efficiency coefficients of these types of equipment, depending on the load, can be estimated by the equations:

pump system

$$\mathrm{COP}_{PUMP} = 0{,}0044 \cdot PLR + 7{,}1872; \qquad (12)$$

cooling towers

$$\mathrm{COP}_{CT} = 0{,}0619 \cdot PLR + 8{,}9424. \qquad (13)$$

3. Thermodynamic analysis of CTES

Exergetic analysis, as one of the fundamental methods in thermodynamic analysis, supplements the energy analysis to evaluate the operation of the CTES system. The distinction between exergetic and energetic efficiency arises from the former accounting for irreversibility losses, apart from losses related to energy dissipation. It is widely acknowledged that this difference is particularly crucial in assessing CTES and applying exergetic analysis to it.

Charging Process. During the charging period, the total «cold» (charge), Q_c, supplied to the heat storage system can be expressed as:

$$Q_c = m_c c_p \left(T_{c_0} - T_{c_i}\right) = m_{ice}\left(c_p T_l + \lambda + c_{p_{ice}} T_{ice_m}\right), \qquad (14)$$

where c_p, T_{ci}, T_{c0} – specific heat capacity and calculated temperatures of the coolant at the inlet and outlet during charging, respectively; m_{ice} – amount of accumulated ice, T_l – water temperature, λ – latent heat of ice melting, c_{pice}, T_{icem} – heat capacity and average temperature of ice. The value of mc represents a certain coolant flow rate over the charging period, t_c (s), and can be expressed as:

$$m_c = \int_0^{tc} m \cdot t_c dt_c, \qquad (15)$$

where $m(t_c)$ – mass flow rate of the liquid, kg/s. For constant liquid flow rate:

$$m_c = m \cdot t_c. \qquad (16)$$

The total exergy charged into the heat storage system during charging is determined by:

$$Ex_{Q_c} = m_c c_p \left[\left(T_{c_0} - T_{c_i}\right) - T_0 \ln\left(\frac{T_{c_0}}{T_{c_i}}\right) \right] \qquad (17)$$

Storage Process:

$$Q_l = kF\left(T_0 - T_s\right), \qquad (18)$$

where k and F – are the average heat transfer coefficient and the surface area of heat exchange with the surrounding environment. The overall exergy losses (external) from the heat storage system during accumulation are:

$$Ex_{Q_l} = Q_l \left(1 - \frac{T_s}{T_0}\right). \qquad (19)$$

Discharging Process. During the discharge period, the obtained cooling capacity, Q_d, provided by the chilled water storage system can be calculated by:

$$Q_d = m_d c_p \left(T_{d_i} - T_{d_0}\right) = m_{ice}\left(\lambda + c_{p_{ice}} T_{ice_m}\right), \qquad (20)$$

where c_p, T_{di} та T_{d0} – specific heat capacity, inlet, and outlet temperatures of the chilled fluid. The value of m_d

represents the total flow rate of the chilled fluid during the discharge period, t_d (s):

$$m_d = m \cdot t_d. \tag{21}$$

The total exergy discharged from the heat storage system during the discharge process is determined as:

$$Ex_{Q_d} = m_d c_p \left[\left(T_{d_i} - T_{d_0} \right) - T_0 \ln \left(\frac{T_{d_i}}{T_{d_0}} \right) \right] \tag{22}$$

The energy efficiency of the heat storage system throughout the entire operating cycle (charging, storage, and discharging) can be evaluated as the ratio of the total amount of cooling energy recovered from the system during the discharge process (Q_d) to the total amount of cooling energy charged into the system (Q_c):

$$\mathrm{COP} = \frac{Q_d}{Q_c}. \tag{23}$$

Similarly, the exergy efficiency of the system can be assessed as:

$$\psi = \frac{Ex_{Q_d}}{Ex_{Q_c}}. \tag{24}$$

Let's consider a basic example with the following assumptions: 1) The storage tank surfaces are non-adiabatic (losses – 10%); 2) The mass flow rate of the chilled fluid is adjusted to maintain a constant inlet and outlet temperature; 3) T_{c0} = 10 °C, T_{d0} = 5 °C, T_{ci} = -1°C, T_{di} = 15°; 4) Ambient conditions (T_0 and P_0) are at 20 °C and 1 atm. As a result, the overall energy efficiency and exergy efficiency are determined to be: η = 90%, ψ = 28%. As expected, a high value of energy efficiency is obtained, significantly higher than the thermodynamic (exergy) efficiency. This disparity arises because the energy analysis does not account for the quality of «cold» energy associated with temperature, considering only the quantity of released «cold» energy. Losses of cold energy during storage in the energy analysis are entirely due to losses through the system's boundaries and to the environment. It can be concluded that both energy and exergy analyses provide different perceptions of CTES efficiency. While both analyses consider the amount of energy lost during storage, the exergy analysis also considers the degradation of «cold» energy quality, thus more comprehensively and objectively reflecting the actual efficiency of CTES.

4. Conclusions

The study presents an optimization strategy for managing the low-potential thermal energy storage (CTES) system based on Ice Thermal Energy Storage (ITES) amid fluctuating electricity costs. Utilizing optimization criteria objectively assessing the system's viability in cooling applications, an optimal management strategy has been devised. Incorporating novel approaches to data collection and analysis enables the creation of more efficient management based on actual system performance data. This approach suits evaluating the current system status and enhancing operational metrics to attain maximum efficiency potential. A data-centric approach allows for a more precise resolution of optimizing specific ITES tasks.

The thermodynamic analysis of CTES systems conducted aims for more effective utilization of energy resources. It assists in identifying areas, types, and the actual extent of losses and waste. This signifies that the thermodynamic analysis showcases opportunities for creating a more efficient cooling system design by reducing inefficiencies within existing systems.

CRediT author statement

Roman Gryshchenko: Conceptualization, Formal analysis, Writing – Original Draft, Project administration. **Andrii Forsyuk**: Methodology, Writing – Review & Editing, Supervision. **Nataliia Ivashchenko**: Investigation, Data Curation, Writing – Review & Editing. **Maksym Kryvosheiev**: Funding acquisition, Resources, Software. **Oleksii Pylypenko**: Visualization, Validation.

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Оптимізаційна стратегія керування системою зберігання низькопотенціальної енергії CTES в умовах динамічної зміни вартості енергоносія

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У світлі сучасних викликів, пов'язаних із постійним зростанням попиту на енергетичні ресурси та відповідним забрудненням навколишнього середовища, виникла необхідність у розробці та впровадженні передових технологій для зменшення енергоспоживання. Це вимагає підвищення ефективності використання енергії та оптимізації систем виробництва енергії з урахуванням використання альтернативних та відновлюваних джерел енергії. Зокрема, зберігання теплової енергії стає вирішальним як ефективний економічний варіант. Системи зберігання теплової енергії дозволяють задовольняти потреби в опаленні або охолодженні в оптимальні періоди, коли це більш енергоефективно. Традиційні методи управління рідко виявляються оптимальними через коливання тарифів на електроенергію, холодильного навантаження та температури навколишнього середовища. Це призводить до неоптимального досягнення максимальної економії при використанні систем накопичення теплової енергії. У цій роботі були проаналізовані переваги систем зберігання низькопотенціальної енергії (CTES) на основі льоду (ITES), разом з існуючими стратегіями управління, реалізованими на більшості підприємств і будівель, що використовують ITES. Запропоновано спрощену інженерну методологію для аналізу термодинамічної ефективності CTES. Було визначено, що втрати холоду під час аналізу ексергії при акумулюванні викликані як втратами через поверхні, так і внутрішніми втратами ексергії (тобто споживанням ексергії внаслідок незворотності всередині резервуару). Для сучасних систем втрати ексергії охоплюють як зовнішні, так і внутрішні компоненти. Як приклад, якщо теплопередача при температурі зовнішньої поверхні резервуара для зберігання дорівнює температурі навколишнього середовища, втрати зовнішньої ексергії будуть дорівнювати нулю, тоді як загальні втрати ексергії будуть повністю зумовлені внутрішнім споживанням. І навпаки, якщо передача тепла відбувається при температурі рідини для зберігання, більша частина втрат ексергії буде зумовлена зовнішніми втратами. У всіх випадках кумулятивні втрати ексергії, що складаються з внутрішніх і зовнішніх втрат ексергії, залишаються постійними. Впровадження CTES дозволяє перенести споживання електроенергії з пікових годин на непікові. У непікові години електрична енергія використовується для зарядки сховища для задоволення (повністю або частково) пікового попиту на холодильне обладнання. ITES на основі льоду має потенціал для зменшення максимального споживання енергії, пікового попиту та, що найважливіше, середньої вартості спожитої енергії.

Ключові слова: *Енергетичні ресурси; Споживання енергії; Відновлювані джерела енергії; Утилізація; Накопичувач теплової енергії; Теплопередача*

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