2. ENERGETIC, EXERGETIC, ENVIRONMENTAL AND SUSTAINABILITY ASPECTS OF THERMAL ENERGY STORAGE SYSTEMS

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Abstract. Thermal energy storage (TES) systems and their applications are examined from the perspectives of energy, exergy, environmental impact, sustainability and economics. Reductions possible through TES in energy use and pollution levels are discussed in detail and highlighted with illustrative examples of actual systems. The importance of using exergy analysis to obtain more realistic and meaningful assessments, than provided by the more conventional energy analysis, of the efficiency and performance of TES systems is demonstrated. The results indicate that cold TES can play a significant role in meeting society's preferences for more efficient, environmentally benign and economic energy use in various sectors, and appears to be an appropriate technology for addressing the mismatches that often occur between the times of energy supply and demand.

Keywords: Energy, exergy, environment, efficiency, sustainability, thermal energy storage.

2.1. Introduction

Thermal energy storage (TES) is considered an *important energy conservation technology* and, recently, increasing attention has been paid to its utilization, particularly for HVAC applications [1, 2]. Economic factors involved in the design and operation of energy conversion systems have brought TES forefront. It is often useful to make provisions in an energy conversion system for times when the supply of and demand for thermal energy do not coincide. Research conducted by several researchers (e.g., [1–4]) has revealed a wide range of practical opportunities for employing TES systems in industrial applications. Such TES systems provide significant potential from an economic perspective for more effective use of thermal equipment and for facilitating large-scale energy substitutions. A coordinated set of actions is required in

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several sectors of the energy system for the maximum potential benefits of TES to be realized. TES appears to be an advantageous option for correcting the mismatch between the supply and demand of energy, and can contribute significantly to meeting society's needs for more efficient, environmentally benign energy use. TES is a key component of many successful thermal systems. An effective TES incurs minimum thermal energy losses, leading to energy savings, while permitting the highest possible recovery efficiency of the stored thermal energy.

Today, several energy storage technologies exist that can be used in combination with on-site energy sources to economically buffer variable rates of energy supply and demand. TES is considered by many to be one of the most important of these energy technologies and, recently, increasing attention has been paid to utilizing TES in a variety of thermal engineering applications, ranging from heating to cooling and air conditioning.

Although TES is a somewhat mature technology, it is receiving renewed consideration today in commercial and institutional building applications. In a recent study, Dincer [2] points out that TES technology has been successfully applied throughout the world, particularly in developed countries, and states that advantages of TES exceed disadvantages. Some of the advantages of utilizing TES often are [1–2]:

- reduced energy consumption and hence costs,
- reduced initial and maintenance costs,
- reduced equipment size,
- increased flexibility of operation,
- improved indoor air quality,
- conservation of fossil fuels, by facilitating more efficient energy use and/or fuel substitution,
- reduced pollutant emissions (e.g., CO_2 and CFCs),
- increased efficiency and effectiveness of equipment utilization.

2.2. TES Methods

TES systems contain a thermal storage mass, and can store heat or cool. In many hot climates, the primary applications of TES are cold storage because of the large electricity peak demands and consumptions for air conditioning. TES can be incorporated relatively straightforwardly into building air-conditioning or cooling systems. In most conventional cooling systems, there are two major components: a chiller, which cools water or some other fluid, and a distribution system, which transports the cold fluid from the chiller to where it is needed for cooling air for building occupants. In conventional systems, the chiller is operated when cold air is required. In a TES-based cooling system, the chiller can operate at times other than when cooling is needed, so that cooling capacity can be produced and stored during off-peak hours (generally at night) and the cooling capacity used during the day.

There are two principal types of TES: sensible (e.g., water, rock) and latent (e.g., water/ice, salt hydrates). The selection of a TES is mainly dependent on the storage period required (i.e., diurnal, weekly or seasonal), economic viability, operating conditions, etc. The use of TES in thermal applications can facilitate efficient energy use and energy conservation. Efficient TES systems minimize thermal energy losses and attain high energy recovery during extraction of the stored thermal energy with little degradation in temperature. Many researchers have cited exergy as the most appropriate tool for analyzing TES efficiency and performance (e.g., [2–9]).

2.3. Economic Aspects of TES

TES-based systems are usually economically justifiable when the annualized capital and operating costs are less than those for primary generating equipment supplying the same service loads and periods. TES is often installed to reduce initial costs of other plant components and operating costs. Lower initial equipment costs are usually obtained when large durations occur between periods of energy demand. Secondary capital costs may also be lower for TES-based systems. For example, the electrical service equipment size can sometimes be reduced when energy demand is lowered.

In comprehensive economic analyses of systems including and not including TES, initial equipment and installation costs must be determined, usually using manufacturer data, or estimated. Operating cost savings and net overall costs should be assessed using life cycle costing or other suitable methods for determining the most beneficial among multiple systems.

TES use can enhance the economic competitiveness of both energy suppliers and building owners. For example, one study for California [10] indicates that, assuming 20% statewide market penetration of TES, the following financial benefits can be achieved in the state:

- For energy suppliers, TES lowers generating equipment costs (by 30–50% for air-conditioning loads), reduces financing requirements (by US$1–2 billion), and improves customer retention.
- For building owners, TES lowers energy costs (by over one-half billion US dollars annually), increases property values (by US$5 billion), increases financing capability (by US$3–4 billion), and increases revenues.

Comprehensive studies are needed to determine details for the selection, implementation and operation of a TES system since many factors influence these design parameters. Studies should consider all variables which impact the economic benefits of a TES. Sometimes, however, not all factors can be considered. The following significant issues should be clarified and addressed before a TES system is implemented (for details, see [1, 2]):

- management objectives (short- and long-term),
- environmental impacts,
- energy conservation targets,
- economic aims,
- financial parameters of the project,
- available utility incentives,
- the nature of the scenario (e.g., if a new or existing TES system is being considered),
- net heating and/or cooling storage capacity (especially for peak-day requirements),
- utility rate schedules and associated energy charges,
- TES system options best suited to the specific application,
- anticipated operating strategies for each TES option,
- space availability (especially for a storage tank),
- the type of TES (e.g., short- or long-term, full or partial, open or closed).

2.4. Environmental Aspects of TES

TES systems can help increase efficiency and reduce environmental impacts for energy systems, particularly in building heating and cooling and power generation. By reducing energy use, TES systems provide significant environmental benefits by conserving fossil fuels through increased efficiency and/or fuel substitution, and by reducing emissions of such pollutants as CO_2, SO_2, NO_x and CFCs.

TES can impact air emissions in buildings by reducing quantities of ozone-depleting CFC and HCFC refrigerants in chillers and emissions from fuel-fired heating and cooling equipment. TES helps reduce CFC use in two main ways. First, since cooling systems with TES require less chiller capacity than conventional systems, they use fewer or smaller chillers and correspondingly less refrigerant. Second, using TES can offset the reduced cooling capacity that sometimes occurs when existing chillers are converted to more benign refrigerants, making building operators more willing to switch refrigerants.

The potential aggregate air-emission reductions at power plants due to TES can be significant. For example, TES systems have been shown to reduce CO_2 emissions in the UK by 14–46% by shifting electric load to off-peak periods [11–13], while an EPRI co-sponsored analysis found that TES could reduce CO_2 emissions by 7% compared to conventional electric cooling technologies [11–13]. Also, using California Energy Commission data indicating that existing gas plants produce about 0.06 kg of NO_x and 15 kg of CO_2 per 293,100 kWh of fuel burned, and assuming that TES installations save an average of 6% of the total cooling electricity needs, TES could reduce annual emissions by about 560 tons of NO_x and 260,000 tons of CO_2 statewide [10].

2.5. Sustainability Aspects of TES

A secure supply of energy resources is generally agreed to be a necessary but not sufficient requirement for development within a society. Furthermore, sustainable development demands a sustainable supply of energy resources. The implications of these statements are numerous, and depend on how sustainable is defined. One important implication of these statements is that sustainable development within a society requires a supply of energy resources that, in the long term, is readily and sustainably available at reasonable cost and can be utilized for all required tasks without causing negative societal impacts. Supplies of such energy resources as fossil fuels and uranium are generally acknowledged to be finite; other energy sources such as sunlight, wind and falling water are generally considered renewable and therefore sustainable over the relatively long term. Wastes (convertible to useful energy forms through, for example, waste-to-energy incineration facilities) and biomass fuels are also usually viewed as sustainable energy sources. A second implication of the initial statements in this section is that sustainable development requires that energy resources be used as efficiently as possible. In this way, society maximizes the benefits it derives from utilizing its energy resources, while minimizing the corresponding negative impacts (such as environmental damage). This implication acknowledges that all energy resources are to some degree finite, so that greater efficiency in utilization allows such resources to contribute to development over a longer period of time, i.e., to make development more sustainable. Even for energy sources that may eventually become inexpensive and widely available, increases in energy efficiency will likely remain sought to reduce the resource requirements (energy, material, etc) to create and maintain systems and devices to harvest the energy, and to reduce the associated environmental impacts.

TES systems can contribute to increased sustainability as they can help extend supplies of energy resources, improve costs and reduce environmental and other negative societal impacts.

Sustainability objectives often lead local and national governments to incorporate environmental considerations into energy planning. The need to satisfy basic human needs and aspirations, combined with increasing world population, make successful implementation of sustainable development increasingly needed. Requirements for achieving sustainable development in a society include [14]:

- provision of information about and public awareness of the benefits of sustainability investments,
- environmental education and training,
- appropriate energy and energy storage strategies,
- availability of renewable energy sources and clear technologies,
- a reasonable supply of financing, and
- monitoring and evaluation tools.

2.6. Thermodynamics and Energy Technologies

Thermodynamics is broadly viewed as the science of energy, and energy engineering is concerned with making the best use of energy resources and technologies. Thermal systems include power generation, refrigeration, TES.

2.6.1. THE DOMAIN OF THERMODYNAMICS

The science of thermodynamics is founded primarily on two fundamental natural principles, the first and second laws. The first law of thermodynamics expresses the conservation of energy principle, and asserts that during an interaction energy can change from one form to another but the total amount of energy remains constant. The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes reduce the quality of energy (e.g., high-temperature heat is degraded when it is transferred to a lower temperature body). Quantification of the quality or “work potential” of energy in the light of the second law has resulted in the definition of the quantities entropy and exergy.

The scope of thermodynamic concepts is schematically illustrated in Figure 1, where the domains of energy, entropy and exergy are shown. This paper focuses on the intersection of the energy, entropy and exergy fields as given in Figure 3 [15]. Note that entropy and exergy are also used in other fields (e.g., economics, management and information theory), and therefore are not subsets of energy. Some forms of energy such as shaft work are entropy-free, and thus entropy subtends only part of the energy field. Likewise, exergy subtends only part of the energy field since some systems (such as air at atmospheric conditions) possess energy but no exergy. Most thermodynamic systems possess energy, entropy and exergy, and thus appear at the intersection of these three fields.

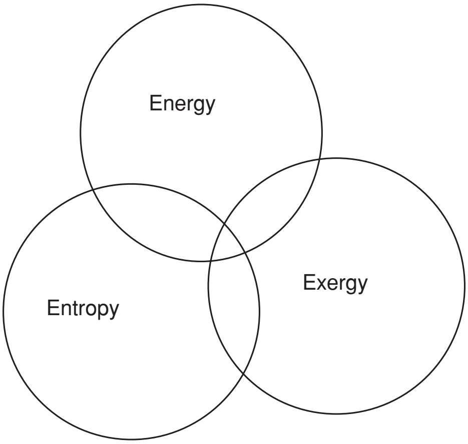

Figure 3. Interactions between the domains of energy, entropy and exergy

2.6.2. ENERGETIC AND EXERGETIC ASPECTS AND SUSTAINABILITY

Energy is a key element in interactions between nature and society and is considered a key input for economic development. Environmental issues span a continuously growing range of pollutants, hazards and eco-system degradation factors that affect areas ranging from local through regional to global. Some of these concerns arise from observable, chronic effects on human health, while others stem from actual or perceived environmental risks such as possible accidental releases of hazardous materials. Many environmental issues, e.g., acid rain, stratospheric ozone depletion and global climate change, are caused by or relate to energy production, transformation, transport and use. Energy, consequently, is a key consideration in discussions of sustainable development.

Energy use is governed by thermodynamic principles and, therefore, an understanding of thermodynamic aspects of energy can help us understand pathways to sustainable development. The impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed by considering exergy. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change, and provides the basis for an effective measure of the potential of a substance or energy form to impact the environment. In practice, a thorough understanding of exergy, and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems, are required for the engineer or scientist working in the area of energy systems and the environment. During the past decade, the need to understand how exergy and energy are linked to environmental impact has become increasingly

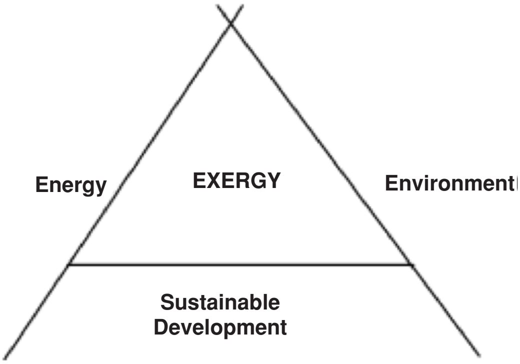

Figure 4. The interdisciplinary triangle of exergy

significant [15–17]. Generally, exergy can be viewed as the confluence of energy, environment and sustainable development (Figure 4), mainly due to its interdisciplinary character.

2.6.3. SUSTAINABLE DEVELOPMENT AND THERMODYNAMIC PRINCIPLES

Thermodynamic principles can be used to assess, design and improve energy and other systems, and to better understand environmental impact and sustainability issues. For the broadest understanding, all thermodynamic principles must be used, not just those pertaining to energy. Thus, many researchers feel that an understanding and appreciation of exergy is essential to discussions of sustainable development.

An inexpensive and stable energy supply is a prerequisite for social and economic development, in households as well as at the national level. Indeed, energy is essential to human welfare and quality of life. However, energy production and consumption generate significant environmental problems (at global, regional and local levels) that can have serious consequences and even put at risk the long-term sustainability of the planet’s ecosystems. The relationship between energy consumption and production and sustainability is, therefore, complex [16]. Decisions by the individual, and society regarding how to meet energy needs require careful thought about many issues, including energy resource selection, efficiency and the role of hydrogen and fuel cell technologies.

We consider sustainable development here to involve four key factors (Figure 5): environmental, economic, social and resource/energy sustainability. The connections in Figure 3 illustrate that these factors are interrelated and thus each must taken into consideration to increase sustainable development.

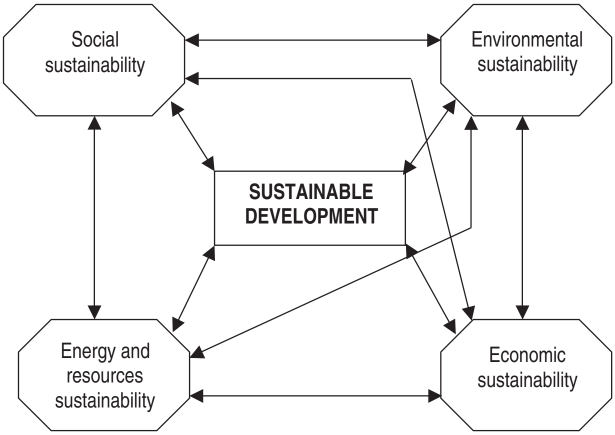

Figure 5. Four key factors for sustainability

2.6.4. EXERGY AND THE ENVIRONMENT

Increasing energy efficiency reduces environmental impact by decreasing energy losses. From an exergy viewpoint, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumption). Thus, a thorough understanding of the relations between exergy and the environment may reveal underlying fundamental patterns and forces affecting changes in the environment, and help researchers deal better with environmental damage.

The second law of thermodynamics is instrumental in providing insights into environmental impact. The most appropriate link between the second law and environmental impact has been suggested to be exergy, in part because the magnitude of the exergy of a system depends on the states of both the system and the environment and because exergy is a measure of the departure between these states. This departure is zero only when the system is in equilibrium with its environment. The authors have discussed this concept extensively previously [1, 2, 9, 14–16].

2.6.5. EXERGY AND SUSTAINABILITY

Mass and energy balances are normally evaluated prior to performing an exergy analysis. The energy information quantifies only the energy transfers and conversions in a system or process, whereas the exergy results, since exergy is a measure of the quality of energy, quantify the degradation of energy or material in the system. Exergy is conserved only for reversible or ideal processes. Exergy analysis uses the first and second law of thermodynamics to pinpoint the losses of quality, or work potential, in a system. Exergy analysis is consequently linked to sustainability because to increase the sustainability of energy use, we must be concerned not only with loss of energy, but also loss of energy quality (or exergy).

One principal advantage of exergy analysis over energy analysis is that the exergy content of a process flow is a better valuation of the flow than the energy content, since the exergy indicates the fraction of energy that is likely useful and thus utilizable. This observation applies equally on the component level, the process level and the life cycle level. Application of exergy analysis to a component, process or sector can lead to insights into how to improve the sustainability of the activities comprising the system by reducing exergy losses.

Sustainable development requires not just that sustainable energy resources be used, but that the resources be used as efficiently as possible. Many feel that exergy methods can help improve sustainability. Since energy can never be "lost" as it is conserved according to the first law of thermodynamics, while exergy can be lost due to internal irreversibilities, exergy losses which represent potential not used, particularly from the use of nonrenewable energy forms, should be minimized when striving for sustainable development.

Furthermore, some studies (e.g., [15–17]) show that some environmental effects associated with emissions and resource depletion can be expressed based on physical principles in terms of an exergy-based indicator. It may be possible to generalize this indicator to cover a comprehensive range of environmental effects, and such research is ongoing.

The relation between exergy, sustainability and environmental impact is illustrated in Figure 6. There, sustainability can be seen to increase and environmental impact to decrease as the exergy efficiency of a process increases. Two limiting efficiency cases, as shown in Figure 5, are of practical significance:

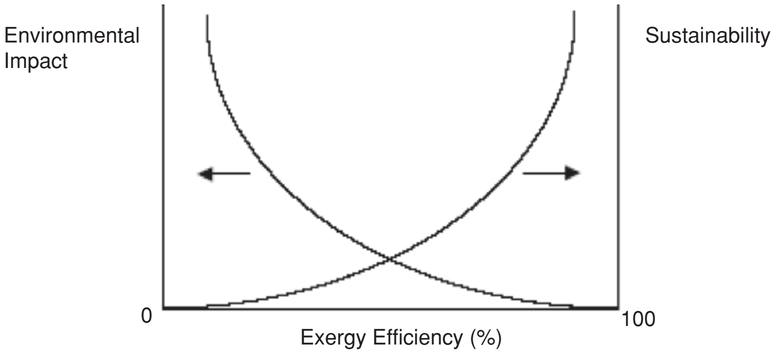

Figure 6. Qualitative illustration of the linkages between the environmental impact and sustainability of a system or process, and its exergy efficiency

- As exergy efficiency approaches 100%, the environmental impact associated with process operation approaches zero, since exergy is only converted from one form to another without loss. Also sustainability approaches infinity because the process approaches reversibility.
- As exergy efficiency approaches 0%, sustainability approaches zero because exergy-containing resources (fuel ores, steam, etc) are used but nothing is accomplished. Also, environmental impact approaches infinity because, to provide a fixed service, an ever-increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes are emitted.

Research into the benefits of using thermodynamic principles, especially exergy, to assess the sustainability and environmental impact of energy systems is relatively new, and further research is needed to ascertain a better and more comprehensive understanding of the potential role of exergy. Required research includes (i) better defining the role of exergy in environmental impact and design, (ii) identifying how exergy can be better used as an indicator of potential environmental impact, and (iii) developing holistic exergy-based methods that simultaneously account for technical, economic, environmental and other factors.

2.7. Energy and Exergy Analyses of Cold TES

An important application of TES is in facilitating the use of off-peak electricity to provide building heating and cooling. Recently, increasing attention has been paid in many countries to cold TES (CTES), an economically viable technology that has become a key component of many successful thermal systems (Figure 7). Although CTES efficiency and performance evaluations are conventionally based on energy, energy analysis itself is inadequate for complete CTES evaluation because it does not account for such factors as the temperatures at which heat (or cold) is supplied and delivered. Exergy analysis overcomes some of these inadequacies in CTES assessments.

Here we assess using exergy and energy analyses CTES systems, including sensible and/or latent storages (e.g., [1, 2]). Several CTES cases are considered, including storages which are homogeneous or stratified, and some which undergo phase changes. A full cycle of charging, storing and discharging is considered for each case. This section demonstrates that exergy analysis provides more realistic efficiency and performance assessments of CTES systems than energy analysis, and conceptually is more direct since it treats cold as a valuable commodity. An example and case study illustrate the usefulness of exergy analysis in addressing cold thermal storage problems.

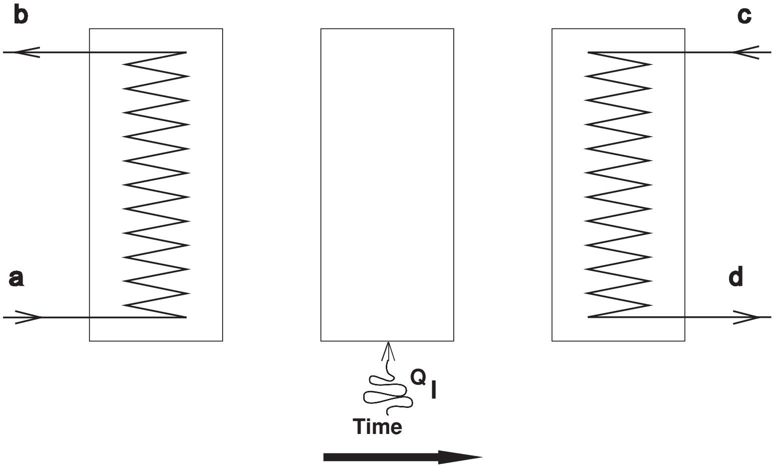

Figure 7. The three processes in a general CTES system: charging (left), storing (middle), and discharging (right). The heat leakage into the system Q_1 is illustrated for the storing process, but can occur in all three processes

2.7.1. ENERGY BALANCES

Consider a cold storage consisting of a tank containing a fixed quantity of storage fluid and a heat-transfer coil through which a heat-transfer fluid is circulated. Kinetic and potential energies and pump work are considered negligible (see [1] for details). An energy balance for an entire cycle of a CTES can be written in terms of "cold" as follows:

$$\textit{Cold input} - [\textit{Cold recovered} + \textit{Cold loss}] = \textit{Cold accumulation}. \quad (1)$$

Here, "cold input" is the heat removed from the storage fluid by the heat-transfer fluid during charging; "cold recovered" is the heat removed from the heat transfer fluid by the storage fluid; "cold loss" is the heat gain from the environment to the storage fluid during charging, storing and discharging; and "cold accumulation" is the decrease in internal energy of the storage fluid during the entire cycle. The overall energy balance for the simplified CTES system illustrated in Figure 5 becomes

$$(H_b - H_a) - [(H_c - H_d) + Q_l] = -\,\Delta E \quad (2)$$

where H_a, H_b, H_c and H_d are the enthalpies of the flows at points a, b, c and d in Figure 5; Q_l is the total heat gain during the charging, storing, and discharging processes; and ΔE is the difference between the final and initial storage-fluid internal energies. The terms in square brackets in Equations (1) and (2) represent the net "cold output" from the CTES, and $\Delta E = 0$ if the

CTES undergoes a complete cycle (i.e., the initial and final storage-fluid states are identical).

The energy transfer associated with the charging fluid can be expressed as

$$H_b - H_a = m_a c_a (T_b - T_a) \tag{3}$$

where m_a is the mass flow of heat-transfer fluid at point a (and at point b), and c_a is the specific heat of the heat transfer fluid, which is assumed constant. A similar expression can be written for $H_c - H_b$. The energy content of a storage which is homogeneous (i.e., entirely in either the solid or the liquid phase) is

$$E = m(u - u_o) \tag{4}$$

which, for sensible heat interactions only, can be written as

$$E = mc\,(T - T_o) \tag{5}$$

where, for the storage fluid, c denotes the specific heat (assumed constant), m the mass, u the specific internal energy and T the temperature. Also, u_o is u evaluated at the environmental conditions.

For a mixture of solid and liquid, the energy content of the solid and liquid portions can be evaluated separately and summed as follows:

$$E = m[(1 - F)(u_s - u_o) + F(u_t - u_o)] \tag{6}$$

where u_s and u_t are the specific internal energies of the solid and liquid portions of the storage fluid, respectively, and F is the melted fraction (i.e., the fraction of the storage fluid mass in the liquid phase).

For a storage fluid which is thermally stratified with a linear temperature profile in the vertical direction, the energy content can be shown with Equation (5) to be

$$E = mc\left(\frac{T_t + T_b}{2} - T_o\right) \tag{7}$$

where T_t and T_b are the storage-fluid temperatures at the top and bottom of the linearly stratified storage tank, respectively.

The change in CTES energy content from the initial (i) to the final state (f) of a process can be expressed as

$$\Delta E = E_f - E_i \tag{8}$$

where E_i and E_f denote the initial and final energy contents of the storage. In the case of identical initial and final states, $\Delta E = 0$ and the overall energy balance simplifies.

2.7.2. EXERGY BALANCES

An exergy balance for a CTES undergoing a complete cycle of charging, storing and discharging can be written as

$$\begin{aligned} &\textit{Exergy input} - [\textit{Exergy recovered} + \textit{Exergy loss}] - \textit{Exergy consumption} \\ &\quad = \textit{Exergy accumulation} \end{aligned} \tag{9}$$

or

$$(\in_a - \in_b) - [(\in_d - \in_c) + X_l] - I = \Delta\Xi \tag{10}$$

where $\in_a$, $\in_b$, $\in_c$ and $\in_d$ are the exergies of the flows at states a, b, c and d, respectively; and X_l denotes the exergy loss associated with Q_l;I is the exergy consumption; and $\Delta\Xi$ is the exergy accumulation. In Equation (10), $(\in_a - \in_b)$ represents the net exergy input and $(\in_d - \in_c)$ is the net exergy recovered. The quantity in square brackets represents the net exergy output from the system. The terms I,X_l and $\Delta\Xi$ are given respectively by

$$I = \sum_{j=1}^{3} I_j \tag{11}$$

$$X_l = \sum_{j=1}^{3} X_{l,j} \tag{12}$$

$$\Delta\Xi = \Xi_f - \Xi_i \tag{13}$$

where, I_1, I_2 and I_3 denote respectively the consumptions of exergy during the charging, storing and discharging periods; $X_{1,1}$,$X_{1,2}$ and $X_{1,3}$ denote the exergy losses associated with heat losses during the same periods; and Ξ_i and Ξ_f denote the initial and final exergy contents of the storage. When the initial and final states are identical, $\Delta\Xi = 0$.

The exergy content of a flow of heat transfer fluid at state k (where k = a, b, c, or d in Figure 4) can be expressed as

$$\in_k = (H_k - H_o) - T_o\,(S_k - S_o) \tag{14}$$

where $\in_k$, H_k and S_k denote the exergy, enthalpy and entropy of state k, respectively, and H_o and S_o the enthalpy and the entropy at the temperature T_o and pressure P_o of the reference environment. The exergy expression in Equation (14) only includes physical (or thermomechanical) exergy. Potential and kinetic exergy components are, as pointed out earlier, considered negligible for the devices under consideration. The chemical component of exergy is neglected because it does not contribute to the exergy flows for sensible CTES systems. Thus, the exergy differences between the inlet and outlet for the charging and discharging periods are, respectively:

$$\in_a - \in_b = (H_a - H_b) - T_o\,(S_a - S_b) \tag{15}$$

and

$$\in_d - \in_c = (H_d - H_c) - T_o\,(S_d - S_c) \tag{16}$$

where it has been assumed that T_o and P_o are constant, so that H_o and S_o are constant at states a and b, and at states c and d.

The exergy loss associated with heat infiltration during the three storage periods can be expressed as

$$X_{l,j} = \left(1 - \frac{T_o}{T_j}\right) Q_{l,j} \tag{17}$$

where j represents the particular period, and T_1,T_2 and T_3 are constant during the respective charging, storing and discharging periods. Sometimes T_j represents a mean temperature within the tank for period j.

The thermal exergy terms are negative for sub-environment temperatures, as is the case here for CTESs, indicating that the heat transfer and the accompanying exergy transfer are oppositely directed. That is, the losses associated with heat transfer are due to heat infiltration into the storage when expressed in energy terms, but due to a cold loss out of the storage when expressed in exergy.

The exergy content of a homogeneous storage can be expressed as

$$\Xi = m[(u - u_o) - T_o(s - s_o)] \tag{18}$$

where s is the specific entropy of the storage fluid and s_o is s evaluated at the environmental conditions. If only sensible heat interactions occur, Equation (18) can then be written as

$$\Xi = mc[(T - T_o) - T_o \ln(T/T_o)]. \tag{19}$$

For a mixture of solid and liquid, the exergy content can be written as

$$\Xi = m\{(1 - F)[(u_s - u_o) - T_o(s_s - s_o)] + F[(u_t - u_o) - T_o(s_t - s_o)]\} \tag{20}$$

where s_s and s_t are the specific entropies of the solid and liquid portions of the storage fluid, respectively.

Consequently, the exergy content of a storage which is linearly stratified can be shown as

$$\Xi = E - mcT_o \left[\frac{T_t(\ln T_t - 1) - T_b(\ln T_b - 1)}{T_t - T_b} - \ln T_o\right]. \tag{21}$$

The change in TES exergy content can be expressed as in Equation (13).

2.7.3. ENERGY AND EXERGY EFFICIENCIES

For a general CTES undergoing a cyclic operation, the overall energy efficiency η can be evaluated as

$$\eta = \frac{\textit{Energy in product outputs}}{\textit{Energy in inputs}} = 1 - \frac{\textit{Energy loss}}{\textit{Energy in inputs}} \tag{22}$$

where the word energy represents the cold. Then, following Figure 5, the overall and charging-period energy efficiencies can be expressed as

$$\begin{aligned}\eta &= \frac{\textit{Energy recovered from TES during discharging}}{\textit{Exergy input to TES during charging}}\\ &= \frac{H_d - H_c}{H_a - H_b} = 1 - \frac{Q_l}{H_a - H_b}\end{aligned} \tag{23}$$

$$\eta_1 = \frac{\textit{Energy accumulation in TES during charging}}{\textit{Energy input to TES during charging}} = \frac{\Delta E_1}{H_a - H_b}. \tag{24}$$

The energy efficiencies for the storing and discharging subprocesses can be written respectively as

$$\eta_2 = \frac{\Delta E_1 + Q_l}{\Delta E_1} \tag{25}$$

$$\eta_3 = \frac{H_c - H_d}{\Delta E_3} \tag{26}$$

where ΔE_1 and ΔE_3 are the changes in CTES energy contents during charging and discharging, respectively.

The exergy efficiency for the overall process can be expressed as

$$\begin{aligned}\psi &= \frac{\textit{Exergy recovered from TES during discharging}}{\textit{Exergy input to during charging}}\\ &= \frac{\epsilon_d - \epsilon_c}{\epsilon_a - \epsilon_b} = 1 - \frac{X_l + I}{\epsilon_a - \epsilon_b}.\end{aligned} \tag{27}$$

If the TES is adiabatic, $Q_{l,j} = X_{l,j} = 0$ for all j. Then the energy efficiency is fixed at unity and the exergy efficiency simplifies to

$$\psi = 1 - \frac{I}{\epsilon_a - \epsilon_b}. \tag{28}$$

The exergy efficiencies for the charging, storing and discharging processes, respectively, can be expressed as

$$\psi_1 = \frac{\textit{Exergy accumulation in TES during charging}}{\textit{Exergy input to TES during charging}} = \frac{\Delta \Xi_1}{\epsilon_a - \epsilon_b} \tag{29}$$

$$
\begin{aligned}
\psi_2 &= \frac{\textit{Exergy accumulation in TES during charging and storing}}{\textit{Exergy accumulation in TES during charging}} \\
&= \frac{\Delta\Xi_1 + \Delta\Xi_2}{\Delta\Xi_1}\mathcal{M} \qquad (30) \\
\psi_3 &= \frac{\textit{Exergy recovered from TES during discharging}}{\textit{Exergy accumulation in TES during charging and storing}} \\
&= \frac{\in_d - \in_c}{\Delta\Xi_1 + \Delta\Xi_2}. \qquad (31)
\end{aligned}
$$

Further information on energy and exergy analyses of TES and CTES systems can be found in Dincer and Rosen [1].

2.8. Illustrative Example

2.8.1. CASES CONSIDERED AND SPECIFIED DATA

Four different CTES cases are considered as given in [1]. In each case, the CTES has identical initial and final states, so that the CTES operates in a cyclic manner, continuously charging, storing and discharging. The main characteristics of the cold storage cases are as follows:

(I) Sensible heat storage, with a fully mixed storage fluid.
(II) Sensible heat storage, with a linearly stratified storage fluid.
(III) Latent heat storage, with fully mixed storage fluid.
(IV) Combined latent and sensible heat storage, with fully mixed storage fluid.

The following assumptions are made for each of the cases:

- Storage boundaries are nonadiabatic.
- Heat gain from the environment during charging and discharging is negligibly small relative to heat gain during the storing period.
- The external surface of the storage tank wall is at a temperature 2 °C greater than the mean storage-fluid temperature.
- The mass flow rate of the heat transfer fluid is controlled so as to produce constant inlet and outlet temperatures.
- Work interactions, and changes in kinetic and potential energy terms, are negligibly small.

Specified data for the four cases are presented in Table 1 and relate to the diagram in Figure 7. In Table 1, T_b and T_d are the charging and discharging outlet temperatures of the heat transfer fluid, respectively. The subscripts 1, 2 and 3 indicate the temperature of the storage fluid at the beginning of charging,

TABLE 1. Specified temperature data for the cases in the CTES example

	Case			
Temperature (°C)	I	II	III	IV
T_b	4.0	15	−1	−1
T_d	11.0	11	10	10
T_1	10.5	19/2*	0 (t)	8
T_2	5.0	17/–7*	0 (s)	– 8
T_3	6.0	18/–6*	0 (t&s)	0 (t&s)

* When two values are given, the storage fluid is vertically linearly stratified and the first and second values are the temperatures at the top and bottom of the storage fluid, respectively.

storing or discharging, respectively. Also, *t* indicates the liquid state and s the solid state for the storage fluid at the phase-change temperature.

In addition, for all cases, the inlet temperatures are fixed for the charging-fluid flow at $T_a = -10$ °C and for the discharging-fluid flow at $T_c = 20$°C. For cases involving latent heat changes (i.e., solidification), $F = 10\%$. The specific heat c is 4.18 kJ/(kg K) for both the storage and heat-transfer fluids. The phase-change temperature of the storage fluid is 0 °C. The configuration of the storage tank is cylindrical with an internal diameter of 2 m and internal height of 5 m. Environmental conditions are 20 °C and 1 atm.

2.8.2. RESULTS AND DISCUSSION

The results for the four cases are listed in Table 2, and include overall and subprocess efficiencies, input and recovered cold quantities, and energy and exergy losses. The overall and subprocess energy efficiencies are identical for Cases I and II, and for Cases III and IV. In all cases the energy efficiency values are high. The different and lower exergy efficiencies for all cases indicate that energy analysis does not account for the quality of the "cold" energy, as related to temperature, and considers only the quantity of "cold" energy recovered.

The input and recovered quantities in Table 2 indicate the quantity of "cold" energy and exergy input to and recovered from the storage. The energy values are much greater than the exergy values because, although the energy quantities involved are large, the energy is transferred at temperatures only slightly below the reference-environment temperature, and therefore is of limited usefulness.

The cold losses during storage, on an energy basis, are entirely due to cold losses across the storage boundary (i.e., heat infiltration). The exergy-based

TABLE 2. Energy and exergy quantities for the cases in the CTES example

	Energy quantities				Energy quantities			
Period or quantity	I	II	III	IV	I	II	III	IV
Efficiencies (%)								
Charging (1)	100	100	100	100	51	98	76	77
Storing (2)	82	82	90	90	78	85	90	85
Discharging (3)	100	100	100	100	38	24	41	25
Overall	82	82	90	90	15	20	28	17
Input, recovered and lost quantities (MJ)								
Input	361.1	361.1	5,237.5	6,025.9	30.9	23.2	499.8	575.1
Recovered	295.5	295.5	4,713.8	5,423.3	4.6	4.6	142.3	94.7
Loss (external)	65.7	65.7	523.8	602.6	2.9	2.9	36.3	48.9
Loss (internal)	—	—	—	—	23.3	15.6	321.2	431.4

cold losses during storage are due to both cold losses and internal exergy losses (i.e., exergy consumptions due to irreversibilities within the storage). For the present cases, in which the exterior surface of the storage tank is assumed to be 2°C warmer than the mean storage-fluid temperature, the exergy losses include both external and internal components. Alternatively, if the heat transfer temperature at the storage tank external surface is at the environment temperature, the external exergy losses would be zero and the total exergy losses would be entirely due to internal consumptions. If heat transfer occurs at the storage-fluid temperature, on the other hand, more of the exergy losses would be due to external losses. In all cases, the total exergy losses, which are the sum of the internal and external exergy losses, remain fixed.

The four cases demonstrate that energy and exergy analyses give different results for CTES systems. Both energy and exergy analyses account for the quantity of energy transferred in storage processes. Exergy analyses take into account the loss in quality of "cold" energy, and thus more correctly reflect the actual value of the CTES.

In addition, exergy analysis is conceptually more direct when applied to CTES systems because cold is treated as a useful commodity. With energy analysis, flows of heat rather than cold are normally considered. Thus, energy analyses become convoluted and confusing as one must deal with heat flows, while accounting for the fact that cold is the useful input and product recovered for CTES systems. Exergy analysis inherently treats any quantity which is out of equilibrium with the environment (be it colder or hotter) as a valuable commodity, and thus avoids the intuitive conflict in the expressions associated with CTES energy analysis. The concept that cold is a valuable commodity is both logical and in line with one's intuition when applied to CTES systems.

2.9. Conclusions

TES systems generally are attracting increasing interest in several thermal applications, e.g., active and passive solar heating, water heating, cooling and air conditioning. Also, TES is presently identified as an economic storage technology for building heating, cooling and air-conditioning applications. The main conclusions of the present study follow:

- TES can play a significant role in meeting society's preferences for more efficient, environmentally benign energy use in various sectors, and appears to be an appropriate technology for addressing the mismatch that often occurs between the times of energy supply and demand.
- Using TES systems substantial energy savings can be obtained when implementing appropriate demand side management strategies and emissions, e.g., CO_2, SO_2 and NO_x, can significantly be reduced.
- For complete performance and efficiency evaluation of TES systems, both energy and exergy analyses should be undertaken. Exergy analysis often provides more meaningful and useful information than energy analysis regarding efficiencies and losses for TES systems, partly because the loss of low temperature in cold TES is accounted for in exergy-based performance measures, but not in energy-based ones.
- Assessments of the sustainability of processes and systems, and efforts to improve sustainability, should be based in part upon thermodynamic principles, and especially the insights revealed through exergy analysis.
- To realize the energy, exergy, economic and environmental benefits of TES technologies, an integrated set of activities should be conducted including research and development, technology assessment, standards development and technology transfer. These can be aimed at improving efficiency, facilitating the substitution of these technologies and other environmentally benign energy currencies for more harmful ones, and improving the performance characteristics of these technologies.

Consequently, exergy analysis can likely assist in efforts to optimize the design of CTES systems and their components, and to identify appropriate applications and optimal configurations for CTES in general engineering systems.

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Nomenclature

A	surface area
c	specific heat
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
C	heat capacity rate
e	specific energy
E	energy
f	fraction; mean height fraction
F	fraction of storage-fluid mass in liquid phase
h	specific enthalpy; height
H	enthalpy; TES fluid height
I	exergy consumption due to irreversibilities
k	thermal conductivity
ke	specific kinetic energy
l	distance of plates
L	latent heat
m	mass
$\dot{m}$	mass flow rate
N	moles
pe	specific potential energy
P	absolute pressure, perimeter
Q	heat
R	thermal resistance
s	specific entropy
S	entropy
t	time
T	temperature
u	specific internal energy
U	internal energy
v	specific volume; velocity
V	volume
W	shaft work
x	coordinate; distance
X	thermal exergy (i.e., exergy associated with heat Q)
y	mole fraction; coordinate

Greek Symbols

α	constant parameter
ε	specific flow exergy

$\in$	flow exergy
η	energy efficiency; parameter ($= s/l$)
θ	parameter; temperature; dimensionless T temperature ($= (T_m - T_s)/(T_m - T_\infty)$)
μ	chemical potential; dynamic viscosity
ζ	specific exergy; parameter ($= x/l$)
Ξ	exergy
$\prod$	entropy production
ρ	density
ϕ	zone temperature distribution; general dependent variable
ψ	exergy efficiency
ΔT	temperature difference $= T_w - T_m$

Subscripts

a	inlet flow during charging; adiabatic; parameter
amb	ambient
b	outlet flow during charging; bottom; parameter
c	injected during charging period; charging; inlet flow during discharging
d	recovered during discharging period; discharging; outlet flow during discharging
e	exit; equivalent; effective
f	final
i	initial
ini	initial
k	number of zones
min	minimum
kin	kinetic component
l	loss; liquid; liquid phase
m	mixed; melting; melting point
n	nonadiabatic; phase
net	net
o	environmental state; chemical exergy; outlet
oo	dead state
p	product
PCM	phase change material
ph	physical component
pot	potential component
r	region of heat interaction
s	solid; solid phase; solid state; storage fluid

st	storage (overall)
t	threshold; top; liquid state
T	total
th	thermocline zone (zone 2)
w	working fluid; wall
1	charging period
2	storing period
3	discharging period

References

1. Dincer, I., and M.A. Rosen, 2002. Thermal Energy Storage Systems and Applications, John Wiley & Sons, London, 580 pp.
2. Dincer, I., 2002. Thermal energy storage as a key technology in energy conservation, Int. J. Energy Res, 26 (7), 567–588.
3. Dincer, I., and S. Dost, 1996. A perspective on thermal energy storage systems for solar energy applications, Int. J. Energy Res., 20, 547–557.
4. Dincer, I., S. Dost, and X. Li, 1997. Performance analyses of sensible heat storage systems for thermal applications, Int. J. Energy Res., 21, 1157–1171.
5. Bjurstrom, H., and B. Carlsson, 1985. An exergy analysis of sensible and latent heat storage, Heat Recovery Syst., 5, 233–250.
6. Krane, R.J., 1989. Second-law optimization of thermal energy storage systems: Fundamentals and sensible heat systems, in Energy Storage Systems, edited by B. Kilkis and S. Kakac, Kluwer Academic Publishers, pp. 37–67.
7. Rosen, M.A., 1992. Appropriate thermodynamic performance measures for closed systems for thermal energy storage, ASME J. Solar Energy Eng., 114, 100–105.
8. Gunnewiek, L.H., S. Nguyen, and M.A. Rosen, 1993. Evaluation of the optimum discharge period for closed thermal energy storages using energy and exergy analyses, Solar Energy, 51, 39–43.
9. Dincer, I. 1999. Thermal energy storage technologies: Energy savings and environmental impacts, Proceedings of the 11th International Conference on Thermal Engineering and Thermogrammetry, 16–18 June, House of Technology, Budapest-Hungary, pp. 13–23.
10. Anon. 1996. Source Energy and Environmental Impacts of Thermal Energy Storage, California Energy Commission, Technical Report No. P500-95-005, California.
11. ARI 1997. Thermal Energy Storage: A Solution for Our Energy, Environmental and Economic Challenges, The Air-Conditioning and Refrigeration Institute, Arlington, VA.
12. Beggs, C.B., 1994. Ice thermal storage: impact on United Kingdom carbon dioxide emissions, Building Services Eng. Res. Technol. 15 (1), 756–763.
13. Reindl, D.T., 1994. Characterizing the Marginal Basis Source Energy Emissions Associated with Comfort Cooling Systems, Thermal Storage Applications Research Center, Report No. TSARC 94-1, USA.
14. Dincer, I., and M.A. Rosen, 2005. Thermodynamic aspects of renewables and sustainable development, Renewable Sustain. Energy Rev., 9 (2), 169–189.
15. Dincer, I. and Y.A. Cengel, 2001. Energy, entropy and exergy concepts and their roles in thermal engineering, Entropy, 3, 116–149.

16. Dincer, I., and M. Rosen, 2004. Exergy as a drive for achieving sustainability, Int. J. Green Energy, 1 (1), 1–19.
17. Bejan, A., I. Dincer, S. Lorente, A.H. Reis, and A.F. Miguel, 2004. Porous Media in Modern Technologies: Energy, Electronics, Biomedical and Environmental Engineering, Springer Verlag, New York, p. 39.