Process integration of thermal energy storage systems – evaluation methodology and case studies

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Abstract

As a key tool for decarbonization, thermal energy storage systems integrated into processes can address issues related to energy efficiency and process flexibility, improve utilization of renewable energy resources and thus reduce greenhouse gas emissions. However, integration of these systems is dominated by the variety of potential processes in which the storage technologies can be deployed as well as the various benefits they deliver. Therefore, the requirements for thermal energy storage systems vary greatly depending on the chosen application, just as the systems themselves have different capabilities depending on their technical principles. This paper addresses this issue by developing a systematic methodology that approaches the challenge of characterizing and evaluating thermal energy storage systems in different applications in three concrete steps. To begin, a set of guidelines for process analysis has been created to disclose process requirements for storage integration. The methodology continues by explicitly defining the system boundary of a thermal energy storage system, as well as addressing technical and economic parameters. Finally, the approach concludes by determining the benefit of an integrated thermal energy storage system to an application and examines how key performance indicators vary based on the perspectives of different stakeholders. Within this work, the methodology is then applied to two case studies of high-temperature storage in concentrating solar power and cogeneration plants. Also introduced are the concepts of retrofit and greenfield applications, which are used to clarify differences between integrated storage systems. The paper shows how such a systematic approach can be used to consistently analyse processes for storage integration, facilitate comparison between thermal energy storage systems integrated into processes across applications and finally grasp how different interests perceive the benefits of the integrated storage system. This type of systematic methodology for technology integration has not been previously developed and as such, is a novel and important contribution to the thermal energy storage community. In the long term, this work builds the basis for a discussion on benefits of thermal energy storage system integration with diverse stakeholders including storage system designers, process owners and policy makers.

Keywords

Thermal Energy Storage (TES)
Technology assessment
Process integration
Process analysis
System boundary
Key Performance Indicators (KPI)

1 Introduction

For the first time in history, in the 2015 Paris Climate Accord, over 130 countries agreed that current levels of CO_2 emissions are leading to potentially catastrophic global warming events [1]. Three years later, a global stabilization of emissions has nevertheless resulted in a still-rising concentration of atmospheric CO_2, outlining the increasing urgency for a reduction of future emissions. Displacement of fossil-fuel technologies and an overall reduction in energy consumption through energy efficiency methods are key solutions to this crisis. Nevertheless, the increasing shares of renewable energy and available options for boosting energy efficiency pose important energy management problems that must be addressed through a variety of measures [2]. One of these possibilities is the efficient management of heat. Due to the abundance of waste heat and heat demand in industrial processes [3,4], a critical need for increased flexibility in all types of power plants [2], the demand for low-temperature heating and cooling solutions in buildings [5], as well as the emergence of new technologies for enabling the coupling of energy-intensive sectors, the storage of thermal energy is more relevant than ever [4,6]. Integration of these systems into processes is thus an important step towards reducing CO_2 emissions and advancing the integration of variable renewable energy [7].

Thermal energy storage (TES) systems are diverse technologies that are suitable for deployment in a wide variety of applications. There is, however, no 'one-size-fits-all' version of a TES system. Each storage concept has its own advantages and disadvantages that make it more or less appropriate for a specific application. A challenge is in identifying these factors and subsequently matching the most beneficial storage system(s) with an appropriate process. Processes are similarly variable and complex, usually with a series of interdependent steps and often with significant variations in the sectors themselves. The type of energy available or required can be inconsistent. A process can provide heat, cold, or electricity as a source, or can require any of these as a sink. Most importantly, there is no standard process, even within specific sectors or industries. These aspects make the integration of a TES unit quite complex. It is therefore important to characterize both the process and available TES systems independently, before joining them in an application.

Furthermore, integration of a TES system into a process can be categorized into one of two types: retrofit and greenfield. Retrofit applications examine an existing process where the storage system must be designed to fit the needs of an already dimensioned and built process. The challenge is in designing a storage system that fulfils the process requirements. In a greenfield analysis, the storage parameters are designed from the very beginning in parallel with the rest of the process. While no two greenfield projects are the same, it is noteworthy that the fundamental principles of the integration remain consistent and as such, a ground-up engineering of the system is not required and best practices can be employed.

Within this paper, processes are considered to be an organized collection of operations that engage in the transmission (e.g. district heating), use (e.g. steelmaking) or transformation (e.g. steam production in a power plant) of energy. An important point is that the boundaries of a process can be inexplicit, thus process definition is a major step addressed in this work. Two processes are detailed here: steam production in a cogeneration power plant and electricity production in a concentrating solar power plant.

As introduced in Fig. 1, the TES system and the process are interlinked with each other. Shown on the right, the process has requirements that must be fulfilled by the TES system. These are conditions that must be met in order for the integration to be considered at all. Shown on the left, the TES has system parameters that indicate the specifications for which the storage is appropriate. These dictate the technical and economic boundaries of the storage and the basic connection between process and TES system that should be further characterized.

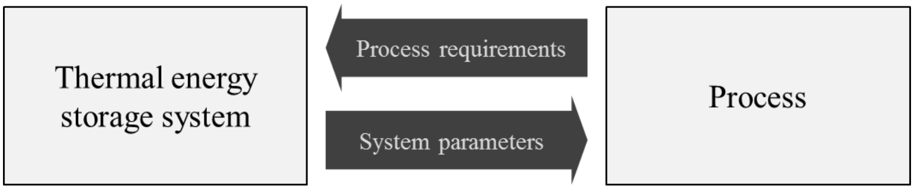

Fig. 1. Linking of process and TES system by process requirements and system parameters.

Following this characterization step, the benefit delivered by storage integration should be identified and the TES system and process evaluated for the specific application. This can be done by determining the key performance indicators (KPI) of the integrated technology.

Developed in Annex 30 of the IEA technology collaboration programme Energy Conservation through Energy Storage (ECES) [8], the methodology presented in this paper is a first step towards a systematic evaluation procedure for TES systems integrated in different applications. Through such novel technology assessment methods, the potential of an integrated TES system can be properly evaluated and the deployment of these systems can be advanced.

2 Existing methodologies for process integration of thermal energy storage systems

A complete methodology for the evaluation of TES systems integrated in processes is not known. Nevertheless, there exists literature regarding process analysis, TES system characterization and KPI across a wide selection of fields in the energy sector.

Regarding process analysis, Wallerland et al. [9] reported on the development of a methodology for the integration of heat pumps into processes. This technical methodology focused on a computational mathematical approach, however, they did not take on a holistic view of the process itself nor recommend generalized measures for process analysis. On a larger scale, Zhang et al. looked at a waste heat recovery network that dealt with the identification of waste heat source and sink plants. This methodology then set up a waste heat transportation system and engaged in optimization procedures [10]. Furthermore, certain optimization strategies have been investigated that include process design and techniques for storage integration. Olsen et al. [11] developed software tools for optimization of heat recovery based on process integration techniques while Fazlollahi et al. [12] created a heat storage optimization model that demonstrates the utility of integrating thermal storage.

Concerning the methodology to describe the TES system itself, the focus of this paper is laid on the boundary of the storage system. Even within literature regarding a specific application, there is little consensus on where the system boundary should be placed. In some studies on indirect TES systems integrated into concentrating solar power (CSP) plants, the boundary is considered to contain the storage module and selected components of the power block [13,14]. In others, no power block components are considered in the economic evaluation of the storage system [15–17]. Furthermore, Kapila et al. [18] found that many earlier studies with technology assessments on large-scale energy storage relied primarily on vendor data or a top-down approach that did not take a consistent definition of system boundary into account. This inconsistency and ambiguity underscores the need for a precise definition for the TES system boundary. Though not covered in this paper, it is important to note that research work has also been conducted in economic considerations regarding thermal energy storage integration. Rathgeber et al. [19] developed a methodology for determining an acceptable storage price for integrated TES systems and Welsch et al. [20] performed an LCA assessment for district heating systems with borehole TES that outlines additional possibilities for economic assessment.

The necessity of a clear and methodical approach for identification of key performance indicators has been investigated by Giacone and Mancò, who found that the complexity and variety of definitions for several energetic properties makes a structured KPI framework necessary [21]. Lindberg et al. also admit that the KPI themselves are too complex to define uniformly across industrial processes, yet offer suggestions on how to proceed with the KPI identification process [22]. The need for a comprehensive and flexible framework is clear.

Key performance indicators have been previously addressed in only one study involving TES systems. Cabeza et al. looked at prior efforts to benchmark KPI for TES systems, specifically focusing on work in CSP plants and the building sector [23]. In this case, specific metrics for performance evaluation were defined, quantified, and presented as future benchmarks. This type of approach has also been used in several other academic studies that present a version of KPI identification focusing on numerical targets [24–27]. One example is the study by Portillo et al. that developed a parametric model for evaluating performance of TES in CSP plants in which the model gave numerical values for TES integration that can help optimize technical choices [27]. In these cases, the KPI represent values of parameters that would already demonstrate the success of a particular technology, instead of providing a framework for KPI identification, as suggested by Giacone and Mancò [21]. The latter is an approach more appropriate to technology integration and performance assessment.

There are many examples of identification processes for specific KPI in which the studies explicitly identify the KPI for their particular fields [28–37]. These chosen indicators address a similarly broad selection of decision-making criteria, encompassing sustainability for manufacturing, production reliability, energy efficiency, delivery of industrial services, general energy management, and flexibility in building energy systems. In some cases, the indicators were weighted and an overall value was assigned [28], while other studies defined a hierarchy or grouped the indicators that supported the explicit selection of KPI [30,33,34,38]. In three publications, the final selection was validated in one or more case studies [30,31,33]. Wang et al. compared performance indicators between a hot water storage tank and a molten salt storage tank that laid the basis for comparison, but still explicitly defined its own indicators [39].

It is clear that the inherent variety of processes in which TES can be integrated requires flexibility in KPI identification. Therefore, it is necessary to create a basic methodology that will assist in determining the most relevant indicators for integrated TES systems in order to properly perform a technology evaluation for the diverse list of applications.

This approach can be seen foremost in May et al. [40], in which KPI for energy efficiency are defined as reference parameters that must be taken into consideration. In Cassettari et al. [41], a decision tool rooted in KPI was developed for sustainability in industrial manufacturing and applied to a case in a tannery. This study was an in-depth analysis into the industrial manufacturing process to derive a method in which both CO_2 emissions and production costs were minimized. Toor et al. [42] developed a method for ranking KPI in construction projects through the use of a survey. In that study, the authors remarked on discrepancies between stakeholder KPI that were largely caused by differing viewpoints on what constitutes project success. A study by Matino et al. [28] also developed a decision support tool with the aim of identifying process-related KPI that were ultimately normalized, scored and aggregated into a unique, global indicator. The study most relevant to the work presented in this paper is that of Li et al. [43], which focused on KPI in building performance. Here, the authors identified stakeholders and KPI, used a bi-index method to select the KPI that underlie stakeholder performance and finally validated the method using a case study. These works from literature highlight the importance of the stakeholder perspective, as well as support the idea that KPI are always application-dependent and a comprehensive framework for their identification in a case-by-case basis is required.

In order to advance the use of TES systems, it is necessary to better characterize the benefit that the technology brings to the processes. Due to the variability and diversity of processes and storage integration strategies, KPI for TES systems should not be uniformly defined without paying detailed consideration to the application. However, there are sufficient similarities between technologies and processes to pursue the development of a comprehensive and flexible framework for analyzing and evaluating an integrated TES system. This framework is useful for evaluating the potential of an integrated TES system in a specific application. Furthermore, it is widely recognized that studies on stakeholder analysis for technology integration and assessment are limited [43]. As such, the stakeholder perspective forms a fundamental element of the analysis methodology.

3 Developed methodology for process integration of thermal energy storage systems

Evaluating processes with integrated TES systems requires a detailed characterization of three features: the process, the storage system, and the benefits of storage integration within an application. The methodology is structured around these ideas. Expanding on the theoretical background from Fig. 1, the suitability of the TES system is dictated through the process requirements and subsequently the TES performance in an application, as shown in Fig. 2. It is important because the application recontextualizes the TES system integration; now, its performance is established via the application.

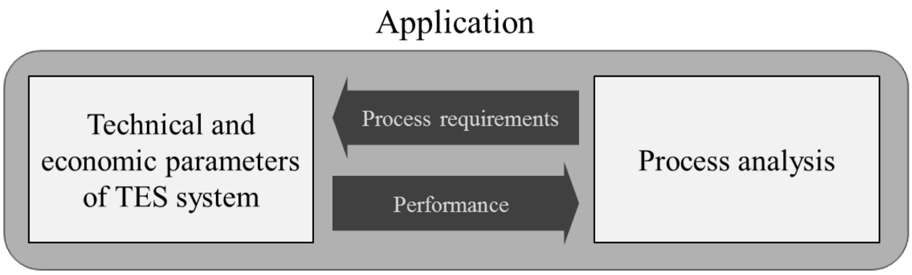

Fig. 2. Interaction between the process analysis and the TES system parameters for a successful integration.

In the following subsections, the stages of the analysis methodology are described in detail before being applied to two case studies in Section 4.

3.1 Process analysis guidelines

The goal of the process analysis step is to address all information relevant to the integration of a TES system in order to provide a comprehensive overview of the critical process information. The complexity of the relation between the process and the TES system can thusly be simplified. As such, a set of guidelines has been developed to provide a clear and comprehensive overview of both technical and non-technical issues regarding the integration of a TES system into a process. The main step in this procedure is the structured collection and analysis of process information. Following that, a storage concept can be evaluated and roughly planned, while the aspects of detailed engineering become relevant after this first step. Fig. 3 shows a flowchart of the process analysis guidelines while the following paragraphs describe the goals of and issues addressed in each step.

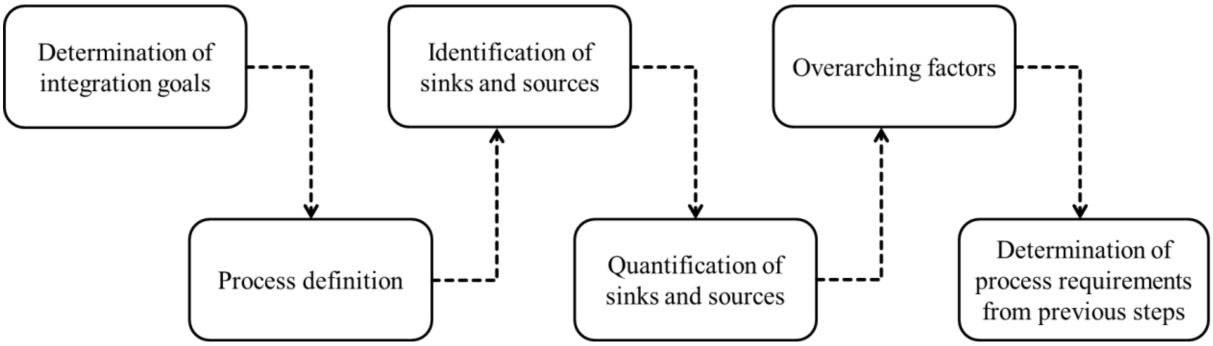

Fig. 3. Flowchart of process analysis guidelines.

In the first step, the overall goal of integration is determined and the functionality of the TES system within the process broadly outlined. Secondly, an important step in process analysis for the possible integration of a TES system is to determine and delineate which process is being analyzed, and where the boundaries of that process are. This addresses what factors can and need to be analyzed. For example, in the context of a power plant it has to be distinguished whether the process consists of the whole power plant or just one functional unit within the overall plant.

With the process defined, the thermal sink(s) and source(s) available within and at the boundaries of the process should be determined. This can be done via discussions with specialists, analysis of piping and instrumentation diagrams, process database analysis, estimation via extrapolation of fuel usage or measurement, among other information sources. There is a wide range of thermal sinks and sources normally under consideration, with sinks such as a steam turbine, a heat pump, process heat (direct integration), water or steam main, or an organic Rankine cycle. Sources investigated within Annex 30 include waste heat, direct combustion, heat provided directly for charging (e.g. from heat recovery steam generator), solar radiation e.g. in concentrating solar power, cooling water, and many others. Sources that are not directly within the existing process, such as electricity, as well as sinks such as a neighbouring process, should also be considered.

The sink(s) and source(s) must be quantified in order to evaluate the potential applicability for TES integration. Here there are two major groups of parameters: thermodynamics and spatial properties. Thermodynamic parameters can initially be analyzed independently of the physical environment. The three most important aspects of the thermodynamic properties that must be expanded upon are heat transfer medium, temperature levels and transient profiles. The heat transfer medium of the sink or source influences the heat transfer rate, types of containment and materials used and applicable storage concepts. The temperature levels and transient profiles of the sink and/or source are key for the development of a TES concept, especially regarding power level and capacity. Furthermore, mass flow rates and pressure levels have an important role in determining power, capacity, phase of heat transfer fluid, and heat transfer characteristics. A section on spatial properties addresses problems or opportunities regarding available or usable space, obstacles and distances between process parts, and already-existing infrastructure.

Once the source(s) and sink(s) have been quantified, non-technical issues regarding the process including the recurrence of the process, company targets, and any environmental aspects need to be addressed. Finally, the last step of the process analysis is a summary and initial estimation of the integration possibilities for TES systems in the analyzed process. Ultimately these steps result in an identification of the process requirements for a TES system to be integrated that can be applied to both retrofit and greenfield integrations. This results in a differing viewpoint while applying the process analysis guidelines that will be further considered in the discussion.

3.2 Thermal energy storage system: system boundary

One of the most important aspects of evaluating TES integration is the placement of the system boundary. It has previously been shown that boundary placement can influence calculated parameters significantly [44], so consistency between analyzed cases is crucial for comparability. Despite this, there is an disagreement as to what constitutes the system boundary and perspectives vary significantly as to where the limit of the thermal energy storage system should be set. Thus, it is highly important that there be a robust and applicable definition for proper comparison of integrated systems to be undertaken.

Before doing so, it is necessary to clarify the lower analysis levels of a TES system – component and module. Components are the smallest parts of the TES, which in combination form the overall system. A module is a set of components that fulfils a distinct and specific task within the TES system.

The definition is proposed as follows:

> The TES system boundary is the point of contact between the fluid streams and the thermal sink and thermal source. The system contains all the components and modules exclusively used by it and those necessary to deliver heat to the sink and to retrieve heat from the source.

Included in this definition are all components required for linking the storage system to the process, i.e. components for connecting to the source or sink of thermal energy. As such, a system refers to all the materials, components and modules that allow the TES device to perform its purpose of absorbing, storing, and delivering heat.

An example of the system boundary applied to a concentrating solar power plant can be seen in Fig. 4, in which a two-tank molten salt TES system is integrated. The entire process is the CSP plant, the objective of which is to produce electricity using solar irradiation as the primary energy source. Therefore, it only has one thermal source (the solar field) and one thermal sink (the power block). The TES system is connected in parallel to the thermal source and sink. This means that the process can operate by providing thermal energy directly from the thermal source to the thermal sink to produce electricity. In this example, the boundary comprises the units 4, 5, 6 and 7, because they are the necessary components to connect the TES system to the process. Here the heat exchanger (4) is included because it is required for transferring energy from the source to the storage unit and from the storage unit to the sink. This is an example of indirect storage; the heat exchanger is considered as part of the TES system. In section 4, an example of direct storage is used where the heat exchanger is external to the TES system.

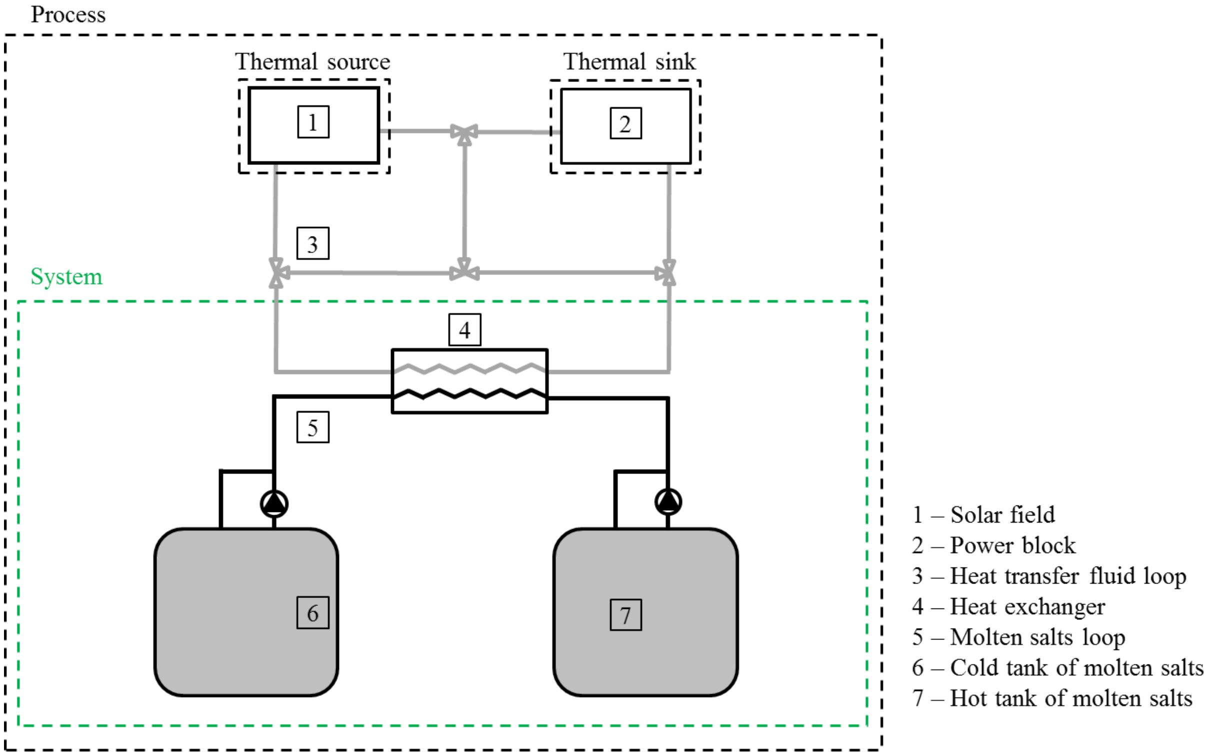

Fig. 4. Definition of the system boundary as applied to an example of indirect storage in concentrating solar power.

In addition to the boundary, a TES system is characterized by a selection of parameters. These include technical properties such as storage capacity, nominal thermal power, temperature levels, and response time, as well as economic parameters including capital expenditures and operating expenditures. While discussing these in detail is beyond the scope of this paper, it is important to note that they are highly relevant in the KPI identification step discussed in the following subsection.

3.3 *Key performance indicators in an application*

The next step in the analysis methodology is the examination of the benefits that a TES system brings to an application. Determination of KPI revolves around the concept of performance. An isolated TES system cannot be evaluated in terms of its performance, as it is still a process unit with a purpose that is unclear – there are not yet any requirements to fulfil. Once it is integrated in an application, its performance in terms of meeting the process requirements can be assessed. Additionally, aspects external to the TES system (e.g. effect on CO_2 emissions) that also characterize the integration are considered. The KPI are then determined by taking different stakeholder perspectives on the integration to determine the most relevant TES system parameters and external factors. This is shown graphically in Fig. 5 and explained in the following subsections.

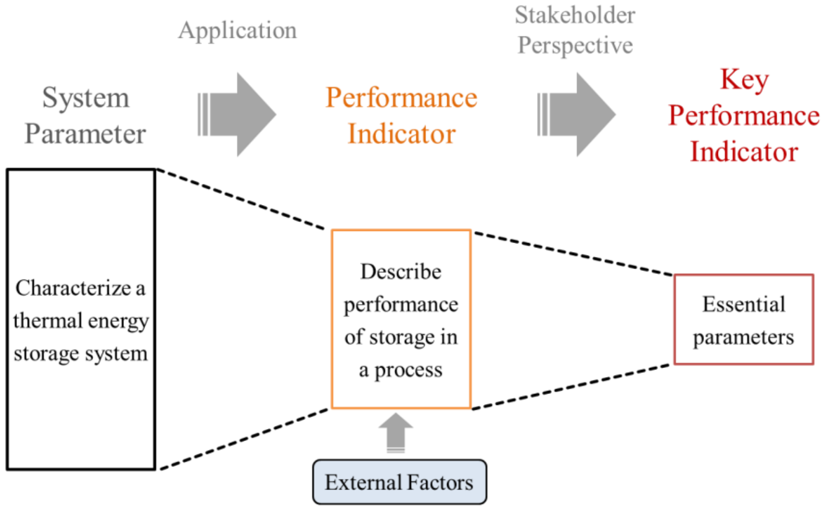

Fig. 5. The KPI funnel showing the transition from system parameter to KPI.

3.3.1 *Performance indicators*

To judge performance, the TES system must be evaluated with a process in an application for which there are specific requirements. In this case, the performance indicators denote the identified TES system parameters that are relevant to the process requirements. For example, a particular process may require a response time or a minimum power to be delivered from the TES system.

Nevertheless, the complete impact that a TES system may have on an application does not necessarily emerge from only the technical and economic parameters. As such, the definition also considers external factors that arise from outside the TES system, for which an understanding of the broader effects of the storage integration are necessary. This consideration could range from qualitative, process-specific factors such as process flexibility, to factors relevant to the local or regional energy system, such as dispatchability or grid flexibility. Further prospects for the category of external factors include a reduction in greenhouse gas emissions and increased renewable energy utilization, both of which are generally favorable from a policy maker perspective. External factors are the overarching impacts of TES integration to the process and the overall energy system that are not directly connected to storage system parameters.

3.3.2 Stakeholder perspective and key performance indicators

Performance of a technology can be defined by its ability to satisfy a specific need [45], however, the performance indicators are prioritized differently depending on the viewpoints of parties interested in the integration of the TES system. The final step in determining the key performance indicators is thus an analysis from various stakeholder perspectives. By introducing the concept of a stakeholder, it becomes possible to determine the most relevant performance indicators. The stakeholders selection process identifies the interests with the most potential to influence the integration or operation of the integrated TES system. They are the parties with the most invested in the integration. With these KPI identified, a stakeholder-based assessment can establish the benefits a specific TES system brings to an application.

The transition from system parameter to performance indicator to key performance indicator tightens the perspective from step to step, as shown in Fig. 5. At each step of the evaluation, a unique assessment of the TES system occurs. It follows that a KPI for technology assessment of TES is an internal (i.e. TES system-related parameter) or external (e.g. process benefits) property that demonstrates its ability to meet external needs as defined by stakeholders. With such a framework for KPI identification created, it is possible to assess the integration of TES systems from a selection of perspectives to form a comprehensive and dynamic view on the integration of the technology.

4 Application of developed methodology to case studies

Two case studies were evaluated using the methodology presented in this paper. These were selected to highlight the diversity of applications of high-temperature TES technologies and to facilitate distinction between the integration examples that will be further elaborated in the discussion.

A prominent application of high-temperature TES systems is in concentrating solar power plants. Most often installed in a two-tank molten salt storage configuration, this system allows the plant to provide dispatchable power that complies with an intermediate load profile [46]. These integrated systems are commercially available and well-known. They are to be considered “greenfield” cases according to the logic explained in the introduction.

In contrast, a first-of-its-kind example of an integrated TES system was selected as a second case study. A high-temperature latent heat storage unit has been developed for the integration in a cogeneration plant in Saarland, Germany [47]. The TES system produces steam for an industrial customer in case a turbine trips. It will be integrated into an existing process and therefore reflects the “retrofit” situation.

The following sections begin by describing the purposes of TES integration in each application, followed by the implementation of the method from Section 3. Ultimately, a process analysis is performed, the system boundary is determined, and KPI are derived and prioritized based on the perspectives of three relevant stakeholders.

4.1 *Case descriptions*

4.1.1 *Concentrating solar power case study*

The specific CSP case analyzed is the solar tower power plant in Crescent Dunes, Nevada, USA. This is an example of direct thermal energy storage, where the solar salt comprises both sensible storage medium and heat transfer fluid, as shown in Fig. 6. The storage medium has a temperature range of 288 °C to 566 °C and the plant has a storage duration of 10 hours. With a turbine power of 110 MW_e, this corresponds to approximately 3.3 GWh_{th} storage capacity [48].

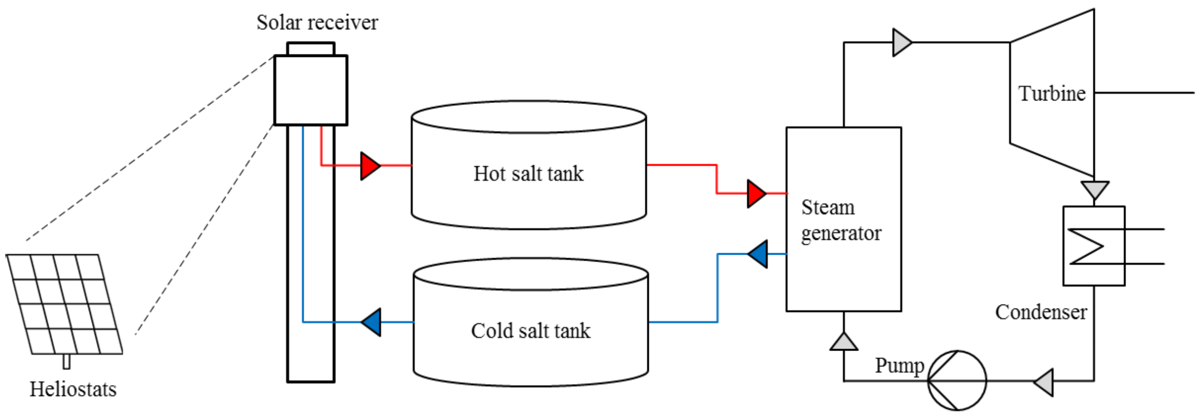

Fig. 6. Schematic of the CSP plant with direct molten salt storage in Nevada, USA (adapted from [49] and [50]).

To proceed with the analysis, it is important to understand the role TES plays in CSP plants. Of primary importance is an increase in the plant capacity factor, which is the ratio of the plant nominal power to its rated power [51]. This occurs largely due to two effects. For one, the turbine is able to operate when the solar receiver has no direct insolation, i.e. during the night. The second effect is buffering by the storage system during cloudy periods or other weather-related disturbances. During these times, the storage provides enough thermal power to stop the turbine from entering transient mode or in the worst case, shutting down completely [49]. Use of the storage also minimizes a need for back-up capacity or start-up buffering, both of which are often provided by natural gas combustion turbines [52,53].

TES also improves the overall energy efficiency of the plant by lowering turbine start-up losses and by reducing curtailment during times of high generation [49]. Furthermore, the now-dispatchable electricity allows the plant to align its generation with peaks in power demand, creating a direct economic benefit as well as ancillary economic incentives through arbitrage, culminating in a decrease in the levelized cost of electricity (LCOE) of the plant [52]. Dispatchable power also provides flexible generation for the power system, which is a critical aspect for the integration of variable renewable energy [2]. Another grid-relevant effect is the potential for the power plant to act as a frequency regulator by balancing generation and supply with inertia provided by the turbine [54].

Further impacting the LCOE is a reduction of the solar multiple, thereby lowering the required solar field size or allowing for an increased solar field size (i.e. higher capacity factor) without considerable cost escalation [52]. Capacity factor and LCOE are closely related. However, it is important to highlight the direct impacts on both, so that the integration benefits may be fully characterized.

These main motivators are summarized in Table 1.

Table 1. Outcomes of TES integration into CSP plants.

Outcome of TES integration	Description
Increased plant capacity factor	- Night-time generation - Buffering during weather events
Improvements in energy efficiency	- Less curtailment during periods of high generation - Lowering turbine start-up losses
Dispatchable power	- Economic incentives - Improved grid flexibility
Reduced LCOE	- Maximized generation at peak demand - Reduction in solar multiple (i.e. smaller solar field)
Ancillary benefits	- Start-up buffering & minimizing back-up capacity - Frequency regulator for power grid

4.1.2 Cogeneration power plant case study

A TES unit is currently in development and build for the integration in a cogeneration plant in Saarland, Germany [55]. The plant supplies steam to several customers, with a minimal load being a constant supply of superheated steam at 6 MW_{th} and 300 °C. Under normal operating conditions, the steam is generated by delivering the exhaust air from a mine-gas-fired turbine to a heat recovery steam generator (HRSG). The steam produced by this HRSG is then temperature-controlled and sent to the customers through the steam main. If the turbine trips due to fluctuations in the mine-gas network and supply, an additional boiler serves as back-up and ensures the steam meets the required specifications until the turbine can be brought back to full load. In order to ensure continuous steam quality, a back-up solution must ramp up to full load within the two minutes that the HRSG is still producing a rest-steam amount. Therefore, a back-up boiler runs on ‘warm load’, meaning that it is constantly burning fossil fuels so that it can be transitioned to full load within two minutes [55].

The latent heat TES system is designed to be integrated in parallel to both the HRSG and the existing back-up boiler. The critical advantage following integration is that the back-up boiler is run on ‘cold load’, meaning that it burns fewer fossil fuels to satisfy a prolonged transition time of 15 minutes [55]. The TES system provides the steam for the industrial customer while the boiler undergoes the transition to full load. The process diagrams before and after TES integration are shown in Fig. 7.

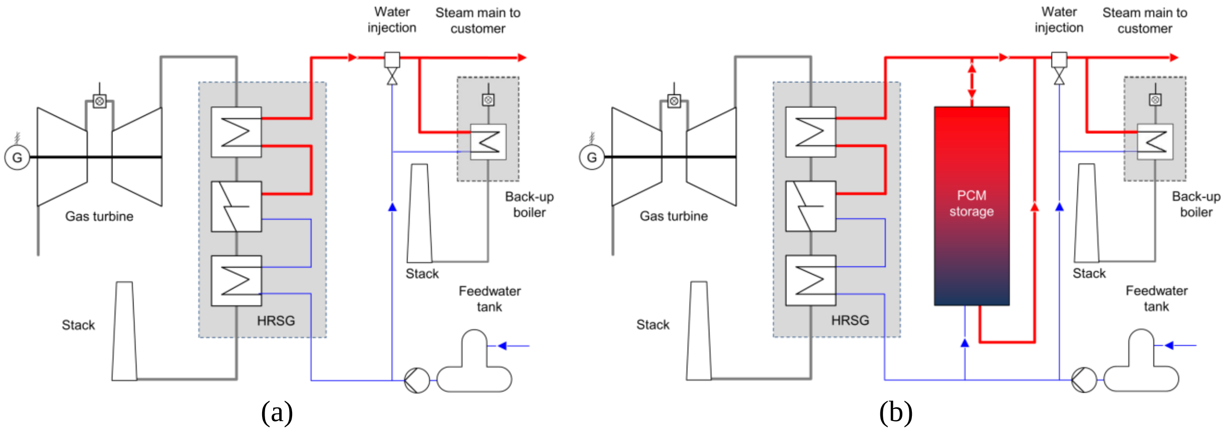

Fig. 7. Process diagrams of cogeneration plant (a) prior to and (b) following TES integration (adapted from [55]).

The TES system is directly enhancing the functionality of a currently-operational process unit and must meet precise specifications for the industrial steam client. There are therefore specific TES system properties that are critical to storage operation, especially related to the discharging procedure. On the one hand, the storage must meet the two minute ramp-up time for producing the full load of steam. On the other, it must discharge for 15 minutes while the back-up boiler transitions from warm to full load [47]. Finally, it must produce steam that meets the required steam parameters from the industrial client. In other words, the steam must be delivered at the required temperature of at least 300 °C, pressure of minimum 21 bar at a flow rate of 8 t/h, which corresponds to a thermal power of 6 MW. These three factors form the main process requirements that characterize the integration.

4.2 Process analysis

As described in Section 3.1, the process analysis is a structured guideline for identifying critical information that directly concerns the integration procedure and suitability of the storage. For the purposes of this paper, an abridged version of the process analysis results, shown in Table 2, illuminate the contrast between the different processes.

Table 2. Abridged results of process analysis of the two evaluated cases.

Process variable	**Concentrating solar power (“greenfield process”)**	**Cogeneration power plant (“retrofit process”)**
Integration goal	Increase capacity factor, reduce LCOE, reduce back-up utilization and improve efficiency	Decrease fossil fuel use by reducing combustion in back-up boiler
Process definition	Solar tower power plant with molten salt as heat transfer fluid	Cogeneration plant consisting of a gas turbine, steam generator, two back-up boilers and steam main
Thermal source(s)	Solar insolation	HRSG outlet steam
Thermal sink(s)	Power block (steam generator)	Steam customer
Medium of thermal source(s) and sink(s)	Molten salt	Steam
Cycle length	24 hours	15 hours

Acceptable TRL for TES	8 – 9	5 – 6

4.3 System boundary

Fig. 8 and Fig. 9 show the system boundaries of the CSP and cogeneration case studies, respectively, based on the definition from Section 3.2. As according the definition, in Fig. 8 only the storage tanks are considered within the boundary. The steam generator (heat exchanger) is not included because it is not a component used exclusively by the TES system and belongs primarily to the power block. This direct storage configuration can be distinguished from Fig. 4, in which the heat exchanger was included due to its necessary role in transferring energy between the source, storage unit and sink. In Fig. 9, the TES system boundary is similarly restricted to the storage tank and surrounding piping because the HRSG and other process components were present before the retrofit integration. These components are not used exclusively by the TES and as such, are not within the system boundary.

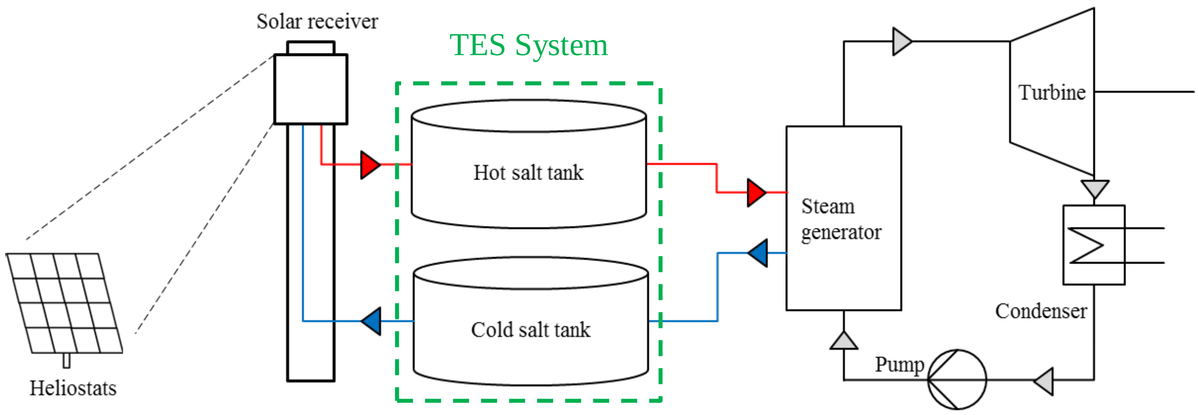

Fig. 8. System boundary for the concentrating solar power case study (diagram adapted from [49] and [50]).

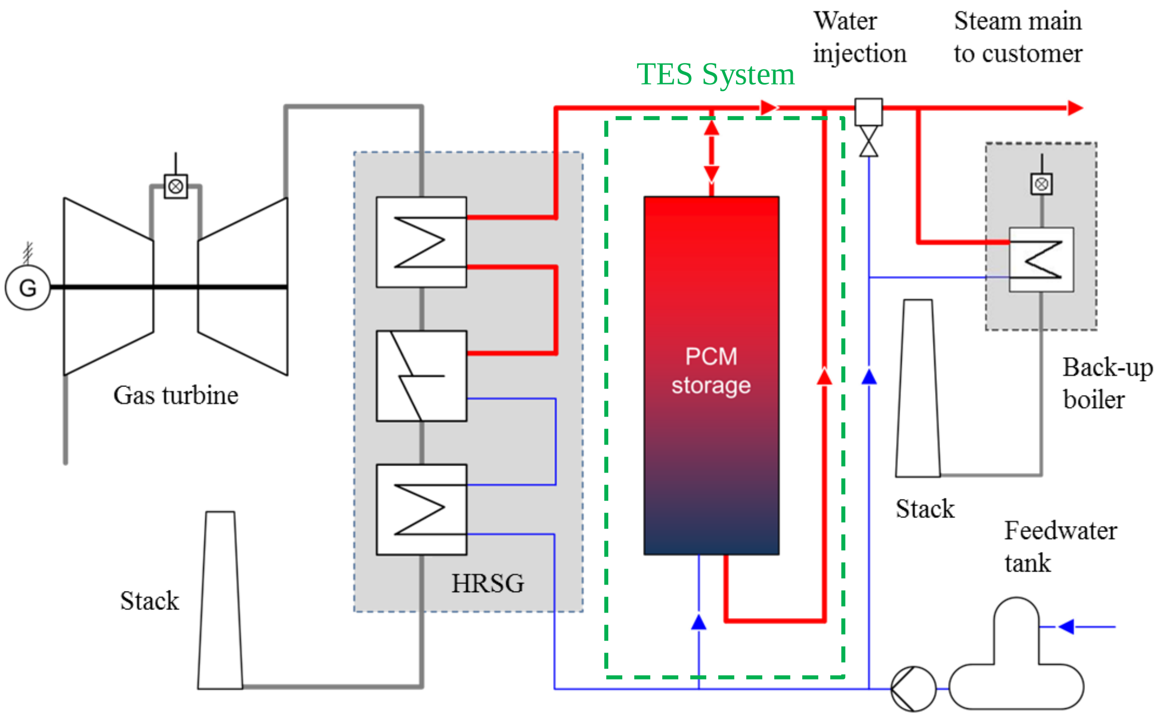

Fig. 9. System boundary for the cogeneration power plant case study.

4.4 Key performance indicators

The performance indicators and key performance indicators were determined for both cases following the method described in section 3.3.

4.4.1 Concentrating solar power case study

The performance indicators are derived from Table 2 by associating the TES advantages with system parameters or external factors. The most important system parameters are selected based on required storage performance in a CSP application; the external factors that TES integration delivers to the solar power plant and its electric system are added to this list. The list of these performance indicators and an explanation of their importance is shown in Table 3.

Table 3. Performance indicators and their justification for TES integration in CSP plants.

Performance indicator	Justification of importance (Crescent Dunes requirements)
TES system-related factors	
Storage capacity of TES system	Increased plant capacity factor, (3.3 GWh_{th})
Power delivered by TES system	Required to meet turbine design power, (110 MW)
Response time of TES system	Response to weather events or other disruptions, (<1 minute)
Lifetime of TES system	Critical to economic viability of the plant, (>20 years)
External factors	
Dispatchable power	Reduced dependence on intermittent nature of solar thermal resources
Reduced LCOE	Optimization of economic potential through generation at peak demand, increased capacity factor, avoided back-up capacity and reduction in solar field.
CO_2 mitigation	Further displacement of fossil-fuel generation, especially relevant due to flexible dispatch. Reduced natural gas combustion during buffering and start-up.
Increased use of renewable energy	Expanded generation from solar thermal resources
Improved grid stability and flexibility	Potential to serve as frequency regulator by reducing imbalances between generation
Boosted energy efficiency	Start-up buffering and reduced curtailment

Allocation of the KPI depends on a stakeholder perspective. In this case, three relevant stakeholders were identified (CSP plant operator, electric utility, and policy maker) and the performance indicators were considered from their perspectives. The results are shown in Table 4.

Table 4. KPI for stakeholders in CSP application.

CSP plant operator	Electric utility	Policy maker
Storage capacity	Dispatchable power	CO_2 mitigation
Power	Response time	Increased use of renewable energy
Lifetime		Grid stability
Reduced LCOE		
Boosted energy efficiency		

4.4.2 Cogeneration power plant case study

The main process requirements outline the storage integration in terms of its TES system parameters, thus forming the basis for a derivation of performance indicators. In addition, there are external factors that arise due to the storage integration. These results for the cogeneration case study are shown in Table 5.

Table 5. Performance Indicators for TES integration in a Cogeneration Plant.

Performance indicator	Justification of importance
TES system-related factors	
Response time of TES system	Must ramp to 6 MW_{th} within two minutes
Steam quality (temperature, pressure)	Generated steam must meet process requirements
Discharge time	Must provide 6 MW_{th} for 15 minutes
Lifetime of TES system	Critical to economic viability of the integration and permitting procedure
External factors	
Reduced fossil fuel use	Fewer fossil fuels burned during ‘warm load’ of backup boiler
Reliability	TES delivers process services that improve reliability
Increased process flexibility	Delivered by TES in several ways beyond the scope of this paper
CO_2 mitigation	Reduced combustion of fossil fuels

Through the implementation of three stakeholder perspectives (process operator, industrial customer, and policy maker), the importance of the performance indicators can be prioritized into KPI, as shown in Table 6.

Table 6. KPI for stakeholders in cogeneration case study.

Process operator	Industrial customer	Policy maker
Response time	Steam quality	Reduced fossil fuel use
Discharge time	Reliability	CO_2 mitigation
Lifetime		
Reliability		
Increased process flexibility		

5 Discussion

The results provide key insights on the methodological steps of process analysis, TES system boundary determination and KPI selection. Focus of the discussion is on how the methodology differentiates between greenfield and retrofit applications, how the boundary of the storage system varies depending on the application, and how KPI change significantly for different stakeholders.

5.1 Greenfield vs. retrofit applications

The process analysis guidelines highlight an important difference between greenfield and retrofit applications. In the CSP example, with the case being a greenfield installation, it can be seen that the emphasis is laid on the integration benefits. The fundamental question is determining what the storage delivers to the application itself, with the process analysis guidelines used to identify the integration goal as a first step. This is necessary because the process will be designed from the ground up and it is important to know precisely what function the storage will serve. An adjustment of this function could have profound implications on the design of the process itself, e.g. on temperature levels, mass flows, etc.

In the cogeneration example, the power plant itself already exists with the storage being integrated as a supplementary process unit; it is thus a retrofit integration. For these processes, a specific engineering design is required that fully grasps the potentially novel aspects of the integration. Here, the emphasis is placed on the process requirements, i.e. what does the process require from the storage? There is little flexibility in these cases and for retrofit, the integration goal may only be quantitatively understood once the process analysis has been completed. This shows the key difference in how the process analysis guidelines are applied.

Such variations can be seen in the results, wherein the discussion in CSP revolves around the services the TES provides to the power plant. Dispatchable power, reduced LCOE and improved energy efficiency are the desired benefits of this storage. In the cogeneration example, the stakeholders place a higher emphasis on technical performance and reliability. Here, the focus is on maintaining steam quality and responding effectively to any disruptions. The key point is that these integrated systems are currently considered differently, yet through the use of this technology assessment methodology, they can be compared more tangibly with one another.

5.2 Boundary of the thermal energy storage system

There are key elements in the two cases that underscore the importance of a consistent system boundary definition. To begin, it can be seen that both system boundaries contain all the components necessary to retrieve heat from the source and deliver it to the sink, as well as those used only for the purpose of storing heat. This means that in the case of direct two-tank molten salt storage within a solar tower CSP plant, the steam generator is not included as is shown in the definition itself in Fig. 4. In a case of indirect TES, when the heat transfer medium is not identical with the heat storage medium, the heat exchanger used to transfer thermal energy from the solar field HTF (e.g. thermal oil) to the storage medium (e.g. molten salt) would be included as part of the storage system and taken into consideration in the technical and economic evaluation.

It is also significant that the placement of the system boundary differs for concentrating solar power with indirect storage as in e.g. Thaker et al. [8], which considers the heat exchanger within the power block to be part of the TES system. This diverges from the definition in this paper and indeed the results as without storage, the heat exchanger would already be a necessary component.

The boundary of the TES system in the cogeneration case is a typical example of a retrofit process. In this instance, the system is integrated into a process with previously existing components that are not used exclusively by the storage, as required from the definition. As such, the TES system boundary remains clearly distinguishable from the HRSG, water injection line and back-up boiler that had already been present in the process.

5.3 Performance indicators and stakeholder perspective

There are some key performance distinctions between the two cases that ultimately define the selection of KPI. In CSP, the storage capacity defines the ability for the power plant to continue producing electricity overnight, for example. In the cogeneration case, the technical suitability is ultimately laid out by the power of the TES system that provides the necessary steam parameters, with pure storage capacity taking secondary importance. Storage reliability is also more pronounced in the cogeneration case, as the TES system constitutes a process unit that is essential to the process. These differences are crucial in the storage design phase and the distinction can be described simply through the use of the KPI results.

Key similarities between the cases are also present. Foremost is the importance of the storage response time, that is distinctive in both the greenfield and retrofit cases. This shows that when a storage is required, it is crucial that it deliver punctually, otherwise the integration is unsuccessful. The storage lifetime is also relevant in both cases, which emphasizes that process components are long-term investments and is related to long-term reliability, which in both cases constitutes an important KPI.

Regarding the stakeholders, it can be seen particularly in the cogeneration example that certain stakeholders are interested purely in a specific product from the process. As such, the industrial steam client is focused on reliably obtaining the steam with the proper quality. The integration of the TES storage system is not relevant for this stakeholder, as long as the steam is delivered. In cases such as these, the TES technology must compete with any alternative solutions.

6 Conclusions

Thermal energy storage systems integrated in processes have been lacking a clear and concise evaluation method that will help exploit their full potential. Until now, no detailed process analysis method has been proposed and there has been significant ambiguity regarding where the thermal energy storage system boundary is placed. Furthermore, previous uses of key performance indicators have either been target-focused, entirely non-technical, or over-specified.

The novelty of this paper is in the methodology, which takes a first step in addressing issues related to further deployment of thermal energy storage technologies in promising applications. The inclusion of both technical and economic storage parameters and external factors of integration present an opportunity to comprehensively and differentially evaluate the application. Through implementation of the methodology to two case studies in high-temperature storage, it has been shown how different applications prioritize different requirements from storage systems. The proposed methodology can also be applied to cases in low- and medium-temperature thermal storage. Moreover, the greenfield and retrofit approaches can be compared through the use of this systematic methodology and the benefits of a thermal energy storage system to an application can be highlighted and discussed more tangibly. In the end, this methodology is highly applicable to real applications and can be used from the very beginnings of process design to the final evaluation of tangible benefits of the storage integration.

Following this work, it is recommended to further expand the methodology by addressing more explicit economic concerns in the process analysis guidelines, e.g. local subsidies, tax benefits, renewable heat incentives. Also suggested is incorporating a ranking function that allows for a weighing of the different key performance indicators based on the stakeholder. This will increase the precision and nuance of the key performance indicator identification. Furthermore, providing the users of the methodology with a suggested list of key performance indicators could help avoid any oversight or bias. Additional stakeholder involvement should be pursued as some thermal energy storage benefits are well-understood, yet others are less evident when first considering an integrated system. Engagement with the research community, industry, and policy makers is a critical step in addressing this gap. Finally, for validation and continued development, the application of the methodology by independent parties to differing cases will be needed, in order to better understand the strengths, weaknesses as well as development potential of these tools.

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Abbreviations

CSP	Concentrating Solar Power
ECES	Energy Conservation through Energy Storage

HRSG	Heat Recovery Steam Generator
IEA	International Energy Agency
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
HTF	Heat Transfer Fluid
TES	Thermal Energy Storage
TRL	Technology Readiness Level

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