Applied Energy 230 (2018) 750–760

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

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HIGHLIGHTS

- A methodology has been developed for evaluating thermal energy storage systems integrated in processes.
- The work defines process analysis guidelines and the thermal energy storage system boundary.
- A definition for key performance indicators based on a stakeholder perspective is developed.
- The methodology was benchmarked using real case studies in concentrated solar power and cogeneration.

ARTICLE INFO

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

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.

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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https://doi.org/10.1016/j.apenergy.2018.09.001
Received 29 May 2018; Received in revised form 8 August 2018; Accepted 1 September 2018
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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.

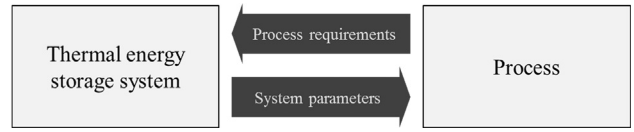

Fig. 1. Linking of process and TES system by process requirements and system parameters.

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

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