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Techno-economic evaluation of solar-based thermal energy storage systems

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ABSTRACT

In this paper, a data-intensive cost model was developed for sensible heat, latent heat and thermochemical storage systems. In order to evaluate the economic feasibility of storage systems, five scenarios were developed depending on the method of storage. The five scenarios considered were indirect sensible heat, direct sensible heat using two tanks, direct sensible heat using one tank, latent heat and thermochemical storage. A Monte Carlo simulation was performed for all the scenarios to examine the uncertainty in the levelized cost of electricity when parameters such as solar multiple, plant capacity, storage duration, capacity factor, and discount rate are changed. The levelized cost of electricity ranges for individual scenarios are; 0.08–0.59 $/kWh for indirect sensible heat, 0.03–0.22 $/kWh for direct sensible heat using two tank, 0.02–0.16 $/kWh for direct sensible heat using one tank, 0.06–0.43 $/kWh for latent heat, and 0.22–1.19 $/kWh for thermochemical storage. The results indicate that when uncertainty is taken into account, the investment cost for thermochemical storage is clearly higher than other scenarios. This study will provide key information for industry and policy makers in decision making and in determining the economic viability of thermal energy storage systems.

1. Introduction

Thermal energy storage (TES) has the potential to store energy in the form of heat over a period of time for later use. It is a promising technology that can reduce reliance on fossil fuels and help avoid penalties related to environmental regulations. The use of TES to meet environmental standards and energy requirement is now receiving the attention it has always deserved. TES is expected to grow by 11% between 2017 and 2022 [1]. The growth rate of TES can be affected by the intermittency issues in solar radiation (i.e., cloudy days and nighttime). For this reason, there is a need to integrate the storage of thermal energy (i.e., sensible heat, latent heat, and thermochemical) with electrical power generating systems. However, despite challenges around the integration of TES, it is not yet known if it is economically feasible. For this reason, the cost-effectiveness of integrating TES into existing technologies is a subject of discussion.

A recent development is to improve the cost-effectiveness of TES by reducing the levelized cost of electricity. For example, in March 2015, the U.S. Department of Energy (DOE) announced a plan to reduce the levelized cost of electricity from solar-based electrical power generation to below $0.06/kWh by 2020 [2]. This plan prompted the search for cost-effective ways to store energy in the form of heat. In view of this, sensible heat, latent heat, and thermochemical storage are considered for storing thermal energy. Sensible heat storage is a commercially available technology that can store thermal energy for up to 15 h using a heat transfer medium such as molten salt [3]. Molten salts have high storage efficiencies that allow sensible heat storage to produce electricity during peak energy demand, thereby making electricity more economical [4]. Latent heat storage can store energy at relatively low investment costs [5]. Because of the high energy densities of the phase change materials (PCMs) used in latent heat storage, there is a potential to reduce storage tank costs compared to sensible heat storage [6]. However, latent heat storage is still in the research and development (R & D) phase to optimize the trade-off between reducing the cost of the PCMs and improving its thermal conductivity. Thermochemical storage is also still in the R & D phase. Because there are insufficient data on it, its economic feasibility has been examined through hypothetical models [7]. A widely used economic indicator to assess the economic feasibility of TES is the levelized cost of electricity (LCOE).

The LCOE is often evaluated while performing techno-economic assessments. To accurately perform a techno-economic assessment, a system boundary needs to be defined. The system boundary determines which components are included. A solar-based TES system boundary has three parts: solar field, storage block, and power block [8]. A study by Sioshansi et al. [4] showed that the size of the equipment in all three affect the economic viability of solar-based power generation systems (i.e., concentrated solar power). The solar field equipment includes mirrors, piping, pumps, valves, and parabolic troughs. The storage block consists of heat exchangers, pumps, piping, valves and storage tanks to store the heat transfer fluid. The power block includes a

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Acronyms

A	total heat exchanger area
C	total investment cost ($)
CSP	concentrated solar power
c_p	specific heat capacity
D	discount rate (%)
Energy	total energy produced (kWh)
G	variable O & M escalation due to inflation (%)
GHG	greenhouse gas
h	enthalpy
LCOE	levelized cost of electricity ($/kWh)
$\dot{m}$	mass flow rate
N	total life (years)
O & M	Operation and Maintenance
PCM	phase change material
$\dot{Q}$	rate of heat transfer
$\dot{Q}_{loss}$	rate of heat loss
SM	solar multiple
S1	Scenario 1: Indirect sensible heat storage using two tanks
S2	Scenario 2: Direct sensible heat storage using two tanks
S3	Scenario 3: Direct sensible heat storage using one tank
S4	Scenario 4: Latent heat storage using one tank
S5	Scenario 5: Thermochemical heat storage
T	temperature of heat transfer fluid
TES	thermal energy storage
ΔT_m	log mean temperature difference
U.S. DOE	Department of Energy
U	overall heat transfer coefficient
$\dot{W}$	rate of work
ΔE_k	change in kinetic energy
ΔE_p	change in potential energy

turbine, condenser, pumps, piping, and valves. The sizing of this equipment affects the investment cost of concentrated solar power (CSP) plants. Several researchers estimated the LCOE and investment costs for TES technologies using different system boundaries. Flueckiger et al. [9] evaluated the LCOE of a thermocline storage system by considering solar field, storage block, and power block as a system boundary. In addition to the aforementioned system boundary, Montes et al. [10] included an auxiliary natural gas-fired boiler for steam generation. However, a study by Heller et al. [11] evaluated the LCOE without considering the power block in the system boundary.

Other than through a system boundary, the LCOE can be evaluated as a function of capacity factor, solar multiple, storage duration, and plant capacity. Storage duration is defined as the length of time heat can be stored in a system. The ability of TES to store energy for long periods suggests greater economic viability as stored heat can be used to generate power during peak load when solar energy is absent or insufficient. As storage time increases, it gives the freedom to dispatch electricity when electricity prices are at their peak and thereby increase profit [4].

Another important factor in evaluating the LCOE is the solar multiple. The solar multiple is the ratio of thermal energy collected in the solar field to the thermal energy input for the turbine [12]. A solar multiple of one, for instance, indicates that the energy produced in the solar field is equal to the energy consumed by the turbine, leaving no excess energy to be stored [4]. A solar multiple of two, on the other hand, indicates that the energy produced in the solar field is twice that consumed by the turbine, leaving excess energy to be stored as heat for later use, thus making the technology more economical. However, the solar multiple is not the sole indicator of economic feasibility. The capacity factor is also used to evaluate economic viability. It is the ratio of actual energy produced to the theoretical energy produced per annum [12]. The capacity factor of TES would affect the LCOE because the energy produced from thermal storage can be sold in the form of electricity. Plant capacity can also be used to evaluate the LCOE. Plant capacity is measured in megawatts (MW) and is defined as the electrical power output that can be provided by the thermal storage system. The LCOE associated with varying plant capacity would demonstrate economies of scale. Thus, storage duration, capacity factor, solar multiple, plant capacity, and system boundary are few of the key factors to be considered when evaluating the LCOE to determine the economic feasibility of TES.

A few studies developed techno-economic models to examine the economics of TES technologies. These models can be classified into three types. Type 1 models examined the economics of sensible heat storage [13]. The costs of thermal storage for parabolic troughs and central tower solar field systems were evaluated by Turchi et al. [14] using the Solar Advisor Model (SAM) software and found to be less than 11 cents/kWh. In a similar study by Hinkley et al. [15], the LCOE was evaluated for both technologies using SAM software. Hinkley et al. [15] showed that at a higher operating temperature, there is a significant potential to reduce LCOE. SAM software performed a techno-economic assessment of TES using input parameters such as unit capital cost ($/kW) and storage duration [15]. Boudaoud et al. [13] evaluated the investment costs of individual equipment using first principles. The estimated LCOE values were approximately 0.66–0.78 $/kWh and 0.6–1.3 $/kWh, respectively, when storage duration and solar multiples were varied [13]. Lund et al. [16] examined the economics of a hybrid system integrating thermal storage with battery storage and liquid fuel storage within the system boundary. The hypothetical storage system proposed in Lund et al. [16] aims to take a holistic approach by integrating cross-sector energy conversion technologies to address the needs of district heating and power generation. The Type 1 techno-economic assessments had different system boundaries and assumptions, making it difficult to compare them. Type 2 models examined the economics of latent heat storage [17]. Hubner et al. [18] evaluated the unit capital cost of various phase change materials to examine its effect on the LCOE. Xu et al. [5] used first principles to evaluate investment costs of individual equipment. The investment costs were used to estimate the LCOE for latent heat storage. Xu et al. [5] estimated the LCOE for various phase change materials to be approximately 0.098–0.10 $/kWh. Seitz et al. [17] estimated the LCOE by evaluating unit costs of equipment in the solar field, power block, and storage block. It is difficult to assess the models developed in the previous studies because the system boundaries, process conditions, and economic parameters are different. Type 3 models examined the economics of thermochemical storage [19]. Wenger et al. [20] evaluated the economics of a hypothetical electrochemical plant that considered a hybrid of both thermochemical and battery systems. The proposed plant aimed to reduce investment costs by replacing turbine systems with a battery system to generate electricity. Luzzi et al. [7] assessed the economic viability of thermochemical storage by evaluating the LCOE for a hypothetical power plant. Luzzi et al. [7] estimated the LCOE to be approximately 0.25 AUD/kWh (Australian dollar per kilowatt-hour) for a 10 MW hypothetical plant capacity.

Few studies assess the economic feasibility of TES. The purpose of this paper is to develop a techno-economic model that concurrently compares the economic feasibility of sensible heat, latent heat, and thermochemical storage. To make an “apples-to-apples” comparison between TES technologies, moreover, the LCOE must be evaluated using a well-defined system boundary. For these reasons, comprehensive cost models for sensible heat, latent heat and thermochemical storage were developed in this study. This study focuses solely on the storage block, which is the study’s system boundary. In other words, the LCOE calculated in this study does not include costs from the solar field or the power block. In addition, a sensitivity analysis of the LCOE was done by varying parameters, i.e., plant capacity, solar multiple, storage