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Performance modeling and techno-economic analysis of a modular concentrated solar power tower with latent heat storage

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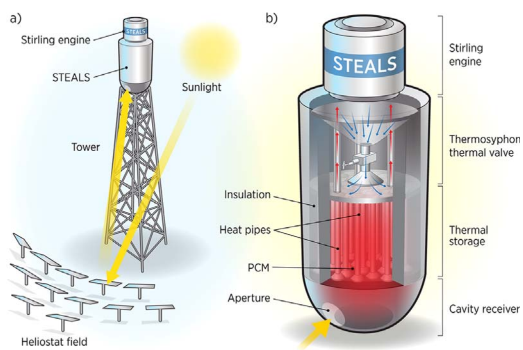
HIGHLIGHTS

- Original thermal and cost analysis of a new solar power tower concept.
- Potential for renewable, dispatchable electricity at low cost.
- Modularity opens concentrated solar power to new markets.
- In-depth comparison to alternative technologies.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we present performance simulations and techno-economic analysis of a modular dispatchable solar power tower. Using a heliostat field and power block three orders of magnitude smaller than conventional solar power towers, our unique configuration locates thermal storage and a power block directly on a tower receiver. To make the system dispatchable, a valved thermosyphon controls heat flow from a latent heat thermal storage tank to a Stirling engine. The modular design results in minimal balance of system costs and enables high deployment rates with a rapid realization of economies of scale. In this new analysis, we combine performance simulations with techno-economic analysis to evaluate levelized cost of electricity, and find that the system has potential for cost-competitiveness with natural gas peaking plants and alternative dispatchable renewables.

1. Background

The decreasing cost of wind turbines and photovoltaic panels (PV) is driving rapid deployment of renewables on electric grids around the world. Notably, renewable electricity in the United States is predicted to double from 2013 to 2040 [1]. However, the inherent variability (intermittency and diurnal cycle) of wind and solar presents a significant challenge. Such variable generation strains the grid by requiring other electricity sources to adjust output to match demand. This adjustment is difficult for today's United States grid that is largely made up of inflexible base load power generators (e.g. nuclear, coal) with just a small subset of generation coming from peaking power plants (mostly natural gas). Fig. 1 highlights this difficulty, and a study by the National Renewable Energy Laboratory [2] quantifies its potential future impact:

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Nomenclature

Acronyms

PV	photovoltaic
LCOE	levelized cost of electricity
TES	thermal energy storage
CSP	concentrated solar power
CO_2	carbon dioxide
STEALS	solar thermoelectricity via advanced latent heat storage
PCM	phase change material
Al-Si	aluminum-silicon
SAM	system advisor model
TMY	typical meteorological year
CAISO	california independent system operator
SolarPACES	solar power and chemical energy systems
K-Ca-Cl	potassium-calcium-chloride salt
Al	aluminum

when solar PV provides 22% of total electricity generation to the western United States grid, 50% of annual electricity generation from each additional unit of PV must be curtailed because large nonflexible power sources cannot decrease output. Thus, if renewables are to continue growth, the current grid system must change.

The current most economic solution to the intermittency of renewables would be a reduction of existing base load generation and addition of natural-gas peaking plants to increase grid flexibility and allow for fluctuations in PV output. Alternatively, energy storage could allow grid operators to time-shift production from renewable resources to times of high electricity demand. Existing technologies include pumped hydroelectric (93.6% of current United States grid storage capacity [3]), thermal (3.4%), electro-chemical (2.4%), and compressed air (0.5%) energy storage. However, these existing grid storage options account for only 2.1% of total electricity capacity in the United States, in contrast to the 43% from natural gas plants [1,3]. Further, the mature technologies in this group (pumped hydroelectric, compressed air) have barriers to future growth; common challenges include low energy density, geological and environmental concerns, high installation cost, and slow manufacturing learning curves [3–5]. This means that, in the pursuit of a 100% renewable energy grid, there is a tremendous opportunity for new, innovative energy storage technologies to grow and make an impact on the future grid.

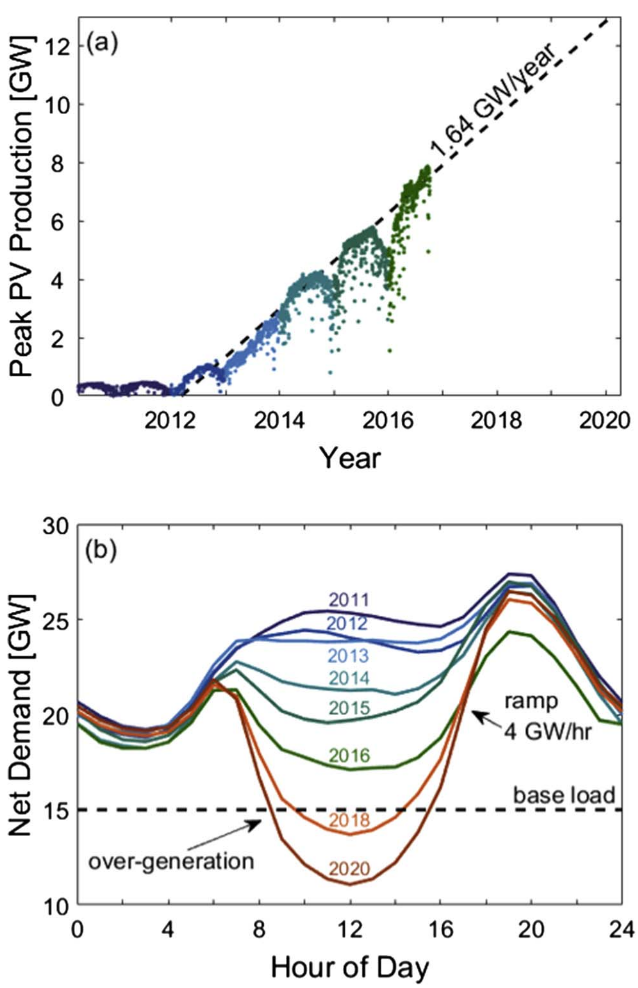

Fig. 1. (a) Daily peak solar PV output on the California Independent System Operator grid has been growing at ~1.6 GW/yr since 2012. (b) As a result, net demand (after taking into account solar and wind electricity production) is projected to drop in the middle of the day, leading to overgeneration and high ramp rates. Hourly net demand for 2011–2016 is from publicly available data (Supplementary Figs. 1–4). Curves for 2018 and 2020 are extrapolated from 2016 data based on projected growth in demand and installation of wind and solar.

Emerging technologies that may provide grid flexibility include electrochemical batteries, electrolyzers coupled to fuel cells, and thermal energy storage with concentrated solar power. In 2016, electrochemical batteries represented ~0.05% of grid capacity in the United States [1,3]. Several battery technologies are currently receiving significant investment, and the United States Department of Energy aims to reduce levelized cost of electricity (LCOE) from > 20 down to 10 ¢/kW h [6–9], or to 14 ¢/kW h for the combination of batteries with PV [10]. While this cost goal is competitive for many applications, it may be difficult to reduce capital costs from near 300 to below 150 $/kW h within the next few years [7–12], with raw material costs that add up to over 100 $/kW h [11]. Similar to electrochemical batteries, renewable electricity may be coupled to electrolyzers that produce chemical fuels that can later be used for electricity generation by fuel cells. However, fuel cell storage systems have levelized costs ranging from 18–50 ¢/kW h [13,14], and high capital costs will have to be reduced in order to reach competitive prices.

Significant efforts to develop thermal energy storage (TES) with concentrated solar power (CSP) are also underway. Fundamentally, thermal energy storage appears to be a low cost method: current TES capital costs are 20–25 $/kW h, and the United States Sunshot program has set a target of 15 $/kW h by 2020 [15,16]. These values are well below the cost of battery storage even after accounting for the efficiency of converting heat to electricity. Integration into CSP plants has already led to full system costs near the 2020 Sunshot goal of 6 ¢/kW h [17], and several pathways for further development have been proposed [18].

Current state-of-the-art CSP tower storage systems use molten salt for sensible heat storage. The next generation of this technology is being developed to operate at elevated temperatures, using high temperature salts and a supercritical CO_2 power cycle to increase power block efficiency [16,18]. Alternatively, particle-based storage and receivers have potential to enable high power block temperatures with lower cost materials, and may use particles both as a storage media and receiver heat transfer fluid [19,20]. A third direction that future CSP systems may move towards is in the use of phase change materials (PCMs) for latent heat thermal energy storage. This method has advantages of increased energy density, isothermal operation, and potential to reduce cost [21–23]. Some latent heat storage designs use salt PCMs, and research efforts are working to improve their effective thermal conductivity with heat transfer enhancements [24,25]. Other designs use metal PCMs, which have higher thermal performance, but