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Optimized dispatch in a first-principles concentrating solar power production model

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HIGHLIGHTS

- A profit maximizing solution operates concentrated solar power towers.
- Dispatch optimization integrates a techno-economic analysis tool.
- An optimized strategy improves plant profitability by 5–20%.
- Further improvements derive from a reduction in the number of cycles by 50%.
- Power cycle start-ups reduce from 370 to 250 per year without affecting energy output.

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ABSTRACT

Concentrating solar power towers, which include a steam-Rankine cycle with molten salt thermal energy storage, is an emerging technology whose maximum effectiveness relies on an optimal operational and dispatch policy. Given parameters such as start-up and shut-down penalties, expected electricity price profiles, solar availability, and system interoperability requirements, this paper seeks a profit-maximizing solution that determines start-up and shut-down times for the power cycle and solar receiver, and the times at which to dispatch stored and instantaneous quantities of energy over a 48-h horizon at hourly fidelity. The mixed-integer linear program (MIP) is subject to constraints including: (i) minimum and maximum rates of start-up and shut-down, (ii) energy balance, including energetic state of the system as a whole and its components, (iii) logical rules governing the operational modes of the power cycle and solar receiver, and (iv) operational consistency between time periods.

The novelty in this work lies in the successful integration of a dispatch optimization model into a detailed techno-economic analysis tool, specifically, the National Renewable Energy Laboratory's *System Advisor Model* (SAM). The MIP produces an optimized operating strategy, historically determined via a heuristic. Using several market electricity pricing profiles, we present comparative results for a system with and without dispatch optimization, indicating that dispatch optimization can improve plant profitability by 5–20% and thereby alter the economics of concentrating solar power technology. While we examine a molten salt power tower system, this analysis is equally applicable to the more mature concentrating solar parabolic trough system with thermal energy storage.

1. Background

The ability of renewable energy to be dispatched flexibly enables significant market penetration compared to renewable energy systems that are highly variable (e.g., wind) and/or that lack associated storage systems (e.g., photovoltaics without storage). We examine one type of solar technology, concentrating solar power (CSP), that manifests itself as: parabolic trough, linear fresnel, dish stirling, and power tower. The latter, and the one

Abbreviations: CSP, Concentrating Solar Power; HTF, Heat Transfer Fluid; MIP, Mixed-Integer Linear Program; MSPT, Molten Salt Power Tower; PPA, Power Purchase Agreement; SAM, System Advisor Model; TES, Thermal Energy Storage; TOD, Time-of-Dispatch.

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addressed in this paper, is thought to possess the most significant potential for improvements in efficiencies and reductions in cost [1]. Concentrating solar power tower technology uses thousands of sun-tracking mirrors (heliostats) that focus on a central receiver to heat molten salt to temperatures above 565°C (1050°F). The molten salt can then be pumped to a power cycle to generate electricity or efficiently stored for use when sunlight is not available [2]. However, the economic viability and widespread implementation of CSP technologies are strongly tied to their ability to extend their diurnal operational characteristics across peak demand time periods and during periods when solar energy is curtailed due to the sun setting or cloud cover [3]. Thermal energy storage (TES) is an enabling technology which can amass the energy captured by the receiver as a reserve for dispatch at a later, more economical time. In fact, TES integration enables CSP to be a dispatchable renewable resource whose economics are enhanced by both improved utilization of the power cycle and an ability to shift power production to better coincide with peak demands and high-value-electricity time periods [4].

High-temperature molten salt TES has been successfully implemented in CSP tower systems [5,6] and in parabolic trough systems, the latter in an *indirect* manner through use of an intermediate oil-to-molten salt heat exchanger. So-called *direct* TES systems such as the power tower technology use molten salt both as the storage medium and as the heat transfer fluid in the receiver, thereby avoiding the intermediate heat exchanger and improving system efficiency and dispatchability [7].

The maximum storage capacity of the TES system is determined during a plant design process that considers several factors including the thermal power rating of the solar field and power cycle subsystems, plant location, project economics, and the desired *capacity factor*, which is defined as the quotient of total annual electrical energy production and the electrical energy production should the plant operate continuously at rated power output. Thermal energy storage sizing also depends on the operational scheme. For example, a plant that intends to operate primarily during high-revenue morning or evening periods while reducing production during daylight hours requires more TES capacity than a plant with an identical capacity factor that generates power during all daylight hours. CSP plants that target dispatch during high-revenue periods operate differently than those that minimize the average cost of energy. The former relies more extensively on a carefully planned dispatch schedule that anticipates the timing and level of thermal power production in the solar field, energy consumption for receiver and plant start up, and the charge state of TES over time. Formal optimization methods can determine the dispatch profile that maximizes electricity sales revenue over a particular time horizon given a specific system configuration, expected solar resource, pricing or time-of-dispatch (TOD) profile, and operational constraints – a process referred to as *dispatch optimization.*

The intelligent dispatch of stored energy can greatly enhance the value of electricity by providing firm capacity and ancillary services, and by generating electricity during time periods in which rates are especially high [8]. Dispatch optimization involves the manipulation of the timing and rate at which electricity is generated by the power cycle and captures both physical processes and time [9]. This paper presents a methodology, implementation, and publicly available tool for simulating CSP power tower systems with optimized dispatch. The method expands on previous work by directly incorporating formal optimization techniques into the SAM [10] simulation software, for which previous research has relied on heuristics or on optimizing dispatch using simulation output *a posteriori* as optimization model input. SAM assesses CSP performance, simulating renewable technologies including CSP, wind, geothermal, photovoltaic, biomass, solar hot water, and generic systems. The software is free to download and use, and the tools developed in the current work are freely available [11]. Each technology can be paired with a financial model to evaluate the economic performance of a project within particular market, incentive, and cost environments.

1.1. Related work

Optimization modeling has been applied to many types of energy systems, e.g., [9] who retrofit an existing building and determine a corresponding dispatch strategy, and [12] who examine multiple objectives in optimizing stand-alone hybrid energy systems, also with the corresponding dispatch. Other authors examine only dispatch, e.g., [13], who apply a simulation model to a hybrid photovoltaic and tri-generation power system to decrease waste from excess heat, while [14] formulate an optimization model (a mixed-integer linear program, like ours) that combines both dispatchable and intermittent power, the latter as a result of a virtual plant, to maximize profits. Similarly, [15] develop an optimization model that dispatches wind, but, in contrast to the previous work, theirs focuses on minimizing active power losses in the system while constraining reactive power; the model is solved heuristically. Thorin et al. [16–18] operate in a market environment (as does [14]), the former for a unit commitment problem, applying an exact approach (i.e., Lagrangian Relaxation) to a mixed-integer program; Cho et al. [17] optimize a combined cooling, heating, and power system to optimize the tradeoffs between system cost, energy production and emissions, and test their model on a variety of geographic sites in the U.S. with differing weather conditions; Fürsch et al. [18] examine the expansion of a power network and the corresponding dispatch strategies in Europe; using an optimization model which combines both investment and dispatch decisions, they conclude that even optimal grid extensions, coupled with capital cost reductions for renewable technologies, leads to significantly higher overall average electricity system costs over a time horizon of three to four decades. Parisio et al. [19] use model predictive control within an optimization (mixed-integer programming) framework in which the goal is to minimize costs subject to microgrid system constraints such a capacities, minimum up- and down-times, and start-up and shut-down requirements. They test instances of their model on an experimental microgrid in Greece. Zheng et al. [20] provide a review of bio-inspired optimization of sustainable energy systems. These works examine problems similar to ours in that dispatch policies are considered, some even using the mathematical framework in this paper. However, none of these examines concentrating solar power in particular, with its own sets of objectives and rules. We next discuss the research specific to power tower technology.

Simulation is used to predict the total electrical energy production from an existing or previously designed CSP plant over its lifetime in order to evaluate the financial return on investment, the cost of energy, the environmental (mitigation) impact, or some other measure of interest. The standard method for CSP simulation requires calculation of plant behavior over a time horizon (typically, one year with one-hour time steps) [21], and it develops a picture of long-term energy production by sequentially modeling performance at relatively short time steps compared to the overall time window of interest (e.g., hourly calculations to establish lifetime metrics). CSP systems are primarily constrained by immediate concerns, such as component or subsystem operational states, conservation of mass and energy, and heat transfer, thermodynamic, or thermo-mechanical principles.

The previous dispatch approach implemented in SAM uses a simple heuristic that allows the user to specify requirements before thermal storage can be dispatched; this heuristic does not