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Hybrid concentrated solar thermal power systems: A review

Kody M. Powell[a,*], Khalid Rashid[a], Kevin Ellingwood[a], Jake Tuttle[a], Brian D. Iverson[b]

[a] University of Utah, Department of Chemical Engineering, 50 S Central Campus Drive, Salt Lake City, UT 84112, United States
[b] Brigham Young University, Department of Mechanical Engineering, United States

ABSTRACT

Concentrated solar power (CSP), or solar thermal power, is an ideal technology to hybridize with other energy technologies for power generation. CSP shares technology with conventional power generation and can be readily integrated with other energy types into a synergistic system, which has many potential benefits including increased dispatchability and reliability, improved efficiency, reduced capital costs through equipment sharing, and the opportunity for flexible operation by alternating between energy sources, which can lead to improved overall efficiency through synergy of the different energy sources. Another advantage of CSP technology is the ability to readily store via thermal energy storage (TES), making the intermittent solar resource dispatchable. A review of CSP hybridization strategies with coal, natural gas, biofuels, geothermal, photovoltaic (PV), and wind is given. An overview of different configurations for hybridizing CSP with these other energy sources is also provided. Hybridized CSP plants present different types and levels of synergy, depending on the hybrid energy source, the location of the plant, the CSP technology used, and the plant configuration. Coal, natural gas, and biofuel hybrids with CSP present many opportunities to inject solar heat at various temperatures. These combustible fuels provide reliability, dispatchability, and flexibility but are not entirely renewable solutions (with the exception of biofuels). Geothermal, wind, and PV hybrid designs with CSP can be entirely renewable, but lack some of the benefits of hydrocarbon fuels. Effective geothermal-CSP hybrid designs require low temperature operation where efficiency is limited by the power cycle. Wind-CSP and PVT (photovoltaic/thermal) lack dispatchability, but have other advantages. The pursuit of ideal CSP hybrid systems is an important research topic as it allows for further development of CSP technologies while providing an immediate solution that increases the use of solar power.

1. Introduction

Large-scale integration of solar energy into the electric grid presents some major technical challenges. As an intermittent energy source, solar energy requires either energy storage or fuel-based backup power so that it can provide dispatchable power (i.e., power that is available on demand). Solar photovoltaic (PV) technologies are promising for power generation, particularly with falling costs in recent years. However, because of their variable power output, widespread adoption of photovoltaics without storage may lead to grid reliability issues [1], which means that fast-ramping (and often inefficient) peaking fossil fuel technologies must be used as a backup source of power generation [2]. Alternatively, expensive battery technology may be used to increase the reliability and dispatchability of the grid.

Concentrated solar power (CSP) offers specific benefits as a renewable energy source due to the ability to readily incorporate energy storage. CSP, also known as solar thermal energy, involves heating a working fluid using concentrated sunlight. The heated fluid can then be used with conventional power generation equipment (i.e., turbines, generators, etc.) to produce electricity. The use of solar heat as an energy source in CSP makes low-cost energy storage feasible as heat can be readily stored with thermal energy storage (TES), which requires heating of a storage material and containing it in an insulated tank. CSP is also advantageous because of its amenability to hybridization. Aside from the thermal energy collection, the balance of a CSP plant may use conventional power generation equipment, making it easy to combine with other energy sources in ways that are synergistic, including the following:

Abbreviations: CSP, Concentrated solar power; DSG, Direct steam generation; HRSG, Heat recovery steam generator; HTF, Heat transfer fluid; IGCC, Integrated Gasification Combined Cycle; ISCC, Integrated Solar Combined Cycle; LCOE, Levelized cost of electricity; ORC, Organic Rankine cycle; PCM, Phase-change material; PVT, Photovoltaic thermal; SPCC, Solar-assisted post-combustion carbon capture; STIG, Steam injected gas turbine; TEG, Thermoelectric generator; TES, Thermal energy storage

* Corresponding author.
E-mail address: kody.powell@utah.edu (K.M. Powell).

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Definitions

Capacity factor or capacity utilization factor — The fraction of power supplied by a plant relative to its maximum capacity
Cogeneration — A plant that simultaneously produces electric power and usable heat
Direct steam generation — A method of solar heat collection where steam is generated directly in a solar collector
Multi-generation or polygeneration — A plant that simultaneously produces electric power and other useful products such as heat, cooling, chemicals, or purified water
Overall efficiency — The total efficiency of the plant with both solar and other inputs
Power Tower or Central Receiver — A type of concentrated solar power plant where an array of flat mirrors concentrate sunlight at a single point, typically on top of a tower
Solar multiple — The amount of solar energy available relative to the amount required for full-capacity power production in the power block.
Solar share or solar fraction — The fraction of the total energy to the plant that is supplied by solar
Solar-to-electric efficiency — The marginal efficiency of the plant when adding solar power
Stand-alone plant — A plant that relies on a single energy source

- Reduced capital costs by sharing equipment between multiple energy sources
- Increase in dispatchability by combining renewable energy with dispatchable energy
- Increase in capacity utilization of power generation equipment
- Increase in reliability
- Opportunity for flexible operation
- Synergies between technologies enhanced by design and operation optimization

Realizing these benefits requires consideration of the hybrid energy source, hybrid plant configuration, solar collector technology selected, location, and many others. Economics and technical feasibility play a key role in selecting the best technologies for hybridization [3]. Peterseim et al. classified CSP hybrid systems by the synergies with the hybrid energy source. Lightly synergistic hybrid systems share minimal infrastructure and the operation of the two energy sources are not dependent on each other. Medium hybrid synergies occur when the components of the two systems are physically connected and share major equipment (such as a steam turbine). In light and medium synergistic systems, the CSP component plays a minor role and cannot operate without the hybrid host components to generate power; the hybrid host on the other hand, can operate independently of the CSP technology. Generally, these systems have a low solar share (the fraction of energy supplied by solar energy) as the solar heating is purely supplemental. Strongly synergistic hybrids share major equipment and have a higher solar share, making the CSP component more critical to plant operation [4].

Hybridization can take competing energy technologies and make them complementary. However, realizing the benefits of hybridization requires careful consideration of the technical feasibility as well as the economic and environmental benefits of a proposed system. The purpose of this review article is to highlight different energy sources with which CSP may be hybridized and provide an overview of the possible hybrid configurations, with advantages and disadvantages discussed. These energy sources include coal, natural gas, biofuels, geothermal energy, solar PV, and wind energy.

2. Hybridization with coal

Hybridization of solar thermal power with coal has many benefits. Coal is an abundant, prevalent, and low-cost energy source. It therefore presents many opportunities to retrofit with supplemental solar thermal energy. Coal power plants have multiple points for injecting solar heat, such as boiler feedwater pre-heating, direct steam generation, boiler air pre-heating, and solvent regeneration in post-combustion CO_2 removal [5]. Coal also provides a dispatchable fuel source to ensure reliability, while solar thermal energy can reduce the plant's overall CO_2 emissions [6]. Hybridizing with coal can reduce the overall CSP plant cost, with one study indicating that a hybrid plant would only be 72% of the cost of a stand-alone solar plant and would generate over 25% more electricity [7].

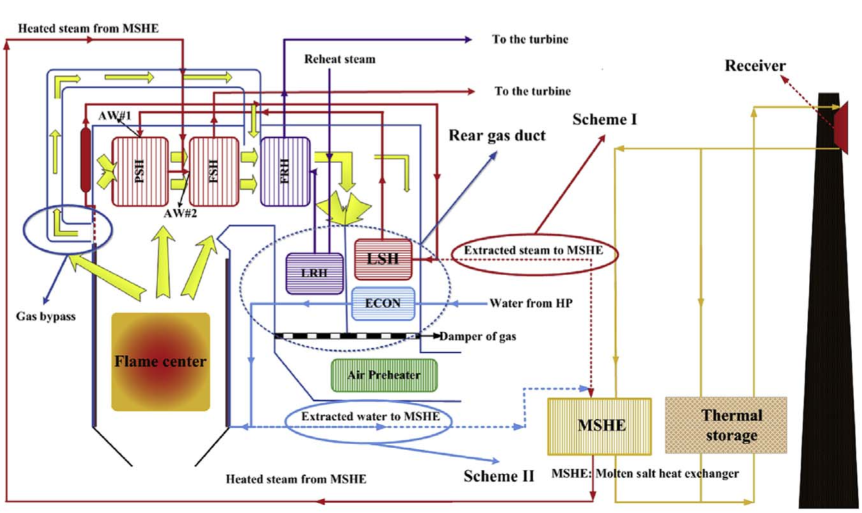

Fig. 1. : A dual-source boiler configuration with a molten-salt-based power tower used in parallel with coalfired heat to produce steam [9].