

Concentrated solar power on demand

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Abstract

A concentrating solar power system is presented which uses hillside mounted heliostats to direct sunlight into a volumetric absorption molten salt receiver with integral storage. The concentrated sunlight penetrates and is absorbed by molten salt in the receiver through a depth of 4–5 m, making the system insensitive to the passage of clouds. The receiver volume also acts as the thermal storage volume eliminating the need for secondary hot and cold salt storage tanks. A small aperture and refractory-lined domed roof reduce losses to the environment and reflect thermal radiation back into the pond. Hot salt is pumped from the top of the tank through a steam generator and then returned to the bottom of the tank. An insulated barrier plate is positioned within the tank to provide a physical and thermal barrier between the thermally stratified layers, maintaining hot and cold salt volumes required for continuous operation. As a result, high temperature thermal energy can be provided 24/7 or at any desired time.

The amount of storage required depends on local needs and economic conditions. About 2500 m³ of nitrate salt is needed to operate a 4 MW_e steam turbine 24/7 (7 h sunshine, 17 h storage), and with modest heliostat field oversizing to accumulate energy, the system could operate for an additional 24 h (1 cloudy day). Alternatively, this same storage volume can supply a 50 MW_e turbine for 3.25 h without additional solar input. Cosine effect losses associated with hillside heliostats beaming light downwards to the receiver are offset by the elimination of a tower and separate hot and cold storage tanks and their associated pumping systems. Reduced system complexity also reduces variable costs. Using the NREL Solar Advisor program, the system is estimated to realize cost-competitive leveled production costs of electricity.

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1. Background

A robust solar energy portfolio is likely to include solar thermal systems that enable energy storage with electricity production when there is limited sunlight. Concentrating solar power (CSP) systems that use a central receiver with integral thermal energy storage have the potential to produce 24/7 base load and/or peak electric power. Power towers use heliostats to focus sunlight on a receiver placed

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Nomenclature

Abbreviations

CSPonD Concentrated Solar Power on Demand

Symbols

α attenuation coefficient
 δ optical thickness
 ε emissivity
 ϕ beam-down angle
 θ_i incident angle

θ_t transmitted angle
 θ_r reflected angle
 D diameter
 I_o incident intensity
 I transmitted intensity
 n index of refraction
 R reflection coefficient

atop a tower to reduce heliostat shadowing, increase optical efficiency, and to achieve high solar flux concentration and steam plant efficiency (Viebahn et al., 2008). Conventional high temperature CSP systems have evolved to use a central tower where a heat transfer fluid circulates through tubes onto which the sunlight is focused. However, maximum allowable fluxes are limited to avoid thermal degradation of the receiver tubing. Lata et al. (2008) cites the tradeoffs between tube diameter, wall thickness, receiver durability and pressure drop in conventional tubular receiver designs while describing an external tubular receiver capable of achieving slightly higher maximum fluxes, up to 1.0 MW/m², thereby reducing receiver surface area and losses while increasing overall plant efficiency.

Utilizing molten salts as the working fluid enables simple subsequent thermal storage, due to their high heat capacities and wide operating temperatures. Unfortunately, daily receiver filling requires ancillary heaters and presents additional risks should the salt freeze, requiring electric heat tracing on long piping runs, valves and manifolds. Despite these measures, operating problems still occur; for example, the Solar Two CSP demonstration plant was disabled by frozen salt in pipes (Reilly and Kolb, 2001). Another approach is direct absorption of sunlight by several-centimeter thick salt waterfalls, but the cost of pumps, manifold and piping preheaters, and fluid flow variations as a function of varying solar flux, limited the practicality of such systems (Bohn, 1987).

To minimize receiver fluid pumping losses and enable alternative receiver designs, Rabl (1976) proposed a beam-down reflective tower with a ground-based CSP receiver. Similarly, Yoge (1997) and Epstein et al. (1999) suggested a beam-down system where the light was to be beamed directly into a molten salt/metal filled container. It has even been proposed for tall buildings to use balcony-mounted heliostats to direct sunlight to a receiver placed atop the building (LeBarre, 2010). Since Rabl's proposal in 1976, significant experimental work has occurred on beam-down towers and ground receivers, especially for reforming materials (Yoge et al., 1998; Segal and Epstein, 2003). The Odeillo solar furnace facility uses a north facing parabola focused on a target built into one wall of a building that holds offices and laboratories.

Sixty-three south-facing flat mirror heliostats track the sun's movement and focus it down on the north facing parabola (Trombe and Le PhatVinh, 1973). NREL also has a high-flux solar furnace system where heliostats aim light towards a ground-based secondary reflector system that redirects and concentrates the sunlight to a small aperture receiver, although up to 10% of the energy is lost with each reflection (Skinrood et al., 1974). These systems achieve high concentrations and receiver temperatures with large, precision secondary optical elements – whose cost has prevented the commercial adoption of beam-down CSP.

Conventional thermal storage systems require two molten salt storage tanks, each capable of storing the entire system volume (Herrmann et al., 2004). In traditional CSP systems, cost-savings have been obtained with single tank systems relying on temperature stratification via natural thermocline formation (Pacheco et al., 2002). Copeland and Green (1983) and Copeland et al. (1984) have shown “rafted thermocline” designs effective at boosting thermal stratification in water tanks, with suggested designs for molten salt thermal storage tanks. However, passive rafted thermoclines would rely on two parameters difficult to control in high temperature molten salt tanks: maintaining neutral buoyancy at the hot–cold thermocline interface; and a near perfect seal with the side walls to prevent leakage around the divider raft. Indeed, tests performed in water showed the neutrally buoyant raft design may display instabilities and tilt and/or jam in the storage tank. Demonstration CSP plants without storage have typically been designed with a co-firing gas turbine scheme to enable continued operation when the solar system is down (European Commission, 2005).

2. CSPonD: collocated receiver and storage system

Here we present a new system with heliostats mounted on a hillside that beam light directly into an open container of molten salt at the base of the hill, or into a one-bounce system with the receiver at the top of the hill (Fig. 1). A small aperture in the receiver lets the sunlight penetrate the surface of the large molten high temperature salt pond. Volumetric absorption enables a simpler receiver design

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