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News & Views

Concentrated solar energy – the path for efficient thermal conversion to power and fuels

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Concentrated solar energy provides an unlimited clean source of high-temperature process heat. It can be therefore used for power generation by driving heat engines, as well as for fuel production by driving endothermic chemical transformations [1]. Currently, the main optical configurations to concentrate the direct (beam) solar radiation at large scale are the line-focussing parabolic trough and linear Fresnel systems, and the point-focussing solar tower and dish systems. They are characterized in terms of their solar flux concentration ratio C – the solar radiative power over the solar receiver's aperture area at the focal plane, normalized with respect to the direct normal irradiation (DNI). C is typically at the level of 100 and 1,000 suns for line-focusing and point-focusing optical configurations, respectively. These solar concentrating systems have been proven to be technically feasible in large-scale commercial applications aimed at electricity generation in which a heat transfer fluid, typically air, water, synthetic oil, helium, sodium, or molten salt, is solar-heated and further used to drive conventional Rankine, Brayton, and Stirling heat engines in concentrated solar power (CSP) plants. On the other hand, solar thermochemical fuel processing, referred here as concentrated solar fuel (CSF) plants, are not as far developed as CSP, but they employ the same aforementioned solar concentrating systems.

Both CSP and CSF applications utilize the entire solar spectrum as high-temperature thermal energy, and as such provide thermodynamically favorable paths for converting solar energy into electrical and chemical energy, respectively, i.e. into work. This capability is expressed by the ideal solar-to-work energy conversion efficiency, given by Ref. [2]:

$$\eta_{\text{solar-to-work, ideal}} = \left[1 - \left(\frac{\sigma T_{\text{H}}^4}{IC}\right)\right] \times \left[1 - \left(\frac{T_{\text{L}}}{T_{\text{H}}}\right)\right],$$

where I is the DNI, σ is the Stefan-Boltzmann constant, and T_{H} and T_{L} are the upper and lower operating temperatures of the thermal reservoirs. Because of the Carnot limitation, one should try to operate the solar conversion process, either CSP or CSF, at the highest T_{H} possible, but at the expense of higher re-radiation losses. On the other hand, increasing C is advantageous because it implies higher attainable temperatures and lower re-radiation losses from a smaller solar receiver's aperture, but at the expense of more precise and costly optics. To some extent, C can be further augmented with the help of non-imaging secondary (in-tandem) reflectors. Nevertheless, the potential of concentrated solar energy is remarkably high: for a solar-driven process operated at 1,500 K and 5,000 suns concentration, $\eta_{\text{solar-to-work,ideal}}$ peaks at 75%. In practice, when considering convective and conductive losses in addition to radiative losses, as well as the inherent optical losses of the solar concentrating system, the efficiency reaches significant lower values. Current commercial technologies are based on solar receivers that usually operate with C below 1,000 suns and at T_{H} below 500 °C, and are therefore limited in their potential. Next generation of solar receivers and reactors will surpass 1,000 °C to enable higher efficiencies as well as better integration of thermal storage and hybridization for round-the-clock power and fuels dispatchability. This in turn will lead to economic competitiveness since the solar concentrating infrastructure, the dominant investment cost, becomes obviously smaller with increasing efficiency. It is up to scientists and engineers to develop the next generation of solar technologies that approach the high efficiency values set by thermodynamics.

One valuable contribution in this direction is given by the commissioning of the high-flux solar simulator of Prof. Yong Hao at the Chinese Academy of Sciences in Beijing [3]. High-flux solar simulators are sophisticated experimental platforms to perform advanced R&D on CSP and CSF technologies [4–9]. Prof. Hao's research facility is unique in terms of its concentrating optics by coupling truncated ellipsoidal reflectors with angle-modifier, integrator, and collimating lenses. With this optical arrangement, a continuous beam of concentrated and non-concentrated radiation can be generated from an array of Xe-arcs to mimic the four solar concentrating configurations, both line-focusing and point-focusing systems. It delivers a wide range of C up to a peak of 9,200 suns, which allows attaining stagnation temperatures exceeding 3,000 K. Thus, novel solar receivers/reactors can be engineered and tested in this experimental facility under realistic operating conditions to push the frontier for achieving energy-efficient and cost-effective solar power and fuel technologies.

Conflict of interest

The author declares that he has no conflict of interest.

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