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Solar thermal hybrids for combustion power plant: A growing opportunity

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ABSTRACT

The development of technologies to hybridise concentrating solar thermal energy (CST) and combustion technologies, is driven by the potential to provide both cost-effective CO_2 mitigation and firm supply. Hybridisation, which involves combining the two energy sources within a single plant, offers these benefits over the stand-alone counterparts through the use of shared infrastructure and increased efficiency. In the near-term, hybrids between solar and fossil fuelled systems without carbon capture offer potential to lower the use of fossil fuels, while in the longer term they offer potential for low-cost carbon-neutral or carbon-negative energy. The integration of CST into CO_2 capture technologies such as oxy-fuel combustion and chemical looping combustion is potentially attractive because the same components can be used for both CO_2 capture and the storage of solar energy, to reduce total infrastructure and cost. The use of these hybrids with biomass and/or renewable fuels, offers the additional potential for carbon-negative energy with relatively low cost. In addition to reviewing these technologies, we propose a methodology for classifying solar-combustion hybrid technologies and assess the progress and challenges of each. Particular attention is paid to "direct hybrids", which harness the two energy sources in a common solar receiver or reactor to reduce total infrastructure and losses.

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1. Introduction

Concentrating solar thermal energy (CST) technologies make use of the entire solar spectrum to provide a source of high-temperature process heat in the range 500–2000 °C, which is compatible with temperatures generated by combustion, to produce power, fuels, and materials [1]. CST technology is commercially available at the lower end of this temperature range for power production, while higher temperatures in a wide range of applications presently performed by combustion have been demonstrated at lab or pilot-scale using CST [1–3]. Another driver for CST is its compatibility with thermal energy storage, which is a very low-cost method of storage. Nevertheless, its reliance on the intermittent and variable direct solar radiation resource makes it complimentary with combustion, which utilizes the energy-dense source of stored energy in fuels. This, combined with the strong temperature compatibility, provides a strong driver to integrate them to achieve one continuous process rather than two variable ones. This combination is hereafter termed "CST-hybrids" for brevity.

CST-Hybrids offer both low net CO_2 emissions and firm supply, providing greater security of supply than is possible with only "dispatchability" . Firm supply is increasingly sought in OECD nations because the growth in intermittent renewables is leading to the increased curtailment of their output, while the strong growth in total demand in non-OECD nations is providing strong incentive to install new plants that cannot provide firm supply [4]. In addition to the capacity to provide firm supply, CST-hybrids offer more cost effective power generation than is possible with the equivalent stand-alone solar thermal and combustion power plants because of the opportunities for infrastructure sharing, increases in efficiency, and greater capital utilisation [5,6]. For example, Spelling and Laumert [7] found that hybridising the topping cycle of a Gas Turbine Combined Cycle (GTCC) is more economic under most conditions than "hybridising" with solar photovoltaic (PV) energy behind the meter (to share electrical infrastructure), which results in the gas turbine being turned down to operate at lower efficiency to accommodate the solar resource. However, many other possible hybrid configurations are also possible and no systematic review is available of their relative merits. The overall aim of the present review is to meet this need.

Given the wide range of technologies under development for both concentrating solar thermal and combustion technologies in isolation, the number of potential combinations of hybrids between them is even greater. It includes those that harness a relatively small fraction of solar energy into commercially available combustion plant without carbon-capture, such as the low temperature solar heating of the feedwater to a steam boiler [8–12], hybrids with a gas turbine [7], hybrids that integrate solar thermal into a CO_2 capture process [13–17], including hybrids with chemical looping combustion [18–21]. However, the majority of hybrid technologies reported to date have combined components developed for stand-alone CST or combustion technologies. It is only relatively recently that fully integrated components are also beginning to emerge that are purpose-designed to harness both energy sources, such as the Hybrid Solar Receiver-Combustor [6,22,23]. Given this diversity, a systematic approach is needed to classify and compare them. Another aim of the present review is to provide this classification.

The available reviews of hybrids-CST technologies have been limited mostly to the configuration for which a regenerative Rankine cycle is hybridised by the addition of relatively low temperature to the feedwater in to the boiler [24,25]. In contrast, the recent review by Nathan et al. [3], addressed the combustion-related research challenges associated with the range of emerging hybrid technologies, but did not review the strengths and limitations of these technologies directly. For this reason, the present review aims to meet the need for a review of the wide range of hybrid technologies that have been proposed previously, and also to propose an overarching framework with consistent definitions against which to evaluate their relative merits.

In light of drivers described above, the aims of the present review are as follows:

1. To identify the potential benefits of hybridising CST and combustion technologies;
2. To identify and classify the range of approaches with which CST and combustion can be combined into a hybrid system;
3. To identify the CST-hybrid technologies with greatest potential to meet the need for carbon-neutral or carbon-negative emissions;
4. To identify technology development challenges for those technologies found to exhibit strong potential;

These aims are addressed firstly by reviewing the key drivers to hybridisation. Following this, the key elements of concentrating solar thermal technologies are reviewed, together with the key parameters that influence their efficiency, with a view to identifying the implications of these features on hybridisation. We then review hybrids compatible with the steam Rankine cycle, despite its relatively low efficiency, owing to its compatible temperature with CST, suitability to use with tubular receivers and relevance to CO_2 capture technologies. Some of these approaches are also compatible with emerging power cycles such as the CO_2 power cycle [26–29]. Approaches to hybridising CST with the air Brayton (gas turbine) cycle are then reviewed, owing to the potential to operate at higher temperature and hence achieve higher cycle efficiency than a Rankine cycle. This leads to consideration of hybridising with chemical looping combustion. Chemical looping is a class of reduction-oxidation (redox) technology using metal oxides, which has received considerable attention both in combustion-only cycles [30–41], and in solar-only cycles [1]. Chemical looping combustion uses an oxygen carrier to oxidise the fuel (and reduce the carrier), following which the metal particle is oxidised in air. This approach avoids direct contact between the fuel and air to achieve inherent CO_2 capture and has been the subject of several reviews [41–45]. Redox cycles under development for solar thermochemical processes include those directed to the splitting of water and CO_2 [1, 46, 47]. Particular attention is paid in the present review to the hybrids between CST and chemical looping combustion, in which the endothermic energy for

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