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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.

Contents

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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 the reduction reaction is provided with CST. Thus, these cycles have great potential for application in solar-combustion hybrids with integrated CO_2 capture and re-use/sequestration, to separate O_2 from air for oxy-fuel combustion [48] or to regenerate a fuel from the captured CO_2 [1]. Furthermore, the fuel reactor can potentially also be used to provide energy dense storage of solar energy, combining both chemical and sensible heat [18,19,49].

2. Key drivers to hybridise concentrating solar thermal energy with combustion

2.1. Global drivers

Fig. 1 presents the IEA's anticipated mix of energy sources in the year 2035 [50]. This assessment, which is similar to other major assessments of future global energy supply [51], anticipates an ongoing role for the combustion of both fossil fuels and biomass, despite a rapidly growing contribution from intermittent renewable energy sources such as solar and wind. This expectation of an ongoing need for both energy sources leads to an economic driver to integrate them, due to the economic advantages of hybridisation over standalone systems. Furthermore, when combined with a low-carbon fuel, such as one derived from biomass, such systems have potential to achieve carbon-negative emissions, a component of which is expected to be needed to meet the global CoP-21 emission targets [52,53]. For example, Guo et al. [2], calculated that the solar thermal gasification of a biomass that is 80% carbon-neutral, has potential to achieve carbon negative production of Fisher Tropsch liquids, when combined with CCS. The low-carbon syngas could alternatively be used directly in a combustion plant to meet the need for process heat, for example.

2.2. Firm supply

Hybridisation offers to CST the potential to increase the cost effectiveness of thermal energy storage (TES) by enabling the capacity of the TES to be optimised independent of any commitments to meet supply. This is important on the one hand because of the growing demand for energy storage [54] and, on the other hand, because the maximum economic utilisation of TES occurs at much smaller storage capacities than that needed to maintain firm supply [55]. Furthermore, the much lower cost of the storage of heat relative to that of electricity has been identified as a key driver for the ongoing development of CST technology despite the rapidly reducing costs of solar photo-voltaic (PV) for un-stored energy [54]. Hybridisation also offers capacity for a CST plant to provide firm supply and to further increase its capacity to provide other electrical services such as inertia. The need to provide firm supply may often be greater for chemical process plants than for electrical generation. This is firstly because the demand is more difficult to turn down, secondly, because it is often more difficult to harness distributed energy sources in a chemical process than in an electrical network and, thirdly, because both process efficiency and product quality are greater with steady-state than variable operation. Nevertheless, the present review is limited to hybrids for power generation.

Fig. 2 presents the dependence of the calculated probability of an unscheduled reduction in output from a single solar thermal plant (electrical or chemical) due to solar resource variability as a function of storage capacity for six sites of excellent solar resource. This particular analysis was performed as the lower limit of the amount of storage required to maintain supply, since it assumes the storage device is 100% efficient and ignores the exergetic losses associated with charging and discharging. However, it does account for the unavoidable need to dump energy when the storage device is full. It can be seen that, even under this best-case scenario, the capacity of a dedicated storage system required to provide continuous output from a single generator is unlikely to be economic for the foreseeable future. For example, for the case that the probability of an unscheduled reduction is 0.3% (i.e. 1 day in 3 years), not only would the storage capacity need to be between 50 and 300 hours (depending on the site), but the peak capacity of the heliostat field relative to the required input to the thermal conversion unit (e.g. power block or chemical process) is a factor of ten [55]. This degree of oversizing is so great that 90% of the energy is dumped at solar noon in mid-summer, which would be very expensive. In addition, given that the capacity of the molten salt storage systems employed in commercially available solar thermal plants is 12–16 hours [56], substantial further development of the storage technology would be required to achieve the required 50 – 300 hours, even for this idealised system.

The above study also shows that the storage facility becomes increasingly under utilized as the storage capacity of the plant is increased above about 12 hours (depending on the site). That is, the storage facility and the heliostat field must be progressively oversized to reduce the probability of an unscheduled shut-down, which increases cost. Hence, while many other demand scenarios and turndown scenarios are possible than those shown here, this assessment is sufficient to illustrate that it is likely to be uneconomic to provide sufficient oversizing for firm supply under “worst-case” scenarios of relatively rare periods of extended cloud cover. Instead, it will be cheaper to design the storage facility to be near-fully utilised and to provide the capacity for firm supply through an alternative approach such as a hybrid [55]. Many other approaches are also under

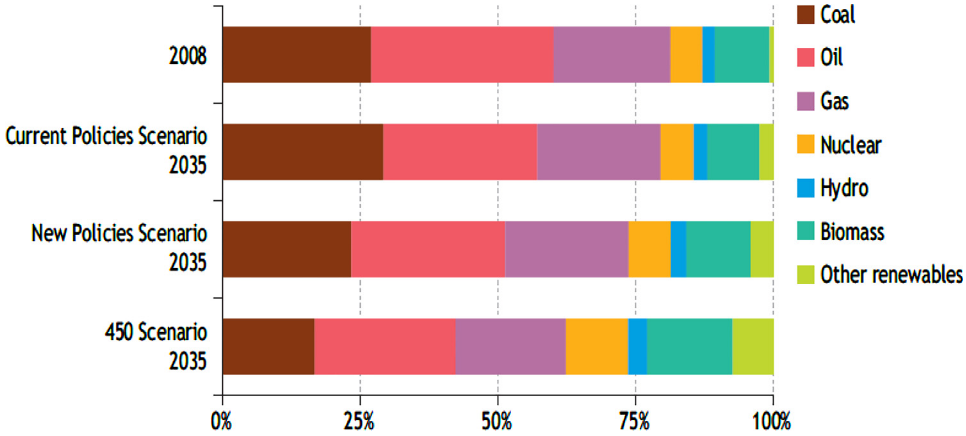


Fig. 1. Alternative scenarios of expected sources of primary energy to 2035, showing the anticipated ongoing role for combustion of both fossil and biomass resources, together with a growing role of renewable energy [50].

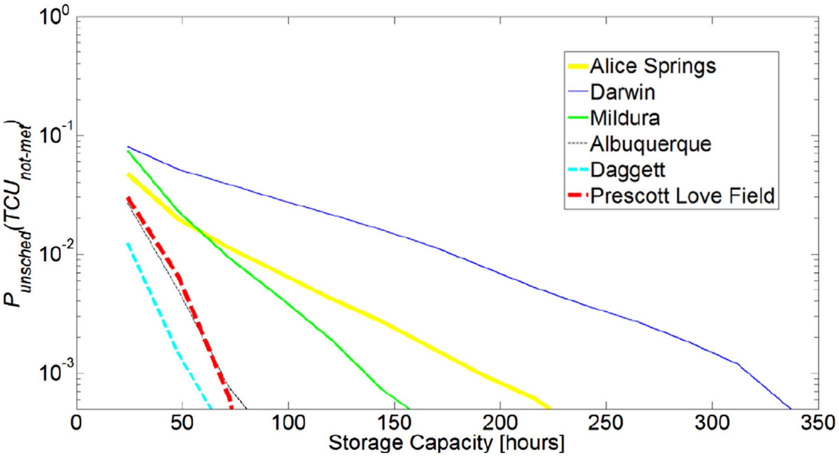


Fig. 2. The calculated capacity of thermal storage that is required to achieve a given probability of unscheduled failure to meet the steady demand of a single thermal conversion unit (TCU), based on a model of a plant that assumes steady state at each half-hour time-step from a 10-year time series of historical direct normal irradiance at six sites with excellent resource. The peak capacity of the heliostat field is also a factor of 10 larger than that of the TCU [55]. *Note:* Alice Springs, Darwin and Mildura are in Australia, while Albuquerque, Daggett and Prescott Love Field are in the USA.

development to contribute to meeting the challenge of matching supply and demand with the use of intermittent renewable energy at both the supply and demand end of the challenge. Nevertheless, a significant component of firm supply is anticipated to be needed into the future. Furthermore, it is also possible to generate fuels renewably, including from the same plant using excess electricity during high flux periods. These become tradable stored chemical energy and are utilisable in a hybrid in the same way as a fossil fuel.

2.3. Technical compatibility

Table 1 presents a high level comparison of the compatibility of the four classes of thermal energy source for which hybrids have been proposed or are already commercially available. These are the combustion (of fossil, biomass and/or solar fuels), CST and geothermal energy. (Note that, although nuclear energy is also a type of thermal energy, to the best of our knowledge, no hybrid system with nuclear energy has been proposed to date[1]). Table 1 shows that combustion and CST are the most compatible for hybridisation of these three energy sources. Furthermore, combustion is also more widely available than geothermal (and nuclear) power. Thus, hybrids between CST and combustion are likely to be developed first and also to be more prevalent than between any other types of thermal energy sources in the short to medium term.

The key technical drivers to hybridise CST with combustion in preference to other combinations of thermal energy sources (as shown in Table 1), are as follows:

- **Temperature compatibility:** Of the renewable thermal energy sources, CST is more compatible with combustion than is geothermal because both can generate the maximum inlet temperatures of currently envisaged thermal power plant, currently ~1350 °C for gas turbine power plant [58], while geothermal cannot. The relatively low temperature of geothermal energy sources (typically < 300 °C) implies that they must inevitably either provide only the low temperature heat into a high temperature cycle, which will result in them providing only a small fraction of the total energy of the plant, or else limit the maximum temperature of the cycle, which would lower the thermal efficiency of the plant.
- **Availability compatibility:** Of the three options for steady output to complement the inherent variability of the solar resource, combustion offers the lowest cost source of flexible high temperature heat. The rapid response of combustion systems to a change in demand has made natural gas open cycle gas turbines the dominant form of peaking power plant with well-established capacity to rapidly respond to changes in either supply or demand [50]. The main limitation of the use of hydrogen-derived fuels (e.g. NH_3) or hydrogen-blended fuels (e.g. syngas) is their availability and cost.

Some of the options for solar-geothermal hybrids to be proposed to date include solar super-heating of the working fluid with geothermal energy and the geothermal pre-heating of the feedwater to a solar thermal plant [59]**.** However, while the thermal efficiency of a hybrid solar geothermal power plant is typically higher than that of a stand-alone geothermal power plant, it is also lower than that of a stand-alone solar power plant [60–62]. This implies that there is little incentive to hybridise solar with geothermal plants given the alternative option to hybridise with combustion, which typically lowers the cost of CST [5,6]. Furthermore, there is a relatively low probability of co-location of high quality solar and geothermal

Table 1
A comparison of the relative compatibility of the various alternative thermal energy sources for hybridisation with solar thermal.

Energy source	Availability	Carbon intensity	Cost	Stage	Temp °C	Suitable hybrids	Main challenges
Fossil fuel	high	high	Low	Mature	1000–2500	Direct high T	High net carbon intensity
Biomass	moderate	low	Mid-high	Mature	1000–2500	Direct high T	Availability and cost
Solar fuels (H_2, NH_3, syngas, etc.)	Low but growing	low	Low-Mid	Early	1000–2500	Direct, high T	Availability and cost
Geothermal	low	low	Low-	Mature for < 150 °C Early for > 250 °C	100–300	Semi-direct	$T_{firm} < T_{solar}$* Capture

*Note that a lower temperature of the geothermal resource than the solar implies a reduction in output when the stored solar energy is no longer available.

resources, at least until such time as Engineered Geothermal Systems, sometimes known as “hot-dry rocks”, may potentially become economically attractive. For example, locations at which geothermal energy is presently attractive such as New Zealand and Iceland, do not have a high quality solar resource. For these reasons, together with those already discussed with regard to Table 1, it is reasonable to conclude that the potential to hybridise CST with combustion is much greater than that for CST and geothermal for the foreseeable future.

3. Definitions and classification of thermal energy hybrids

We define a hybrid thermal process to be ‘*a process that integrates multiple types of thermal energy sources*’. The word “integration” implicitly implies an improvement, relative to the stand-alone counterparts, in performance via reduced cost, decreased CO_2 emissions intensity, and/or increased dispatchability. This definition is more general than those proposed previously. For example, Williams et al. [24] define a solar hybrid system to be one that uses a combination of solar and fossil energy to generate electricity. Such a definition is limiting because it does not include non-fossil sources of combustion or other applications than electricity generation.

Given the wide range of systems that can be identified as a hybrid under the above definition, we further propose a series of classifications with which to compare different types of thermal hybrid. While the focus here is on CST-combustion hybrids, the classifications are more broadly applicable**:**

3.1. *Classification by solar share*

The solar share is typically defined as the fraction of the input energy that is derived from a solar source. Importantly, this should be based on the annually averaged values derived from unsteady calculations of historical time-series to fully account for solar resource variability. The proposed classes and ranges of solar share are as follows:

a. Solar Aided Combustion Generation (<33% solar, annually averaged). This name is adapted from the name “Solar Aided Power Generation” given to the use of solar feedwater preheating in a Rankine Cycle [12,63], where 30% is approximately the upper limit of energy that can be provided in this way [64].
b. Balanced Solar-Combustion Generation (33–66% solar, annually averaged);
c. Combustion Aided Solar Generation (>66% Solar, annually averaged)

3.2. *Classification by extent of integration*

Here, the criterion assesses the extent of integration between CST and combustion (or other energy sources), and hence the relative potential to reduce capital cost and energy losses through hybridisation. Hence, the proposed sub-classifications are as follows**:**

- **Auxiliary:** shares only the supporting infrastructure, such as electrical cabling and control systems;
- **Indirect:** Transfers reactants and/or products from a solar thermochemical cycle to a power cycle, together with the auxiliary infrastructure;
- **Semi-direct:** Shares the major non-solar components of the solar and combustion power cycle (e.g. the turbine and the condenser), together with the auxiliary infrastructure;
- **Direct:** shares the solar and combustion thermal harvesting equipment (e.g. receiver and combustor), together with the semi-direct and auxiliary components;

3.3. *Classification by comparison with the best alternative option*

Here the performance of the hybrid compared with the relevant state-of-the-art stand-alone technology, after accounting for start-up and shut-down losses. We further propose that the default reference combustion cycles be a gas turbine combined-cycle and an open cycle gas turbine, as the most efficient power plants for schedulable and peaking plant, respectively, while the default reference cycle for a solar thermal plant is a two tank, molten salt plant. However, other reference cycles can be adopted as appropriate. The proposed sub-classifications are:

a. **Solar positive – combustion negative hybrid:** A system efficiency that equals or exceeds the efficiency of the relevant state-of-the-art solar-only system, but not of the relevant state-of-the-art combustion plant;
b. **Solar negative – combustion positive hybrid:** A system efficiency that equals or exceeds the efficiency of the relevant state-of-the-art combustion-only system, but not of the relevant state-of-the-art solar plant;
c. **Solar positive – Combustion positive hybrid:** A system efficiency that equals or exceeds the efficiency of both the relevant state-of-the-art solar system and of the relevant state-of-the-art combustion-only plant.

It is important to note that the above comparisons should be based on case-by-case, dynamic assessment over a one year period. This is because the net benefit from a hybrid will depend on a range of case-specific conditions, including the solar resource variability. For example, it is possible that a net benefit may still be derived from a hybrid whose steady-state operation may be poorer than the stand-alone counterpart because of the role of compensating benefits such as avoided (or reduced) start-up and shut-down losses and less total infrastructure.

4. General considerations of solar thermal power generation

The efficiency of solar thermal power generation $\eta_{solar\text{-}to\text{-}work}$ is determined by the product of: (1) the efficiency of concentrating the direct solar normal irradiation (DNI) η_{conc}, (2) the efficiency of absorption of the high-temperature heat by the solar receiver η_{rec}, and (3) the conversion into power by the heat engine $\eta_{heat\text{-}engine}$. The limitations and trends of these combined influences is illustrated by considering: the theoretical maximum efficiency for an ideal solar concentrator (no reflectivity or spillage losses), an ideal solar receiver (no convection/conduction heat losses and blackbody absorption), and an ideal heat engine. For this case, the maximum theoretical solar-to-work energy conversion efficiency of an ideal system is given by [1],

$$\eta_{solar\text{–}to\text{–}work,ideal} = \left[1 - \left(\frac{\sigma T_H^4}{IC}\right)\right] \times \left[1 - \left(\frac{T_L}{T_H}\right)\right], \quad (1)$$

where C is the mean solar flux concentration ratio over the receiver's aperture area, normalized by the DNI I, σ is the Stefan-Boltzmann constant, and T_H and T_L are the upper and lower operating temperatures of the equivalent Carnot heat engine, respectively. This ideal solar-to-work efficiency $\eta_{solar\text{-}to\text{-}work,ideal}$ is plotted in Fig. 3 as a function of T_H, for $T_L = 298$ K, and for various solar flux concentration ratios. From the perspective of the Carnot cycle alone, it is desirable to operate the heat engine at the highest possible temperature, assuming that the cold reservoir temperature, T_L is that of the atmosphere. However, from the perspective of the solar receiver alone, it is desirable to lower T_H to minimise the re-radiation losses (as well as the convective/conductive heat losses). This results in the optimum temperature for the power-plant-receiver combination, $T_{optimum}$, being lower than that for the power cycle alone (i.e. a non-solar

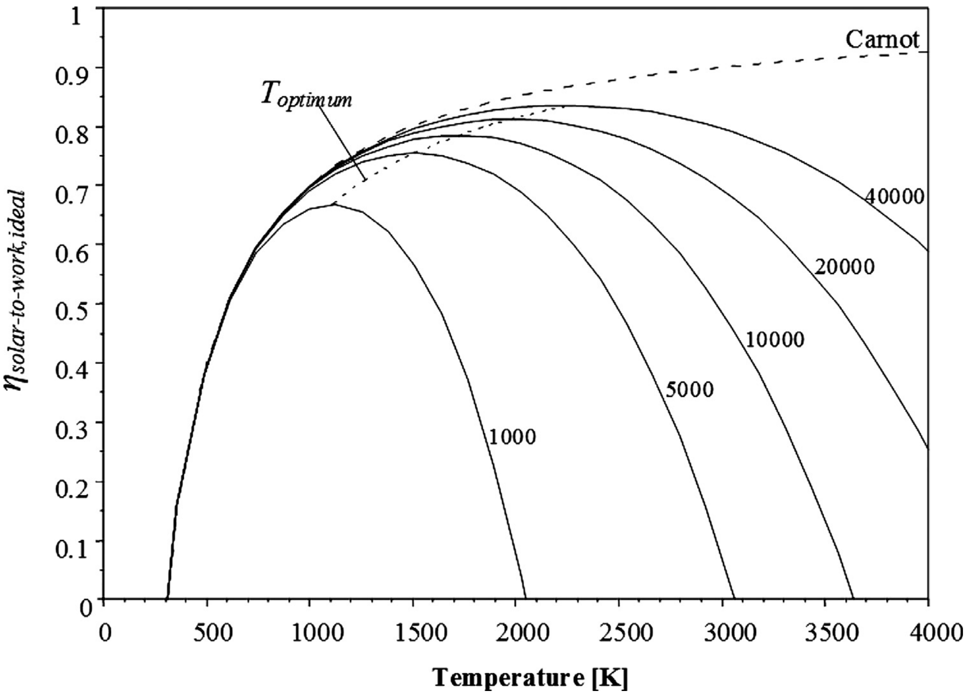


Fig. 3. Variation of the ideal solar-to-work energy conversion efficiency, $\eta_{solar\text{-}to\text{-}work,ideal}$, as a function of the operating temperature. Data are plotted for a range of values of the mean solar flux concentration ratio, while $T_{optimum}$ is the locus of maximum $\eta_{solar\text{-}to\text{-}work,ideal}$, reproduced from [1] with permission from the Royal Society of Chemistry.

power plant), as shown in Fig. 3. In practice, when considering convection/conduction losses in addition to radiation losses, the efficiency will peak at a temperature even lower than that shown, while the efficiency will also be lower owing to the use of cycles less efficient than Carnot. Furthermore, the need to operate throughout the solar year also implies that the concentration ratio will sometimes be lower than the design value, requiring operation over a range of values of *C* in practice.

From Fig. 3 we can derive the following important implications for solar hybrid systems:

1. There is an incentive to minimise re-radiation losses from a solar receiver, which does not apply to combustion plant. This may lower the optimal temperature of the hybrid relative to that of the combustion process. Notwithstanding this, re-radiation losses can be reduced by increasing the concentration ratio of the concentrating optics, although the associated increase in efficiency must be weighed against the additional cost of high-precision concentrating optics.
2. There is an incentive to operate the solar receiver at higher temperatures for coupling to more-efficient heat engines. However, the associated increase in efficiency must be weighed against the additional cost of high-temperature materials. Where air is the working fluid, the enthalpy of combustion does not need to be transferred through a wall, offering the potential to mitigate this limitation.
3. In a hybrid, there is an incentive to introduce the enthalpy of combustion downstream, rather than upstream, from the receiver. This increases the temperature of the power cycle above that of the receiver, reducing the limitation of the re-radiation losses described above. Several potential routes to achieve this are discussed below, with the use of hybrid chemical looping cycles offering a particular significant opportunity because it also offers the potential for both stored high temperature output and integrated CO_2 capture.

The dependence of radiation losses on the fourth power of temperature also has important implications on the shape of the receiver, and hence also on the maximum thermal scale. For temperatures below ~600 °C, radiation losses from a solar receiver can be managed by careful choice of the surface material to yield low emissivity in this temperature range. This allows the use of the "surround field" configuration, in which a tower-mounted tubular receiver is surrounded by heliostats, allowing radiation to be collected from all directions (see Fig. 4a). The collection of radiation from all directions allows the greatest thermal input that is possible for a single tower, which maximises the economies of scale, minimises the surface area to volume ratio and also offers some advantages in managing the variability of the solar resource by careful control of the heliostat focus. On the other hand, the use of a cavity receiver makes use of the lower radiation losses from a cavity and therefore becomes increasingly advantageous for higher temperature cycles or processes (see Fig. 4b). Nevertheless, cavity receivers suffer from the disadvantage of a lower thermal capacity due to the need to limit the collection angle from the field and due to the greater precision required from the heliostats to concentrate the radiation into the aperture of the cavity receiver, together with a degradation in-efficiency at larger distances from the tower. The beam down option offers another possibility to increase the thermal scale, reduce capital cost and heat losses. However, this option also suffers from reduced concentrating ratio resulting in reduced overall efficiency, together with increased vibration and the anticipated requirement for a large secondary concentrator on the tower, so that the conditions for which a net benefit can be derived is yet to be adequately evaluated. The third class of receiver, termed a "billboard" receiver is intermediate between these. It has a flat receiver that also collects from a narrow field angle. The above considerations of solar receivers have the following further implications on solar combustion hybrids:

- Lower temperature cycles, such as the Rankine cycle, are suitable for either surround field or bill-board style receivers. These types of receivers are difficult to hybridise at the receiver, so must be hybridised in other ways. Also the relatively low efficiency of these cycles implies that hybridisation without carbon capture will be "combustion negative" (i.e. lower efficiency than other combustion options);

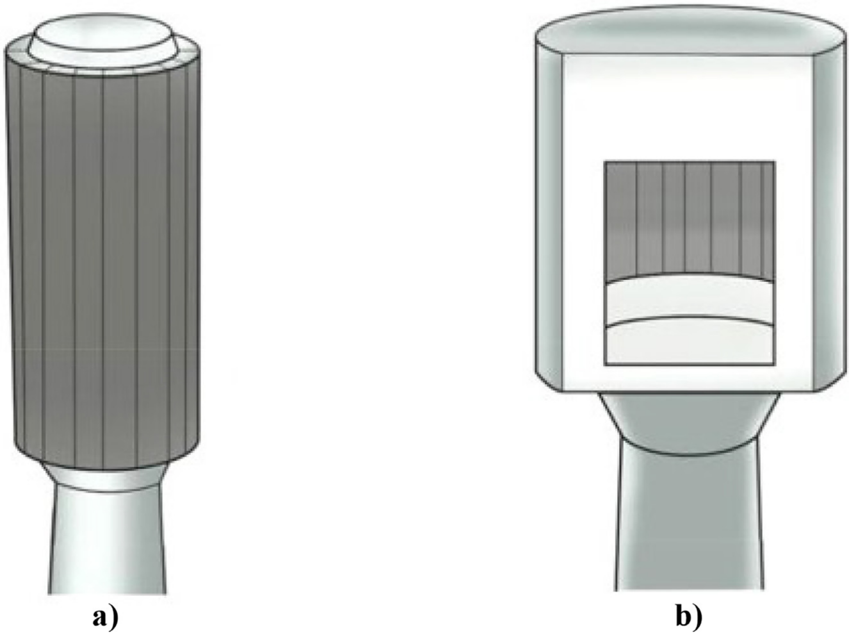


Fig. 4. The two main classes of tower-mounted solar receiver, namely (left) a surround field, which collects radiation from all 360° allowing the largest possible thermal scale but also suffers from relatively high radiation losses, and (right) a cavity receiver, which collects from a narrow arc generated by a polar field to yield much lower radiation losses, but at the expense of a smaller field, adapted with permission from [65].

- Higher temperature cycles, such as the Brayton cycle, are most compatible with cavity receivers. Cavity receivers offer the opportunity to hybridise the receiver by introducing combustion into it, but are limited to a smaller scale by the need to collect from a smaller segment of the heliostat field.

5. Hybridising with the steam side of a Rankine cycle

5.1. General options to hybridise a steam cycle

A wide range of options for hybridising a Rankine cycle are available, particularly for cycles involving CO_2 capture, for either storage or re-use, since solar energy can potentially be added not only to the working fluid (i.e. the steam), but also to the reactants and/or products (discussed in section). The two main options for adding solar thermal heat to the working fluid in a semi-direct hybrid system are shown diagrammatically in Fig. 5. These two options, which could potentially be employed together in the same power plant, are as follows:

- **Provision of low temperature solar heat, $Q_{sol,LT}$,** typically less than 300 °C, notably to heat the feedwater to the boiler. Multiple stages of feedwater preheating are typically employed, although only one is shown in Fig. 5 for clarity. This low temperature heating has the dual advantages of allowing the use of low-cost

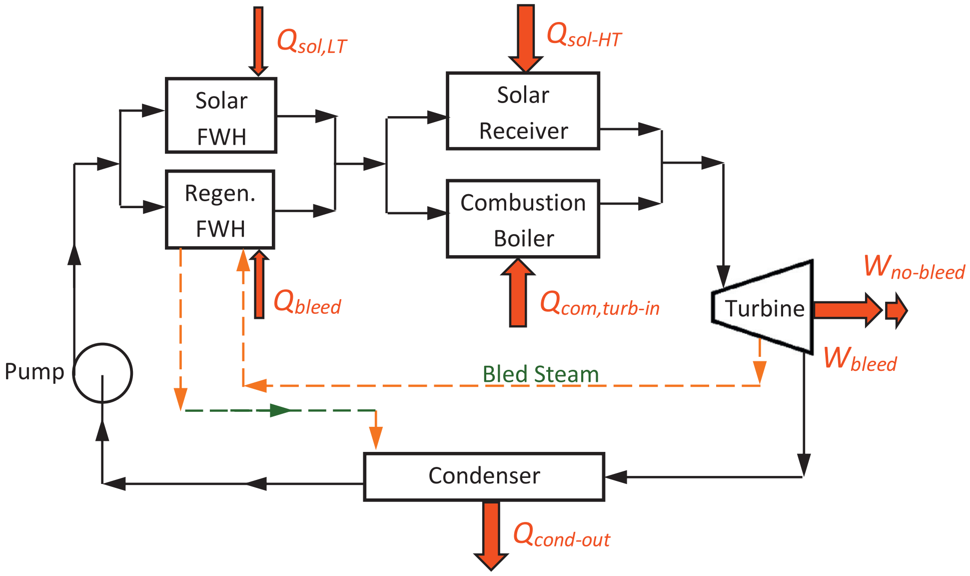


Fig. 5. Basic options for thermal indirect hybridisation of solar heat into the steam side of a Rankine cycle powered by combustion technology. The use of solar feed-water heating displaces the higher temperature steam, which is otherwise “bled” from the turbine in a regenerative Rankine cycle, to achieve higher thermodynamic efficiency than a stand-alone solar system of the same temperature.

Table 2
A qualitative comparison of the advantages and disadvantages of high and low temperature options of introducing heat into the steam-side of a Rankine cycle.

	Advantages	Disadvantages
Low temperature (feedwater) solar heat (< 300 °C typ.)	• Thermodynamic leverage • Low temp solar heating • Simple and robust	• Low solar share (< 8% typ.) for sub-critical, but could reach ∼17% for super-critical • Expensive TES (low temp) • Inefficient power cycle - Rankine • Indirect heat transfer
High temperature solar heat(∼ 600 °C typ.)	• High solar share • Suits state-of-art TES • Commercially established	• Inefficient power cycle - Rankine • Indirect heat transfer

solar concentrators and also of achieving thermodynamic leverage in a regenerative Rankine cycle since it displaces higher temperature steam that is otherwise extracted from the turbine to heat the feedwater (Table 2). In this way solar feedwater preheating achieves higher efficiency than is possible from a solar-only cycle at the same temperature [64]. However, it has the disadvantage of achieving a relatively low solar share of typically less than 8% if employed as the only solar input to a power cycle [66]. In addition, the cost of commercially-available low temperature thermal storage is presently relatively high due to its relatively low energy density, although this may change as new TES technologies emerge;

- **Provision of high temperature solar heat, $Q_{sol,HT}$**, to meet the high temperature boiling and superheating loads of a boiler. This can be performed either directly with the working fluid, typically steam, or with a separate heat transfer fluid, such as molten salt, which is the leading commercially available heat transfer fluid for which thermal storage of up to 13 hours capacity has been demonstrated [67]. Hence a major advantage of the high temperature hybridisation is its compatibility with thermal storage, which increases the solar share of the process (Table 2). The temperature limit of currently available commercial technology is approximately 650 °C [67], due to the temperature limit of the molten salt heat transfer fluids employed, although this is expected to increase as commercial systems for other heat transfer fluids are developed. Another disadvantage of this approach to hybridisation is the inefficient heat transfer associated with indirect heat transfer process through tubes, together with the materials limitations. However the other limitation is associated with the use of the Rankine cycle, whose efficiency is relatively low;

Fig. 5 also illustrates a key disadvantage of a semi-direct hybrid system, in that two sets of heat exchangers are required to collect (or transfer) each of the high and low sources of temperature heat. That is, the solar heat is collected when it is available with the solar receiver, while the alternate component is employed to harvest the enthalpy of combustion when the solar resource is insufficient. The need to operate two devices intermittently results in additional heat losses over what would be possible with operation of a single device, particularly when the transients are significant, which in turn, generates the incentive to replace these two components with the single component counterpart of a direct hybrid. While direct hybrids are not yet commercially available, they are now under development [6, 68-70].

5.2. Specific options for low temperature Rankine cycle hybridisation

Despite its limitations of a relatively low efficiency, the Rankine cycle is not only the dominant thermal power cycle in use today, it is also expected to continue to be important because of its relatively low cost and high reliability, together with its relevance to combined heat and power. The Rankine cycle is incorporated into the majority of contemporary base load thermal power stations in the world, for coal, biomass and waste fuels [63]. It is also used as the bottoming cycle in the more efficient natural gas combined cycle power generators. Furthermore, it is the dominant power cycle for solar thermal power generation because its relatively low temperature is compatible with solar receivers and thermal storage technologies as is noted above. However, its relatively low efficiency also offers an opportunity to achieve highly efficient and relatively low cost solar boosting through a process termed Solar Aided Power Generation. While this approach has typically been considered for boosting of coal-fired boilers in the past, it is not limited to these applications and can also be used in combination with other energy sources and cycles, as is explained in Fig. 5.

Modern power stations typically employ a regenerative Rankine cycle, which modifies the basic Rankine cycle to increase the thermal efficiency. In the regenerative Rankine cycle, part of the steam from each of the stages of the turbine is extracted to pre-heat the feedwater to the boiler in Feed-water Heaters (FWHs). This offers the potential to employ solar heat (or indeed for another source of low grade heat including geothermal) to heat the feedwater and thereby displace the extracted steam and allow it to continue to expand through the turbine to generate additional work. The key feature of this approach, typically referred to as Solar Aided Power Generation, SAPG [12,63], is that the solar heat does not enter the turbines directly so that the thermal efficiency of the solar power is capped by the temperature of the boiler rather than that of the solar collector [10]. This allows higher efficiency for the solar plant than is possible for a solar-only cycle at the same receiver temperature and also allows the use of lower cost concentrators for this solar boosting step. However, this is achieved at the expense of a lower solar share and can also be limited by practical considerations such as the turndown capability of the steam turbine.

A schematic diagram of a typical SAPG configuration is presented in Fig. 6 [71]. This shows that the heat provided to the FWHs is typically required at temperatures ranging from 90-350 °C. At these relatively low temperatures, relatively low cost concentrators can be employed and the heat losses can also be managed to achieve relatively high collection efficiency. Indeed, while previous assessments of SAPG have only considered solar concentrators [72,73], the lower end of its temperature range can even be provided by non-concentrating technologies. The net solar (to power) efficiency of non-concentrating solar collectors has potential to be even greater than that from higher temperature concentrators [74].

Fig. 7 presents the calculated steady-state efficiency of the input of SAPG into different types of cycle for a range of temperature inputs. It can be seen that the use of low temperature heat in a SAPG cycle is 2 to 3 times more efficient than in the stand-alone cycle at the same temperature of the solar receiver. Furthermore, the efficiency boost is greatest for the super-critical cycle owing to the higher temperature of the displaced steam (typically at 350 °C) in the super-critical cycle over the sub-critical counterpart (typically at 330 °C). In addition, the extent of the boost increases as the temperature of the renewable input decreases, owing to the greater

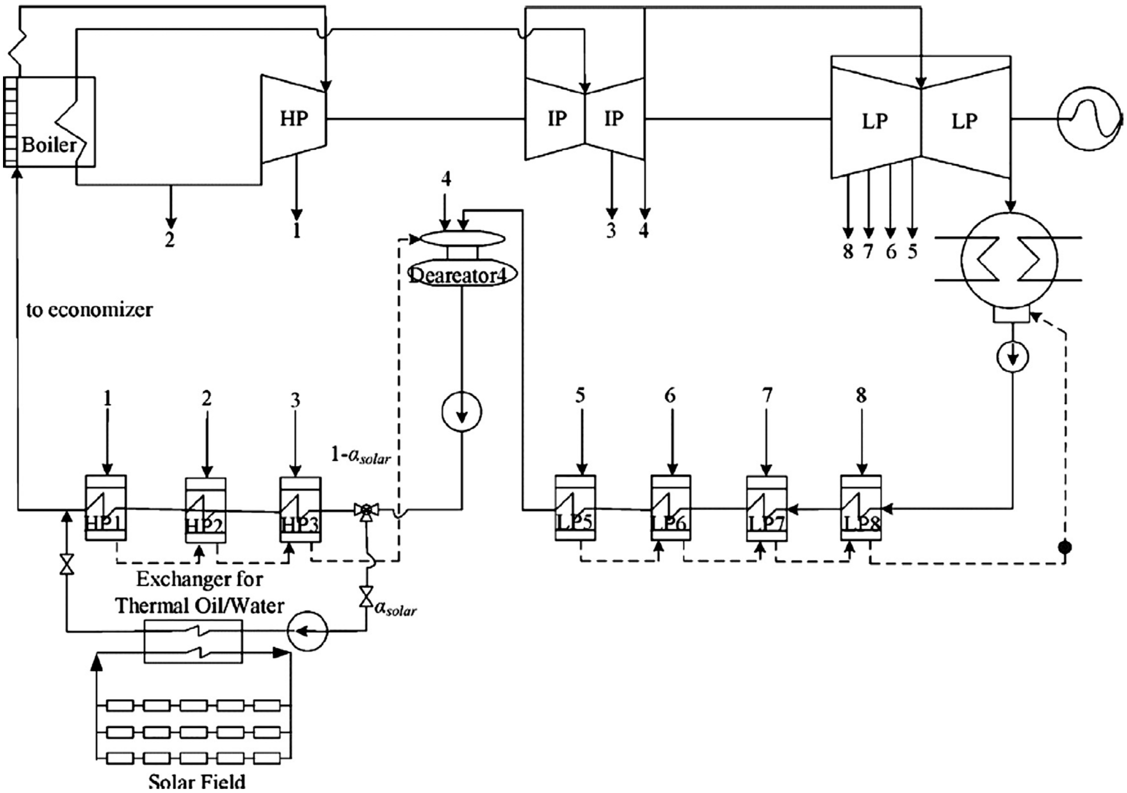


Fig. 6. A schematic diagram of a Solar Aided Power Generation plant, for which solar thermal energy is used to displace steam otherwise bled from the turbines in a regenerative Rankine cycle, adapted with permission from [71].

difference between the boiler temperature and the renewable temperature. Finally it can also be seen that, for the case in which the solar (or geothermal) input is provided at 260 °C to the super-critical boiler, the efficiency of the solar power in the SAPG is 45.3%, which is higher than the Carnot efficiency of 42.2% at the same solar temperature of 260 °C [9]. This trend is consistent with those reported for other assessments with the lower temperature range [10,75].

Fig. 8, which is modified from previous work [76], presents the instantaneous solar share at various solar input temperatures. The instantaneous solar share is defined as instantaneous solar heat input on the (instantaneous) boiler thermal load. The other way to define the solar share is the solar input on the total plant thermal loads including boiler load and solar heat input. The instantaneous solar share (in terms of Q_{solar}/Q_{boiler}) is only ~5%, when solar thermal input is provided at 90 °C, while it approaches ~25% at 260 °C in the super-critical case. While data for the annually averaged solar share are not available, it is reasonable to anticipate that this could approach ~17% with sufficient storage, which is a worthwhile target.

The possibility of operating a SAPG plant in either the Power Boost or Fuel-Saver modes was first noted by Kolb [5]. These models are illustrated qualitatively in Fig. 9 [11]. The power boosting mode

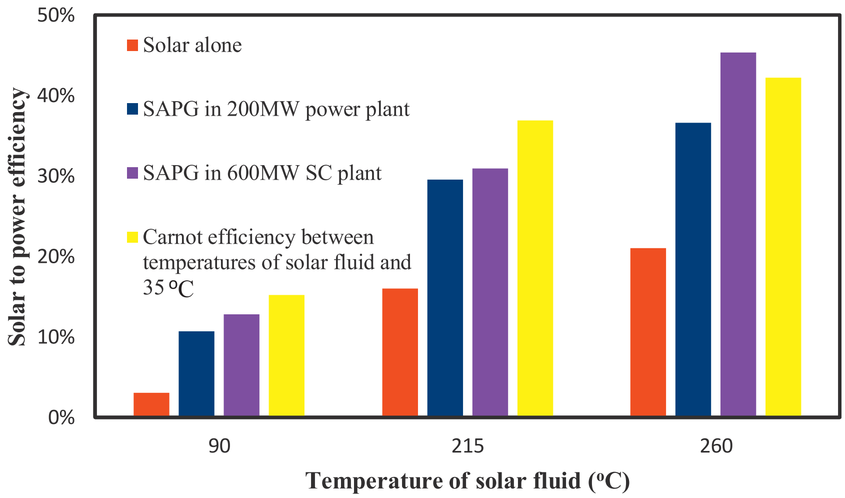


Fig. 7. The steady-state, but short-term, efficiency of solar energy added to the feedwater to displace bled steam for a sub and supercritical Regenerative Rankine cycle at the temperatures of 90 °C, 215 °C and 260 °C. Also shown is the equivalent efficiency of a stand-alone solar (or geothermal) cycle and a Carnot cycle at the same temperature. Adapted from earlier work [76].

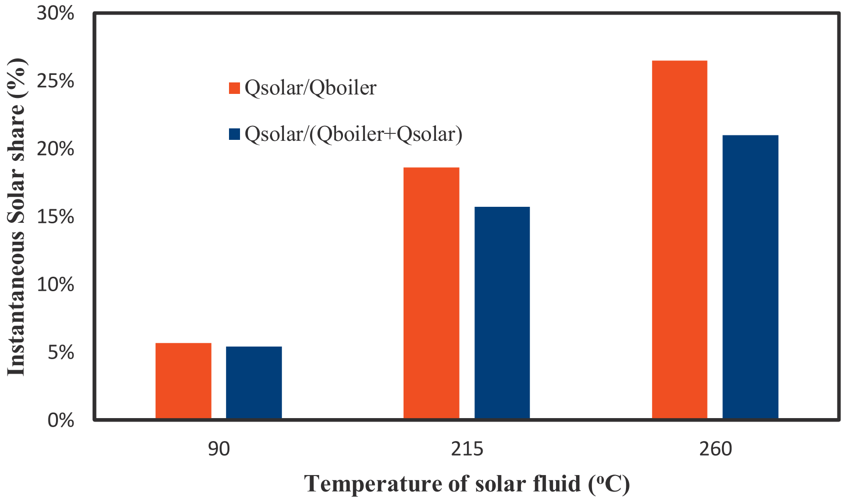


Fig. 8. The instantaneous solar share at various solar input temperatures for a solar aided Rankine cycle [76].

results in additional power being generated when the solar resource is available without changing the fuel consumption of the boiler, while the fuel-saving mode maintains a constant generating capacity by reducing the fuel consumption from the boiler. The power-boost mode typical offers greatest economic return either from reducing the need to install additional generating capacity [5] or from the potential to sell more power during periods of high demand, with the associated high price of power. Furthermore, the extent of fuel-savings in the Fuel-Saver mode may be less than the solar input because the efficiency of the boiler typically reduces with turn-down. Perhaps more significantly, the extent to which SAPG can be implemented in a retrofit configuration is limited by the design point of the turbine and a range of practical constraints [66]. These include limited land-access for solar concentrators and a limited solar resource at many pre-existing sites. It was found that the annual solar share of a 300 MW power plant in Greece was only about 7.91% (120,000 m^2 solar collectors) [73]. However, no assessment of the potential for new plant that incorporated SAPG together with other CO_2 mitigation strategies has been performed to date to the best of our knowledge.

In the power boosting mode solar to (electric) power efficiency (η_{se}) can be described as:

$$\eta_{se} = \frac{\Delta W_e}{Q_{solar} \pm \Delta Q_{boiler}} \times 100\%. \tag{2}$$

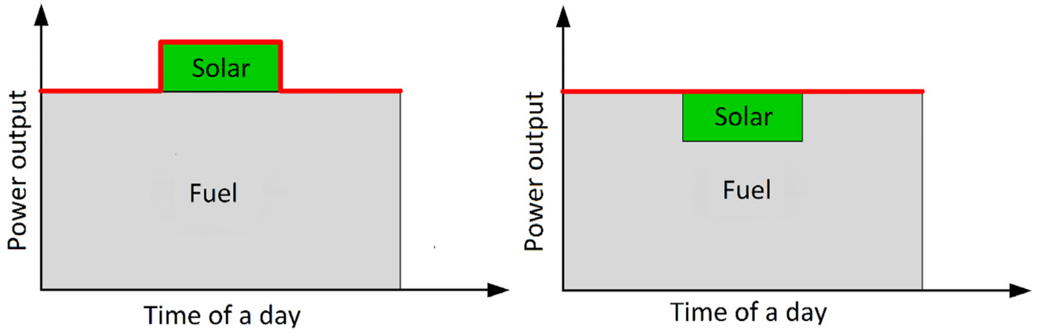
Here ΔW_e is the increased power output (from the plant) due to the solar heat input, Q_{solar} is solar heat transferred into feedwater, and ΔQ_{boiler} is the possible change of the boiler load after solar input [12].

If the SAPG plant is operated in the power boosting mode, ΔW_e could be determined relatively easily, as the difference between the output from the power plant with and without a solar heat input. However, it is not straightforward to determine the values of η_{se} or ΔWe, in the fuel saving mode, because the output from the turbine does not change significantly with the solar input. Two possible ways to quantify η_{se} or ΔW_e, for the fuel saving mode are as follows:

(1) The annual solar power generation ($E_{solar,a}$), i.e. annual ΔW_e, can be defined as that component of the electricity generated by solar energy [73], as follows:

$$E_{solar,a} = \sum_{n=1}^{8760}\left(E_{z,n} - \frac{Q_{b,n}\eta_{ref,n}}{3600}\right), \tag{3}$$

where n represents the n^{th} hour of the year; $E_{z,n}$ is the total output from the SAPG system in the n^{th} hour (kWh); $Q_{b,n}$ is the (reduced) heat load of the boiler in the n^{th} hour (kJ), $\eta_{ref,n}$ is the efficiency of the reference fuel-fired power unit in the n^{th} hour [72,73]. However, this method of calculation over-estimates the solar contribution because it does not consider the efficiency changes of the boiler and/or the turbine due to changes in the flow rates.



(a) Power boosting mode

(b) Fuel saving mode

Fig. 9. The alternative “(a) power boosting” and “(b) fuel saving” modes of operation mode in a SAPG plant, modified from [11].

(2) In the absence of measured data of boiler efficiency with turn down, it is possible to estimate ΔW_e from the difference between the plant's power output at a reduced boiler flow rate (in fuel saving mode) but without any solar input, and the designed plant's output [74]. This approach requires the efficiency changes of the turbine with turn down to be known or estimated.

The two ΔW_e definitions described above can be used to bench-mark solar performance in the fuel saving mode against power boosting mode. However, neither the estimates of η_{se} or ΔW_e are absolute.

The performance of an SAPG plant also depends on the detailed configuration of the connections to the plant's feedwater heaters and the operational strategies adopted to adjust the flow-rates of extraction steam with variation in the solar input [77,78]. Of the 12 possible “configuration and operation” combinations, it found when all the extraction steam to the displaced feed water heaters (FWHs) has been displaced by the solar thermal energy, SAPG plant's technical performance would be identical for all 12 proposed combinations. However, when for reduced quantities of displaced steam, a particular configuration has the highest annual solar share, annual solar power output per collector area and solar thermal to power efficiency [77]. In addition, the operation of the non-displaced FHWs also has an impact on performance of the SAPG plant [78]. That is, adopting the constant temperature flow (CT) strategy for each non-displaced FWHs is generally better than that adopting the constant mass flow (CM) strategy. However, if the SAPG plant is to be located in a region of rich solar resource, a SAPG plant adopting the CM strategy can achieve better performance [78].

Previous economic evaluations on the use of SAPG with coal-fired boilers have shown that it increases the LCOE [79] comparing with coal fired power generation without CO_2 mitigation. However, the LCOE of the SAPG plant is lower than the same size of solar-only power plant [73]. In addition, while there is an optimal solar area for an SAPG plant to achieve the lowest LCOE [80,81], these previous assessments do not account for resource variability. The economic potential of the use of power boosting to capitalise on the market pricing using SAPG is yet to be evaluated either for use with a coal-fired boiler or for alternative system configurations including other types of system with lower net CO_2 emissions such as those shown in Fig. 5. Similarly, there is significant potential to develop alternative configurations of FWH and solar plant configuration to further lower the cost of SAPG.

5.3. *Specific options for high temperature Rankine and emerging efficient cycles*

The Hybrid Solar Receiver Combustor, HSRC, is a new patented concept that integrates the combustion system within a solar cavity receiver [6], shown in Fig. 10. The cavity receiver is fitted with multiple burners to heat the same heat exchanger that is also used for the solar mode. Heat is recovered from the exhaust gases and is used to preheat the combustion air and to provide an aerodynamic curtain as described below. Noteworthy is that cavity receivers are well suited to high temperatures due to their lower radiation losses, when compared to other configurations, but are currently limited in scale, as is described above [82]. The HSRC can be operated in three modes:

- Solar-only: here the operation is similar to a conventional solar-only device.
- Combustion-only: here the aperture is sealed with a flap to avoid the additional radiation and convection losses during the combustion-only mode. The device incorporates heat recovery from the combustion products to pre-heat the combustion air. The heat transfer to the heat transfer fluid is similar to a stand-alone combustor [22,23], although additional exergy losses may be incurred relative to heating the working fluid directly.
- Mixed mode: here the two energy sources can be introduced at the same time, which offers the potential to manage rapid changes in solar heat flux and/or operate at lower solar heat

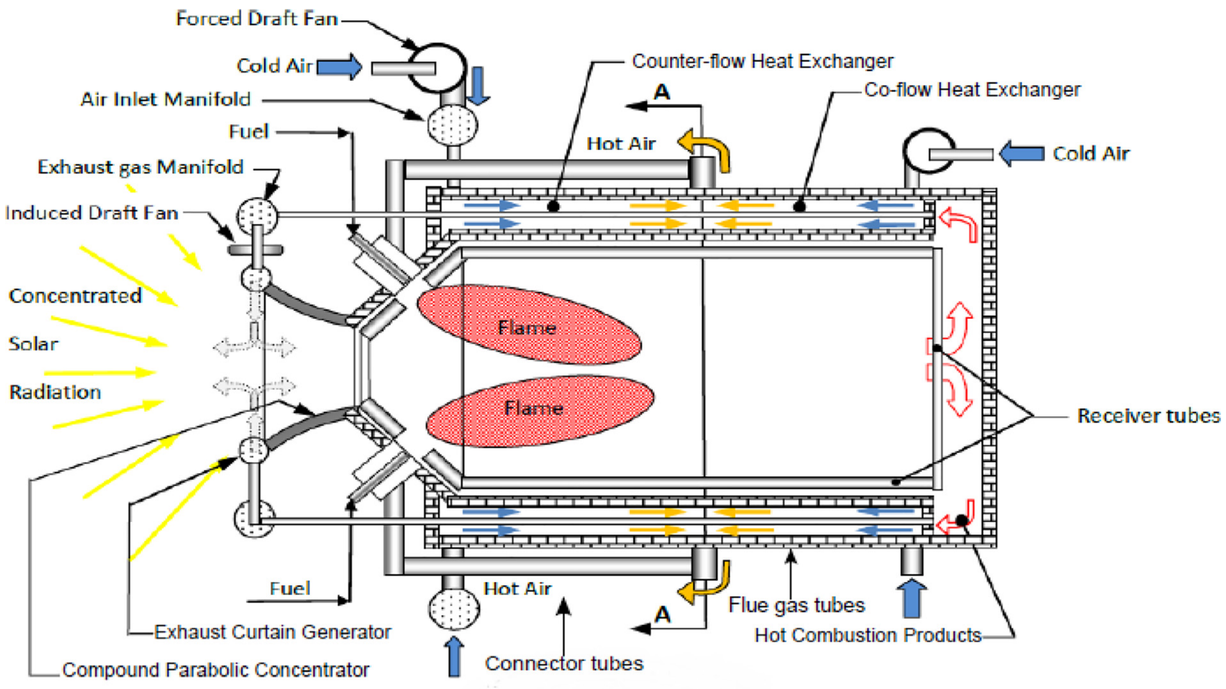


Fig. 10. Schematic representation of a direct hybrid between a solar cavity receiver and a combustor, adapted from previous work, adapted with permission [23].

fluxes than would otherwise be possible [6]. Net benefits are anticipated, despite some additional heat losses through the open aperture.

The integration of the combustor and solar receiver has the advantages of reduced infrastructure relative to a back-up combustion system (such as a stand-alone boiler on the same site), reduced losses from both start-up/shut-down and heat exchange surface area and greater capacity to manage heat flux during periods of rapid change in solar resource. On the other hand, it has the disadvantage of a compromised receiver-combustor design to extract the heat efficiently from both a radiation source (solar energy) and a combined radiation and convection source (combustion energy). An added disadvantage is the additional control required to address the challenge of a potential reduction in thermal efficiency during mixed mode operation arising from hot products escaping the cavity or cold air (induced by wind) entering the cavity. The combustion-related challenges associated with operation in the mixed mode have recently been reviewed [3]. However, the technology-related challenges have not been reviewed before. Therefore this section addresses this need for the HSRC.

Lim et al. [22] conducted a techno-economic assessment using a piecewise-continuous (i.e. pseudo-dynamic) model that accounts for solar variability on performance for different sites with high DNI. They compared the performance of the HSRC with a conventional standalone solar system backed up by a conventional boiler (termed a Solar Gas Hybrid system) sharing the same power block. They found that, for a 100 MW_{th} system, the Hybrid Solar Receiver-Combustor (HSRC) reduces the net fuel consumption relative to the equivalent Solar Gas Hybrid system by 12% to 31% depending on the size of thermal storage capacity. The benefits were attributed predominantly to the avoidance by the HSRC of the start-up and shutdown losses of the backup boiler of the SGH [22,83]. In addition, significant benefit is also derived from the reduced electrical energy consumption from the trace heating associated with the need to prevent molten salt from solidification. The combined value of these benefits is a reduction in the Levelised Cost of Electricity (LCOE) by up to 19%, depending on the price of the natural gas [22].

To achieve a reasonable match in the heat flux profile across the different modes, while also achieving low NO_X emissions, the use of Moderate or Intense Low oxygen Dilution, MILD, combustion has been proposed. MILD combustion is characterised by a volumetric reaction, high recirculation, wide stability limits, low pollutant emissions and a relatively uniform temperature distribution [84–86]. These features increase the thermal efficiency of the system, provide a more distributed heat flux to the heat exchanger and maintain a clean combustion process. Low sensitivity to variation in external air ingress into the cavity is also anticipated. To mitigate the convective heat losses during operation in the mixed mode, the use of an aerodynamic curtain (i.e. a fluidic "seal") using the combustion exhaust gases has been proposed, as is illustrated in Fig. 10. This aerodynamic curtain is under development to reduce the external air flow into the cavity without the use of a window. Noteworthy, is that the MILD combustion mode operates with high level of exhaust gas recirculation and any part of the shielding gas that enters the cavity is expected to be manageable through a control system and a sensor of the O_2 concentration at the exhaust. Lim et al. [68], also considered the potential benefits of integrating MILD combustion with the HSRC. They found that there is potential to achieve up to 41% in fuel saving and 4% saving in LCOE for the MILD HSRC relative to the HSRC operating with conventional combustion for a receiver size of 30 MW_{th}.

Fig. 11 presents the effect of the cavity length to diameter ratio on heat transfer and its impact on thermal efficiency. From this Fig. it is clear that for $L_c/D_c > 4$ the thermal efficiency can be higher than a standard boiler for several scenarios. For example, the rate of hot combustion products recirculation (denoted by S as the ratio of recirculated versus exhausted gases) which provides a favourable thermal efficiency is found to be 75:25 (75% of the hot combustion products recirculated directly and 25% released via exhaust). The figure also shows that MILD combustion has potential to increase heat transfer and efficiency from the high rates of heat transfer to the heat transfer fluid.

Chinnici et al. [69,70] conducted an extensive CFD study to investigate the thermal performance of the HSRC under the three operating modes for a range of design and operating parameters. They confirmed many of the findings of the analytical models presented by Lim et al. [22,23,68] and showed that it is possible to select a HSRC geometry that provides similar efficiency under the three modes, with low energy losses. Configurations suitable for achieving

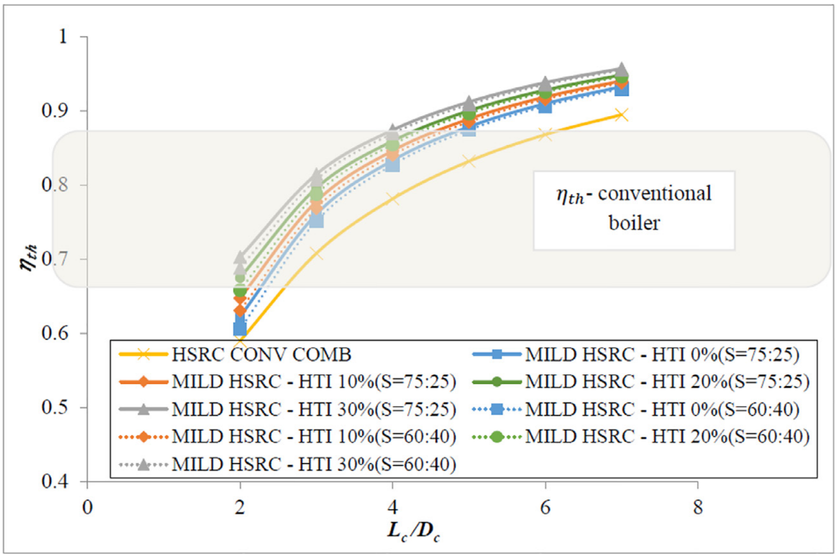


Fig. 11. Effect of varying the length to the diameter ratio of the Hybrid Solar Receiver Combustor (HSRC) on the overall thermal efficiency for an overall output of 30MWth. Results are reported for several configurations of MILD combustion and the conventional combustion for a range of assumed values of Heat Transfer Improvements (HTI) from use of the MILD combustion mode spanning the range of 0 - 30%. Various configurations of split ratios of recirculated gases of ??= 75:25 and ??= 60:40 are also shown. The performance of a conventional combustion boiler is also shown for reference, adapted with permission from [68].

HTF temperatures of up to 800 °C were also identified under realistic assumptions. These temperatures are greater than those usually employed for Rankine cycles and demonstrate the compatibility of the two energy sources and their suitability for integration.

Recent unpublished work at The University of Adelaide has provided further support for the findings reported above using a 20 kWth experimental prototype of the HSRC. Using natural gas as a fuel and a 5 kWe Xenon lamp (to simulate solar radiation), the device has operated at thermal efficiency of up to 88% in all three of the three modes of operation (i.e. solar only, combustion only and the mixed mode), with measured NOx and CO concentration in exhaust of less than 5 ppm and 100 ppm, respectively.

5.4. *Critical research challenges for the HSRC*

The research challenges of greatest priority to support the further development of the HSRC technology can be summarised to be as follows:

1. Better understanding the scaling parameters that will allow the effective operation under the three modes at greater thermal scale;
2. Development of fuel flexible burners to allow the use of alternative fuels; such as syngas, ammonia or hydrogen within a highly confined reactor;
3. On-sun testing of larger scale HSRC to identify any unforeseen potential practical problems and assess methods with which to manage solar flux variability;
4. Development of control systems that mitigate destructive thermal stresses due to rapid reductions in solar flux induced by the passing of clouds by ramping up the combustion system to compensate for short term reductions in solar flux;
5. Developing effective strategies to mitigate convective losses through the aperture (e.g. through aerodynamic curtains) and increase efficiency in the mixed mode;
6. Investigating the feasibility of utilizing the HSRC technology for combined heat and power.

6. Hybridising via the fuel or oxidant

6.1. *General options to hybridise with the fuel side of a power cycle*

A range of additional options for hybridising CST with combustion technologies are emerging from the plethora of new technologies under development for CO_2 mitigation. One class of these technologies are associated with the range of options for introducing thermal energy into the fuel side of a combustion process for which carbon capture technology is potentially applicable. These are applicable to a range of power cycles including the Rankine and Brayton cycles, but also to alternative power cycles under development such as the CO_2 Thermodynamic Cycle. These options, illustrated in Fig. 12, are as follows:

- **Solar thermal fuel upgrading:** CST can be used to drive a wide range of endothermic reactions to increase the heating value of a fuel, such as through the gasification of solid carbonaceous feedstocks or solar steam reforming of natural gas [87]. This approach offers potential to increase the heating value of the original fuel by up to 40% depending on the carbon-hydrogen ratio of the feedstock and 20% of natural gas [88]. This would correspond directly to a reduction in the net carbon intensity of the process if the fuel were to be upgraded entirely with renewable energy and if the fuel were to be utilised with the same efficiency in the power generation plant. However, the conversion of a solid fuel into syngas introduces some parasitic losses. The production of a gaseous fuel enables it to be used in as a gas-turbine or combined cycle as an alternative to a Rankine Cycle, or to other thermodynamic cycles under development. However, further work is required to better evaluate the relative techno-economic merits of these various options for CO_2 mitigation. For example, the present cost of CO_2 capture from a Brayton cycle is more expensive and energy intensive than for the Rankine cycle.
- **Solar thermal oxygen production:** Technologies are also under development to employ CST to drive the endothermic reactions for oxygen production from the thermochemical splitting of water or thermochemical oxygen separation [48,89,90]. The former process is targeted at the production of H_2 and CO from H_2O and CO_2 [91,92], although pure O_2 or O_2-rich inert gas can also be co-produced. Similarly technologies are also under development for thermochemical energy storage that offer potential for the co-production of industrially pure O_2 with power [90,93,94]. Solar oxygen production has potential to avoid the 0.4 kW h/m^3 parasitic loss that is associated with the present state-of-the art in oxygen production via cryogenic air separation that is needed to enable CO_2 capture via oxy-fuel combustion [95,96]. However, considerable work is required to better evaluate both the net CO_2 mitigation after all energy requirements of the process are considered, together with the relative techno-economic potential of the various technology options under development for oxygen production with CST, particularly in a manner that reliably accounts for the variability of the solar resource. In

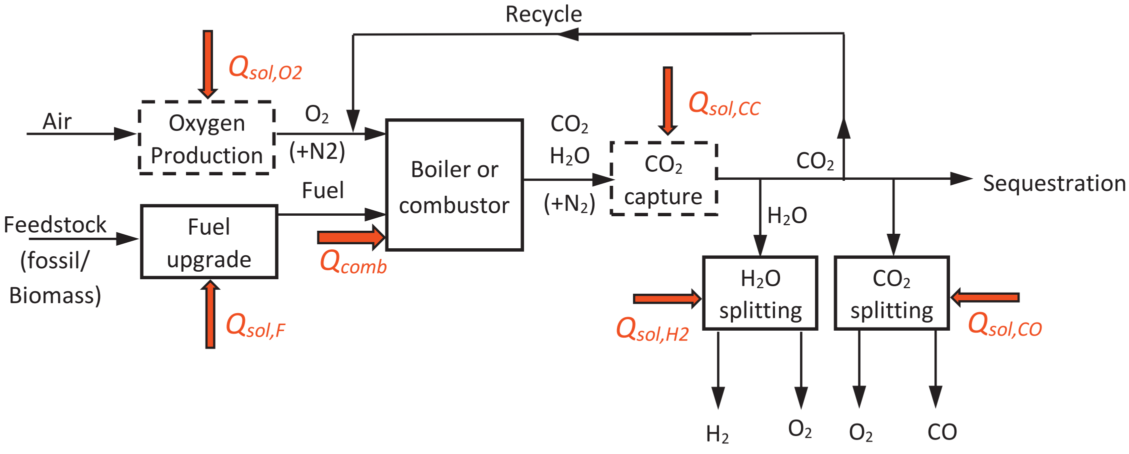


Fig. 12. Basic options for hybridising solar thermal heat (thermo-chemically) into a Rankine cycle with CO_2 capture, or into another combustion with near-stoichiometric ratios of fuel to air.

Table 3
A qualitative comparison of the advantages and disadvantages of the various options for introducing solar thermal energy into the combustion side of a Rankine cycle.

	Advantages	Disadvantages
Solar thermo-chemical fuel upgrading (Typ. > 900 °C)	• Increases solar share • Reduced net CO_2 emission	• Unlikely to be commercially attractive because syngas is more valuable as a chemical feedstock than a fuel • Difficult to match solar resource variability to demand for fuel
Solar thermo-chemical oxygen production (Typically > 700 °C)	• Increases solar share • Displaces expensive ASU • Avoids parasitic energy loss and net CO_2 emissions over conventional ASU • Can operate with moderate purity of O_2 (~30%)	• Technology is at an early stage of development; • Difficult to match solar resource variability to demand for O_2 • May require an O_2 storage system
Solar thermo-chemical CO_2 splitting (Typ. > 1500 °C)	• Provides a high concentration source of CO_2 for chemical splitting; • Potential to provide a low net-emission CO_2 source if the feedstock has a low carbon footprint; • Potential to synergise with other thermal cycles	• The level of net CO_2 mitigation depends on the net carbon footprint of the fuel; • Technology is at an early stage of development;
Solar thermo-chemical H_2O splitting (Typ. > 1500 C)	• Source of H_2O is co-located with source of CO_2 • Potential to synergise with other thermal cycles	• Technology is at an early stage of development

particular, the purity of oxygen produced in thermo-chemical splitting of water depends on the method used to achieve a low partial pressure of O_2 in the reduction reactor. While high purity O_2 can be produced with a vacuum, this approach incurs the parasitic losses of generating a vacuum. On the other hand the costs of vacuum production can be avoided by use of CO_2 as the purge gas in the reduction reactor, although this comes with the penalty of making oxygen storage more expensive.

- **Solar thermal CO_2 reuse:** A range of technologies are under development to employ CST to regenerate CO_2 into a fuel [1]. These technologies have potential to be used to regenerate the CO_2 captured from combustion processes (Fig. 12). Nevertheless, these technologies can be considered to be an indirect approach to hybridisation and are also in the early stage of development. Hence they are considered to be beyond the scope of the present review.

Table 3 presents a summary of the advantages and disadvantages of the various options presented above. It can be seen that, while there is significant potential for these approaches, they are at a relatively early stage of development so that further research and technology development is required to realise this potential.

7. Hybridising with a Brayton cycle

7.1. The need to consider CO_2 capture

The Brayton cycle, which is the present state-of-the-art in heat engines for power generation, is particularly well suited to the combustion process because its use of air as the working fluid allows the enthalpy of combustion to be added directly to the pressurised fluid through the chemical reaction. This direct process of heat addition avoids the need to transfer heat to a high pressure fluid through a wall. This, in turn, avoids both the exergy loss of indirect heat transfer and the need for expensive and specification-constrained materials that must provide both high rates of heat transfer and resistance to high temperature and pressure. In this respect the Brayton cycle is better suited to combustion than solar thermal, because the low absorptivity of the solar spectrum by air makes it necessary to rely on indirect heat transfer. On the other hand, the use of combustion must bear the compensating penalty of the need to achieve zero-net CO_2 emissions, which brings alternative penalties that offset, and can even outweigh, the above advantages. Although a few sources of low-carbon gaseous fuel are available (e.g. from methane generated from the digestion of biomass), its future use with natural gas will require either CO_2 capture, whose penalty is greater than for a Rankine cycle owing to the higher dilution of CO_2 in the exhaust [97]. Alternatively, carbon-neutral fuels, such as those derived from renewable energy, are another option although this path is likely to be energy intensive and expensive in the immediate future. On the other hand, a CST hybridised Brayton cycle requires either that the radiation be transmitted through a window to a radiation absorbing surface, which is technically challenging and expensive, or that the heat be added indirectly, either through a conducting, high pressure materials or through an indirect process such as via particles. These points explain why a CST Brayton cycle is typically less efficient than a combustion cycle without carbon capture, but have strong potential to achieve comparable efficiencies to a carbon neutral combustion cycle. Furthermore, hybridising offers potential to achieve higher net efficiency than either of the stand-alone processes for a given level of CO_2 mitigation.

Brayton cycles are employed in one of two configurations, each of which performs a different function in power networks that must be considered separately in their comparison with a CST hybrid. These two options are:

- Open cycle gas turbines (OCGT): These are predominantly used to provide peaking power, owing to their high availability and short start-up time. They are used to meet periods of relatively high demand that can result either from peak periods of uncontrolled demand or to compensate for the rapid reduction in power that arises from the cessation in supply from intermittent generation from wind-power and/or solar PV without electrical storage. The efficiency of current open-cycle gas turbines for power generation typically spans the range 35–40%, depending on the scale, so that the efficiency increases with thermal input [98–102]. In addition, no CO_2 capture technology has yet been proposed for OCGT. This is because the cost penalty for CO_2 capture will increase very significantly for peaking plant, since the capital cost for the capture technology must be repaid over a relatively short operating time through the year;
- Combined cycle gas turbines (CCGT): While CCGT offer much greater efficiency over OCGT of 55–60%, also depending both on scale and on the ambient temperature. These have a longer start-up time caused by the greater inertia of the steam turbine cycle, which limits their application for peaking load.

The need to integrate CO_2 capture with an intermittent combustion system generates a further opportunity for hybrid technology, particularly for higher temperature cycles such as the Brayton cycle.

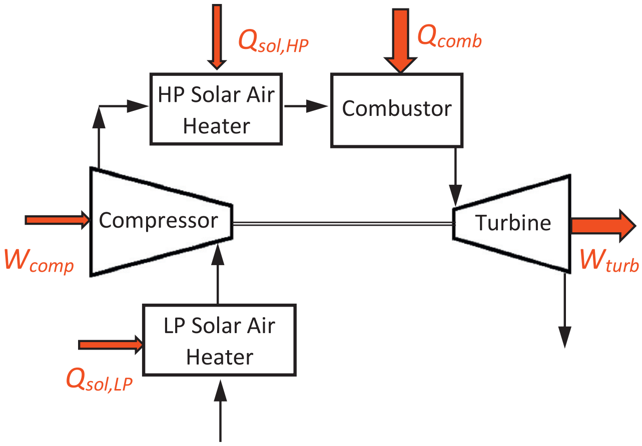


Fig. 13. Basic options for thermal hybridisation using sensible solar heat into a Brayton cycle. This option has limited options for carbon-capture (and storage or re-use) owing to the high level of dilution of the combustion air, but can use fuels that have been thermo-chemically upgraded with solar energy.

That is, the cost penalty associated with intermittent use of CO_2 capture technology can be avoided by sharing the infrastructure associated with capture CO_2 with that employed for the solar thermal process itself. This is possible with the hybrid solar thermal chemical looping processes described below.

7.2. *Different options for hybridising a Brayton cycle*

In a Brayton cycle, as shown in Fig. 13, air at ambient conditions is first drawn into a compressor to pressurise it to 5–30 bar and increases the temperature through the compression process [103]. For a conventional Brayton cycle, the pressurised and heated air is then introduced to a combustion chamber where the fuel is burned to further increase the temperature of the pressurised air. Finally, the high pressure and temperature flue gas is passed through a gas turbine, expanding to the atmospheric pressure and thus producing power [103]. The operating temperature of the commercially available gas turbines is presently approximately 1250 °C [58] and is anticipated to increase to 1700 °C in the foreseeable future [104]. The thermal efficiency of a simple Brayton cycle is typically higher than that of a simple steam Rankine cycles due to its higher operating temperature. Similarly, a higher solar to electrical efficiency can be achieved using hybrid Brayton cycles than for hybrid Rankine cycles and could be applied to a wide range of power levels from 1 to 100 MW_e [105]. A solar hybrid Brayton cycle can be also combined with a “bottoming” Rankine cycle [7] or other processes that need low to medium operating temperature such as desalination [106]. High temperature concentrated solar power introduced into the Brayton cycle of a combined cycle plant can be converted into electricity with a solar to electrical efficiency of up to 30% [106–108].

In a hybrid solar Brayton cycle, the combustion of a fuel is employed together with the concentrated solar thermal energy to heat the pressurised air before introduction to the gas turbine [109]. The potential points in a Brayton cycle into which solar thermal energy can be added to the system are shown in Fig. 13. While solar thermal energy could hypothetically be used to preheat atmospheric air prior to its introduction to the compressor, this increases the work required for compression, which decreases the efficiency of the cycle, even though it enables the use of volumetric air preheaters. On the other hand, heating the air after compression introduces the challenge of sealing the high pressure air stream, although this comes with the benefit of a higher heat transfer coefficient. Several high temperature solar air heaters suitable for pressurised air have been experimentally demonstrated at laboratory scale [105,110,111]. An after-burner can also be employed both to close the temperature gap between the receiver outlet temperature and the desired turbine inlet temperatures of ~1300 °C and to compensate for any reduction in the fluctuating solar input relative to the design value [109,112]. In a such a hybrid, the solar share increases with the temperature of the output pressurised air from the solar receiver [6], highlighting the significance of the receiver. Also, while TES has not been demonstrated at these temperatures, several technologies are under development that target these temperatures, such as the porous bed technologies with a thermocline [113,114]. Nevertheless, thermal storage would only make sense in a hybrid device where combustion is used to provide a small supplement to the solar energy. Otherwise, the additional losses from the storage device and from operating at a lower temperature, than is possible with a combustion-only device, can outweigh the gains [7].

Various configurations of solar receivers for heating pressurised air have been proposed, using either directly or indirectly irradiated concepts. For directly irradiation configurations, such as the one developed at DLR (Figs. 14 & 15) and the small particle solar receiver designed at San Diego State University [115], the working fluid is heated by a volumetric absorber that is directly exposed to concentrated solar radiation. This provides an efficient means of heat transfer but requires the use of a transparent window to achieve high pressure, which is then a critical component since it must also operate at high-temperature [105]. In contrast, for an indirect irradiation configuration, such as the one developed at ETH Zurich (Fig. 16), the working fluid is heated by a porous structure that in turn is heated by an opaque cavity-type absorber, eliminating the need of a window at the expense of having a less efficient heat transfer by conduction through the absorber walls.

While the approach of indirectly hybridising a conventional gas turbine (Fig. 13) is technically feasible, significant challenges remain to be overcome before it is likely to be implemented

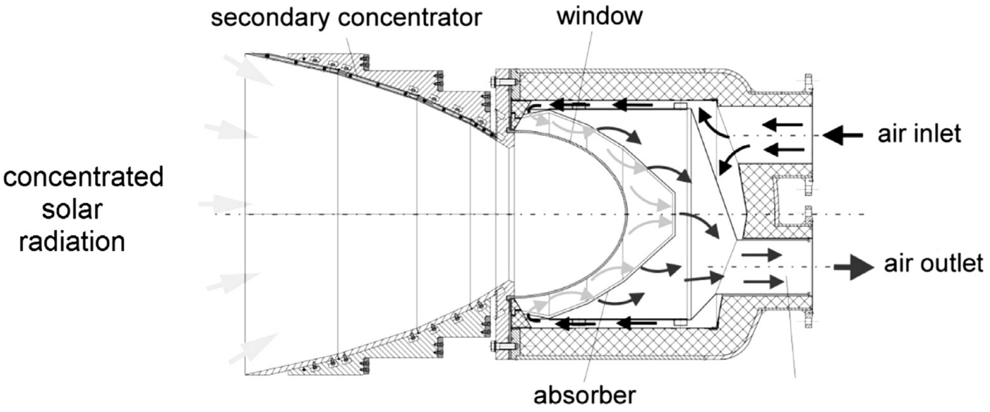


Fig. 14. The REFOS receiver module used to preheat pressurised air for a gas turbine, modified from [105].

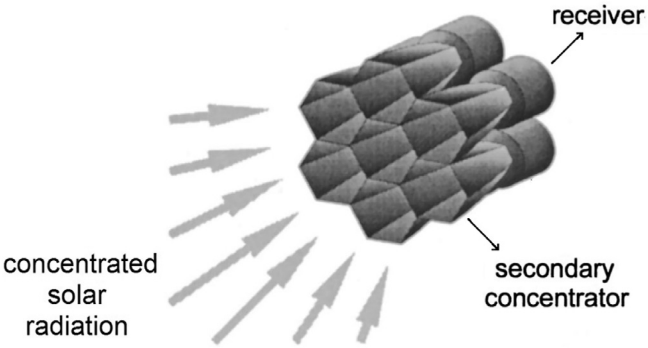


Fig. 15. Modular receiver arrangement, modified from [105].

widely. For example, the solar share of the European REFOS project, which employed an after-burner system, was measured to be only 28.6% during periods where the solar resource is available [105]. This would reduce significantly if it is to be used when the solar resource needs to be supplemented. Furthermore, this configuration does not achieve CO_2 capture and, while capture is technically possible from a gas turbine, it is also both expensive and energy intensive with currently available technology. Indeed Mathieu and Bolland [97] found that there is little benefit in the use of natural gas combined cycle over pulverised coal combustion in a boiler when the added costs of CO_2 capture are accounted for. Given that this high cost results from the much lower concentration of CO_2 in the exhaust from a gas turbine over a boiler, the penalty will be even greater for a hybrid, since the combustion products are even more dilute.

The integration of the pressurized-air solar receiver into a gas turbine cycle involves a trade-off. The power cycle efficiency increases with the turbine inlet temperature, although the efficiency of a solar receiver decreases at a higher average operating temperature due to re-radiation losses. Up to a temperature of 700 °C, the air receiver based Brayton cycle would not always be competitive vis-a-vis a steam receiver based Rankine cycle. The main advantage of the air receiver becomes evident at temperatures above 700 °C where the higher achievable efficiency provides a competitive advantage. The downside is that the high-temperature air needs to be contained and transported to the power generation unit using expensive piping made of nickel-based alloys. Table 4 presents a summary of the advantages and disadvantages of the various options presented above.

8. Hybrid solar chemical looping combustion

New concepts are emerging for technologies that hybridise CST with chemical looping combustion (CLC), termed Hybrid Solar Chemical Looping Combustion (Hy-Sol-CLC). This concept is shown schematically in Fig. 17.

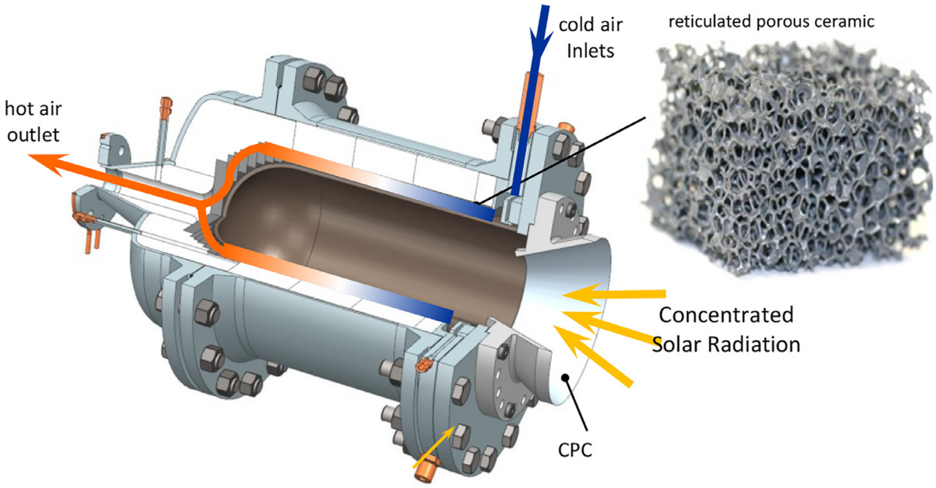


Fig. 16. Scheme of the pressurized-air solar receiver configuration developed at ETH Zurich. The modular design consists of a cylindrical SiC cavity surrounded by a annular reticulated porous ceramic foam contained in a stainless steel pressure vessel, with a secondary concentrator (CPC) attached to its windowless aperture, adapted from previous work, modified from [111].

Table 4
A qualitative comparison of the advantages and disadvantages of high and low pressure options of introducing heat into the air-side of a Brayton cycle.

	Advantages	Disadvantages
Low pressure solar air heating (Typically ~ 500 °C)	• Receiver does not need to be pressurised (Atmospheric) • Allows semi-direct heat transfer without window – e.g. volumetric receiver • Relatively robust	• Need to compress hot air • Low solar share; • Insufficient temperature to operate Rankine cycle alone; • CO_2 emissions from after burner are expensive to capture because they are dilute.
High pressure solar heating (Typically < 1200 °C)	• Allows higher solar share • Can reach sufficient temperature for combined cycle	• Requires indirect HX • Requires non-metallic HX, which are brittle; • Max temperature, and hence efficiency, is still less than combustion; • Trade-off between Solar Share and η; • CO_2 emissions from after burner are expensive to capture because they are dilute.

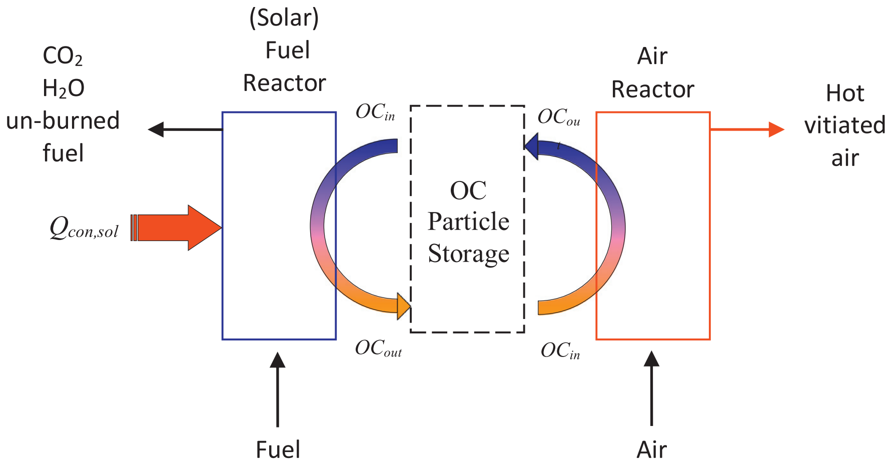


Fig. 17. Schematic representation of a hybrid solar chemical looping combustion (Hy-Sol-CLC). Solar thermal energy can be stored in the oxygen carrier (OC) particles as both chemical and sensible heat, which are reduced in the Solar Fuel Reactor and oxidised in the Air Reactor, while also achieving inherent capture of the CO_2 emissions from the combustion.

Stand-alone CLC technology is under development owing to its potential to achieve efficient CO_2 capture using Reduction-Oxidation (redox) reactions, with low energy penalty [116]. In CLC a metal oxide, referred to as oxygen carrier (OC), is employed to oxidise the fuel in one reactor (the fuel reactor), thus avoiding direct contact between the fuel and the nitrogen in the air while also reducing the OC. The reduced OC is then oxidised in a second reactor (the air reactor) using oxygen from air [42,43,117]. The reduction of Me_aO_b (as oxygen carrier) to Me_gO_h with C_nH_{2m} within the fuel reactor, and the oxidation of Me_gO_h to Me_aO_b with oxygen from air within the air reactor are described as follows [118]:

In the Fuel Reactor:

$$C_nH_{2m}O_p+\left(\frac{m+2n-p}{b-ah/g}\right)Me_aO_b\rightarrow\left(\frac{m+2n-p}{b-ah/g}\right)\frac{a}{g}Me_gO_h+mH_2O+nCO_2 \quad \Delta H>0 \text{ or } \Delta H<0, \tag{4}$$

In the Air Reactor:

$$\left(\frac{m+2n-p}{b-ah/g}\right)\frac{a}{g}Me_gO_h+\left(\frac{m+2n-p}{2}\right)O_2\rightarrow\left(\frac{m+2n-p}{b-ah/g}\right)Me_aO_b \quad \Delta H<0\,. \tag{5}$$

Loop seals are currently the leading method employed to mitigate gas leakage between the air and fuel reactors during the cycling of the oxygen carriers between the reactors [42]. The oxygen carriers are typically in the form of particles and comprise an active metal oxide and an inert support. The inert support is typically used to increase the mechanical strength and reactivity of the OC particles in successive redox reactions [117].

The key driver for CLC technology is its strong potential to achieve low cost CO_2 capture. Indeed, it has been identified as a preferred approach from the four classes of carbon capture technologies of CLC, pre-combustion capture, post-combustion capture and oxy-fuel combustion [51,119,120]. Nevertheless, the use of a solid OC limits the operating temperature of the CLC systems to typically around 1000 °C to avoid softening, sintering or other damage to OC in successive redox reactions [42,121–123]. This is significantly lower than both the temperature that can be achieved through combustion of the fuels in conventional combustion systems and the operating temperature of the state-of-the-art in commercially available gas turbines, which is currently around 1250–1300 °C [104,124]. Hence, the use of CLC results in an exergy loss that lowers the maximum thermodynamic efficiency of the CLC-based power cycles relative to that which can be achieved with conventional natural gas combined cycles (NGCC) [125,126]. In contrast, this temperature is higher than the state-of-the-art in commercial solar thermal systems, which typically operate at temperatures of ~600 °C but are expected to reach temperatures of ~1000 °C in the near future [67]. That is, Hy-Sol-CLC can be classified as both solar-positive and combustion-positive", because the temperature range of CLC is compatible with solar thermal technology and also does not involve a compromise relative to the equivalent combustion technology with carbon capture.

Another synergistic element between CST and CLC is the inherent use of thermo-chemical storage in CLC systems [19,20]. More specifically, for those CLC systems in which the reduction reaction in the fuel reactor, Eq. (4) is endothermic (noting that exothermic reductions are also possible for some combinations of fuel and the metal oxide [118,127]), there is potential to supply the enthalpy of the OC reduction reaction with CST. That is, there is potential to use the same reactor to also provide chemical storage of solar energy [118]. Additional storage of solar thermal energy can be achieved using the thermal mass of the OCs to provide sensible storage. This stored energy can then be recovered from the oxidation of the reduced oxygen carriers (within the air reactor), which always employs an exothermic reaction (Eq. (5)) [118,127]. The stored energy can be used to either increase the output from the CLC-based power plant or decrease the specific fuel consumption [19,20]. Furthermore, integration of storage vessels for the OC particles to manage their circulation between the fuel and air reactors, as shown in Fig. 17, enables both the long-term storage of solar thermal energy and dispatchable/base-load power production [19,20]. That is, the two reactors in a CLC system (Fig. 17) offer potential for shared infrastructure in achieving thermochemical and sensible storage, and hence reduced costs, through a hybrid system while also achieving inherent carbon capture from the combustion component of the energy source [19,20,118].

The hybridising of CST with CLC technology offers potential to increase the exergetic efficiency relative to a solar-only process. This is because the use of a fuel as reducing agent within the fuel reactor enables the stored heat to be released at a higher temperature than the solar receiver through oxidation reaction within the air reactor [21,118]. This stands in stark contrast to all other thermal energy storage systems previously proposed to our knowledge, for which the storage process results in a significant reduction in temperature, and hence in exergetic efficiency [128,129]. The slight exception to this is the closely related thermochemical energy storage system proposed by Haseli et al. [90] and Jafarian et al. [93] for which changes to the partial pressure of oxygen in the gas phase is employed as the driving force for the reduction and oxidation of the metal oxide. Nevertheless, these processes are estimated to achieve a similar temperature for storage and release of solar thermal energy, while the Hy-Sol-CLC achieves a temperature increase in the oxidation reactor. It is also worth reiterating that, for a conventional solar-only plant, exergy losses are incurred both in the transfer of heat from the receiver to the storage vessel and in the subsequent transfer to the working fluid [67,128].

In summary, the potential advantages of Hy-Sol-CLC concept are as follows [18–20,130]:

- an increase in exergetic efficiency over a solar-only equivalent by adding the enthalpy from the fuel downstream from the solar receiver;
- inherent CO_2 capture which, to our knowledge, is one of the few solar-combustion hybrid technologies that achieves carbon capture;
- similar exergetic efficiency relative to the equivalent non-solar CLC technology with CO_2 capture;
- the sharing of infrastructure, in that the thermal storage system is also utilised for the CO_2 capture. This offers potential to lower cost over the stand-alone counterparts;
- firm supply through potential to revert to conventional CLC operation in the event of extended periods of low solar radiation [20];
- high energy density of the thermal storage relative to present sensible energy storage systems due to the use of both thermochemical and sensible energy [17].

Table 5 summarises the Hy-Sol-CLC systems that have been proposed to date. As can be seen, solar hybridization of CLC with CST was first proposed by Hong and Jin [18]. This Hy-Sol-CLC gas turbine cycle proposes to employ the concentrated solar radiation to provide heat to reduce NiO with CH_4 at a temperature of 530 °C, within the reduction reactor. This process advantageously converts the CST to chemical energy at a temperature of 530 °C, which is achievable with commercially available solar thermal technology. The stored heat is then released within the air reactor at a temperature of 1200 °C. However, this cycle does not provide any energy storage and is estimated to offer an instantaneous solar share of only 10–16%, during periods when the solar resource is available. Furthermore, the use of the pure NiO particles for the OC at temperatures of more than 1000 °C, as was proposed both for the cycles of Hong et al.'s [18,130] and of Jafarian et al.'s first cycle [19], is not realistic with present technology. When subjected to repeated reduction/oxidation at these conditions, both agglomeration and deactivation were observed [43]. Pure NiO particles also have a low reaction rate due to their low porosity [131,132].

More recently, Jafarian et al. [20] proposed a Hy-Sol-CLC gas turbine combined cycle (GTCC), in which the operating temperature of the solar fuel reactor is maintained constant by varying the flow rates of fuel and OC particles in response to the variations in the input of CST. The configuration of this Hy-Sol-CLC GTCC is shown in Fig. 18. The cycle comprises two main sections: (i) a hot gas generator and (ii) a combined cycle power generation plant. Concentrated solar thermal radiation from the solar collector field is proposed to be captured and stored within the solar fuel reactor of the hybrid-CLC section by the OC particles. The stored heat is then released in the air reactor at a higher temperature to produce a steady stream of hot gas. Two reservoirs are also proposed to store the OC particles. This provides a means with which to control the flow rate of OC particles to the air reactor despite variation in the solar energy input. A direct air-particle heat exchanger is also proposed to be added to the process between the air reactor and reservoir R_1 both to lower the temperature of the stored OC particles in reservoir R_2, which increases their thermal mass without reducing the oxidation reaction rate in the air reactor, and to preheat the input air to the air reactor. An after-burner was also proposed as an option with which to further heat the hot and pressurised outlet stream from the air reactor before its introduction to the gas turbine. However, this option requires additional fuel, so that the increase in power cycle efficiency comes at the trade-off of releasing some uncaptured CO_2 and lowering the solar share. Table 5 also shows that the estimated solar share of this Hy-Sol-CLC GTCC for the cases with and without the supplementary heating from the after-burner, is 41% and 60%, respectively, while the corresponding first law efficiencies are 44% and 35.4%. This efficiency includes the energy needed to capture and compress the CO_2 ready for reuse or storage. It can also be seen that the after-burner offers a trade-off between cycle efficiency and CO_2 capture.

8.1. Critical research challenges for the Hy-Sol-CLC

Notwithstanding the potential advantages of hybrids between CST and CLC, they are at a relatively early stage of development. Hence further research, development and demonstration is required if they are to be implemented. In particular, there is a critical need to develop further improved OC materials that are robust to a very large number of cycles without significant degradation. There is also a need to develop, or adapt, reduction reactors that convert the concentrated solar radiation to sensible and chemical energy with high efficiency at the desired temperature, since these hybrid cycles are yet to be demonstrated. Finally, further research in alternative power cycles is warranted to identify alternative reactions and/or configurations with even further potential than those proposed to date.

The vulnerability of the particles to breakage leads to serious challenges both in their efficient circulation between the reactors and in the application of the CLC to gas turbine combined cycles (GTCC), which are vulnerable to fine particles. Hence, arguably the biggest challenge to their commercial implementation is the need to develop OC materials that satisfy the multiple criteria of high oxidative capacity together with both physical stability and good kinetics over large number of redox reactions. This, in turn, implies the need for a large active surface area, such as can be obtained with high porosity. For the cases where the OC is to be circulated between interconnected fluidised beds, the requirement for mechanical robustness is even greater, while suitability for fluidisation is also required. In addition, the OC material employed in Hy-Sol-CLC need to react endothermically with the fuel (Eq. (4)), which imposes further restrictions on the material selection [118].

While no solar fuel reactor has been developed specifically for Hy-Sol-CLC process, there is potential to draw on those reactors that have been developed to heat particles for other processes, employing both direct and indirect in different processes [136–138]. This work has shown that it is desirable to employ direct heat transfer systems if possible, since these offer the potential advantages of high heat transfer and low exergy loss [137]. However, for the reactors proposed to date, this comes at the expense of relying on a windowed reactor, which have thus far proven to be vulnerable to particle deposition, thermal shock, high pressure and the need for effective sealing [87,136,139,140]. On the other hand, indirect heating systems offer more robust configurations at the expense of lower rates of heat transfer [3,138]. A suitable reactor for Hy-Sol-CLC will also need to avoid excessive radiative heating rates of the OC particles to avoid overheating and deactivation from melting, sintering or carbon deposition [141]. Hence the challenge of developing solar fuel reactors for the Hy-Sol-CLC process can benefit from, or contribute to, that of reactors for a number of similar solar chemical processes.

Table 5
Summary of the previously proposed Hy-Sol-CLC systems.

	Solar concentrator type	Power cycle type	Oxygen carrier	Temperature of reduction reactor (fuel reactor)	Temperature of hot gas generated	Solar share		First law efficiency	Exergy efficiency	Solar to electrical efficiency	Location
						Instant	Annually and hourly averaged				
Hong et al. [18]		Brayton	NiO	530 °C	1200 °C	10–16%		47%	57%		
Hong et al. [130]	Parabolic trough	Combined cycle	NiO	530 °C	1200 °C	18.6%			60%	30%	
Hong et al. [21]		Combined cycle	Fe_2O_3	200 °C	1400 °C	15.4%		59%	58.4%	22.3%	
Jafarian et al. [19]	Tower		NiO	708–1027 °C	1112 °C		6.5%				Port Augusta, South Australia [133]
Jafarian et al. [20]	Tower		$NiO/NiAl_2O_4$ [135]	750 °C	950 °C		60%				Port Augusta, South Australia [133]
Jafarian et al. [134]	Tower	Combined cycle	$NiO/NiAl_2O_4$ [135]	750 °C	With after burner 1250 °C		41%	50%	57%	40%	Port Augusta, South Australia [133]
					Without after burner 950 °C		60%	44%	55%	35%	Port Augusta, South Australia [133]

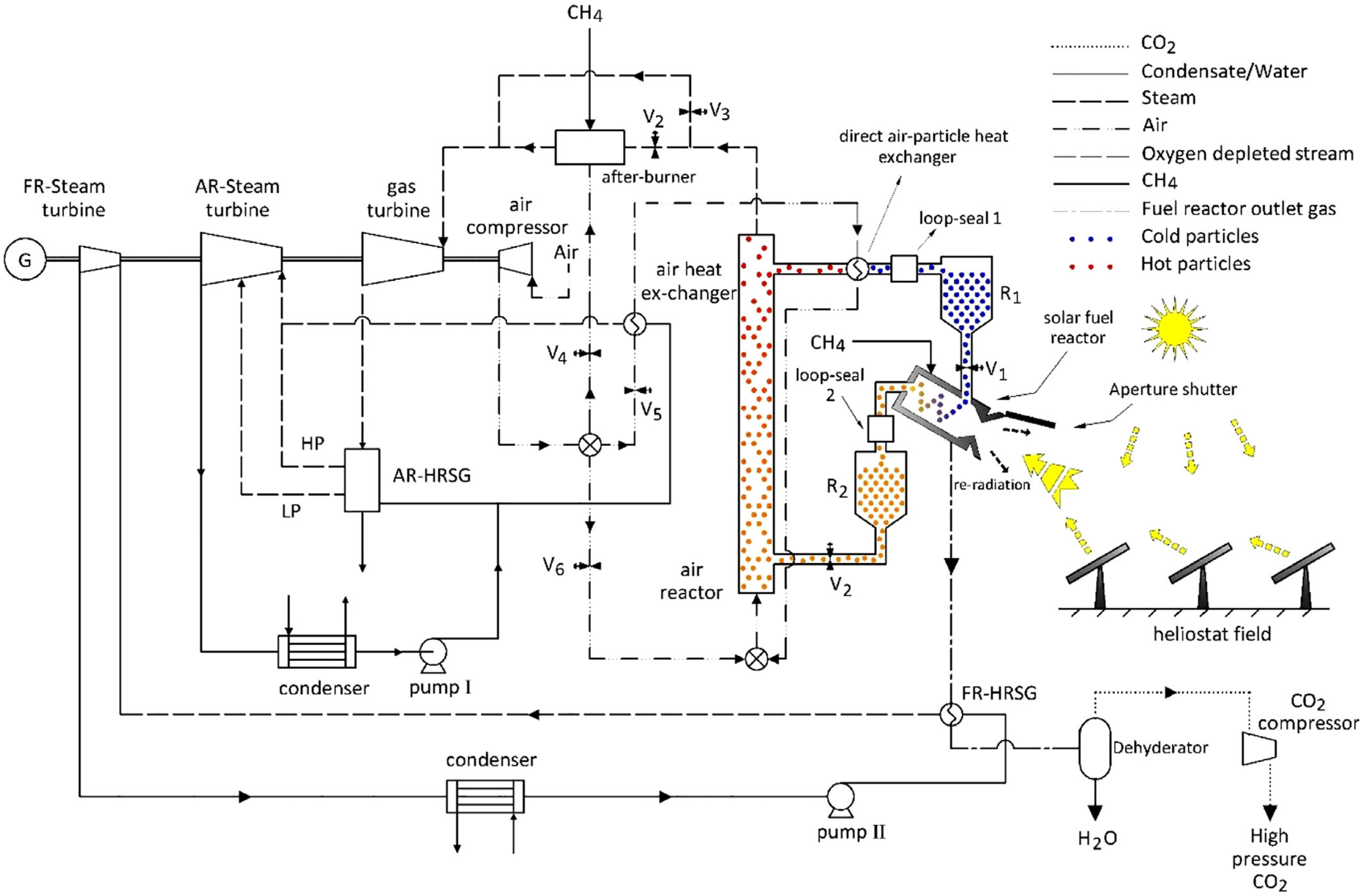


Fig. 18. A schematic diagram of hybrid solar-CLC combined cycle, modified from [134]. Reservoirs R_1 and R_2 are used to store the hot and cold particles, respectively. A direct air-particle heat exchager is proposed to also incoprorate sensible thermal storage. The hot and pressurised stream from the air reactor is used to generate power by means of a three-stage gas turbine. Additional heat is recovered with the heat recovery steam generators (AR-HRSG and FR-HRSG). An after-burner can optionally be used to increase the temperature to the gas turbine inlet using valves V_2 and V_3.

9. Comparison of technology options and scientific challenges

The overall potential of the various alternative types of hybrid technology that have been proposed to date is summarised in Table 6 and discussed in turn below

- **Solar feedwater preheating:** This technology has limited potential as a stand-alone technology, primarily because of its relatively low solar share of below 2% on an annually averaged basis reported to date, although this could be increased with the use of thermal storage. In addition TES is yet to be demonstrated with SAPG, to our knowledge. Furthermore, the potential for retro-fit of this technology to existing (mostly coal-fired) boilers is limited by the relatively few sites with sufficient solar resource, available land on which to accommodate a solar heliostat field and/or by the constraints of the existing turbine [66]. Hence the main potential of this option is likely to be either to augment the carbon-mitigation potential of a future plant designed with carbon capture or to augment a Hybrid-Solar Receiver Combustor. This latter option offers potential to offer power boosting and/or increased flexibility with the use of lower cost solar concentrators.
- **Direct integration of solar receiver and combustor:** Strong potential is anticipated for the direct integration of solar receivers and combustors, pending its demonstration at sufficient scale. This technology has potential to be compatible both with existing CSP technology and TES, offering firm supply at a greater efficiency than from a stand-alone combustion back-up. The technology also has potential to be made compatible with carbon capture during the combustion-only mode, and can also be used with low carbon fuels such as natural gas or syngas derived from biomass. However, since it is limited to cavity receivers, it is most likely to be applicable mostly to relatively high temperatures where cavities are desirable, such as greater than about 500 °C.

The challenges associated with the further development of this technology are:

a. Quantifying the impact of the different design and operating parameters on performance (i.e. efficiency and emissions) as a function of scale for all three modes, namely: solar only, combustion only and the mixed mode;
b. Developing effective strategies to mitigate convective losses through the aperture (e.g. with an aerodynamic curtain) to increase efficiency in the mixed mode;
c. Investigating burner designs that allow fuel flexibility and the use of alternative fuels;
d. Deeper understanding of the effect of concentrated solar radiation on the structure of, and emission from, turbulent flames in the HSRC;
e. Investigating the feasibility of utilizing the HSRC technology for combined heat and power.

- **Hybridising a gas-turbine with an after-burner:** Despite the relative ease with which an after burner can be used to boost

Table 6
Summary of the expected potential and research needs of the various alternative hybrid technologies under development, where TES is thermal energy storage and FWH is feed-water heater.

Hybrid type	Solar share		Extent of integration	Comparison with the best comb. options		Comparison with the best CST option	Stage of Development [144]	Potential for CO_2 neutral/negative	Comments
	Instant	Annual		Net η, LHV (%) CCGT – 57 [145] OCGT – 39 [146] CCGT+CCS – 48 [145]	CO_2 (kg/MWh) CCGT – 370 [145] OCGT – 600 [146] CCGT+CCS – 55 [145]				
Solar feed water preheater (power boosting mode)	1.0–11.5% [64]	0.5–2% [64] (could be increased with storage)	Semi-direct	20% lower η. re OCGT	At least 66% higher CO_2 emission re OCGT if coal as feedstock.	Lower cost re stand alone CST Rankine cycle [60]	Parabolic trough system is commercially available	Applicable to Rankine cycle with CCS	Limited retrofit potential, but could be used to boost other solar cycle.
HSRC	Up to 100% [22]	50–70% with 10 hours storage [22]	Direct	Similar η to OCGT	35% lower CO_2 emission re OCGT and 5% higher emission re CCGT	-Avoid start-up and shut-down losses [22]	TRL-4 (Technology validated in laboratory)	Nothing proposed to date	Limited to gaseous fuel; and
						-Reduced losses from trace-heating for storage			Requires cavity, i.e. high temperature applications
Solar pre-heat to gas turbine	29% [105]	Not reported.	Semi-direct		Lower CO_2 emission according to the solar share	Higher power cycle efficiency	TRL-6 [105]	Not available	No storage technology is available to date
Hy-Sol-CLC	60% [134]	60% [134]	Semi-direct	Similar η to OCGT (with after burner)	46% lower CO_2 emission re CCGT (with after burner)	-Higher η due to lower receiver losses	TRL-2 (Technology concept formulate)	Inherent	Requires a receiver and robust method for CLC implementation
				10% lower η re OCGT (without after burner)	68% lower CO2 emission re CCGT (with after burner)	-Avoids the exergy losses of solar energy storage			
Solar syngas (to be used in as a gas-turbine or combined cycle)	~23% for solar reforming of NG [88,147]	Not reported.	Indirect	Increase GT η by 20–25% [148]	Lower CO_2 emission for solar syngas with GT	Higher power cycle efficiency	TRL-6 for Solar reforming of NG [149]	Possible role in providing CO_2 neutral or negative if renewable carbonaceous feedstock is used	High cost of solar syngas
	~40% for solar gasification of wood [87]	Not reported.					TRL-4 for solar gasification [138]		

the temperature of air from a pressurised solar air heater, this approach appears to have relatively limited potential without a break-through. This is, in part, because the costs of TES are significantly increased by the need to store pressurised air and, in part, because gas turbines are poorly suited to carbon capture owing to the low concentration of CO_2 in the exhaust from a gas turbine. Furthermore, without storage, a relatively low solar share is anticipated. Hence, without a breakthrough, other options are likely to be more attractive.

- **Hybridising with chemical looping combustion:** The hybridisation of CST with Chemical Looping Combustion (Hy-Sol-CLC) has significant potential to make a contribution to a low-carbon energy sources on the proviso that the technical challenges associated with chemical looping (or redox) technology can be overcome. The value proposition for this hybrid relative to NGCC with carbon capture is the potential to achieve both a lower fuel consumption (and hence running costs) and a lower production of captured CO_2 for sequestration or re-use, relative to NGCC with carbon capture, which will also lower running costs. The development of new materials for the oxygen carrier offers potential to further increase this potential. A state-of-the-art NGCC with carbon capture has an efficiency of around 50% and produces approximately 0.395 kg CO_2/kWh [97], while a Hy-Sol-CLC GTCC (without an after burner) is estimated to achieve an efficiency of approximately 44% and to produce approximately 0.18 kg CO_2/kWh, which is around 45% of the CO_2 produced in NGCC with carbon capture [134]. Furthermore, relative to the equivalent solar-only technology, the Hy-Sol-CLC offers an increased exergetic efficiency because the fuel increases the temperature of the outlet gas relative to the solar reactor, which reduces radiation losses. It also offers a high solar share and capacity for firm supply. Nevertheless, to achieve this potential, significant technology development is required both for the solar receivers and for the oxygen carrier to enable the process to operate for many cycles of oxidation and reduction without significant degradation or attrition.
- **Hybridising through low carbon oxidants and fuels:** The potential to introduce solar oxygen into a combustion plant for oxy-fuel combustion technology can avoid approximately a decrease in the net efficiency of a power cycle by approximately ten percentage points, caused by the energy consumed in air separation units [142,143]. The potential use of solar syngas via solar gasification of solid carbonaceous feedstocks or solar steam reforming of natural gas in a Rankine cycle can reduce the net carbon intensity of the process due by increasing the heating value of the feedstock with CST by ~40% (or 23% for natural gas) [87,88,147]. Alternatively, the solar syngas can be utilised in a more efficient gas-turbine combined cycle.

10. Summary and conclusions

Hybrids are expected to play an increasingly important role in future power generation, both for centralised power plant and for combined heat and power. This is because combustion can play as an important complement to thermal energy storage in being able to accommodate both seasonal (i.e. long term) and weather-based (i.e. short term) variability in the solar resource. Hybridising combustion with CST upstream from the turbine offers the potential to avoid (or reduce) the need to turn-down the turbine, with the associated loss in efficiency. In the short-term, hybrids offer potential to reduce the amount of fossil fuel needed to provide firm supply, while in the longer term they offer potential to lower the cost of carbon-neutral cycles over their stand-alone counterparts.

While some hybrids systems are already commercially available, these are limited to "indirect" systems, which combine within one plant components developed for stand-alone operation. Nevertheless, even these existing systems demonstrate the potential to achieve firm supply with both a higher solar share and lower net CO_2 emissions than their stand-alone counterparts. They also offer potential to lower capital cost through the sharing of infrastructure and to increase efficiency through reduced heat losses arising from the use of fewer components, through improved cycle efficiency and reduced turn-down, and through reduced start-up and shut-down losses. The potential benefits of hybridisation are potentially even greater with "direct hybrids", which integrate the solar receiver and the combustor, the turbine, the cooling system, the thermal storage systems and/or the CO_2 capture system.

The two classes of CST-hybrids that are commercially available today are the use of CST to preheat the feedwater to a regenerative Rankine cycle, termed Solar Aided Power Generation, and the use of back-up boiler in a solar thermal Rankine cycle plant. The SAPG system is solar positive, in that it offers improved performance over a solar-only option because it displaces steam that is withdrawn at a higher temperature than the solar receiver. However, it has a relatively low annual solar share of 3–15% and can be applied only to a limited number of sites for a retrofit. Nevertheless, SAPG also has potential to be used upgrade other solar plants employing a regenerative Rankine cycle, although this is yet to be implemented to our knowledge. A conventional solar hybrid provides increased plant efficiency by reducing turn-down compared with a stand-alone solar plant, together with infrastructure sharing of the turbine and cooling cycle.

An emerging technology that is applicable (but not limited) to the Rankine cycle, is the hybrid solar receiver-combustor. This is a direct hybrid that has been estimated to offer up to 17% reduction in LCOE, together with a reduction in net fuel consumption by up to 40%, relative to an equivalent hybrid from stand-alone components through reduced capital cost and further reduced start-up and shut-down losses. This option is both solar-positive and combustion-positive for the case where the reference combustion process is an equivalent boiler, although it is combustion negative when compared with a gas-turbine combined cycle. The hybrids are also compatible with post-combustion carbon capture, although the economics of these options are yet to be evaluated to the best of our knowledge. Furthermore, while none of these options offer integrated CO_2 capture, they appear to be well suited to combined heat and power applications.

The hybrid between chemical looping combustion technology and solar thermal (Hy-Sol-CLC) has potential to be both solar positive and combustion positive for the case of hybrids with integrated CO_2 capture, although the technical feasibility is yet to be demonstrated. Its potential advantages, relative to both combustion-based peaking plant and to baseload combustion technologies with CO_2 capture, are as follows:

- **Similar efficiency to combustion process with CO_2 capture:** The turbine inlet temperature for a Hy-Sol-CLC process is similar to that of the CLC process, so that the base-load efficiency is the same. However, hybridising before the turbine avoids the need to turn down the turbine in response to the solar load, so that part-load operation is greater.
- **Integrated thermal energy storage:** this concept offers the potential for relatively low cost thermal energy storage because the same reactors required for the chemical looping process can be used to provide chemical (and sensible) storage of solar energy.
- **Greater efficiency than the equivalent solar-only process:** Because the solar energy is added to the reduction reactor, the temperature of the receiver is lower than the turbine inlet temperature. For this reason, the radiation losses from the receiver (which scale with the fourth power of the temperature difference between the receiver and ambient) are lower than for the

equivalent solar-only process. In addition, this process avoids the exergy losses of solar energy storage that are inherent in conventional solar only processes that follow from the temperature of the turbine being lower than that of the receiver;

Finally, while the potential benefits of hybridising concentrating solar thermal energy with combustion are significant, further research and technology development is required to harness their full potential. Critical among these research needs, which the present review aims to stimulate, are the following:

- New approaches and understanding are needed to mitigate losses from direct hybrids between CST and combustion, such as the mitigation of convective losses through the aperture for the hybrid solar receiver combustor during the mixed mode of operation.
- Development of a robust approach and understanding with which to implement chemical looping combustion, such as through use of robust oxygen carriers;
- Development of a reliable hybrid fuel reactor to enable the implementation of the reduction of the oxygen carrier with concentrated solar radiation.
- Development of alterative configurations of direct hybrids between concentrating solar thermal energy and combustion, such as those that can be suited for the heating of particles.
- Further identification of novel hybrid cycles and/or materials involving chemical looping, together with integration into low carbon cycles such as oxy-fuel combustion.

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