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Techno-economic evaluation of modular hybrid concentrating solar power systems

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This paper assesses the influence on techno-economic performance of modularising hybrid Concentrating Solar Power (CSP) systems with fossil fuel backup for both a Hybrid Solar Receiver Combustor (HSRC), which integrates a combustor into a solar cavity receiver, and a Solar Gas Hybrid (SGH) system with a similar cavity receiver and a back-up boiler. It was found that the energy losses in a system of small-sized modules, which employs molten salt as its Heat Transfer Fluid (HTF), are dominated by trace heating owing to the increased piping over their larger receiver counterpart. However, this can be reduced significantly by using alternative HTFs with a lower melting point such as sodium. In addition, for modularisation to be cost effective requires it to also enable access to alternative, lower-cost manufacturing methods. That is, the benefit of standard learning rates is insufficient to lower the Levelized Cost of Electricity (LCOE) on its own. For a plant with 30 units of 1 MW$_{th}$ modules the LCOE is competitive, relative to a single unit of 30 MW$_{th}$, after ~10 plants are installed if the modularised components (i.e. heliostats, receivers and towers) can be decreased by >80% and >40% for molten salt and sodium as the HTF, respectively.

1. Introduction

There is a growing interest in modular electrical power systems with distributed and off-grid power generation as a potential method to lower the cost of renewable electrical energy generation and thereby increase its penetration [1]. Smaller modules of solar power generation also tend to be particularly attractive for off-grid applications, where fossil fuelled systems lose the comparative advantage associated with economies of scale [1]. One of the renewable energy technologies under development is Concentrating Solar Power (CSP) technologies, which offer the comparative advantage of low cost energy storage, owing to the lower cost of thermal storage over electrical storage [2]. However, to provide a firm, continuous supply of electricity throughout the year, the size of storage becomes very large, with one study estimating up to 10 days capacity, even for sites with high average annual solar resource [3]. The cost of such large thermal storage capacities is expected to be prohibitive [4]. As a result, hybridization of solar thermal power systems with combustion is likely to offer a lower cost approach to maintaining supply, with the fuel coming from fossil resources in the short term and alternative low-net-CO$_2$ [5] in the longer term. However, little information is available of the economics of modular hybrid CSP systems.

One hybrid technology of interest is the Hybrid Solar Receiver Combustor (HSRC), recently proposed by Nathan et al. [6]. The HSRC concept is based on combining the functions of a solar-only cavity receiver and a combustor into a single component. This integration was found for a single tower system to reduce the overall LCOE relative to its nearest equivalent system, the Solar Gas Hybrid (SGH), by up to 17% depending on the price of fuel, for a 100 MW$_{th}$ receiver size [7]. This estimate was based on an analytical model of heat transfer with energy balance equations [8,9], together with a piecewise-continuous (i.e. pseudo-dynamic) model that accounts for solar variability on performance [7]. Lim et al. also found that of the HSRC reduces the net fuel consumption relative to the SGH by 12%–31% depending on the size of thermal storage capacity, predominantly due to the HSRC avoiding the start-up and shut-down losses of the backup boiler for the SGH [7,10]. Since this technology is particularly robust and can potentially be configured in different sizes [11], it is of interest to analyse the techno-economic implications of modularising the HSRC system relative to its equivalent SGH. Hence, this paper aims to estimate the LCOE

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Nomenclature

$\dot{Q}$	heat transfer rate (W)
$\dot{W}$	work rate = power output (W)

Greek Symbols

ε	experience parameter

Abbreviations

CSP	Concentrating Solar Power
EPGS	Electrical Power Generating System
HSRC	Hybrid Solar Receiver Combustor
HTF	Heat Transfer Fluid
IEA	International Energy Agency
LCOE	Levelized Cost of Electricity
SG	Steam Generator
SGH	Solar Gas Hybrid

Subscripts

air	air from surrounding
ap	aperture
boil	boiler
cap	capacity
comb	combustion air
conv	conventional
crit	critical or threshold value
cum	cumulative
decom	decommissioning
dump	dumped
elec	electric al
exh	exhaust
gas	hot gases from combustion
gen	generator
helio	heliostat
int	internal
invest	investment
mat	material
max	maximum
min	minimum
mod	modular
Na	liquid sodium
noz	nozzle opening losses
rec	solar receiver
salt	molten salt
sec	secondary air
sol	solar
stm	steam
sto	storage
t	time (years)
th	thermal output
trace	trace heating
use	useful
wall	wall losses

of several modular units of the HSRC as compared with a single unit of the HSRC for the same power block size comparing these systems to their equivalent counterparts.

Modular systems are being introduced in power generation technologies including wind turbines, solar PV, CSP [1,12] and nuclear reactors [13,14]. This is driven by the potential to lower the cost by mass production of standardized components of much smaller scale. Other advantages are claimed with the use of lower-cost materials [15], which offers the potential for additional options to identify the economic optimum in LCOE. The complexity and technical challenges of construction are also lower for smaller/modular CSP systems [16]. In addition, for a large power plant with multiple modules, there is no need to shut down the entire plant in the event where there is a problem with one of the modules. This provides greater flexibility when operating a power plant. Another potential advantage is that the power station can be constructed in stages, therefore allowing cash-flow to be generated in stages [17]. Nevertheless, these potential advantages must be compared against the disadvantages that include an increase in operations and maintenance (O&M) costs, an increase in the number of components, and an increase in the thermal and parasitic losses due to an increase in surface area to volume ratio associated with reduced thermal scale of the components. However, to our knowledge, no assessment of the direct economic merit of modularisation of hybrid CSP plants has been reported. Therefore, the paper aims to evaluate the trade-off between the aforementioned pros and cons for modular hybrid CSP systems.

In light of the discussion above, the first aim of the present investigation is to extend the pseudo-dynamic model of the HSRC and SGH developed previously for the evaluation of modules of different sizes. The next aim is to estimate the dominant losses associated with both types of modular hybrid CSP systems. The third aim is to assess the economic trade-off between these losses and lower manufacturing costs due to improved learning/cheaper materials for both modular HSRC and SGH systems.

2. Methodology

The pseudo-dynamic model of Lim et al. [7], written in Matlab, was extended to assess the modularisation of selected components in the HSRC and SGH systems. The same model, which calculates the pseudo-dynamic performance of each system by assuming steady-state operation at each time-step from a time-series of hourly Direct Normal Irradiation data, was revised to incorporate multiple modularised components in both systems. This model has been previously verified to show that the dynamic response of the system to various time-series is consistent with expectation [7].

2.1. Site selection

The pseudo-dynamic model uses data from the National Solar Radiation Database and Bureau of Meteorology at selected sites from the USA and Australia respectively for the year 2000–2004. In particular, the sites selected are Daggett (34.85 N 116.8 W, USA), Prescott Love Field (34.65 N 112.42 W, USA), Darwin (12.45 S 130.83 E, AUS) and Mildura (34.18 S 142.15 E, AUS) because of their have high average annual solar radiation [3]. Of these sites, Daggett has the lowest vulnerability to unscheduled reduction in output due to the variability in solar resource. Hence, this site was selected as a reference case for all of the calculations performed in this paper.

2.2. System components for modularisation

Figs. 1 and 2 present schematic diagrams of the modules of heliostat field and receiver that are combined to power a central