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Hybridisation of solar and geothermal energy in both subcritical and supercritical Organic Rankine Cycles

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ABSTRACT

A supercritical Organic Rankine Cycle (ORC) is renowned for higher conversion efficiency than the conventional ORC due to a better thermal match (i.e. reduced irreversibility) presented in the heat exchanger unit. This improved thermal match is a result of the obscured liquid-to-vapor boundary of the organic working fluid at supercritical states. Stand-alone solar thermal power generation and stand-alone geothermal power generation using a supercritical ORC have been widely investigated. However, the power generation capability of a single supercritical ORC using combined solar and geothermal energy has not been examined. This paper thus investigates the hybridisation of solar and geothermal energy in a supercritical ORC to explore the benefit from the potential synergies of such a hybrid platform. Its performances were also compared with those of a subcritical hybrid plant, stand-alone solar and geothermal plants. All simulations and modelling of the power cycles were carried out using process simulation package Aspen HYSYS. The performances of the hybrid plant were then assessed using technical analysis, economic analysis, and the figure of merit analysis. The results of the technical analysis show that thermodynamically, the hybrid plant using a supercritical ORC outperforms the hybrid plant using a subcritical ORC if at least 66% of its exergy input is met by solar energy (i.e. a solar exergy fraction of >66%), namely producing 4–17% more electricity using the same energy resources. Exergy analysis shows that with a solar exergy fraction of more than 66% the exergetic efficiency of the hybrid plant is about 27–34% for the supercritical hybrid plant and 23–32% for the subcritical hybrid plant. The figure of merit analysis indicates that the hybrid plant produces a maximum of 15% (using a subcritical ORC) and 19% (using a supercritical ORC) more annual electricity than the two stand-alone plants. Economically, the hybrid plant using the supercritical ORC has a solar-to-electricity cost of approximately 1.5–3.3% less than those of the subcritical scenario.

1. Introduction

The world economy, fuelled by conventional energy resources such as fossil fuels, has come to a transition point where renewable energy starts to play an increasingly important role. Large-scale utilisation of renewable energy resources, such as solar and geothermal energy, is greatly promoted to cope with the environmental concerns (e.g. global warming) resulting from the use of fossil fuels [1]. A great number of solar thermal power plants and geothermal power plants have been built throughout of the world. However, current investigations of these renewable energy systems have highlighted the high cost of generating electricity using stand-alone renewable power plants [2–6], and indeed suggest that one of the most effective approaches to reduce the cost of electricity generation and improve plant efficiency is the hybridisation of different renewable technology platforms [7–10].

Solar and geothermal energy resources are of particular interest in Australia for hybridisation due to their wide availability and enormous reserves. It is estimated that about 1% of the geothermal energy reserved between 3 km and 5 km in depth could provide for about 26,000 times Australia's annual power usage [11]. The annual solar radiation falling on Australia, on the other hand, is about 10,000 times Australia's annual energy consumption [12].

Specifically, the hybridisation of solar and geothermal energy in a supercritical air-cooled Organic Rankine Cycle (ORC) is of particular interest in this paper. Such hybridisation is expected to greatly improve the utilisation of finite geothermal resources in a specified region. For example, for non-conventional geothermal resources (e.g. Hot Dry Rock resources) and low-enthalpy hydrothermal

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Nomenclature

Variables

A_{solar}	solar aperture area (m^2)
E_{geo}	the exergy of geothermal reservoir (kW)
E_{in}	total exergy input of the hybrid solar–geothermal power plant (kW)
ER_{solar}	solar exergy ratio
E_{solar}	the exergy of solar radiation (kW)
F_{annual}	annualised figure of merit
h_{IW}, h_{PW}	the fluid enthalpies of the injection well and production well, respectively
h_0	the enthalpy of the energy resource evaluated at the same temperature and pressure of the environment
h_{out},h_{in}	the enthalpy of the outlet and inlet streams, respectively
I	effective solar beam irradiance of the collectors (W/m^2)
IAM	incident angle modifier
L	total length of solar collectors (m)
m_{wf}	working fluid mass flow rate
m_{geo}	mass flow rate of geothermal fluid (kg/s)
Q	the net heat exchanged between the system and the environment
$Q_{collector}$	useful heat received by solar collectors (kW)
Q_{geo}	raw geothermal heat input (kW)
Q_{in}, Q_{out}	total heat input and heat rejection of the hybrid solar–geothermal power plant, respectively (kW)
Q_{loss}	heat losses of the HCEs per unit length (W/m)
$Q_{loss,piping}$	solar piping heat losses (W)
$Q_{loss,\ total}$	total heat losses in the HCEs (W)
$Q_{net,\ solar}$	the net solar heat input contribution to the hybrid power cycle
Q_{solar}	raw solar heat input (kW)
R_{solar}	solar energy fraction
S_{PW}	the entropy of the brine in the production well
s_0	the entropy of the energy resource evaluated at the same temperature and pressure of the environment
T_{solar}	the blackbody temperature of the sun (°C)
ΔT	temperature gradient between the ambient temperature and the solar heat transfer fluid temperature (°C)
T_{in}, T_{out}	solar loop inlet and outlet temperatures (°C)
T_0	air temperature (°C)
W	the total work done by the system on the environment (negative) or the work gain by the system from the environment (positive)
W_{drive}	power required to drive the collectors and electronics
$W_{geo\text{-}only}$	net electrical power output of the geothermal-only power plant
W_{hybrid}	net electrical power output of the hybrid plant
$W_{hybrid,\ annual}$	the annual electricity generation of the hybrid plant
W_{net}	net power output of the hybrid plant (cycle based)
$W_{net,elec}$	net electrical power output of the hybrid plant (plant based)
$W_{pump,\ solar}$	power consumption of the solar pump
$W_{stand\text{-}alone\ solar,\ annual}$, $W_{stand\text{-}alone\ geo,\ annual}$	the annual electricity generation of the stand-alone solar and geothermal plants, respectively
W_T, W_P, W_o	work of turbine, work of pump, work of air cooler, and the total electrical parasitic load in the solar field, respectively (kW)
W_{unit}	power output per unit mass flow rate of brine
$\Delta W_{net,elec}$	net boosted power output contributed by solar energy

Greek symbols

$\eta_{1st,plant}$, $\eta_{2nd,\ plant}$	the first- and second-law thermal efficiency of the hybrid power plant, respectively
$\eta_{optical}$	optical efficiency of solar collectors
η_{solar}	solar conversion factor
$\eta_{u,solar}$	solar utilisation efficiency
θ	the incidence angle of solar radiation

resources, the cost of electricity is usually high due to the low efficiency of the power plant. A higher energy utilisation rate is possible if higher grade forms of energy (e.g. solar energy) are incorporated into the system, thereby, uplifting the thermal efficiency.

Moreover, the stand-alone geothermal plant, especially in arid regions such as central Australia, faces many challenges. One of them is the ineffective cooling issue associated with the air-cooled condenser unit in the geothermal plant due to a high ambient air temperature. Previous research [13,14] has shown that this issue can be alleviated if geothermal and solar energies are effectively hybridised through an air-cooled subcritical ORC. Another benefit of hybridising geothermal and solar power is to decelerate the depletion of the heat content of geothermal reservoirs overtime and hence, extending the geothermal reservoir's lifespan.

The idea of hybrid solar–geothermal power generation has been studied extensively over the past few decades. A range of different hybrid configurations were investigated including:

- Solar Superheating Configuration – where solar energy is mainly used to superheat the working fluid of the geothermal power cycle [6,9,10,15–20].
- Solar Preheating Configuration – where solar energy is used to preheat the brine either by increasing the brine temperature or its dryness fraction (i.e. the steam quality) [8,9,17,18,21–25].
- Geothermal Preheating Configuration – where geothermal energy is used to preheat the feedwater in a steam Rankine cycle type solar thermal power plant [7].

Specifically, Mathur [7] examined a number of potential solar–geothermal hybrid configurations based on a binary cycle arrangement. He demonstrated that solar heating provides the geothermal plant with a higher steam quality which is a thermodynamic advantage over the stand alone system, and also enables the hybrid plant to make a more efficient use of the low to medium grade geothermal resources. Lentz et al. [23,24] discussed a hybrid solar–geothermal system which can increase the steam quality and power production of the geothermal plant by introducing a parabolic solar trough system. Lentz and Almanza [23,24] however, did not consider a binary cycle arrangement for the geothermal component of their proposed solar–geothermal plant. Problems associated with not using a binary arrangement can be quite serious within the context of hybrid solar–geothermal power plants. For example, the direct contact between high temperature