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Performance analysis of a near zero CO_2 emission solar hybrid power generation system

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HIGHLIGHTS

- A novel solar hybrid power system with near zero CO_2 emission has been proposed.
- The system integrates fuel reforming, solar-driven steam generation and CO_2 capture.
- Solar heat upgrading and high-efficiency heat-to-power conversion are achieved.
- The system accomplishes near zero CO_2 emission with oxy-fuel combustion.
- The system thermodynamic performances have been investigated and compared.

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ABSTRACT

A novel solar hybrid power generation system with near zero CO_2 emission (ZE-SOLRGT) has been proposed in the previous work, which is based on a GRAZ-like cycle integrating methane–steam reforming, solar-driven steam generation and CO_2 capture. Solar heat assistance increases power output and reduces fossil fuel consumption. Besides near zero CO_2 emission with oxy-fuel combustion and cascade recuperation of turbine exhaust heat, the system is featured with indirect upgrading of low-mid temperature solar heat and its high efficiency heat-to-power conversion.

A performance analysis of ZE-SOLRGT cycle has been carried out using ASPEN PLUS code to explore the effects of key parameters on system performances. It is concluded that ~54% exergy efficiency can be attained with ~100% CO_2 capture. The net solar-to-electricity efficiency can reach up to 34.7% in the base case. Steam-to-methane molar ratio of 2–3 is suitable for system performance improvement. High system efficiency can be obtained as the HPT pressure ratio is in the range of 15–18. The system integration achieves the complementary utilization of fossil fuel and solar heat, as well as their high-efficiency conversion into electricity.

1. Introduction

Solar thermal power generation is considered an efficient way to use concentrated solar radiation. However, due to its relatively low intensity, intermittent availability and uneven distribution of solar radiation, solar thermal power generation which uses solar energy as the exclusive or main input is generally costly and with low efficiencies. Therefore it is strategically desirable to develop hybrid solar/fossil processes and systems which use multiple heat sources at different temperature levels, for example in a way that low/mid-temperature solar thermal energy are used when they are relatively inexpensive, and higher temperature fossil fuel energy resources are integrated according to their cost to raise the energy efficiency. Hybrid system offers a solution for saving depletable fossil fuel and increasing the solar heat-to-power conversion efficiency simultaneously.

An earlier such hybrid system was proposed by Lior and coworkers [1,2], named SSPRE (solar steam powered Rankine Engine). Solar heat about ~100 °C collected by low-cost flat-plate solar collector provides the latent heat of steam generation and accounts for nearly 80% of the total system input, and fossil fuel is added to boost the steam temperature up to 600 °C for a higher efficiency (18%) power generation in a Rankine power cycle. The solar thermal aided power generation (SAPG) proposed by Hu et al. uses solar heat to replace some bleed steam in the regenerative Rankine power cycle for feedwater heating, attaining either additional power generation or reduced fuel consumption [3]. Besides its application in Rankine power systems, solar heat integration has also been introduced to gas turbine system and

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Nomenclature

C_p	specific heat (kJ/kg K)
DNI	direct solar radiation (W/m^2)
E	exergy (MW)
m	mass flow rate (kg/s)
NG	natural gas
Q_f	fuel low heating value input (MW)
Q_{sol}	absorbed solar heat (MW)
Q_{rad}	solar energy irradiated to solar field (MW)
SF	split fraction
SR_f	fossil fuel saving ratio
T	temperature (K)
t	temperature (°C)
TIT	turbine inlet temperature (°C)
VF	vapor fraction
W_{net}	net power output (MW)
X_s	steam-to-carbon molar ratio
X_{sol}	solar thermal share
ε	blade cooling efficiency (%)
η_{col}	solar collector efficiency (%)
η_e	exergy efficiency (%)
η_{th}	thermal efficiency (%)
η_{sol}	net solar-to-electricity efficiency (%)
π	pressure ratio

Subscript

a	ambient state
b	turbine blade
c	cooling, coolant
col	solar collector
e	exergy
f	fossil fuel
g	gas
net	net value
rad	radiation
ref	reference system
sol	absorbed solar heat
th	thermal

combined cycle power systems. Depending on its temperature level, solar thermal energy into combined cycle systems can principally be integrated with either the gas turbine topping cycle (for air preheating prior to the combustor) or into the steam turbine bottoming cycle (for steam generation) [4–7]. Based on the solar aided steam generation with parabolic trough technology, the integrated solar combined cycle systems (ISCCS) were proposed and demonstrated with different projects in Egypt, Iran, Germany and many other countries. It was concluded that solar hybridization in combined cycle systems has a high potential for cost reduction as compared with other solar hybrid power systems [4,7].

Besides solar thermal conversion, another technical option exists which converts the collected solar heat into chemical energy in an endothermic process using fossil fuels as chemical reactants and solar energy as the source or process heat [8–10]. The absorbed solar heat is stored chemically as the incremental heating value of the produced solar fuel, and will further covert into electricity when the solar fuel is used in advanced power systems. Solar thermochemical power generation system is thus composed of solar fuel production and power generation sectors, and methanol and methane are the commonly used fossil fuel for the solar thermochemical power generation.

Methanol–steam reforming and methanol decomposition can achieve over 90% conversion into H_2-rich syngas at around 250 °C. Hong, Jin and co-workers proposed a combined cycle system that integrates mid-temperature solar heat driven methanol decomposition [11]. Via heating the endothermic decomposition reaction, solar thermal energy is upgraded to chemical energy of the produced syngas. The net solar-to-electricity efficiency can reach 35% with the solar thermal share of 18%, and the CO_2 emission is 310 g/kW h without regard for turbine blade cooling requirements and CO_2 capture. The same authors also proposed a solar hybrid combined cycle system integrating methanol-fuel chemical-looping combustion and low temperature solar thermal energy [12], in which Solar-driven endothermic reduction of Fe_2O_3 by methanol is carried out. The CO_2 can be easily separated from vapor by condensation, with no extra energy penalty.

Methane steam reforming is highly endothermic, and higher temperature favors methane conversion. Tamme et al. proposed and analyzed a high temperature solar methane reforming process (>1000 °C) and power generation with the produced solar fuel in a combined cycle system. [13]. Compared with a conventional gas–steam combined cycle system, the introduced solar heat may substitute about 30% fossil fuel and lead to equal percent CO_2 emission reduction.

To avoid the high cost and low collector efficiency associated with the high temperature solar heat collection, and to enable low/mid-temperature solar heat (below ~400 °C) to achieve its high-efficiency heat-power conversion, Zhang and co-workers proposed a solar-assisted chemically recuperated gas turbine system (SOLRGT) with solar heat indirect upgrading [14–16]. Rather than driving the endothermic reforming reaction directly, the solar thermal energy collected at ~220 °C is used for steam generation and thus first transformed into the latent heat of vapor supplied to a reformer, and then via the reforming reactions to the produced syngas chemical exergy. This is a two-step conversion, a combination of thermal integration and thermo-chemical conversion process. The resulting syngas is burned to provide high temperature working fluid to a gas turbine. The solar-driven steam production helps to improve both the chemical and thermal recuperation of the system. Researching result shows that overall exergy efficiency could be about 5.6%-points higher than a compared intercooled chemically recuperated gas turbine cycle (IC-CRGT) without solar assistance. Since 80% of the total energy input is provided by methane, 342.7 g/kW h CO_2 emission still reaches. In order to reduce CO_2 emission, the authors proposed a low CO_2 emission hybrid solar combined cycle (LEHSOLCC) power system [17] with solar-driven methane–steam membrane reforming and pre-combustion decarbonization. With 91% CO_2 capture ratio, the system attains a net exergy efficiency of 58% at design point. The solar driven membrane reformer calls for further R&D efforts.

Based on the combination of oxy-fuel combustion and the concept of SOLRGT cycle, an improved system configuration with CO_2 capture (named ZE-SOLRGT) was proposed in [16], which employs water as the main working fluid. It is a solar assisted oxy-fuel combustion system, integrating with solar-driven steam generation, steam reforming of methane and CO_2 capture. The power subsystem configured is similar as a Graz-like cycle [18–20] to benefit from the combination of a high temperature Brayton topping cycle with a high-pressure ratio Rankine like bottoming cycle. As compared with other solar hybrid power plant concepts including steam Rankine power systems or integrated solar combined cycle systems (ISCCS), the ZE-SOLRGT system offers the significant advantage of high conversion efficiency of mid-temperature solar