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Development of an integrated hybrid solar thermal power system with thermoelectric generator for desalination and power production

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HIGHLIGHTS

- An integrated desalination system is developed.
- A thermoelectric unit is incorporated into the integrated system.
- An efficiency assessment of the integrated system is performed through energy and exergy efficiencies.
- A parametric study is undertaken to investigate how operating conditions affect the system performance.

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ABSTRACT

In this study, an integrated system for desalinated water and electricity production is developed and thermodynamically analyzed. The proposed system consists of a solar-natural gas hybrid power plant, thermoelectric generator (TEG), Rankine cycle to produce electricity and flash distillation unit to produce fresh water. The proposed electricity-fresh water co-generation plant uses solar driven volumetric pressurized air receivers as main power supply and uses natural gas to compensate power when the direct normal irradiance is below 900 W/m^2. Thermoelectric materials are used to generate electricity from waste heat of gas turbine. Flash distillation unit is used to produce fresh water from seawater by the waste heat of Rankine cycle. All thermodynamic quantities, such as energy and exergy efficiencies, exergy destructions are calculated for all system components. The combustion reaction is modelled on ASPEN Plus software package. TEG unit is modelled on COMSOL Multiphysics software package, and the rest of the elements of the system are analyzed in the Engineering Equation Solver (EES). The overall exergy and energy efficiencies of the system are determined to be 54.9% and 44.5% respectively where the total energy input comes 50% from solar system and 50% from natural gas. The results show that TEG unit can generate power more than 32 kW by using the waste heat. The present results indicate that it is possible to produce 3.36 kg/s of fresh water from proposed system. Furthermore, the effects of direct normal irradiance level, ambient wind speed, seawater temperature, various cool side cooling options for the thermoelectric generator on the system performance are investigated.

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1. Introduction

The purpose of using renewable energies is mainly reducing carbon emissions in the world. CO_2 emissions are expected to cause a very vital problem in the world as the growth rate of the population and quality of life continue rising [1]. The most significant benefit of solar energy, when it is compared with other energy sources, is that it is clean and can be provided without any ecological pollution. Fossil fuels have supplied most of the world's energy demand over the past century. As they are less inexpensive and more useful than energy from alternative energy sources, they are more preferable. By the development of solar power systems, it is possible to operate a gas turbine with direct normal heating of pressurized air.

In 2005, the European Commission [1] published their final report on SOLGATE project. In their project, a volumetric solar receiver is developed to heat up the pressurized air to 1000 °C. Hot pressurized air provides energy to gas turbine. Peng et al. [2] proposed a solar tower thermal power system integrating the intercooled gas turbine top cycle and the Kalina bottoming cycle. Solar part of the proposed system is using pressurized air receivers as in SOLGATE project. Consequently, the highest solar-to-electric efficiency of the suggested system is obtained 27.5% at a gas turbine inlet temperature of 1000 °C.

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Nomenclature

Cp	Specific heat at constant pressure (kJ/K)
DNI	Direct normal irradiance (W/m^2)
$\dot{E}x$	Exergy rate (kW)
ex	Specific exergy (kJ/kg)
h	Specific enthalpy (kJ/kg)
k	Thermal conductivity (W/m K)
LHV	Lower heating value (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
$\dot{Q}$	Heat rate (kW)
s	Specific entropy (kJ/kg K)
S	Seebeck Coefficient (V/K)
T	Temperature (K)
X	Salinity (ppm)
$\dot{W}$	Work rate (kW)

Greek letters

η_{en}	Energy efficiency
η_{ex}	Exergy efficiency
σ	Electrical conductivity (S/m)
σ_{SB}	Stefan Boltzmann constant ($5.76\ 10^{-8}$ $W/m^2\ K^4$)
E	Surface emissivity

Subscripts and superscripts

b	Brine water
cw	Cooling seawater
C	Compressor
CC	Combustion chamber
Ch	Chemical
d	Destruction
de	Desalinated water
f	Intake seawater
field	Heliostat field
GT	Gas turbine
HEX	Heat Exchanger
i	State number
In	Inlet of a component
n	n-type thermoelectric material
NG	Natural Gas
Out	Outlet of a component
ov	Overall
P	Pump
p	p-Type thermoelectric material
Ph	Physical
Sys	System
ST	Steam turbine
T	Turbine
ZT	Dimensionless figure of merit
0	Ambient condition
1, 2, … i	State points

Acronyms

C	Compressor
CO_2	Carbon dioxide
EES	Engineering Equation Solver
FDU	Flash Distillation Unit
HEX	Heat exchanger
N	Total number
PR	Performance Ratio
TEG	Thermoelectric generator

Meriche et al. [3] proposed a hybrid solar tower power plant using pressurized air receiver and investigate it with and without the presence of regenerator. The suggested power plant has 27% and 33% overall thermal efficiency with and without the presence of regenerator, respectively.

Thermoelectric materials are semiconductor materials, which can convert heat to electricity by Seebeck effect and vice versa. As thermoelectric generators do not have any moving parts, they are easy to operate and have low maintenance cost. Hence utilization of these systems is a reasonable method to generate clean energy. However, thermoelectric generators have low thermal efficiencies [4]. As a result of this situation, they are mostly used for waste heat management applications. Orr et al. [5] made an experimental work for waste heat recovery from exhaust gases of a car by using thermoelectric cells. The temperature difference between hot and cold sides of the thermoelectric cells was maintained by heat pipes in the proposed system. As a result of their study, the maximum power which the cells can produce was 6.03 W with 1.43% efficiency. Omer and Infield [6] proposed a two-stage parabolic concentrator and thermoelectric materials be attached on absorber plates to use waste heat. Sahin et al. [7] also made a similar study by investigating the performance of a conventional solar concentration power plant with and without the presence of thermoelectric devices. In the suggested system, thermoelectric devices are installed on heat collector element. As a result, the thermal efficiency of the system with thermoelectric devices is calculated slightly higher than the same system without the thermoelectric generators. Thermoelectric generators are also used to recover the waste heat of gas turbines. Francis et al. [8] proposed a gas turbine system in which the efficiency was increased by 10% with the presence of thermoelectric generator.

Desalination is a technology to get rid of dissolved solids and ions from briny water, seawater, or industrial wastewater. The purpose is to produce clean water from seawater or brackish water or recover polluted water in an engineering process [9]. Desalination technologies can be categorized as the membrane-based and thermal-based separation processes. Reverse osmosis (RO), multi-stage flash (MSF), and multi-effect distillation (MED) are the core technologies for commercial-scale [9]. Khalid et al. [10] made a comparative assessment of two systems for nuclear desalination. The systems use Reverse Osmosis (RO) for desalination and are coupled with either a CANDU 6 nuclear reactor or a Sodium-cooled Fast Reactor (SFR). As a result of the study, the co-generation exergy efficiency and RO process exergy efficiency of the CANDU 6-based system are obtained higher than the SFR-based system. Cardona et al. [11] proposed an integrated system for the desalination of the seawater. In the proposed system, reverse osmosis and multistage flash distillation units connected in series. As a result of the study, the proposed plant provides cost reduction for the fresh water, when it is compared to the equivalent systems in parallel. Hawlader et al. [12] proposed and built a system with a single effect desalination unit. The desalination unit is connected to a solar assisted heat pump. They investigated the effects of feed seawater temperature and flashing. As a result, the maximum performance ratio of the desalination unit is obtained 1.15.

Seawater desalination plants with solar thermal power are considered a clean way to produce fresh water from seawater. There are various applications in this area such as solar energy multi-stage flash systems (MSF), solar energy MED systems, solar energy compressing distillation systems, etc. For example, a solar energy driven multi-stage flash desalination system was constructed in Kuwait with a 7000-liter reservoir and a 220 m groove-shaped parabolic heat collector and a capacity of 10 t of fresh water per day [13]. Ortega-Delgado [14] made a thermo-economic analysis of electricity and water cogenerative Solar Thermal Power Plant (STPP) of 5 MW. Their system is equipped with parabolic trough mirrors and Direct Steam Generation (DSG). They compared two distillation technologies which were Multi-Effect Distillation (MED) and Reverse Osmosis (RO) to find the best arrangement of integration with the STPP. An average daily operation of the

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