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Development and assessment of a novel solar heliostat-based multigeneration system

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ABSTRACT

In this paper, a comprehensive study on thermodynamic analysis and assessment, through energy and exergy approaches, is conducted for a multigenerational solar based integrated energy system. The system proposed in this study is based on heliostat solar system integrated with steam turbine. The system is also integrated with seawater reverse osmosis desalination unit and absorption cooling system. The desalination unit operates with energy recovery through the utilization of Pelton turbine. The system produces cooling, heating, fresh water and hydrogen through electrolysis. It is furthermore designed to cover the demand of 4 MW electric power with the production of 1.25 kg/h of hydrogen and 90 kg/s of fresh water. The system advisor model software is applied on a case study for the solar heliostat optimization analysis.

Introduction

For remote areas and new communities built in desert areas and new costal extensions, the renewable energy based systems with energy storage technology is the most inspiring option to be utilized. There are limitations of using the regular Diesel generators for such applications. The nature of remote areas increases the difficulties and expenses of fuel supply. Batteries are commonly used for storing energy for certain application in remote areas; however, they are not a sustainable alternative as they lose 1–5% of the energy content every hour. They can be only used for short periods of time [1]. Hydrogen based systems are a great alternative. There are wide variety of hydrogen based technologies that can be used for electric power production for remote areas. On-site solar based produced hydrogen can be used to fuel heat engines coupled with electric power generators [2]. Some modifications can be done to the regular fossil fuel internal combustion engines run on hydrogen [3]. Hydrogen fueled gas turbine is considered another alternative [4]. Hydrogen fuel cell technology is the most recent competent in the field. It can be integrated with solar photovoltaic to be used as load-leveling electric system when photovoltaic system is not efficient due to climate and weather conditions [5].

Multigeneration energy systems technology is a step further for achieving a sustainable energy trend and to cope with the market and energy demands. Multigeneration energy systems are producing multi-useful products using the same prime mover. The useful outputs range from hot water supply and potable and fresh water production, to space heating/cooling and hydrogen production. Integrating renewable energy sources with multigeneration systems is

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Nomenclature

A	Area, m^2
C	Concentration ratio
c_p	Specific heat at constant pressure, kJ/kg K
$c_{p.s}$	Slat Specific heat, J/kg K
E_{act}	Activation energy, kJ/mol
ex	Specific exergy, kJ/kg
ex_{ch}	Specific molar chemical exergy, kJ/mol
$\dot{E}x$	Exergy flow rate, kW
F_r	View factor
h	Convection heat transfer coefficient, W/m^2 K
I	Solar radiation, W/m^2
J	Current density, A/m^2
J_{ref}	Pre-exponential factor, A/m^2
$\dot{m}$	Mass flow rate, kg/s
MW	Molecular weight, kg/kmol
$\dot{N}$	Molar flow rate, mol/s
P	Pressure, kPa
$\dot{Q}$	Heat rate, kW
r_r	RO recovery ratio
T	Temperature, K
V	Voltage, V
$\dot{W}$	Work, kW
X	LiBr mass fraction
x	Salt molar fraction
y	Salt mass fraction
λ	Thermal conductivity, W/m K
δ	Thickness, m
ε	Emissivity
ρ	Reflectivity
σ	Stefan-Boltzmann constant, W/m^2 K^4
σ_{pem}	Proton PEM conductivity, S/m
ω	Membrane water content
η	Efficiency, %
$\eta_{en,El}$	Electrolyzer energy efficiency, %
$\eta_{ex,El}$	Electrolyzer exergy efficiency, %
$\eta_{en,all}$	Overall energy efficiency, %
$\eta_{ex,all}$	Overall exergy efficiency, %
π	Osmotic pressure, psi

Acronyms

COP	Coefficient of Performance
CPV	Concentrated Photovoltaic
ECOP	Exergetic Coefficient of Performance
EES	Engineering Equation Solver
HFC	Heliostat Field Concentrator
PEM	Polymer Electrolyte Membrane
RO	Reverse Osmosis
SAM	System Advisor Model
SW	Sea water

one of the most attractive trends [6–8]. It is reasonable to state that the efficiency values of multigeneration systems are higher than that of trigeneration and cogeneration systems and of less environmental impact [9]. For optimizing the useful output of a multigeneration energy system, it should be designed flexible enough to meet the variations in demands. Several studies on the integrated energy systems for multigeneration were published in the literature. El-Emam et al. [10] proposed a renewable based multigeneration energy system powered by solar and biomass energy. Solar parabolic dish with gasification technologies were employed. They performed thermodynamic assessment of the system. The system studied provides potable water, cooling, and hydrogen along with the electric power production. The overall energy and exergy efficiencies were reported as 39.9% and 27.47%, respectively at the selected optimal operating point. A novel multigeneration system based on a biomass combustor was proposed and studied by Ahmadi et al. [11]. The system was integrated with organic Rankine cycle, an absorption chiller and a proton exchange membrane electrolyzer to produce hydrogen, and a domestic water heater for hot water production. Energy and exergy analyses as well as environmental impact assessment of the multi-generation system were performed. Mohan et al. [12] conducted a dynamic simulation for a novel solar thermal multigeneration system for production of cooling, clean water and domestic hot water, considering the weather conditions of United Arab Emirates, using TRNSYS software. Economic benefits were also analyzed for different collectors and fuel costs savings. In terms of environmental benefits, avoiding 109 metric tons/year of carbon dioxide emissions was reported causing a reduction in the overall payback period by 8% based on cost saving through carbon credits. Caliskan et al. [13] conducted an exergoeconomic and environmental impact analyses of a hybrid solar and wind energy system for the production of electricity and hydrogen. A solar heliostat integrated system for multigeneration of useful outputs was developed and analyzed by Khalid et al. [14]. Energy and exergy analyses are performed to assess the system performance. The overall energy and exergy efficiencies of the system were reported as 66.5% and 39.7% respectively.

Note that heliostat field and solar towers technology is one of the most recent concentrated solar power technologies to emerge into commercial utility. The Heliostat Field Concentrators (HFC) are typically designed in large scale (>10 MW) to be economically viable. The first heliostat plants incorporated are the 1 MW plant of the European community that was built near Genoa in 1976 [4] and the 10 MW Solar One and Solar Two that were built in Mojave Desert in California in 1981 and 1995, respectively. The amount of radiation focused on a single receive of a heliostat plant is as high as 200–1000 kW/m^2, and the huge solar flux towards the receiver yields concentration ratios as high as 100–1500 sun, which results in operating temperature value more than 1500 °C. Mounting the receiver on a tall tower helps to decrease the distance between mirrors to avoid shading; however, grounded central receiver has been proposed and studied by mounting a secondary reflector on the tower to reflect the concentrated solar flux to the receiver placed at the ground level [15]. The solar tower reflector technology can be integrated with solar reforming of methane. It can also be integrated with concentrated photovoltaic (CPV) where the solar spectrum is split into thermal and PV-used portions. A HFC-CPV with considering splitting the solar spectrum was studied by Segal et al. [16].

In this study, a novel solar heliostat based integrated energy system is developed and analyzed thermodynamically.

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