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Investigation and assessment of a novel solar-driven integrated energy system

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ABSTRACT

In this paper, a novel integrated energy system driven by solar power is proposed. A concentrated solar trough system is utilized in integration with organic Rankine cycle, absorption cooling system, desalination unit and electrolyzer, for the purpose of polygeneration. The proposed system produces hydrogen, cooling, fresh water, and domestic hot water along with electric power production. The system is analyzed thermodynamically, and its overall performance is assessed through energy and exergy efficiencies. The effects of varying several operating parameters and conditions on the performance are investigated through parametric studies. The cost rate is estimated at different operating points. The overall thermoeconomic multi-objective optimization study shows two extremes of 39% and 21.7% as maximum and minimum overall exergy efficiencies, respectively, as achieved at cost rate of 309.56 $/h and 241.7 $/h, for each corresponding case, respectively.

1. Introduction

Polygeneration (multigeneration) energy systems are achieved by combination of several processes, using single energy input to the system. It also reflects the production of multiple useful output streams, by integrating several systems that would effectively utilize the energy carried by the system waste streams [1]. The concept of integrated polygeneration energy systems is relatively new [2]. For residential application and rural areas, useful products of polygeneration systems would cover the main demands such as heating, cooling, drying, and fresh water, besides electric power, which is generally the main desired output of such systems [3]. Furthermore, hydrogen gas or liquefied hydrogen is another useful product of great interest that can be used as energy storage medium or directly as fuel [4]. Several studies had been conducted on renewable and clean energy source based integrated energy systems in the literature.

Ahmadi et al. [5] performed thermodynamic and environmental impact analyses on biomass-based integrated energy systems for polygeneration. They performed comparative assessment to show the advantage of using the integrated system for polygeneration over cogeneration or operating the system for only power production. Solar based integrated systems technology is considered a promising alternative for covering future demands of energy [6]. It is also promising for the polygeneration and large-scale applications [7]. Numerous solar polygeneration energy systems were proposed in the open literature. Some studies considered solar thermal energy storage, and others used an integrated energy system, such as biomass burner or geothermal source to drive the energy system when solar thermal energy is not available. Ezzat and Dincer [8] studied a polygeneration energy system driven by solar and geothermal energy sources to provide residential demands of electric power, cooling, hot water, space heating as well as drying process for industrial applications. Exergy and energy efficiency values of the overall system performance were reported as 42.8% and 69.6%, respectively. They also studied the exergy destruction of the system components for better understanding of the system performance. Ozturk and Dincer [9] performed thermodynamic assessment of solar tower and biomass integrated energy system. The performance of the system and its subsystems was measured using energy and exergy efficiencies. The maximum overall energy and exergy efficiencies were then estimated as 54% and 57.7%, respectively. Leiva-Illanes et al. [10] performed a thermoeconomic assessment of a solar-based polygeneration energy system for the production of electric power, fresh water, cooling, and heating. A concentrated solar parabolic trough collector of 50 MW with thermal energy storage and backup system was considered, coupled with multi-effect distillation plant, single effect absorption plant, and countercurrent heat exchanger, for freshwater production, cooling, and process heat, respectively. Another solar-geothermal polygeneration energy system for covering the demand of electric power, thermal and cooling energy, and fresh water for a small community was studied by Calise et al. [11]. They performed a dynamic

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Nomenclature

A	area, m^2
C	concentration ratio
c_p	specific heat at constant pressure, kJ/kg·K
$\dot{C}$	cost rate, $/h
CRF	capital recovery factor
ex_{ch}	specific chemical exergy, kJ/kmol
$\dot{E}x$	exergy flow rate, kW
F	Faraday constant
$\overline{F}$	collector efficiency factor
F_R	heat removal factor
h	convection heat transfer coefficient, $W/m^2 \cdot K$
i	interest rate, %
I	solar radiation, W/m^2
J	current density, A/cm^2
J_o	exchange current density, A/cm^2
$\dot{m}$	mass flow rate, kg/s
$\dot{N}$	molar flow rate, kmol/s
n	number of years, y
N	total number of hours, h
O_t	hours of solar system operating on storage, h
P_k	purchase cost of equipment, $
$\dot{Q}$	heat rate, kW
$\dot{q}$	heat flux, kW/m^2
R	gas constant, kJ/kmol·K
R_{ohm}	ohmic resistance, Ω/cm^2
S	solar absorber radiation
S_t	solar system operating hours, h
T	temperature, °C or K
U	overall heat transfer coefficient, $kW/m^2 \cdot K$
V	voltage, V
$\dot{W}$	work rate, kW
X	concentration ratio of LiBr

Greek symbols

δ	thickness, m
ε	emissivity
η	efficiency,%
λ	thermal conductivity, W/m·K
ρ	reflectivity
σ	Stefan-Boltzmann constant, $W/m^2 \cdot K^4$
$\varnothing$	maintenance factor

simulation of the energetic and exergetic performance of the system over 24 h, a week and annual operation, with a comparison of the system performance in winter and summer seasons. Calise et al. [12], in a different study, developed a dynamic model and thermoeconomic analysis of a novel polygeneration system based on photovoltaic/thermal collectors coupled with a solar-assisted heat pump, an adsorption chiller and an electrical energy storage. A solar based polygeneration energy system was proposed and analyzed by Yuksel et al. [13]. Their proposed system was driven by a parabolic trough solar system equipped with two-tank thermal storage system. The system was integrated with a quadruple effect absorption cooing system and an electrolyzer for the multi-useful purposes along with a double-stage organic Rankine cycle for power production. Ahmadi et al. [14] conduced a multi-objective optimization and energy and exergy analyses of a photovoltaic/thermal solar multigeneration energy system. The system was integrated with a Reverse Osmosis (RO) desalination unit for freshwater production, absorption chiller system for cooling, and a Proton exchange membrane (PEM) electrolyzer for hydrogen production. Soltani et al. [15] carried out energy and exergy thermodynamic analyses on a multigeneration energy system to cover the demands of dryer and steaming units, electricity, hot tap water, and space heat for a wood factory and its district. Khalid et al. [16] proposed an integrated renewable based multigeneration system for green building. The system was driven by wind and concentrated solar system, and produced electricity, hot water, heating, and cooling. They analyzed the system thermodynamically and carried out economic analysis for the determination of cost of produced electricity. In another study, Khalid et al. [17] developed a model for an integrated multigeneration system using biomass and solar energy for a community. Electricity, space heating, cooling and hot water were the useful commodities produced from the system. The energy and exergy efficiency values for the system were estimated as 91% and 34.9%, with levelized cost of electricity as $ 0.117/kWh for the optimized system performance. Hogerwaard et al. [18] proposed an integrated concentrated solar-driven gas turbine with organic Rankine cycle, single-stage flash seawater desalination unit, absorption refrigeration system, and direct space heating. The proposed system was designed to generate up to 255 kW of electric power, produce chilled water for space cooling at a design refrigeration capacity of 8.8 kW, produce fresh water up to approximately 1.5 m^3/day at 70 °C, and space heating up to a maximum load of 16.8 kW.

This up-to-date literature review shows that there are only limited studies which are generally related to polygeneration energy systems, especially using some renewable energy sources. Such literature studies mainly focus on improving the overall performances (and hence efficiencies) of such systems. However, this study goes beyond what is normally done by performing both a thermodynamic analysis and a comprehensive optimization study to optimize a novel polygeneration energy system based on solar energy source. Solar trough based integrated energy system is developed in this study for the purpose of polygeneration of several useful commodities. This novel system would serve in providing electric power, fresh potable water, cooling, and domestic hot water supply. The proposed system also produces hydrogen, which can be utilized as stored fuel or fueling fuel cell unit for electric power production during high demand periods or the unavailability of the solar power input. The developed system is thermodynamically analyzed through applying energy and exergy analyses. A thermoeconomic based optimization of the overall system performance is also performed. The effects of different operating parameters on the system performance are investigated and analyzed.

2. System description

The polygeneration energy system proposed in this study is based on concentrated solar thermal energy using parabolic trough technology with a solar thermal energy storage system. A parabolic solar trough assessed with a two-tank storage system is utilized to provide heat to an organic Rankine cycle. It is considered that the system performs steady by providing solar heat during solar radiation availability counted as 12 h including the storage time, and the heat is provided from the molten salts in the tanks to the heat transfer fluid of the solar trough system during the rest of the day when the solar radiation is unavailable. The working fluid used with the solar trough is Therminol-66 which is commercial thermal oil with operating temperature ranging from 0 °C to 345 °C. It has a low relative pressure and its pressure is not sensitive to the variation in the temperature values [19]. As per the operating temperature range, this oil can also be utilized as the working fluid for the storage tanks as well [20]. However, in the current study, the commercial nitrate salt Hitec XL is used as the heat transfer fluid for the storage system [21]. This salt has relatively a low freezing point temperature of about 120 °C, which results in avoiding the risk associated with freezing [22]. Furthermore, molten salts are low-cost, nonflammable, and non-toxic [23]. Hitec XL is a ternary salt consisting of