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Integrated an innovative energy system assessment by assisting solar energy for day and night time power generation: Exergetic and Exergo-economic investigation

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ABSTRACT

Recently, the growing demand for energy along the environmental concerns, as well as the limitation of fossil fuels, have made it necessary to research in and develop the field of renewable energies. The concept of a multi-generation energy system could be a reliable solution for future needs. In the current study, a novel integrated energy system based on solar energy was considered and analyzed in details by assisting the exergy and exergo-economic methodology. Using the concentrative photovoltaic thermal solar collectors, as the prime energy source, the proposed system comprised of both daytime mode and nighttime mode cycles, in order to continuously generate power. The factors influencing the performance of the system were investigated by a parametric study and the overall system outputs are reported in specified conditions. Related to the mentioned conditions, the output power of the electrical demand was 1000 kW in the daytime mode and the refrigeration capacity was 43.11 MW. In the case of nighttime mode, the output power was 823.1 kW. Considering these data, the overall exergy efficiencies were 21.24% and 35.86%, respectively. Furthermore, an economic analysis was done based on the energy generation of the integrated system. Results indicated that the proposed system was shown, great economic viability with a unit cost of generated electrical energy about 4.617 $/GJ and a unit cost of cooling effect about 299.3 $/GJ in daytime mode. Moreover, the unit cost of generated electrical energy in night time mode is 56.21 $/GJ. Moreover, the system provided the required energy sustainably through the year and by using clean energy sources prevented a total amount of 220469.3 ton of annual carbon emission, which is equal to 20,339 ha of forest absorbing carbon.

1. Introduction

On the seventieth anniversary of United Nations foundation, September 2015, seventeen goals were set out to be implemented by 2030, in areas of urgent importance for mankind. Therefore, an agenda was delineated to achieve an integrated sustainable development in social, economic and environmental aspects [1,2]. Hindering global climate change, which results in preserving the “Mother Earth’s” climate is one of the most salient of the seventeen goals. In the recent years, the population growth, which led to a rapid increase in energy demand, while raising the environmental concerns such as global warming, have induced a change of policy and attention toward the clean energies. In order to effectively cope with this problem on the global scale, in November 2016, the Paris agreement was signed by 195 UNFCCC members and 170 have become party to it. The agreement intends to hold global warming to well below 2 °C while, “pursuing efforts” to limit it to 1.5 °C [3,4].

Regarding energy demand as well as environmental concerns, the use of clean renewable energies is inevitable. In particular, solar energy is considered to be one of the most suitable primary energy resources in this regards, which could be harvested by Photovoltaic systems [5,6]. However, a quick glance through the literature would reveal some of the challenges in the development of PV systems, such as dust accumulation [7–9], cost inefficiently [10–12], and transition losses [13]. In order to overcome the dust problem, several cleaning methods are proposed [14,15]. Distributed generation is also known as a solution to overcome the transition lost, which leads to more economically feasible systems [16,17]. Locally Zandi et al. [18], evaluated and compared the economic policies to increase distributed generation capacity in the Iranian household consumption sector using photovoltaic systems. In addition to the fact that, the development of nanotechnology has reduced the final cost of solar energy harvesting, the hybridization of

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Nomenclature

Abbreviations

ABS	absorber
AB	afterburner
AC	air Compressor
Act	activation
CPVT	concentrated PVT
COND	condenser
DC	direct current
e	specific physical exergy [kJ/kg]
Eva	evaporator
Ex	exergy flow rate (kW)
$E_{act,i}$	activation energy in cathode or anode (kJ)
F	Faraday constant (C/mol)
FC	Fuel compressor
G	Gibbs free energy (J/mol)
HEX	heat exchanger
HRSG	heat recovery steam generator
GT	gas turbine
LHV	lower heating value
ORC	organic Rankine cycle
PEME	proton exchange membrane electrolyzer
SOFC	solid oxide fuel cell
Turb	turbine

Mathematical symbols

A	area
Ex	exergy [kJ/kmol]
$\dot{C}$	cost rate [$/h]
c	unit cost of exergy rate [$/GJ]
J	current desity [A/m^2]
$\dot{m}$	mass flow rate [kg/s]
u_f	fuel utilization factor
u_a	air utilization factor
r_P	pressure ratio

Greek symbols

η	efficiency [%]
ε	effectiveness

conventional systems with the solar system could resolve the cost inefficiently of the system, while providing cleaner energy [19,20].

The concept of Multi-Generation Energy System is considered as a creative solution to some of the world's critical challenges. Besides providing energy security and lessening the carbon emissions, these systems could as well produce reliable, cost-effective energy and spur economic growth. Thus recently, multi-generation energy system has been introduced as an integrated approach towards sustainable development of energy, water, and environment systems [21]. In this regard, extensive studies have been done on the multi-generation energy systems which are either based on solar [22–27], geothermal [28–32], or biomass energy [33–35], as well as based on fuel cells [36–38].

Reviewing the literature shows that one of the widely used renewable energies in the multi-generation energy system is solar energy. Using Adaptive PV [39], and concentric PVT (CPVT) in this regard help to increase the energy output of the solar section [40]. An adaptive PV system offers a flexible connection possibility to rearrange the solar modules according to the best-operating conditions based on real-time conditions [41]. CPVT technology was also used in several studies [42], in which by using concentrator the electrical output of PV panels increases due to an increase in the input radiation. However, the excess heat should be removed to increase the efficiency of panels. The removed head could be recovered and used in multi-generation energy systems [43,44].

Using the removed thermal heat, from the PV part, as a waste heat source, absorption refrigeration cycle is a suitable choice in order to achieve a low energy level cooling [45]. Meanwhile, the absorption single-effect cooling chillers have a wider range of applications with small and medium cooling capacities [46,47]. It is proven that a heated fluid with temperature over 70 °C can drive a single effect absorption chiller [48]. Consequently, a single effect absorption chiller could as well be a feasible choice for the domestic applications. The coolant of the absorber and the condenser could be either water or air. Even though most of the commercialized products are water-cooled, there are two main drawbacks in water-cooled systems: first, the difficulty of configuring the cooling tower in domestic areas and second, the risk of causing legionnaire's disease [49]. Furthermore, air-cooled absorption chillers could be built as a single unit, saving both space and water in domestic applications. Thus for the current study, an air coolant was considered.

Recently, a solar-based integrated hybrid system, which can provide 500 MW of electricity as well as hot air and water, was developed by Rabbani et al. [50]. Their results revealed that the energy efficiency of the overall system could be increased from 66% to 68% by varying the pressure ratio from 8 to 25. In another work, in order to produce electricity and hydrogen as well as hot water, while providing cooling and heating, Yuksel et al. [51], employed a multi-generation energy system based on geothermal energy. The proposed system consisted of a waste-to-heat component (ORC), a cooling component (Quadruple Effect Absorption cycle), a domestic water heater (DWH) and a proton exchange membrane electrolyzer (PEME). Using the Engineering Equation Solver (EES) and thermo-economic methodology, the overall energy and exergy efficiencies of 47.04% and 32.15%, were achieved respectively. Furthermore, they have reported that the unit cost of the hydrogen production can be lowered from 4.8 $/kg to 1.1 $/kg, while the geothermal water temperature rises from 130 to 200 °C.

A co-generation system and its mathematical model were introduced by Akikur et al. [45]. the presented model operates in three modes, including low solar radiation mode, high solar radiation mode and during the night. The overall efficiency of the proposed system could reach 23%, 20% and 83.6% for the different mode, respectively. Besides, the unit cost of energy was also reported 0.068 $/kWh, confirming economic viability of the system.

In a recent study by Entezari et al. [52], in order to increase the total efficiency, a Stirling heat engine was coupled with a gas turbine in order to recover the part of the heat loss. Furthermore, the multi-objective genetic algorithm was performed to optimize the overall plant parameters, subjecting three optimization scenarios of maximizing exegetic efficiency, minimizing the levelized cost of electricity and exergo-economic optimization. Their results showed that In the optimal point of the proposed hybrid system, the levelized cost of electricity reduced by 10.3% and exergetic efficiency improved by 16.1% compared with the standalone gas turbine cycle.

In another study, energy, exergy, environmental and economic analysis of an integrated multi-generation plant composed of solid oxide fuel cell stack, gas turbine, steam turbine, organic Rankine and absorption refrigeration cycles was done by Ogorure et al. [53]. Their proposed plant used agro-wastes composed of crops and animals wastes and had a net power of 5.226 MW with energy and exergy efficiencies of 63.62 and 58.46%, respectively. The high operating temperature of SOFC leads to manifold applications [54]. The high-temperature exhaust gases could be used either as a waste heat source or to run a gas