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# Examination of a new solar-based integrated system for desalination, electricity generation and hydrogen production

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ABSTRACT

In this study, we design and analyze a new solar tower based integrated system for desalination, electricity generation and hydrogen production. A reverse osmosis desalination system is incorporated into this integrated system. A proton exchange membrane (PEM) electrolyzer is also used for hydrogen production. A thermodynamic analysis through energy and exergy approaches is conducted to examine and assess the integrated system and its performance. The overall system energy efficiency is obtained as 23.2%. The overall system exergy efficiency is obtained to be 6.2%. In addition, the maximum energy and exergy efficiencies of the reverse osmosis desalination system are 60.3% and 30% respectively. The effects of changing system operating conditions and state properties on the efficiencies of system components and the overall system are also studied. The results of this study provide important inferences about the performance of the solar-based integrated system and the reverse osmosis desalination system.

## 1. Introduction

Energy demands have, during the past many decades, been increasing incessantly in an exponential form. The energy demands across the globe are projected to rise by 50% within 15 years from 2016 to 2030 (USEIA, 2016). Major energy production globally is carried out using fossil fuels. Fossil fuels form nearly 80% of the world's total energy consumption (Worldbank, 2014). The usage of fossil fuels has various environmental detriments. Carbon containing fossil fuels account for nearly 87% of the total carbon emissions caused by humans (Le Quéré and et al., 2015). In addition, fossil fuels are responsible for producing other harmful gasses that have adverse environmental and health effects. Renewable sources of energy, such as solar energy provide a solution to the problems encountered due to the usage of fossil fuels. However, solar-based power generation facilities have low efficiencies. Multi-generation systems provide a solution to improve the efficiencies of renewable energy based power generation facilities.

In locations where immense solar energy utilization potential exists with the requirement of water desalination, multi-generation systems comprising of desalination units can be implemented to achieve high system efficiencies. In addition, hydrogen is a fuel that does not produce any carbon emissions during combustion. Furthermore, hydrogen is an exceptional energy carrier, and is thus considered a possible storage medium. Potential to use hydrogen as a replacement of fossil fuels has been investigated is various studies (Balat, 2008; Ramesohl and Merten, 2006). Nearly 96% of hydrogen production carried out to meet market demands is through conventional fossil fuel based production methods, 50% is carried out using steam reforming of natural gas, 30% from oil refineries and 18% is carried out from coal gasification (Muradov and Veziroğlu, 2005). These methods produce large quantities of greenhouse gas emissions. Approximately 2.5–5 ton of carbon dioxide is released to the atmosphere for each ton of hydrogen produced (Abbasi and Abbasi, 2011). Hence, production of hydrogen from renewable energy resources is being investigated. Integrating hydrogen production systems with renewable energy based power generation facilities provide a viable solution to produce hydrogen in an environmentally benign way and improve the efficiency of multi-generation systems.

Some previous studies have been conducted on solar-based integrated multi-generation systems with desalination. Demir and Dincer (2017) investigated an integrated system comprising of solar and natural gas energy resources for electricity production and water desalination. Volumetric pressurized air receivers were utilized as solar energy absorbers. Further, thermoelectric material technology was utilized to generate power by using the waste heat of the Rankine cycle. The exergy efficiency and energy efficiency of the integrated system was determined to be 54.9% and 44.5% respectively. The proposed system produced fresh water at a rate of 3.36 kg/s. Due to increased demands and continuous usage, ground or surface fresh water resources are declining drastically. Azhar et al. (2017) proposed a multi-

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**Nomenclature**

| | |
|---|---|
| $A$ | area ($m^2$) |
| CPT | chemical pretreatment |
| $D$ | day angle |
| $ex$ | specific exergy (kJ/kg) |
| $E_o$ | eccentricity correction factor |
| $\dot{E}x$ | exergy rate (kW) |
| F | Faradays constant |
| G | Gibbs free energy |
| $h$ | specific enthalpy (kJ/kg) |
| H | enthalpy (kJ) |
| HPT | high pressure turbine |
| J | current density ($A/m^2$) |
| $\dot{I}$ | solar light intensity ($W/m^2$) |
| LHV | lower heating value |
| LPT | low pressure turbine |
| $\dot{m}$ | mass flow rate (kg/s) |
| MW | molecular weight |
| $\dot{N}$ | molar production rate (mol/s) |
| ORC | organic Rankine cycle |
| $P$ | pressure (kPa) |
| PEM | proton exchange membrane |
| PPM | parts per mole |
| $Q$ | heat transfer (kJ) |
| $\dot{Q}$ | heat transfer rate (kW) |
| RO | reverse osmosis |
| RR | recovery ratio |
| s | specific entropy (kJ/kg K) |
| S | entropy (kJ/K) |
| ST | solar time |
| $T$ | temperature (°C) |
| V | voltage, velocity |
| $\dot{W}$ | work rate (kW) |

*Greek letters*

| | |
|---|---|
| $\delta$ | declination angle |
| $\eta$ | efficiency |
| $w$ | hour angle |
| $\phi$ | latitude |
| $\tau$ | scattering transmittance |

*Superscript*

| | |
|---|---|
| Q | heat transfer |
| ref | reference |

*Subscript*

| | |
|---|---|
| a | anode, aerosols |
| act | activation |
| b | beam |
| br | brine |
| c | cold, condenser, cathode |
| cv | control volume |
| d | destroyed |
| $e$ | exit |
| en | energy |
| ex | exergy |
| $f$ | filter |
| frw | fresh water |
| g | ground |
| $gen$ | generated |
| $h$ | hot |
| $HPT$ | high pressure turbine |
| $HX$ | heat exchanger |
| $hf$ | heliostat field |
| $i$ | inlet |
| $l$ | lost |
| $LPT$ | low pressure turbine |
| $MW$ | molecular weight |
| mx | mixing chamber |
| $n$ | normal |
| $o$ | ohmic, ozone |
| $ov$ | overall |
| $p$ | pump |
| PEM | proton exchange membrane |
| $r$ | Rayleigh, received |
| $RO$ | reverse osmosis |
| $RR$ | recovery ratio |
| $s$ | solar |
| $sw$ | salt water |
| $sc$ | solar constant |
| $st$ | salt |
| $T$ | turbine |
| $tv$ | throttle valve |
| $w$ | water, work |
| $x$ | molar ratio |
| $y$ | mass ratio |
| $z$ | zenith angle |
| 0 | dead state |

generation system comprising of renewable energy resources. The integrated system utilized multi-stage flash desalination unit to produce fresh water. Furthermore, the proposed system provided electricity, industrial heating as well as space cooling. Solar, geothermal and ocean thermal energy resources were utilized. The exergy efficiency of the system was obtained as 17.9%. The system energy efficiency was evaluated to be 13.9%. Moreover, several studies on integrated solar and other renewable energy based resources for multi-generation have been conducted. Al-Ali and Dincer (2014) studied a hybrid renewable energy based integrated system comprising of solar and geothermal resources. The system outputs included electricity generation, space cooling and heating as well as hot water. A thermodynamic analysis was conducted to assess the performance of the presented system. The single generation system was found to have an energy efficiency and exergy efficiency of 16.4% and 26.2% respectively. However, the multigeneration system was found to have higher energy efficiency and exergy efficiency of 78% and 36.6%. Xu et al. (2011) performed an energy and exergy analyses on concentrated solar tower power plants, with molten salt as the heat transfer fluid. The energy losses in each component was determined to identify the causes and locations of irreversibilites. In addition, it was found that the efficiencies of the solar tower and the overall system could be increased by increasing the direct normal irradiance and the concentration ratio. However, in order to obtain better conversion efficiencies, solar power plants can be integrated with other systems to produce multiple system outputs. Panchal et al. (2016) designed and thermodynamically analyzed a renewable resources of energy based multigeneration system comprising of solar and geothermal energy. The proposed system was utilized to provide drying, heating, cooling as as power generation. A 37% energy efficiency was obtained for the multigeneration system. Moreover, the multigeneration system was found to have as significantly higher efficiency than the single generation system that was found to have an