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Analysis and performance assessment of a new solar-based multigeneration system integrated with ammonia fuel cell and solid oxide fuel cell-gas turbine combined cycle

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HIGHLIGHTS

- New solar-based system integrated with ammonia fuel cell and SOFC-GT cycle.
- Ammonia fuel cell integrated with molten salt thermal energy storage.
- Thermodynamic analyses and modeling through both energy and exergy approaches.
- Increase of 19.3% in energy efficiency as compared to single generation system.
- Increase of 17.8% in exergy efficiency as compared to single generation system.

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ABSTRACT

In the present study, a new solar-based multigeneration system integrated with an ammonia fuel cell and solid oxide fuel cell-gas turbine combined cycle to produce electricity, hydrogen, cooling and hot water is developed for analysis and performance assessment. In this regard, thermodynamic analyses and modeling through both energy and exergy approaches are employed to assess and evaluate the overall system performance. Various parametric studies are conducted to study the effects of varying system parameters and operating conditions on the energy and exergy efficiencies. The results of this study show that the overall multigeneration system energy efficiency is obtained as 39.1% while the overall system exergy efficiency is calculated as 38.7%, respectively. The performance of this multigeneration system results in an increase of 19.3% in energy efficiency as compared to single generation system. Furthermore, the exergy efficiency of the multigeneration system is 17.8% higher than the single generation system. Moreover, both energy and exergy efficiencies of the solid oxide fuel cell-gas turbine combined cycle are determined as 68.5% and 55.9% respectively.

1. Introduction

Energy demands have increased significantly and incessantly across the globe over the past several decades. The global primary energy demands have been estimated to increase by about 50% between the years 2016 and 2030 [1]. The primary method of energy production globally relies on fossil fuels. They form nearly 80% of the world's total energy consumption [2]. Energy production by fossil fuels is considered the primary cause of environmental pollution. In addition, the associated emissions are also detrimental to human health. It is essential to overcome the massive dependence on fossil fuels. 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 and need to be supplemented with other energy resources in order to meet energy demands. Power generation facilities utilizing combined solar and other resources of energy can reduce the dependence on fossil fuels. For instance, Hosseini et al. [3] proposed and analysed a hybrid solar energy and fuel cell based system for combined heating and power generation. The proposed system was designed for residential applications and was found to have an exergy efficiency of 49% and an energy efficiency of 55.7%.

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It is known that conventional gas turbine power plants utilizing natural gas (i.e., methane) as fuel have high amount of irreversibilities, specifically in the combustion chamber. This particularly leads to the low overall efficiencies and high amounts of greenhouse emissions of the power generation cycle. In order to increase the efficiencies and reduce the greenhouse emissions of gas turbine power plants, a combined solid oxide fuel cell (SOFC)-gas turbine cycle can be utilized. Milewski et al. [4] presented the numerical modeling and simulation of a hybrid SOFC system operating at part load. The results of their study concluded that the hybrid SOFC system attains a stable thermal efficiency and the system operating parameters can be varied along a wide range providing high control flexibility. Moreover, the combined cycle proposed by Haseli et al. [5] was found to have 27.8% and 26.6% higher energy and exergy efficiency than a conventional cycle respectively. Furthermore, it will help in reducing the environmental emissions. In addition, Chan et al. [6] modeled a hybrid SOFC and gas turbine system. The SOFC comprised internal reforming. The proposed system was found to have an efficiency of greater than 60% for single generation and higher than 80% in case of co-generation with waste heat recovery. Furthermore, Calise et al. [7] simulated and performed an exergy analysis on a 1.5 MW hybrid SOFC-gas turbine system. The system electrical efficiency was found to be nearly 60% without waste heat recovery. Moreover, multi-generation energy systems providing multiple useful commodities are also being investigated. These systems help to enhance the overall efficiencies of integrated energy systems. In addition to this, they provide a solution to improve the low efficiencies of conventional renewable energy based power generation facilities. Al-Sulaiman et al. [8] proposed and investigated an organic Rankine cycle and SOFC based integrated system providing electricity, heating and cooling. The trigeneration system was found to have considerably higher efficiencies than the single generation system. Yan et al. [9] investigated a combined SOFC, gas turbine and organic Rankine cycle system with liquefied methane serving as the heat sink. The waste heat of the SOFC was utilized to improve the system efficiencies. The overall system efficiency was obtained as 67%. Malico et al. [10] designed a trigeneration system for power, cooling and heating by utilizing a SOFC. A thermal efficiency of 68% was obtained by them. Tse et al. [11] investigated a SOFC-GT trigeneration system. A maximum overall efficiency of 43.2% was obtained. The utilization of waste heat recovery was found to increase the system efficiencies.

Utilizing hydrogen as a carbon-free fuel that avoids formation of carbon emissions during combustion is considered a promising alternative to fossil fuels. It is an exceptional energy carrier and is thus considered a viable energy storage option. Various studies have investigated the potential to utilize hydrogen as a replacement of fossil fuels [12,13]. However, conventional fossil fuel based hydrogen production methods form nearly 96% of the production carried out to meet market demands, approximately half of the hydrogen production is carried out using natural gas steam reforming, nearly 30% is carried out by utilizing oil refineries and approximately 18% is carried out through coal gasification [14]. These methods produce large quantities of greenhouse gas emissions. Every ton of hydrogen produced may result in the release of approximately 2.5–5 ton of carbon dioxide. Thus, hydrogen production through renewable energy resources needs to be investigated. An environmentally benign way of hydrogen production is to integrate the electrolyzer with renewable energy based power generation facilities. This provides a viable solution to improve the efficiency of multi-generation systems by producing hydrogen in an environmentally benign way. However, there are several challenges associated with the utilization of hydrogen. It does not have a high volumetric energy density. The storage as well as the transportation of hydrogen are hindered with various constraints owing to the low volumetric energy density. Moreover, hydrogen is flammable, which makes it dangerous while transportation or storage. To overcome these drawbacks, studies on alternative hydrogen carriers are being conducted. Several hydrogen carriers including ammonia, alcohols and hydrocarbons have been studied. Ammonia is a promising candidate due to various advantages. It has a high energy density of 4 kWh/kg and is easy to liquefy as it has a boiling point of −33.4 °C at standard atmospheric pressure. Furthermore, it has a comparatively high hydrogen content of 17.7 wt% and has a constricted flammable range of approximately 16–25 vol % in air [15,16]. Ammonia is free of carbon and is cost effective, hence, it provides an alternative fuel source to achieve lower environmentally harmful emissions in the process of energy generation. Generation of electricity through fuel cells is being considered as a clean source of energy production. Currently, hydrogen is the prominent fuel for fuel cell technology. However, in order to overcome the drawbacks of hydrogen, ammonia can be used as an alternative fuel. Incorporating ammonia as a fuel for fuel cells is being considered in various studies. In the utilization of ammonia as a fuel for fuel cells, either it can be decomposed into nitrogen and hydrogen externally or it can be directly fed into the cell. Direct ammonia fuel cells allow feeding of ammonia as a fuel directly without requiring an external decomposition unit. Hence, provide more applicability for various uses. Ammonia was initially investigated as a source of electricity generation from fuel cells as well as a source to produce nitrogen oxide as a useful chemical [17,18]. Several studies have followed which investigated ammonia as a fuel source for different types of fuel cells. Ganley [19] developed and tested a molten KOH-NaOH based ammonia fed fuel cell working at temperatures between 200 and 450 °C. The fuel cell was found to provide a peak power density of 40 mW/cm^2 at a temperature of 450 °C. In addition, Yang et al. [20] investigated a molten NaOH-KOH electrolyte based direct ammonia fuel cell. A peak power density of 16 mW/cm^2 was obtained at a temperature of 220 °C.

Although, separate studies have been conducted on solar-based multi-generation systems, integrated solid oxide fuel cell-gas turbine cycles and ammonia fuel cells. Efforts have not been made to develop a solar-based multi-generation system integrated with molten alkaline electrolyte ammonia fuel cell and solid oxide fuel cell-gas turbine cycle. The molten salt utilized in thermal energy storage systems in solar thermal power plants can be used as an electrolyte for molten alkaline ammonia fuel cells. Furthermore, solar tower based power plants can be integrated with a solid oxide fuel cell-gas turbine cycle to achieve higher energy outputs. Furthermore, these integrated systems can be utilized for multigeneration to produce multiple useful outputs. Hence, in the current study, we develop and thermodynamically analyze a new solar-based multigeneration system integrated with an ammonia fuel cell and solid oxide fuel cell-gas turbine combined cycle to produce electricity, hydrogen, cooling and hot water. The specific objectives of this study include (a) developing a new solar-tower based multigeneration system integrated with ammonia fuel cell and solid oxide fuel cell-gas turbine combined cycle for electricity generation, hydrogen production, cooling and hot water (b) analysing the system through thermodynamic approaches of energy and exergy analyses, (c) determining the energy efficiency and exergy efficiency of the proposed system as well as system components, and (d) conducting a parametric study to analyze how varying parameters will affect both energy and exergy efficiencies of the proposed system and system constituents.