Performance investigation of a novel trigeneration system using solar-biomass energy

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ABSTRACT

In this research, a novel trigeneration system driven by biomass-solar energies has been investigated from energy exergy, economic and environmental viewpoints. The solar energy is used to produce hydrogen (by a PEM electrolyzer powered by thermal photovoltaic panels). To meet the intermittent nature of solar energy, it is used for hydrogen production. The hydrogen is used as fuel in the combustion chamber. The proposed gas turbine cycle consists of two high and low-pressure turbines and two compressors with an intercooler. A combined organic Rankine-vapor compression refrigeration cycle that uses the recovered heat from the gas turbine is used to produce refrigeration and air cooling in the interstage compressor. The obtained results provide that the combination of solar-based hydrogen production and biomass-based gas turbine leads to an increase in power production capacity. The proposed combined system provides an energy and exergy efficiency of 21% and 17% and the emission of 0.00884 kg/s of CO_2. The highest capital cost rate among the components is attributed to the PEM electrolyzer, amounting to 15.44 $/hr, and the total cost of the products has reached 0.5627 $/MJ. Using an intercooler, the energy and exergy efficiencies of the system have increased by 6% and 4%, respectively.

KEYWORDS

Trigeneration, biomass, solar, exergoeconomic, exergoenvironmental

Introduction

To achieve sustainable development, the industrial sector of any country is highly dependent on the production and supply of clean energy. Harmful pollutant emissions from fossil fuels have compelled countries to shift towards renewable energy sources [1]. Among the various types of renewable energy, solar and biomass sources stand out as suitable alternatives due to their availability and abundance [2-3]. However, the inconsistency and fluctuation of solar energy pose significant challenges. To enhance reliability, addressing the drawbacks of using a single source of renewable energy can be achieved by combining sources. For instance, solar energy can be utilized to produce hydrogen, and by burning it, a continuous heat source can be obtained. Recently, there has been considerable attention given to the combined use of solar and biomass energies in energy production systems. In such systems, biomass typically serves as the primary fuel, while solar energy acts as an auxiliary energy source [4].

Many studies have been conducted by researchers to use alternative energies in energy production systems. Anvari et al. [5] introduced novel configurations of biomass-solar combined power generation cycles. In these systems, solar energy was harnessed through a heliostat field to reheat the exhaust gases generated by a biomass-fueled gas turbine. Gaeta [6] analyzed a 100 kW gas turbine using a mixture of natural gas and hydrogen fuels, reporting natural gas savings ranging from 41.5% to 37.5%. In a study by Ahmadi et al [7], a multigeneration system involving power, hydrogen, heating, and cooling was investigated. The results indicated that the use of the multigeneration cycle increased exergy efficiency by 60% compared to a simple energy generation cycle.

The overview of research in the field of multigeneration systems highlights a notable gap in studies focusing on power generation cycles integrating both hydrogen and biomass fuels. Additionally, there are a limited number of studies exploring the combined organic Rankine-vapor compression refrigeration cycle for cooling, especially at the intermediate compression stage, with use of recycled heat from the gas turbine.

Thermodynamic Modelling

Figure 1 illustrates the schematic of the proposed trigeneration system, comprising a gas turbine (representing the upper cycle) and an organic Rankine cycle-vapor compression refrigeration system (representing the lower cycle). The system incorporates a combination of biomass and solar energy sources. Biomass serves as the primary fuel, while solar energy is employed to produce hydrogen. The produced hydrogen is then burned in the combustion chamber to reheat the exhaust gas originating from the high-pressure turbine.

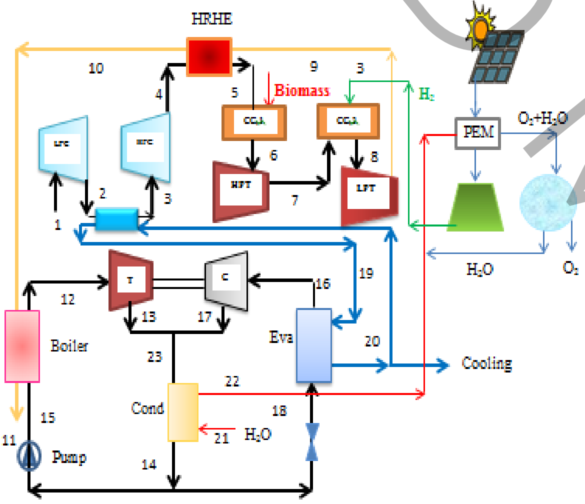

Figure 1. Schematic of the proposed trigeneration system of power, heat and cooling

To model the energy and exergy of the system, the laws of conservation of mass and energy and the equation of exergy balance must be used for each component of the system. Thus, each component is considered as a control volume. These equations are defined through Eqs. (1-3) [8].

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

$$\dot{Q} - \dot{W} = \sum_e \dot{m}_e h_e - \sum_i \dot{m}_i h_i \tag{2}$$

$$Ex_{\dot{Q}} + \sum_i \dot{m}_i ex_i = \sum_e \dot{m}_e ex_e + Ex_{\dot{W}} + Ex_D \tag{3}$$

Results

To determine accuracy, the calculations were compared with the findings of previous research, and the results are depicted in Figure 2. For validation purposes, the systems were compared under similar performance conditions of modelling, and the results indicate a good agreement between them.

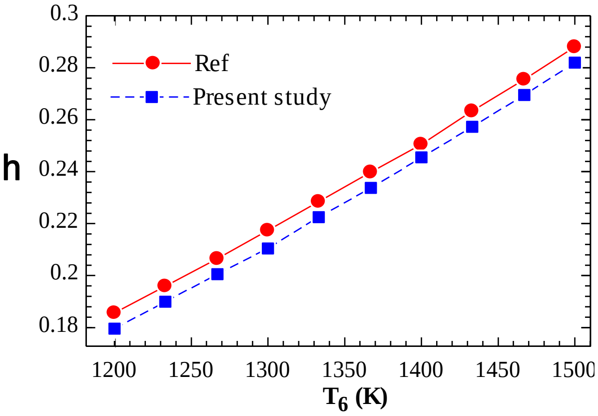

Figure 2. Gas turbine cycle modelling results [9]

The PEM electrolyzer has the most significant economic impact, constituting 44% of the total investment. Meanwhile, the thermal photovoltaic panel accounts for the highest amount of exergy destruction. The increased costs associated with the electrolyzer and thermal photovoltaic panel could potentially be offset by reducing the costs of exergy destruction in these equipment. The high cost of the gas turbine cycle is primarily attributed to the turbine, with the presence of the combustion chamber and heat exchangers being secondary factors. Essentially, the turbine used in gas turbine cycles holds paramount importance from a design perspective.

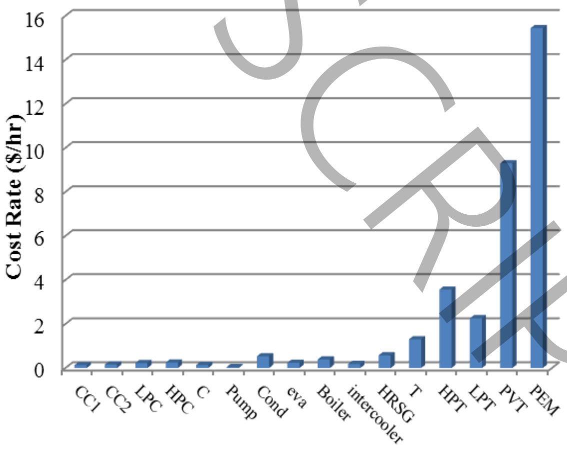

Figure 3. The cost rate of different components of the system

The diagram in Figure 4 illustrates that by incorporating the intercooler and lowering the temperature of the incoming air to the high-pressure compressor to ambient levels, there is a potential increase of approximately 6% in energy efficiency and 4% in exergy efficiency.

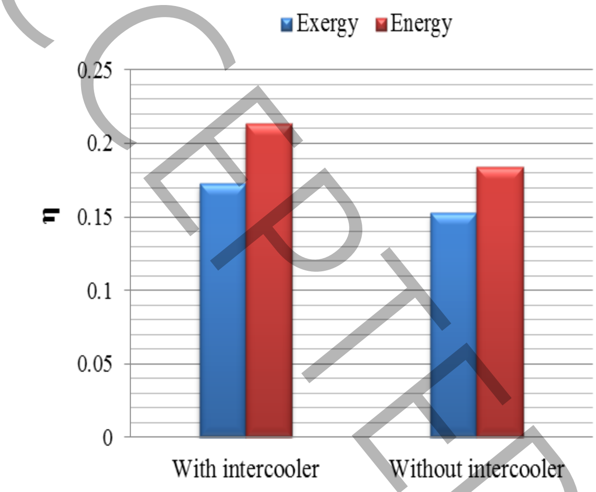

Figure 4. The effect of using an intercooler on the system energy and exergy efficiencies

Figure 5 depicts the carbon dioxide emissions for the investigated triple production system. According to the figure, the amount of carbon dioxide gas emissions increases by 89% in scenarios where hydrogen fuel is not utilized, and biomass fuel is the sole source.

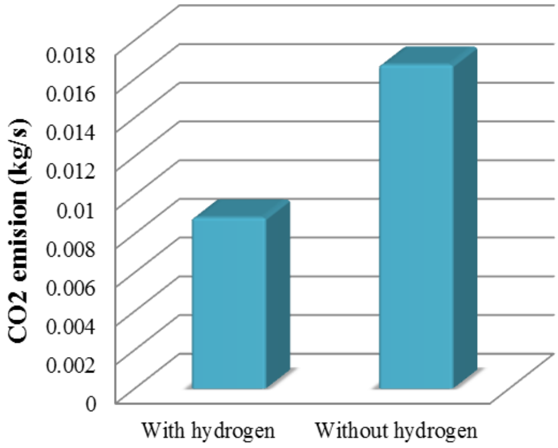

Figure 5. Comparison of the amount of CO_2 emission

Conclusion

In this research, a thermodynamic investigation was conducted on a triple production system involving power, heat, and cooling, utilizing a combination of solar energy sources and biomass. The introduction of a refrigerant production subsystem, with partial utilization for intermediate cooling of compressors, resulted in a 6% increase in energy efficiency and a 4% increase in exergy efficiency for the system. The incorporation of a thermal photovoltaic system and an electrolyzer for hydrogen production, while leading to an increase in exergy destruction and economic costs, contributed to a substantial (89%) reduction in carbon dioxide gas emissions. Also, the proposed combined system has high flexibility and when there is no need for cooling, the power of the organic Rankine cycle turbine can be used directly to produce electricity.

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