INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 1047–1059

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Thermodynamic analyses of a solar-based combined cycle integrated with electrolyzer for hydrogen production

F. Sorgulu [a,b,*], I. Dincer [a,c]

[a] Faculty of Mechanical Engineering, Yildiz Technical University, Besiktas, Istanbul, Turkey

[b] Faculty of Technology, Kahramanmaras Sutcu Imam University, Elbistan, Kahramanmaras, Turkey

[c] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, Ontario, Canada

ARTICLE INFO

Article history:
Received 11 March 2017
Received in revised form
17 July 2017
Accepted 22 September 2017
Available online 27 October 2017

Keywords:
Electrolyzer
Energy
Heat recovery
Hydrogen production
Solar energy

ABSTRACT

In the current study, a combined steam and gas turbine system integrated with solar system is studied thermodynamically. In addition, an electrolyzer is added to the integrated system for hydrogen production which makes the current system more environmental friendly and sustainable. This system is then evaluated by employing thermodynamic analysis to obtain both energetic and exergetic efficiencies. The parametric studies are also conducted to investigate the effects of varying operating conditions and state properties on both energy and exergy efficiencies. The present results show that while gas turbine can generate 312 MW directly, 151.72 MW power is generated by steam turbine using solar collectors and exhausted gases recovered from the gas turbine. Furthermore, by adding electrolyzer to the integrated system, a total of 131.3 g/s (472.68 kg/h) hydrogen is generated by using excess electricity which leads to more sustainability system.

Introduction

An efficient and effective utilization of energy systems plays a major role in the energy consumption of countries. It is important to improve the performance of power plants and to employ new technologies to meet the ever-increasing energy demand. Many studies are carried out on efficient energy utilization and sustainable deployment of energy resources [1–3]. Conventional energy sources, such as wood, coal, natural gas, petroleum, have been used for many years. Renewable energy sources, such as solar, wind, geothermal and biomass, are widely used as main and/or supplemental resources in the combined cycles [4]. This is not only due to the decreasing conventional fuel sources, but also due to environmental concerns about pollution and global warming issues. Nowadays, it is thought that among these sources, solar energy and hydrogen are the most promising energy solution options. Solar energy is essentially the main source for the earth with 170,000 TW of solar radiation and energy of the sun has been stored by earth crust or sea water for thousands of years [1–3]. Solar energy can be converted to electrical energy directly by using photovoltaics (PVs) systems. By decreasing the production cost of required devices to convert solar energy

* *Corresponding author*. Faculty of Mechanical Engineering, Yildiz Technical University, Besiktas, Istanbul, Turkey.
E-mail address: fatihs@yildiz.edu.tr (F. Sorgulu).

https://doi.org/10.1016/j.ijhydene.2017.09.126

to electricity, the PVs will become even more feasible and hence cost effective, as well as the increased capacities of installed solar PVs. Numerous studies are carried out to develop new techniques to cope with the limitations, such as low efficiency and fluctuation of the sun [5–7]. With decreasing prices of installation, it would be more common to harvest the solar energy to generate electricity in addition to the increased efficiency [8,9].

However, solar to electricity conversion efficiency in integrated solar-based combined cycle (ISCC) producing multi generation is higher than the single-commodity producing solar only plants [10,11]. For the past a few decades, the parabolic troughs, acting as direct steam generator (DSG) systems, have been used in many commercial combined cycles to generate heat rather than electricity. Higher energy efficiencies are obtained by using solar heat. Direct steam generation with solar panels has higher temperature and thermal efficiency than the oil-based parabolic trough solar thermal power plants. Furthermore, electricity generation with DSG plants becomes less expensive than oil-based systems [4,12,13].

Hydrogen finds application opportunities primarily in fuel cells to generate electricity with the side products, such as water and a small amount NO_x. There are lots of different processes to produce hydrogen, such as steam reforming from hydrocarbons, electrolysis, and thermolysis. The main method, steam-methane reforming, is a common method to produce hydrogen through fossil fuels. In another common method, water (H_2O) can be disassociated into hydrogen (H_2) and oxygen (O_2) by electrolysis which requires electricity. The power required for electrolysis can easily be supplied from renewable energy sources. Therefore, renewable based hydrogen resources, such as solar, wind and geothermal can be classified as renewable energy resources. Hydrogen production by renewable energy resources is expected to be the main option for hydrogen economy to achieve carbon-free society and overcome the energy and environment dilemma in the industry. There are, in this regard, numerous studies conducted in this field as summarized in Ref. [14].

For providing sustainable energy production, hydrogen must be used in a combined power cycle. Furthermore, hydrogen can be stored, unlike electricity. This means that hydrogen can be generated by a combined power cycle integrated renewable energy system while the electricity is not required. Montes et al. [15] carried out the performance analysis of a combined cycle integrated with solar collectors to produce steam. In their study, solar field is coupled to the bottoming steam cycle of a combined cycle. They analyzed the performance of a combined cycle in Las Vegas with a very hot and dry environmental conditions and also Almeria which mimic the Mediterranean climate. They found that ISCC gives better efficiency than combined cycle gas turbine in hot climate conditions. Their results also confirm that the hybrid system is a cheaper way to exploit concentrated solar energy by economic analysis that they performed.

Regulagadda et al. [16] carried out an exergetic analysis of a thermal power plant with 32 MW coal-fired. They performed a comprehensive evaluation to investigate the effects of operating temperature and pressure on the system performance. The results show that power plant's energy and exergy efficiencies are 30.12% and 25.38% for the power output, respectively. As expected, they have found maximum exergy destruction rate in the boiler. Also they display the environmental impacts and evaluate the sustainability levels with regard to exergy destruction within the system.

Ozlu and Dincer [17] have performed an analysis for a combined cycle integrated with parabolic solar collectors to supply heat and electricity, and also integrated with an electrolyzer to generate hydrogen. They integrated a domestic water heater and fresh water through a heat recovery subsystem to meet the demands for buildings. They calculated both energy and exergy efficiencies as 36% and 44%, respectively. They also calculated the number of apartments can be powered by their system to be at least 38 for an optimum use. Also, Ozturk and Dincer [18] performed a thermodynamic evaluation of a multi-generation energy production system integrated with parabolic dish collector to harvest the solar energy. They determined the exergy destruction rate and power or heat transfer rate for each component. Eventually they obtained energy efficiency as 52.71% and exergy efficiency as 57.35% for their overall system.

Dayem et al. [19] carried out a numerical simulation for a combined power plant integrated with solar parabolic troughs by using experimental measured data from Kuraymat plant, Egypt. They evaluated the same plant under the weather conditions of Makkah, Saudi Arabia. They have determined improvement potential of the plant performance by increasing generated power by gas turbine and steam turbine due to high ambient temperature and the higher DNI at Makkah.

In the current study, a solar-based combined cycle, which is comprised of a gas turbine and three cascade steam turbines, is modified from a literature study [20] by adding an electrolyzer for hydrogen production. In this regard, a comprehensive analysis and assessment study is performed through energy and exergy approaches thermodynamic first and second laws. In order to reach sustainability, an electrolyzer is added to the system to produce hydrogen by using excess electricity from steam turbine generator. Ultimately, a comparison of the systems before and after electrolyzer is performed in terms of energetic and exergetic efficiencies and parametric studies for evaluating how varying operating conditions and state properties affect the performance of the integrated system.

Systems description

As shown in Fig. 1, the main components of combined cycle are gas turbine, which run on natural gas, three cascade steam turbines and an electrolyzer. This cycle is modified from a previously analyzed and presented cycle in Ref. [20] by adding an electrolyzer and optimizing the outputs for application. The steam turbines comprise of two high pressure turbines and a low-pressure turbine, which are preheated by solar system and exhausted gases from the gas turbine. The following assumptions are made for thermodynamic analysis and evaluation:

- The reference state temperature (T_0) and pressure (P_0) are 25 °C and 100 kPa, respectively.