Energy 69 (2014) 592–602

Contents lists available at ScienceDirect

Energy

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

Thermodynamic evaluation of geothermal energy powered hydrogen production by PEM water electrolysis

Ceyhun Yilmaz, Mehmet Kanoglu*

Department of Mechanical Engineering, University of Gaziantep, 27310 Gaziantep, Turkey

ARTICLE INFO

Article history:
Received 12 June 2013
Received in revised form
18 February 2014
Accepted 15 March 2014
Available online 14 April 2014

Keywords:
Geothermal energy
Hydrogen production
Electrolysis
Energy
Exergy

ABSTRACT

Thermodynamic energy and exergy analysis of a PEM water electrolyzer driven by geothermal power for hydrogen production is performed. For this purpose, work is produced from a geothermal resource by means of the organic Rankine cycle; the resulting work is used as a work input for an electrolysis process; and electrolysis water is preheated by the waste geothermal water. The first and second-law based performance parameters are identified for the considered system and the system performance is evaluated. The effects of geothermal water and electrolysis temperatures on the amount of hydrogen production are studied and these parameters are found to be proportional to each other. We consider a geothermal resource at 160 °C available at a rate of 100 kg/s. Under realistic operating conditions, 3810 kW power can be produced in a binary geothermal power plant. The produced power is used for the electrolysis process. The electrolysis water can be preheated to 80 °C by the geothermal water leaving the power plant and hydrogen can be produced at a rate of 0.0340 kg/s. The energy and exergy efficiencies of the binary geothermal power plant are 11.4% and 45.1%, respectively. The corresponding efficiencies for the electrolysis system are 64.0% and 61.6%, respectively, and those for the overall system are 6.7% and 23.8%, respectively.

1. Introduction

Renewable energies are increasing in their use throughout the world. This is motivated by the fact that fossil fuels are depleting and their combustion cause pollution and greenhouse emissions. The increase in utilization of renewable energy requires technical and infrastructural changes. These major changes are energy savings on the demand side, efficiency improvements in the energy production, and the replacement of fossil fuels by various sources of renewable energy [1]. Hydrogen energy can become one of the effective solutions in the future. Hydrogen can play a significant role in reducing environmental emissions if it is produced from renewable energy resources [2,3]. Hydrogen is a subject of many research work and some consider it as the energy of the future. Hydrogen is an energy carrier; it stores and delivers energy in a usable form, but it must be produced from compounds that contain it [4,5]. Hydrogen can be produced using diverse, domestic resources including fossil fuels, such as coal (with carbon sequestration) and natural gas; nuclear; and biomass and other renewable energy technologies, such as wind, solar, geothermal, and hydroelectric power [6].

Producing hydrogen from renewable and nuclear energy sources using the process of electrolysis involves different costs. It is estimated to be 7–11 $/kg for wind, 10–30 $/kg for solar, 2–4 $/kg for nuclear, and 2.2–7.0 $/kg for geothermal [7].

If hydrogen is to become the energy of the future, it must be produced using renewable energy sources and the technical and economic problems on its production, storage, transportation, and use should be solved. There are various methods used in hydrogen production. These methods may require both electricity and heat inputs, and renewable energy such as solar, wind, hydro and geothermal energy use are being investigated [8]. Hydrogen production via electrolysis is being pursued for renewable (wind, solar and geothermal) options. These pathways result in virtually zero greenhouse gas and pollutant emissions [9].

Hydrogen can be produced by using electrolysis techniques. Electrolysis splits water electrochemically into hydrogen and oxygen molecules with the aid of electrical energy. There are three kinds of electrolysis techniques; alkaline, solid oxide and PEM (Proton Exchange Membrane) electrolysis [10,11]. The trend today for the future electrolysis devices, even at high pressure, goes through PEM technology. Many studies and papers demonstrate

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* Corresponding author. Tel.: +90 342 3172508; fax: +90 342 3601104.
E-mail address: kanoglu@gantep.edu.tr (M. Kanoglu).

http://dx.doi.org/10.1016/j.energy.2014.03.054
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the interest in this technology. The PEM electrolyzer uses a solid electrolyte membrane that can be expected to increase the lifetime of the electrolyzer. No caustic alkaline or acidic fluid electrolyte is required. Additional advantages of PEM electrolysis over alkaline electrolysis include lower parasitic energy losses and higher purity hydrogen output. PEM electrolysis is potentially a simple, sustainable, and cost-effective technology for generating, compressing, and storing hydrogen [12]. Many establishments have been involved in the development of high efficiency, high security electrolysers such as alkaline and PEM (proton exchange membrane) electrolysers. For instance, the International Clean Energy Network using Hydrogen Conversion (WE-NET), which is a program funded by AIST (Agency of Industrial Science and Technology) in the MITI (Ministry of International Trade and Industry) of Japan, have been actively involved in the development of large-scale hydrogen production technologies [13]. In our system, we select a PEM electrolyzer mainly because it can operate over a temperature range and it is commonly considered in studies on renewable based hydrogen production.

Among renewable sources, geothermal energy has significant potential in hydrogen production. Electricity output from a geothermal power plant and direct geothermal heat or that resulting from power plants can be used in hydrogen production by means of water electrolysis process. The use of geothermal energy for hydrogen production with the electrolysis operation may prove to be an effective option in the future hydrogen structure. Power production from geothermal energy is well established and various thermodynamic systems such as single flash, double flash, binary, and combined flash/binary designs are commonly used. In this study, we select a binary design geothermal power plant since it is more efficient and more commonly used design for liquid dominated and relatively low-temperature geothermal resources. Both binary geothermal power plant and PEM electrolyzer are common technologies and incorporating them with a heat exchange system can provide a viable option for geothermal powered hydrogen production technology. The systems considered in this study are assumed to have appropriate dimensions to perform the necessary thermodynamic functions as described in the analysis.

Although, there are a large number of studies in using solar, wind and nuclear energies for hydrogen production, limited number of studies exists on using geothermal energy. Next, we provide an overview of some of the more relevant studies in literature. Kanoglu et al. [14] investigated energy, exergy, and exergoeconomic analysis of a geothermal assisted high temperature electrolysis process. Energy and exergy performance parameters such as heat transfer, power, exergy destruction, and exergy efficiencies were determined. Heat exchanger network and high temperature electrolysis unit are primarily responsible for exergy destructions in the system. Ahmadi et al. [15] developed a model for energy and exergy analyses of hydrogen production via an OTEC (ocean thermal energy conversion) system coupled with a solar-enhanced PEM (proton exchange membrane) electrolyzer. The energy and exergy efficiencies of the integrated OTEC system are determined to be 3.6% and 22.7%, respectively, and the exergy efficiency of the PEM electrolyzer is 56.5%. Esmaili et al. [16] analyzed low temperature electrolysis of a hydrogen production system using molybdenum oxo catalysts in the cathode and a platinum bared anode. A thermodynamic model was developed for the electrolysis process in order to predict and analyze the energy and exergy efficiencies. The new electrolysis system with molybdenum oxo catalysts consists of two half cells of PEM (proton exchange membrane) and alkaline electrolysis. The results were presented and compared with previous studies to demonstrate the promising performance of the system.

Kanoglu et al. [17] investigated three cases for the use of geothermal energy for hydrogen liquefaction. A binary geothermal power plant was considered for power production while the precooled Linde Hampson cycle was selected for hydrogen liquefaction. Kanoglu et al. [8] developed four models for the use of geothermal energy for hydrogen production. These models were studied thermodynamically, and both reversible and actual (irreversible) operations of the models were considered. Yilmaz [18] and Yilmaz et al. [19] considered seven models for hydrogen production and liquefaction by geothermal energy, and their thermodynamic and economic analyses were performed. The amount of hydrogen production and liquefaction per unit mass of geothermal water and the cost of producing and liquefying a unit mass of hydrogen are calculated for each model. The effect of geothermal water temperature on the cost of hydrogen production and liquefaction were also investigated.

Balta et al. [20] and Balta et al. [21] investigated various geothermal based hydrogen production methods using energy and exergy methods. Balta et al. [22] conducted an exergy, cost, energy, and mass analysis of a copper–chlorine thermochemical water splitting cycle driven by geothermal energy for hydrogen production. Ratlamwala et al. [23] focused on a comparative assessment of multi-flash geothermal power generating systems integrated with electrolyzers through three definitions of energy and exergy efficiencies. Valdimar et al. [24] presented a feasibility study exploring the use of geothermal energy for hydrogen production. They investigated a newly developed HOT ELLY high temperature steam electrolysis process operating between 800 and 1000 °C. The electrical power of this process is reduced from 4.6 kWh per normalized cubic meter of hydrogen (kWh/Nm^3 H_2) for conventional process to 3.2 kWh/Nm^3 H_2 for the HOT ELLY process with an electrical energy reduction of 29.5%. The price of geothermal energy is approximately 8–10% of electrical energy and therefore a substantial reduction in production cost of hydrogen can be achieved this way. Using HOT ELLY process with geothermal steam at 200 °C can reduce the hydrogen production cost by approximately 19%. Zhang et al. [25] investigated a water electrolysis hydrogen production system, which mainly includes the electrolysis cell, separator, and heat exchangers. Three expressions of the system efficiency in literature are compared and evaluated. Several new configurations of a water electrolysis system are put forward. Some recent studies have focused on various thermodynamic aspects of geothermal district heating systems and enhanced geothermal systems [26–28].

The previous work cited on using geothermal energy on hydrogen production concentrate on (a) geothermal assisted high-temperature electrolysis process, (b) geothermal assisted hydrogen liquefaction, (c) thermodynamic and conventional economic analysis of hydrogen production and liquefaction driven by geothermal energy, and (d) geothermal based hydrogen production methods using conventional energy and exergy methods. In this paper, we consider a thermodynamic system for the production of hydrogen driven by geothermal energy. The system consists of a binary geothermal power plant, a heat exchange system, and a PEM electrolysis unit. The present work represents the first investigation that considers these particular systems with realistic operating conditions and their thermodynamic analysis using the first and second laws. Also, this study extends on Yilmaz et al. [19] for which the possible systems for power production and hydrogen production were not considered and instead these units were only represented by simple boxes.

In our analysis, both thermal and electrical energy outputs of the geothermal system are used in hydrogen production. For thermodynamic evaluation of the system, mass, energy and exergy balances are applied and efficiency and other performance parameters