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Economics of hydrogen production and liquefaction by geothermal energy

Ceyhun Yilmaz [a], Mehmet Kanoglu [a,*,1], Ali Bolatturk [b], Mohamed Gadalla [c]

[a] Department of Mechanical Engineering, University of Gaziantep, 27310 Gaziantep, Turkey
[b] Department of Mechanical Engineering, Suleyman Demirel University, 32260 Isparta, Turkey
[c] Department of Mechanical Engineering, American University of Sharjah, P.O. Box 26666, Sharjah, United Arab Emirates

ARTICLE INFO

Article history:
Received 7 January 2011
Accepted 4 June 2011
Available online 13 July 2011

Keywords:
Geothermal energy
Hydrogen production
Hydrogen liquefaction
Hydrogen economy
Water electrolysis

ABSTRACT

Seven models are considered for the production and liquefaction of hydrogen by geothermal energy. In these models, we use electrolysis and high-temperature steam electrolysis processes for hydrogen production, a binary power plant for geothermal power production, and a pre-cooled Linde–Hampson cycle for hydrogen liquefaction. Also, an absorption cooling system is used for the pre-cooling of hydrogen before the liquefaction process. A methodology is developed for the economic analysis of the models. It is estimated that the cost of hydrogen production and liquefaction ranges between 0.979 \$/kg H_2 and 2.615 \$/kg H_2 depending on the model. The effect of geothermal water temperature on the cost of hydrogen production and liquefaction is investigated. The results show that the cost of hydrogen production and liquefaction decreases as the geothermal water temperature increases. Also, capital costs for the models involving hydrogen liquefaction are greater than those for the models involving hydrogen production only.

1. Introduction

Geothermal energy is the thermal energy within the earth's interior. Geothermal energy is mostly used to generate electricity. It is also commonly used for space heating and cooling, industrial processes, and greenhouse heating [1]. With the increasing scarcity of fossil fuels and increasing concerns over the environmental problems they cause, the use of renewable energy resources will likely increase and diversify. Geothermal energy appears to be a significant renewable energy source for solving some of the environmental problems caused by the use of fossil fuels [2]. The technology for producing power from geothermal resources is well established. Geothermal power plants tap certain high-temperature resources to generate electricity with minimal or no emissions. Different thermodynamic cycles are used in numerous geothermal power plants worldwide. The common designs include dry steam, single-flash, double-flash, binary, and flash/binary cycles.

The total cost of producing hydrogen depends on production, liquefaction, storage and distribution costs [3,4]. Sherif et al. [5] provides some key data on economics of hydrogen production. Today approximately 9 billion kilograms of hydrogen are produced annually. More than 95% of the merchant hydrogen is used for industrial applications in the chemical, metals, electronics, and space industries. There are several methods used to produce hydrogen including natural gas reforming, electrolysis, liquid reforming, high-temperature electrolysis, photo-biological, and photo-electrochemical.

* Corresponding author. Tel.: +90 342 3172508; fax: +90 342 3601104.
E-mail address: kanoglu@gantep.edu.tr (M. Kanoglu).
[1] Visiting professor at American University of Sharjah during 2010–1011.
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2011.06.037

Steam–methane reforming accounts for 80% of the hydrogen produced. A number of existing and planned demonstration projects use electrolysis even though it is an energy intensive process for producing hydrogen. This is because electrolysis provides a pathway for producing hydrogen from renewable energy sources. This is accomplished when the electricity from solar, wind, geothermal, ocean and hydro technologies is used to produce and store hydrogen [6].

Despite the existence of numerous investigations on the use of renewable energy sources for hydrogen production, reports on using geothermal energy sources for hydrogen liquefaction are limited. Jonsson et al. [7] investigated the feasibility of using geothermal energy for hydrogen production and estimated that using geothermal energy could avoid 16% of the work consumption for electrolysis and 2% for liquefaction. Sigurvinsson et al. [8] investigated the use of geothermal heat for the high-temperature electrolysis (HTE) process. This process includes multiple heat exchangers and an electrolyzer based on solid oxide fuel cell (SOFC) technology. A set of relevant parameters were calculated using a techno-economic optimization methodology.

Mansilla et al. [9] performed a techno-economic optimization of the upper heat exchanger network in a high-temperature electrolysis process for hydrogen production. Heat is extracted by coupling the process either to a high-temperature reactor or to a geothermal source. Ingason et al. [10] investigated the most economical ways of producing hydrogen solely via electrolysis from water, using electricity from hydro and geothermal. The mixed integer programming model facilitates the search for optimal choices from 23 potential power plants, 11 of which are based on geothermal sources, and 12 are hydropower stations. In another report, the potential of geothermal resources of the western United States for producing electricity is investigated. This electricity would be used for the production of hydrogen [11]. Balta et al. [12], analyzed a high-temperature electrolysis process where geothermal water is used as the heat source.

The cost of electricity production from geothermal plants ranges between \$0.045/kWh and \$0.074/kWh. Once capital costs for the plant are recovered, the price of power can decrease to below \$0.05/kWh. The price of geothermal energy is within the range of water electricity choices available today when the costs over the lifetime of a plant are considered [13].

In hydrogen production, the most widely used commercial technology is alkaline water electrolysis. The mean electricity energy consumption in the electrolysis of water is about 50 kWh/kg hydrogen. The cost of electricity makes large-scale electrolytic production of hydrogen uneconomical compared with the steam–methane reforming method. Work is underway to improve the alkaline water electrolysis technology with an advanced alkaline electrolyzer that would increase cell efficiency somewhat and reduce the electricity requirement to about 43 kWh/kg [14].

Electricity prices have proven to be a major contributor to the overall hydrogen cost. Cost of hydrogen increases linearly with increasing cost of electricity. Based on reasonable efficiencies, an electricity cost of slightly less than \$0.10/kWh would be needed to produce and deliver central gaseous hydrogen that is cost-competitive [15].

Many research and development projects throughout the world are devoted to sustainable hydrogen production processes. To be sustainable, a hydrogen production process must be carried out without consumption of any raw materials other than water and be driven by forms of energy produced without greenhouse gas emissions. Low-temperature electrolysis driven by electricity produced from renewable energy sources satisfies these criteria. However, steam reforming of natural gas is currently less expensive than electrolysis driven by renewable-based electricity [16].

When hydrogen is produced by electrolysis, the necessary electricity input can be obtained from a geothermal power plant. The cost of producing electricity from a geothermal power plant depends on many factors. The more significant factors are cycle type (single- or double-flash, binary, flash/binary etc.), resource temperature, mass flow rate of geothermal water, and well cost. The other parameters include well spacing, well replacement rate, steam quality, non-condensable gas content, plant site, plant efficiency, and load factor. All of these parameters determine the economic value of a geothermal resource [17].

Kanoglu et al. [18] investigated the use of geothermal energy for hydrogen liquefaction. Three models were developed for the analysis including the use of geothermal electricity for liquefaction, the use of absorption cooling system for pre-cooling hydrogen gas, and a cogeneration option for which both geothermal electricity and geothermal heat are used. In a more recent study, Kanoglu et al. [19] developed four models for hydrogen production by geothermal energy and analyzed these models thermodynamically. In this paper, the seven models developed for using geothermal energy for hydrogen production and liquefaction are investigated economically.

2. Thermodynamic and cost analyses

In this section, we consider both ideal (reversible) and non-ideal (irreversible) operations for thermodynamic and cost analyses.

2.1. Reversible operations

The maximum specific work that can be obtained by a geothermal power plant utilizing a resource at temperature T_s in an environment at T_0 is given by

$$w_{\mathrm{rev,geo}} = c(T_s - T_0) - T_0 c \ln\left(\frac{T_s}{T_0}\right) \tag{1}$$

The reaction of water electrolysis is given by $H_2O + \text{Electrical work} \rightarrow H_2 + 1/2O_2$. The total energy required $H(T)$ is the sum of heat transfer $Q(T)$ and Gibbs function $G(T)$. The change in Gibbs function ΔG represents the reversible electrolysis work:

$$\overline{w}_{\mathrm{rev,elec}} = \Delta G(T) = \Delta H(T) - Q(T) \tag{2}$$

where $Q(T) = T\Delta S(T)$ and $\Delta H(T)$ is the standard enthalpy of the reaction at T.