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Thermoeconomic cost evaluation of hydrogen production driven by binary geothermal power plant

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ABSTRACT

Thermodynamic analysis and exergy based cost formation of hydrogen production by a water electrolysis process powered by a binary geothermal power plant is performed. The exergetic cost formation process is developed applying the specific exergy cost method (SPECO). For a geothermal resource temperature of 160 °C and a geothermal flow rate of 100 kg/s, hydrogen gas can be produced at a rate of 0.0253 kg/s in the electrolyzer. This corresponds to 0.253 g of hydrogen production per kilogram of geothermal water. Thermoeconomic cost analysis reveals that the unit exergetic costs of electricity and hydrogen produced in the system are 6.495 $/GJ (or 0.0234 $/kWh) and 19.7 $/GJ (or 2.366 $/kg H_2), respectively.

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1. Introduction

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 potential solution where it is available to some of the current energy and environmental problems, and a key resource for making society more sustainable (DiPippo, 1991). Geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy. Geothermal power plants tap certain high-temperature resources to generate electricity with minimal or no air emissions (Kanoglu and Cengel, 1999). Geothermal energy is a good renewable energy option for hydrogen production.

Various hydrogen production methods are available. Each method has a different cost structure and range of applications. One of the most reliable, current, and environmentally appropriate hydrogen production processes is water electrolysis. Water electrolysis in its simplest form uses an electrical current passing through two electrodes to break water into hydrogen and oxygen. Electricity input for the electrolysis process can be supplied from geothermal, nuclear, wind and solar energy sources.

Exergoeconomics is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations but crucial to the design and operation of a cost effective system. The plant owner wants to know the true cost at which each of the utilities is generated; these costs are then charged to the appropriate final products according to the type and amount of each utility used to generate a final product. Accordingly, the objectives of the thermoeconomic analysis are: (a) to calculate separately the costs of each product generated by a system having more than one product, (b) to understand the cost formation process and the flow of costs in the system, (c) to optimize specific variables in a single component, and (d) to optimize the overall system (Abusoglu and Kanoglu, 2009).

Kanoglu et al. (2010) 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 et al. (2012) 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 investigated.

Kanoglu et al. (2011) 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

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Nomenclature

A	annuity ($)
c	specific cost of exergy ($/kJ)
C	equipment purchased equipment cost ($)
$\dot{C}$	cost rate associated with exergy ($/h)
$\dot{C}_D$	cost rate of exergy destruction ($/h)
CC	carrying charges ($/year)
CRF	capital recovery factor
$\dot{E}x$	exergy rate (kW)
ex	specific exergy (kJ/kg)
EXC	expenditure costs ($/year)
f	exergoeconomic factor
h	enthalpy (kJ/kg)
i_{eff}	effective rate of return (%)
$\dot{m}$	mass flow rate (kg/s)
OMC	operating and maintenance costs ($/year)
PEC	purchased equipment cost ($)
P_m	present value of the payment ($)
r	relative cost difference (%)
s	entropy (kJ/kg K)
T	temperature (°C)
T_0	environment temperature (°C)
$\dot{W}$	power (kW)
$y_{\text{desk},k}$	component exergy destruction over total exergy input
$y^*_{\text{desk},k}$	component exergy destruction over total exergy destruction
$\dot{Z}^{\text{T}}$	cost rate associated with the sum of capital investment and O&M ($/h)
$\dot{Z}^{\text{CI}}$	cost rate associated with capital investment ($/h)
$\dot{Z}^{\text{OMC}}$	cost rate associated with OMC ($/h)

Greek symbols

η	energy efficiency
ε	exergetic efficiency
τ	capacity factor of plant operation

Subscripts

0	dead states
ACC	air cooled condenser
dest	destruction
D	destruction
e	exit state
en	energy
ex	exergy
Elec	electrolysis
F	fuel
geo	geothermal water
HE	binary cycle heat exchanger
IT	isobutane turbine
i	any stream
i	inlet state
k	any component
L	levelized cost ($/year)
P	product
P	pump
tot	overall system
WPH	electrolysis water preheater

Superscripts

·	time rate
CC	carrying charge
CI	investment cost
OMC	operating and maintenance

efficiencies were calculated. Heat exchanger network and high temperature electrolysis unit are primarily responsible for exergy destructions in the system. Yilmaz and Kanoglu (2014) investigated thermodynamic energy and exergy analysis of a PEM water electrolyzer driven by geothermal power for hydrogen production. The first and second-law based performance parameters were identified for the considered system and the system performance was evaluated. The effects of geothermal water and electrolysis temperatures on the amount of hydrogen production were studied.

Balta et al. (2009) and Balta et al. (2010) investigated various geothermal based hydrogen production methods using energy and exergy methods. Ratlamwala and Dincer (2012) focused on a comparative assessment of multi-flash geothermal power generating systems integrated with electrolyses through three definitions of energy and exergy efficiencies. According to Hand (2008), when the electricity from geothermal technologies is used to produce of hydrogen; the renewable source becomes more valuable and can meet a variety of needs.

Valdimar et al. (1992) presented a feasibility study exploring the use of geothermal energy for hydrogen production. They investigated a HOT ELLY high temperature steam electrolysis process operating between 800 and 1000 °C. Using the HOT ELLY process with geothermal steam at 200 °C can reduce the hydrogen production cost by approximately 19%. Árnason and Sigfússon (2000) described a path towards a future hydrogen energy economy in Iceland. Sigurvinsson et al. (2006) investigated the use of geothermal heat in high-temperature electrolysis (HTE) process. This HTE process includes heat exchangers and an electrolyser based on solid oxide fuel cell (SOFC) technology working in inverse, producing oxygen and hydrogen instead of consuming them. Using features related to the heat exchangers and the electrolyzers, a set of physical parameters was calculated using a techno-economic optimization methodology.

The studies on geothermal energy powered hydrogen production systems generally focus on the first and second law analysis of such systems. This study differs from our earlier papers (Yilmaz et al., 2012; Yilmaz and Kanoglu, 2014) in that conventional thermodynamic and economic evaluations of geothermal powered hydrogen production were previously investigated. This paper extends this coverage by studying the exergetic cost of produced hydrogen. This is a unique contribution to the science of renewable based hydrogen production as it helps an enhanced thermoeconomic understanding of the process. The exergetic cost evaluation of a high temperature electrolysis process in Kanoglu et al. (2011) involves a different system and process than the present one, also not including the costs of geothermal power production and associated components. In this paper, we provide the formulations including mass, energy and exergy balances, as well as exergy and cost parameter definitions. The procedure is applied to a hydrogen production system powered by a binary geothermal power plant. Also, we investigate the effect of geothermal water temperature on the unit cost of hydrogen.

2. System operation

Binary cycle geothermal power plants are similar to conventional fossil or nuclear plants in that the working fluid undergoes an actual closed cycle. As shown in Fig. 1, the working fluid, chosen for its appropriate thermodynamic properties, receives heat from the geofluid, evaporates, expands through a prime-mover, condenses, and is returned to the evaporator by means of a feed pump. These plants operate with a binary working fluid (isobutane, isopentane, pentane, R-114, etc.) that has a low boiling temperature. The working fluid is completely vaporized and usually superheated by the geothermal heat in the vaporizer. The vapor expands in the turbine,

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