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Thermoeconomic modeling and optimization of a hydrogen production system using geothermal energy

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ABSTRACT

Thermoeconomic optimization procedure is applied using genetic algorithm method to an integrated system composed of an alkaline water electrolysis unit for hydrogen production and a combined flash-binary geothermal power plant for providing power input to the electrolysis unit. The objective is to minimize the unit costs of the products (electricity and hydrogen production) of the composed system. The optimization approach is developed based on the cost optimal exergetic efficiency that is obtained for a component isolated from the remaining of the system components. Objectives to be optimized given certain constraints and variables are developed for each subcomponent of the system. Using genetic algorithm method of optimization, the variables, relative cost differences, and exergetic efficiencies with the corresponding optimal values are obtained. Thermoeconomic optimal values for product cost flow rate, fuel cost flow rate, unit cost of electricity, and unit cost of hydrogen production are calculated to be 2412 $/h, 289.4 $/h, 0.01066 $/kWh, and 1.088 $/kg, respectively, whereas the corresponding actual base case values are 2607 $/h, 295.9 $/h, 0.01105 $/kWh, and 1.149 $/kg, 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. Sustainable energy economy requires sustainable production of energy from renewable energy sources. One major problem with renewable energy sources is inability to store the produced energy in a viable manner. This is not a problem with biomass since the fuels produced from biomass such as ethanol and biodiesel can be stored and used anytime. However, the electricity produced from solar systems, hydroelectric dams, geothermal power plants, and wind turbines cannot be stored for later use. Batteries are not a viable option in today's technology due to their very limited capacity. One possible solution to this problem is production of hydrogen from renewable electricity by the electrolysis of water. Once produced, hydrogen can be stored and used anytime. Hydrogen is a clean energy carrier for renewable energies. Geothermal based hydrogen production is a potential pathway for a future hydrogen economy. Geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy to produce clean hydrogen technology. In some countries, with abundant amounts of geothermal energy, geothermal hydrogen has potential to become a major energy vector. Hydrogen is also a clean energy carrier for renewable energies. It stores and delivers energy in a usable form, but it must be produced from compounds that contain it (Yilmaz et al., 2015a,b). Electrolysis is a thermochemical process. It is essentially the conversion of electrical energy to chemical energy in the form of hydrogen, with oxygen as a useful by-product. The most common electrolysis technology is alkaline based, particularly in commercial applications (Rosen, 2010).

An economic analysis can calculate the fuel costs, investments, operation and maintenance costs for the overall system or even individual components but provide no means on how to allocate costs among them and its products. On the other hand, thermodynamic analysis can calculate the efficiency of the individual process of the system and can locate and quantify the losses and destructions but it cannot evaluate their significance in terms of the overall system production process. Accordingly, the claim of the thermoeconomic design and optimization analyses of geothermal hydrogen production system is given some considerations. These are: (a) calculating separately the fuel and product of each component generated by a system having more than one product, (b) understanding the efficiency and losses formation process and the flow of energy and exergy in the system, (c) optimizing specific variables in an individual equipment of system (d) optimizing the overall

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Nomenclatures

c	Specific exergy cost, \$/kJ
C	Cost associated with exergy flow, \$
CRF	Capital recovery factor
$\dot{C}$	Cost rate associated with exergy, \$/h
$\dot{E}x$	Exergy rate, kW
ex	Specific exergy, kJ/kg
f	Exergoeconomic factor, %
h	Enthalpy, kJ/kg
i	Interest rate, %
LHV	Lower heating value, kJ/kg
LC	Levelized cost, \$/yr
$\dot{m}$	Mass flow rate, kg/s
PEC	Purchased equipment cost, \$
r	Relative cost difference, %
s	Entropy, kJ/kg K
T	Temperature, °C
TTR	Total revenue requirement, \$
$\dot{W}$	Power, kW
y	Exergy destruction ratio over total exergy input
y^*	Component exergy destruction over total exergy destruction
$\dot{Z}$	Equipment cost rate, \$/h

Greek symbols

η	Energy efficiency
ε	Exergy efficiency
τ	Capacity factor of system
\$	United state dollars, US\$

Subscripts

0	Dead states
ACC	Air cooled condenser
CC	Carrying charge of system
elec	Electricity
F	Exergy of fuel
FC	Flash chamber
geo	Geothermal
HE	Heat exchanger
i	*i-th* stream
IT	Izobutane turbine
k	*k-th* equipment
D	Exergy destruction
P	Pump
P	Exergy of product
PH	Preheater
SP	Separator
ST	Steam turbine
tot	Overall system
WCC	Water cooled condenser

Superscripts

·	Time rate
CI	Investment cost
CC	Carrying charges
OC	Operation maintenance
N	Operating period, year

system energy and exergy destructions (Sayyadi and Nejatolahi, 2011). This calls for optimization of energy conversion systems, using thermoeconomic principles that combine thermodynamics and economic constraints, to supply best working system conditions. Application of optimization in a study is the process of finding the values of variables that give the minimum or maximum of the objective function of system working condition. When working with energy systems, the meaning of the word optimization is used in cases where the correct word is improvement and development of system performance (Wang et al., 2015).

Thermoeconomics can be viewed as the science of saving natural resources that connects physics and economics by means of the second law of thermodynamics. Thermal power plants are major examples of energy systems formed from a set of subsystems or processes. These systems interact with their environment, consuming some external resources, which are then transformed into products. The final purpose of this transformation is to increase the economic utility. The production process of a complex energy system can be analyzed in terms of its economic profitability and efficiency with respect to resource consumption (Lozano and Valero, 1993).

An introduction to thermoeconomics is given by Bejan and Tsatsaronis (1996). Thermoeconomic evaluations by Tsatsaronis et al. (1994), Valero et al. (1994), Frangopoulos (1994), d'Accadia and de Rossi (1998) represent some developments in this field. With regard to thermoeconomic optimization methodologies, Tsatsaronis and Park (2002) use an iterative technique of thermoeconomic performance improvement where the analyzer can take part in decision making in the optimization process. Valero (2006) has used the concept of assigning appropriate cost to each exergy flow, and thermoeconomic performance improvement of the system is done through local optimization of the subsystems. Calise et al. (2007) have used the functional decomposition of the system in thermoeconomic optimization of the systems. The major fields of application for thermoeconomic optimization are mainly large cogeneration and combined power plants and chemical plants.

There are many studies in the literature about using solar, wind and nuclear energies for hydrogen production but limited number of studies exists on using geothermal energy for hydrogen production. Geothermal energy appears to be an attractive solution to energy problem with the renewable sources for hydrogen production, its low production cost, and high efficiency. Next, we provide an overview of some of the more relevant studies in the literature about the hydrogen production by geothermal energy or heat.

Jónsson 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. (2007) investigated the use of geothermal heat in high-temperature electrolysis (HTE) process. This THE 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. According to Hand (2008), when the electricity from geothermal technologies is used to produce hydrogen, the renewable source becomes more valuable and can meet a variety of needs. Sigurvinsson et al. (2006) have analyzed the performance of electrolysis processes by operating at a high temperature. That can be a supply to a reduction in electricity consumption but requires a part of the energy necessary for the split of water to be in the form of thermal energy. It appears that even with a geothermal temperature as low as 230 °C, the HTE could compete with alkaline electrolysis. They have found that the final cost of producing hydrogen is 1.9 \$/kg H_2, and also alkaline electrolysis plant with a capacity of 0.4 kg/s can provide hydrogen at a cost of 1.8 \$/kg H_2. Mansilla et al. (2007) have conducted an economic opti-