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Hydrogen production by biogas steam reforming: A technical, economic and ecological analysis

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ABSTRACT

Fuel cells are electrochemical energy conversion devices that convert fuel and oxidant electrochemically into electrical energy, water and heat. Compared to traditional electricity generation technologies that use combustion processes to convert fuel into heat, and then into mechanical energy, fuel cells convert the hydrogen and oxygen chemical energy into electrical energy, without intermediate conversion processes, and with higher efficiency. In order to make the fuel cells an achievable and useful technology, it is firstly necessary to develop an economic and efficient way for hydrogen production. Molecular hydrogen is always found combined with other chemical compounds in nature, so it must be isolated. In this paper, the technical, economical and ecological aspects of hydrogen production by biogas steam reforming are presented. The economic feasibility calculation was performed to evaluate how interesting the process is by analyzing the investment, operation and maintenance costs of the biogas steam reformer and the hydrogen production cost achieved the value of 0.27 US$/kWh with a payback period of 8 years. An ecological efficiency of 94.95%, which is a good ecological value, was obtained. The results obtained by these analyses showed that this type of hydrogen production is an environmentally attractive route.

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Nomenclature

C_{BIOGAS}	Biogas cost (US$/kWh)
C_{FUEL}	Fuel cost (US$/kWh)
C_{OP}	Operational cost (US$/kWh)
C_{MAN}	Maintenance cost (US$/kWh)
CH_4	Methane "(-)"
CO	Carbon Oxide "(-)"
CO_2	Carbon dioxide "(-)"
$(CO_2)_e$	Equivalent carbon dioxide ($kg_{emissions}/kg_{fuel}$)
Cp	Specific heat at constant pressure (kJ/kg.K)
dH	Heat of formation (kJ/kmol)
E	Euler number "(-)"
E_{H2}	Power supplied by hydrogen (kW)
E_{fuel}	Power supplied by fuel (kW)
E_{biogas}	Power supplied by biogas (kW)
E_{STEAM}	Power supplied by steam (kW)
f	Annuity factor (1/year).
H	Equivalent period of operation (h/year)
h	Specific enthalpy (kJ/kmol)
H_2	Hydrogen "(-)"
H_2S	Hydrogen Sulfide "(-)"
H_2O	Water "(-)"
Inv_{REF}	Investment cost in hydrogen production system (US$)
k	Payback period (year)
K	Equilibrium constant "(-)"
Kp	Equilibrium constant in function of partial pressure "(-)"
LHV	Lower heat value (kJ/kg)
m	Mass (kg)
n	Moles number (mol)
Na	Reactant a moles number (mol)
Nb	Reactant b moles number (mol)
Nc	Product c moles number (mol)
Nd	Product d moles number (mol)
NO_x	Nitrogen oxide "(-)"
P	Pressure (atm)
PM	Particulate matter "(-)"
P_0	Pressure at reference state (atm)
Q_i	Fuel low heat value MJ/kg
R	Universal gas constant (kJ/kmol.K)
r	Annual interest rate (%)
SO_2	Sulfur dioxide "(-)"
T	Temperature (°C)
T_0	Temperature at reference state (K)
T_2	Reforming temperature (K)
y_i	Molar fractions of gaseous components "(-)"

Greek letters

α	Advance degree "(-)"
η	Efficiency (%)
ΔG^0	Gibbs energy variation (kJ/kmol)
ΔH^o	Enthalpy change (kJ/kmol)
ΔS^o	Entropy change (kj/kmol.K)
π_g	Pollutant indicator (kg/MJ)
ε	Ecological efficiency (%)

1. Introduction

Successive crises in energy and global warming have been instigating the study for more efficient technologies and renewable sources of electricity generation. In this context, fuel cell has got particular attention. The great interest in hydrogen as an energetic carrier has been increasing, due to its high heating value and the low environmental impact of its use as fuel. The hydrogen can be used to generate electricity by a fuel cell and contributes to increase the distributed generation of energy, and to reduce emissions of pollutants into the environment. This energetic carrier does not directly emit pollutants, but it leads to indirect emissions, since it is found combined with other chemical compounds in nature, thus requiring energy to be isolated and, consequently, releasing pollutants into the environment.

Among several hydrogen production processes, the steam reforming process, using natural gas, is widely used in chemical industries, and it is responsible for 50% of the hydrogen produced in the world [1]. The biogas can be an alternative raw material to conventional steam reforming technology. Biogas is similar to the natural gas, and has included additional benefits such as it is a renewable resource, it reduces emissions by preventing methane release in the atmosphere (methane is 21 times stronger than carbon dioxide as a greenhouse gas), and it is commercially produced in large quantities in anaerobic digesters and landfill gas recovery facilities designed to treat bio-wastes such as manure, sewage, energy crops, and organic matter. The biogas production also reduces landfill waste and produces nutrient-rich fertilizer as by-product [2].

The reform process consists in two reactors (reform reactor and shift reactor). In the reform reactor occur the catalytic reforming reactions of hydrocarbons, like methane, naphtha or ethanol with water (pre-vaporized by a steam generator). The products of these reactions are H_2 (main objective of the reform) and CO. In the shift reactor all CO produced in the reform reactor, react with water steam. The products of this reaction are H_2 and CO_2. So, in the end of the reform process, the main products are hydrogen (H_2) and carbon dioxide (CO_2) [3,4]. Based on this background the feasibility of the hydrogen production by biogas steam reforming process stands out in this paper.

2. Biogas steam reforming technical analyses

In the physicochemical analysis of biogas steam reforming, some calculations involving chemical and thermodynamics functions were performed, which made possible to find the optimum pressure and temperature of the reforming reaction, in order to optimize the construction of the reformer prototype.

The analysis was based on the biogas obtained by the bovine manure biodigester located at the Laboratory of Optimization of Energy Systems (LOSE-UNESP); after the purification process, the composition of biogas was 75.7% of CH_4, 24.3% of CO_2.

The biogas reform, according to the literature [5,6], was considered to be the methane steam reforming and the methane dry reforming (in the reform reactor, before of shift reactor) as the following reactions:

$$CH_4+H_2O \rightarrow CO+3H_2 \text{ (methane steam reformer)} \tag{1}$$

$$CH_4+CO_2 \rightarrow 2CO+2H_2 \text{ (methane dry reformer)} \tag{2}$$

Considering 100 g of biogas (75.7 g of CH_4 and 24.3 g of CO_2) and that all CO_2 reacts in the dry reform, it was found that 8.83 g of CH_4 react in dry reform. So, considering that the CH_4 total is 75.7 g, the quantity of this component that reacts in the steam reforming is 66.9 g. Thus, the final reaction of biogas is composed of 66.9% of