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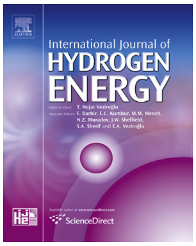

Life cycle assessment of hydrogen production from biogas reforming

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ABSTRACT

A H_2 production system via biogas reforming was comprehensively investigated by life cycle assessment (LCA), after identification of the optimal thermodynamic operating conditions computed from a detailed analysis of the involved chemical reactions. The system boundaries for the LCA include biogas production, biogas reforming as well as construction and decommissioning steps. The biogas production data are adapted from a literature review, whereas the reforming inventory data are obtained from process simulation in Aspen Plus™ software. The life cycle inventory data for the H_2 system are computationally implemented into SimaPro 8. Different environmental impact categories, following the ILCD 2011 midpoint impact assessment method, were calculated. An energy analysis is also carried out, based on cumulative energy demand and on non-renewable primary energy consumption as additional impact categories.

The results obtained show that the total greenhouse gas emissions of the system are estimated to be 5.59 kg CO_2-eq per kg of H_2 produced, which represents about half of the life cycle GHG of conventional H_2 production systems via steam methane reforming. Most environmental impacts are influenced by the amount of artificial fertilizer displaced by the digestate as well as by the impact credits for recycling of the plant construction materials and equipment. Overall, the LCA of the biogas-to-H_2 system shows very advantageous results. Accordingly, the authors recommend the use of biogas as an ecofriendly source for sustainable H_2 production.

Introduction

Rising concerns about the effects of global warming and gradual depletion of non-renewable fossil fuels have led to increasing interest in H_2 for fuel cell (FC) applications owing to their zero emission and high efficiency [1]. However, more

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Nomenclature

AD	anaerobic digestion
ADP	abiotic depletion potential
AP	acidification potential
BG	biogas
Bioeth-ATR-H_2	H_2 production by bioethanol auto-thermal reforming
Bioeth-SER-H_2	H_2 production by bioethanol steam reforming
Biom-gasi-H_2	H_2 production by lignocellulosic biomass gasification
C&D	construction and decommissioning
CED	cumulative energy demand
DMR	dry methane reforming
Electro-H_2	H_2 production by electrolysis
FAO	food and agriculture organization
FC	fuel cells
FEP	freshwater eutrophication potential
FETP	freshwater eco-toxicity potential
FU	functional unit
GHG	greenhouse gas
HTPce	human toxicity with cancer effects
HTPnce	human toxicity with non-cancer effects
HTS	high temperature shift
IRP	ionising radiation potential
ISO	international organization for standardization
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LHV	lower heating value
LTS	low temperature shift
LUP	land use potential
MEP	marine eutrophication potential
NER	net energy ratio
NG	natural gas
NRE	non-renewable energy requirement
ODP	ozone depletion potential
PMP	particulate matter potential
POF	photochemical ozone formation
PSA	pressure swing adsorption
SALCA-P	Swiss agricultural life cycle assessment-Phosphorus
SB	system boundaries
SETAC	society of environmental toxicology and chemistry
SG	synthesis gas
SMR	steam methane reforming
TEP	terrestrial eutrophication potential
W	mechanical work
WGS	water gas shift
WRD	water resource depletion
η	thermal efficiency

than 50% of the world's total H_2 production is derived from steam methane reforming (SMR) of natural gas (NG) [2]. SMR is a mature and cost effective technology which uses fossil fuel as a feedstock so the amount of CO_2 formed would be the same as that formed by direct combustion of the fuel (NG) [3]. For instance, greenhouse gas (GHG) emission of H_2 production via SMR process is estimated as 13.7 kg eq. CO_2 per kg of net H_2 produced [4]. Also, a typical SMR plant with a capacity of one million m^3 of H_2 per day produces about 0.3–0.4 million standard cubic meters of CO_2 per day [4]. In order to help reduce global warming, the use of raw materials and energy from renewable sources should lessen GHG emissions. A palliative way to achieve this goal would consist in reducing the current use of NG in favor of biogas (BG).

BG is the product of the anaerobic digestion (AD) of organic residues from several origins (sewage sludge, food waste, animal manures, crop residues, etc.) and it is basically composed of methane, carbon dioxide and minor species such as hydrogen sulphide, ammonia, humidity, etc. [5]. BG can be directly used as a combustible gas; however, the combustion process of BG to generate heat has a low efficiency. In fact, humidity and CO_2 content of the BG, which dilutes the intake charge, limit the engine peak power due to the decrease in the calorific value of the fuel [6]. As a special case, BG could be used to produce H_2 which would be then supplied to FC [7,8], which reached remarkable progress during the past decade. The utilization of BG as a feedstock for a reforming process to produce H_2 offers several advantages; (i) it is a bio-renewable fuel and can reduce the emission of GHG, (ii) it is easily generated from available local agricultural wastes and residues and (iii) contrarily to combustion, the presence of CO_2 and humidity in BG are advantageous for converting BG into H_2 via steam and dry reforming reactions. In this context, the use of BG as a renewable resource for producing H_2 has been widely investigated in recent years [7,9–11]. Lately, Castillo et al. [11] conducted a steam reforming reaction of a BG mixture with an H_2 permeable palladium–silver membrane reactor under temperatures between 350 and 450 °C and with of reaction side pressure of 0.1–0.4 MPa. The authors showed that, in the experiment, the reaction with permeation achieved a higher H_2 production than the reaction without permeation in identical operational conditions. Iulianelli and co-workers [7] studied the steam reforming of a model BG mixture for generating H_2 by using an inorganic membrane reactor, in which a composite Pd/Al_2O_3 membrane separates part of the produced H_2 through its selective permeation. The authors show that the BG steam reforming reaction, at 380 °C, 2.0 bar, $H_2O/CH_4 = 3/1$, gas hourly space velocity (GHSV) of 9000 h^{-1} the permeate purity of the recovered H_2 is around 96%, although the conversion (15%) and H_2 recovery (>20%) are relatively low; on the contrary, at 3.5 bar, 450 °C, $H_2O/CH_4 = 4/1$, GHSV = 11,000 h^{-1} the conversion increases up to more than 30% and the recovery of H_2 to 70%.

The production of H_2 produced from BG claims to be an environmentally sustainable system. However, significant efforts are still required for its production system to be evaluated from a comprehensive environmental point of view. Currently, life cycle assessment (LCA) is a well-known and widely used method to assess the potential environmental impacts and resources used throughout the entire life cycle of a product or process, including raw material acquisition, production, use, and end-of-life phases as defined by SETAC and coded by ISO 14040 standards [12]. LCA has become an important decision-making tool for promoting new alternative fuels since it can systematically analyse energy use and