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Thermodynamic feasibility and life cycle assessment of hydrogen production via reforming of poultry fat

Noureddine Hajjaji [a,*], Ammar Houas [a,b], Marie-Noëlle Pons [c]

[a] Unité de Recherche Catalyse et Matériaux pour l'Environnement et les Procédés URCMEP (UR11ES85), Ecole Nationale d'Ingénieurs de Gabès, Faculté des Sciences de Gabès, Université de Gabès, Rue Omar Ibn Alkhattab, 6029 Gabès, Tunisia

[b] Al Imam Mohammad Ibn Saud Islamic University (IMSIU), College of Sciences, Department of Chemistry, Riyadh 11623, Saudi Arabia

[c] Laboratoire Réactions et Génie des Procédés – CNRS, Université de Lorraine, 1, rue Grandville, BP 20451, 54001 Nancy Cedex, France

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ABSTRACT

This study aims at contributing to the area of bio-based hydrogen production system development. A hydrogen production system via autothermal reforming of poultry fat was comprehensively investigated by life cycle assessment, after identification of the optimal thermodynamic operating conditions obtained via a detailed analysis of the involved chemical reactions. In the life cycle assessment, the system boundaries include reforming and rendering along with the required transportation processes. The rendering data are adapted from a literature review, whereas the reforming inventories data are derived from the process design and simulation of the entire hydrogen production process in Aspen Plus™ software. The life cycle inventories data for the hydrogen system are computationally implemented into SimaPro 7.3. Six relevant environmental impact categories are evaluated based on the CML baseline 2000. An energy analysis is also carried out based on cumulative energy demand and cumulative exergy demand as additional impacts categories. The life cycle assessment results are subjected to a systematic sensitivity analysis and compared to those achieved by other routes used for hydrogen production.

The results show that poultry fat is a promising option for renewable hydrogen production considering the high productivity achievable with poultry fat (148.5 mol H_2/kg of poultry fat); however, minimization of the heat requirement of the process is highly recommended to improve the system energetics and environmental performance.

1. Introduction

The nations want to minimize their losses of resources (biotic, abiotic and economic) and fight against the causes of these losses. As a result, alternative energy sources have been a hot topic of investigation for researchers worldwide. Finding clean, more secure and diversified energy sources could be a successful strategy to reduce and eliminate greenhouse gas (GHG) emissions and to meet the world's energy needs. Compared to other alternatives, fuel cell H_2 for vehicles application is considered an important energy carrier which could be used to reduce environmental impact and dependence on imported oil. In fact, H_2 is the only carbon-free fuel to produce only water as combustion by-product. Furthermore H_2 has the highest energy content compared to gaseous fuels of equivalent weight (Kotay and Das, 2008). Therefore, stakeholders in Japan, USA, India, China, and several European countries are investing heavily in H_2 related research, development and demonstration projects. For instance, for a period of 28 years, ending in 2020 Japan have allocated about $11 billion to develop basic technologies for achieving a H_2 based energy economy (Fernandes et al., 2005).

Although H_2 seems to be the perfect alternative fuel, there is currently no real environmental benefit from H_2 use, because most of it is produced from fossil fuels (Chatzitakis et al., 2013). In fact, more than 95% of the H_2 produced in the world comes from fossil fuels, with serious ecological and environmental consequences (Abanades et al., 2013). For example, the global warming potential (GWP) of H_2 production by the steam methane reforming (SMR) process is estimated as 13.7 kg CO_2 eq. per kg of H_2 produced (Muradov and Veziroğlu, 2005). A typical SMR-H_2 plant with a capacity of one million m^3 of H_2 per day creates approximately 0.3–0.4 million cubic meters (STP) of CO_2 per day, which is

* Corresponding author. Tel.: +216 24 04 04 00; fax: +216 75 29 00 41.
E-mail address: Hajjaji.nour@gmail.com (N. Hajjaji).

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Nomenclature

ADP	abiotic depletion potential
AF	animal fats
AFBD	animal fat-based biodiesel
AP	acidification potential
ATR	autothermal reforming
Bioeth-ATR-H_2	H_2 production by bioethanol autothermal reforming
Bioeth-SER-H_2	H_2 production by bioethanol steam reforming
Biom-gasi-H_2	H_2 production by lignocellulosic biomass gasification
CED	cumulative non-renewable fossil and nuclear energy demand
CFM	crude fatty materials
CLR	chemical looping reforming
COPROX	carbon monoxide preferential oxidation
EP	eutrophication potential
GHG	greenhouse gas
GWP	global warming potential
HTS	high temperature shift
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LTS	low temperature shift
LHV	lower heating value
m	mass flow
ODP	ozone layer depletion
O/C	oxygen to carbon ratio
P	pressure
POFP	photochemical oxidant formation
POX	partial oxidation
Q	heat duty
SG	synthesis gas
SMR	steam methane reforming
SMR-H_2	H_2 production by steam methane reforming
SR	steam reforming
S/C	steam to carbon ratio
T	temperature
VO	vegetable oil
WGS	water gas shift
$\eta_{Thermal}$	thermal efficiency
$\alpha_{H2,\ renewability}$	hydrogen renewability ratio

normally released into the atmosphere (Muradov and Veziroğlu, 2005). This huge amount of GHG emissions generates some critical doubt as to whether H_2 is the right solution to energy-related environmental, security and sustainability issues or not. Therefore, H_2 derived from fossil fuels appears to have a limited horizon, and the development and implementation of new methods for sustainable H_2 production are indispensable. Unfortunately, H_2 produced from biorenewable feedstocks could be unsustainable considering the environmental damage generated by the entire system applied for its extraction. In fact, according to a previous study, Hajjaji et al. (2013a) showed that bioethanol-to-H_2 systems have harmful environmental effects due to the environmental impacts of agricultural activities for wheat grain production and due to the large amount of heat (i.e., fuel consumption and emissions) required for the bioethanol production process (during distillation, drying, etc.). Therefore, examining resource consumptions, energy requirements and emissions from a life cycle point of view gives a comprehensive picture of the environmental burdens associated with H_2 production (Spath and Mann, 2004). Clearly, the benefits of a true H_2 economy can only be achieved if the H_2 is derived from renewable resources with a sustainable process.

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 (Abdul Hadi et al., 2013). In the last few years, LCA methodology has been used by several authors to evaluate the environmental performance of H_2 systems (Dufour et al., 2012; Kalinci et al., 2012; Cetinkaya et al., 2012; Hacatoglu et al., 2012; Biswas et al., 2013).

In the EU, approximately 17 million tons of slaughter byproducts are produced by the meat industry every year (Woodgate and van der Veen, 2004). From this raw material, over 1.5 million metric tons of animal fat (AF) and three million metric tons of protein are produced annually (Woodgate and van der Veen, 2004). Generally, AF constitutes about one third to one half of the total animal mass (Meeker, 2009). Like vegetable oil (VO), AF is primarily composed of triglycerides and minor amounts of mono and diglycerides. A triglyceride molecule consists of a three-carbon glycerol head group conjugated to three fatty acid chains (Dale et al., 2008). The fatty-acid carbon-chain lengths vary between 4 and 24 carbon atoms with up to six double bonds. A total of 24.64 million tons of animal fats were produced worldwide in 2007 (Lam et al., 2009). Considering this huge amount, the valorization of these renewable and cheap fatty materials remains necessary. The use of AF as a food additive has declined due to changing feeding habits, and the use of AF in animal feed has strongly decreased due to the possibility of severe animal disease (Dias et al., 2009). Recently, however, animal fat wastes have received significant attention for the production of biodiesel all around the globe (Banković-Ilić et al., 2014; Ito et al., 2012; Jørgensen et al., 2012). Animal fat-based biodiesel is a sustainable source of fuel with properties very similar to biodiesel produced from vegetable oil (Goodrum et al., 2003). Nevertheless, there are some differences; the main difference is that animal fat-based biodiesel (AFBD) contains more saturated fatty esters (Teixeira et al., 2010). AF as a biodiesel feedstock has some advantages and disadvantages. AFBD has a higher cetane number than VO biodiesel, which means that AFBD is cleaner and burns more efficiently in diesel engines (Dale et al., 2008). However, AFBD has a higher cloud point because of the high levels of saturated fatty acids. Its higher cloud point means that AFBD tends to crystallize out at low temperatures, creating problems in engines. In the past few years, some researchers have turned their interest toward fatty material-based (VO and AF) H_2. Various processes were theoretically and experimentally proven by many research groups (Marquevich et al., 2001; Pimenidou et al., 2010a, 2010b; Yenumala and Maity, 2011; Hajjaji et al., 2013b; Hajjaji and Pons, 2013) to be a promising alternative for H_2 production. Pimenidou et al. (2010a) used a chemical looping reforming (CLR) route for H_2 production from waste cooking oil in a packed bed reactor and showed that a steam to carbon ratio of 4 and temperatures between 600 and 700 °C yielded the best results. Hajjaji and Pons (2013) investigated H_2 production via steam and autothermal reforming (ATR) of beef tallow, showing that optimum