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Energy Sustainability Analysis of distributed H_2 production

Carlos E. Gómez Camacho, Giorgia Lombardelli, Raffaele Pirone, Bernardo Ruggeri(*)

DISAT, Dep. Applied Science and Technology, Politecnico di Torino,
C/so Duca degli Abruzzi 24, 10129 Torino Italy

**Corresponding author: bernardo.ruggeri@polito.it*

Highlights

- H_2 production by: reformer, electrolysis and dark fermentation at lab scale were tested
- The systems were operated for about one year to acquire all the energy flows
- Energy sustainability analysis of three system by *ESI, EROI* and *EPT* was carried out
- Dark fermentation for H_2 production resulted non-sustainable

1. Introduction

The perspective for H_2 as an energy carrier to decarbonize energy services highlights the relevant role of hydrogen production technologies. As matter of fact, the yearly majority (> 95%) of H_2 is produced from fossil fuels by steam reforming or partial oxidation of methane with only a small quantity by other routes, such as biomass gasification or electrolysis of water, hence the need to explore new routes to produce H_2 seems evident. Stringent is to explore different technologies even at the infancy state, to produce hydrogen using different sources and process configurations. In this respect, the energy sustainability analysis of H_2 production aimed to score technologies is of utmost of importance. This study encompasses the evaluation of different indexes: Energy Sustainability Index (*ESI*), Energy Return of Investment (*EROI*) and Energy Payback Time (*EPT*) which permit to score technologies towards a rational energy-sustainability perspective. To this end, three of the most advanced processes for distributed H_2 production were experimentally tested: *i)* steam reformer (SR) of methane using a lab reformer, *ii)* electrolysis of water by using electrical energy produced by silicon photovoltaic (PV) panel and *iii)* dark fermentation (DF) of organic waste (OW) by mixed microorganisms - Hydrogen Producing Bacteria (HPB) - mainly *Clostridium* spp. The three technologies were tested at laboratory scale for about one year, including the SR owing the necessity to test the feasibility to produce hydrogen at "*the point of use*", rather than trying to distribute it. Even though methane SR is the most consolidated technology for H_2 production at large scale, at minor scales it requires additional research and development efforts to be successfully scaled-down for distributed production. As concerns the electrolysis of water, the siliceous PV technology was selected because it is the most mature in the panorama of solar radiation conversion. The state-of-the-art of bio-H_2 production includes many options among heterotrophic and autotrophic microorganisms, and the choice of DF even at pilot scale technology level, is due to its advantages compare to other technologies : *1)* reactions do not require light, so hydrogen is produced throughout the day and night, *ii)* the liquid end product of DF well-stocked of organic compounds, can be used as feedstock for Anaerobic Digestion (AD) to produce CH_4 with additional energy produced, and *iii)* because the abundance of OW (> 70% of wastes) and its uniform distribution, hence it represents one of the most available *proximity* energy resources. The data acquired by experimental campaigns were used to evaluate and scoring the energy sustainability of the three processes by the application of a previous candidate procedure [1]. The procedure consists into different steps: a first screening is performed by using the Energy Sustainability Index (*ESI*), which considers the Produced Energy under form of hydrogen referred to the direct spent energy (heat and electricity). Only the process with (*ESI* > 1) merits to be analyzed in more detail by the evaluation of *EROI* and *EPT* indexes to estimate the Useful Energy. In the second step, through the support of the Analogical Model of the technology the quantification of chemicals, materials, energy for the maintenance and all the Indirect Energy terms with a Life Cycle Approach (LCA) were estimated. In this step the energy embedded in the feeds, i.e. methane and water were evaluated for the steam reformer and the electrolysis process, respectively, while for the DF process instead, the energy embedded in OW was assumed to be equal to zero, following the common allocation procedures in LCA analysis. The procedure is a useful tool to score the three processes towards sustainability: higher *EROI* and low *EPT*, correspond to higher sustainable technology, while the revers corresponds to low energy-sustainability performances.

2. Methods

Laboratory tests on 10 kW (H_2) steam reformer (SR), corresponding about 56 NL_{H2}/min, for about 1 year were conducted. The device is very compacted: all the reactors (ST, water gas shift WGS and two preferential oxidation reactors PROX1 and 2) are inserted in only one structure of about 80x8x10 cm. The system was fueled with the CH_4 furnished by city grid distribution. Instead, the tested electrolyzer was of 14 kW of power supplied by electrical energy furnished by an assembly of PV panel of about 16 kW of power; the system could produce max 1.23 Nm^3/h of H_2. A long tests campaign (about 1 year) was conducted in order to evaluate the performances of the PV systems under different solar irradiation intensity, assessing mean values of produced energy. DF tests were conducted using two bench scale bioreactors of 2 L and 14 L in series, the first for H_2 production and the second for CH_4 production, respectively, as already described in reference [2]. The system was operated in continuous mode, fed with fruits and vegetables local market refuses. The plant was operated at mesophilic condition (35 °C) under different process conditions: for the H_2 producing bioreactor a retention time (HRT) of 1.5 day and stirring of 250 rpm were set, while the CH_4-producing one operated at 15 days of HRT and 70 rpm in order to assure different microorganisms consortium in each bioreactor.

3. Results and discussion

The three different systems were operated for about 1 year under different operational conditions to acquire all the necessary energy data to evaluate the *ESI*. Table 1 reports the values of the different evaluated indexes. As concerns the *ESI* evaluation, which is the ratio of the obtained energy on the direct energy expenditure, in the case of SR, the CH_4 was computed as reactant as well as energy sources to heat the system. In all the three cases, the water consumption was evaluted in terms of the energy expenditure to produce it and, in addition, in the case of the electrolyzer the required energy expenditure to obtain the distillate water was also taken into account. For all three cases, the energy expenditure to produce the materials, as well as the energy expenditures to build the plants were computed in energy terms.

Table 1. Energy Performances of different H_2 producing systems.

H_2 Production System	***ESI*** **[dimensionless]**	***EROI*** **[dimensionless]**	***EPT*** **[yr]**
CH_4 steam reforming	1.3	2.5	12
PV supplied electrolyser	3.8	5.2	5
Dark Fermentation (H_2)	0.7	0.8	30
Dark Fermentation + Anaerobic Digestion (H_2+CH_4)	2.2	3.5	7

The energy expenditure to produce the energy sources was computed only in the case of CH_4, while in the cases of solar energy and OW following the allocation methodology of LCA it was assumed to be equal to 0. As it can be seen from Table 1, the H_2 produced by PV supplied electrolyser is the most energy sustainable system with an *EROI* of 5.2, as second one the CH_4 via SR, while the hydrogen produced by DF is not sustainable at all since obtained values of *ESI* and *EROI* are lesser than 1. Instead, the system that considers an energy valorization of the residue of DF via Anaerobic Digestion (AD) to produce additional energy under form of CH_4, becomes sustainable.

4. Conclusions

Dissimilar technologies at reduced scale, as representative of distribute H_2 production near the point of utilization, using different energy sources, were analyzed and scored using an energy sustainability approach via the evaluation of different indexes. The tested energy sources were: CH_4, solar radiation and Organic Wasted. The PV plus electrolyzer technology is the most sustainable technology while the DF hydrogen production is unsustainable. In this latest case, considering utilizing the residues of DF as feed for AD technology, the summation of DF plus AD technology reaches a very high energy sustainability level.

References

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Keywords
"Hydrogen production" "EROI, EPT, ESI" "energy sustainability analysis"