INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 7190–7201

Available online at www.sciencedirect.com

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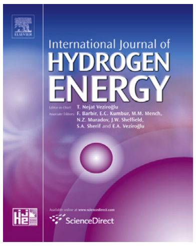

Life cycle assessment of the electrolytic production and utilization of low carbon hydrogen vehicle fuel

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ARTICLE INFO

Article history:
Received 23 September 2013
Received in revised form
31 January 2014
Accepted 7 February 2014
Available online 4 April 2014

Keywords:
Hydrogen
Electrolysis
Wind
Photovoltaic
LCA
Vehicle fuel

ABSTRACT

Environmental burdens associated with small scale (40 L hydrogen per minute) production of hydrogen fuel using electrolysis powered by electricity generated from stand-alone wind turbines (30 kW), stand-alone photovoltaic panels (3 kW peak) and UK grid electricity (current and future) has been undertaken. Utilization of fuel within a proton exchange membrane fuel cell passenger vehicle was included and compared to the operation of a petrol vehicle, a fuel cell vehicle fuelled with non-renewable hydrogen, and an electric (battery only) vehicle. The *production* of renewable hydrogen from wind energy incurs increased climate change burdens compared with extraction and processing of fossil petrol (0.09 mPt compared with 0.07 mPt). However, lower burdens for fossil fuel (1.85 mPt) and climate change (0.26 mPt) are realised by the renewable hydrogen options compared with petrol (4.44 mPt and 0.44 mPt, respectively) following *utilization* of the fuel due to lower emissions at end use. Utilizing a combination of renewable hydrogen fuelled vehicles and grid powered electric vehicles was considered to be a viable option for meeting UK policy ambitions.

Introduction

Hydrogen can be produced by passing an electrical current through pure water within an electrolyser, with hydrogen liberated at the negatively charged cathode and oxygen liberated at the positively charged anode. The ability to utilize primary electrical energy from renewable sources such as wind turbine or photovoltaic derived electricity to drive this process raises the potential to produce hydrogen (and oxygen) via low carbon, fully scalable distributed points. One potential future application of the process is to generate hydrogen vehicle fuel on a local or regional basis, either at the point of fuel distribution (i.e. the service station) or at a regional 'hub' for distribution to a number of local refuelling facilities.

State of the art industrial electrolysis includes the use of alkaline electrolysers and, increasingly, proton exchange membrane (PEM) electrolysers. These have a nominal hydrogen production efficiency of around 70–80% [1] although some configurations of renewable energy technologies and PEM electrolysers can have higher energetic efficiencies within limited operational ranges [2]. Therefore, there is still a strong argument at present to dedicate renewable technologies such as wind turbines to direct electricity production as

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http://dx.doi.org/10.1016/j.ijhydene.2014.02.044

only transmission losses of around 1.6% [3] are incurred and overall energy output is maximised. However, as the deployment of renewable technologies becomes more widespread in the future, the ability to combine hydrogen generation with electricity generation becomes a more realistic prospect [4,5], in particular to avoid the curtailment of wind electricity production during times of high wind speeds and/or low electricity grid capacity. The majority of nations are attempting to increase the proportion of electricity generated using renewable technologies; the UK Government plans to generate 50% of grid electricity using renewable technologies by 2050 [6] which raises the prospect of using this low carbon grid electricity for the production of hydrogen vehicle fuels.

An exergy based LCA of hydrogen production and storage technologies was undertaken by Neelis et al. [7], which found that electrolysis driven by grid electricity incurred the most environmental burdens whilst wind driven electrolysis incurred the least. Gaseous hydrogen storage (340 bar) was also found to minimise environmental burdens compared with liquefaction. A similar conclusion that wind driven electrolysis was a favourable option was reached by Koroneos et al. [8] and Khan et al. [9]. Spath and Mann [10] demonstrated that the production of the wind turbine itself incurred the most significant environmental burdens for this option. Granovskii [11] undertook a detailed exergetic LCA of hydrogen production using renewables which again found that wind and PV driven hydrogen production systems could deliver reductions in environmental burdens, but were not cost effective compared to fossil fuel alternatives. When considering GHG emissions it was found that utilizing primary renewable energy sources (e.g. wind turbines, PV) for electricity production rather than for fuel production was a more cost effective option unless fuel cell efficiency was double that of a fossil fuel internal combustion engine [12]. Lee et al. [13] reached a similar conclusion that wind driven electrolytic hydrogen production could deliver reductions in environmental burdens compared to fossil alternatives, but that using grid electricity (in South Korea) as the primary energy source was more cost effective. The relatively well understood process of renewable energy driven electrolysis also performed comparably in terms of GHG emissions when compared to a number of novel, but as yet unproven, technologies such as two step thermochemical water splitting [14,15].

This study aims to determine the environmental burdens associated with the electrolytic production of hydrogen using renewable technologies (wind and PV power) under UK conditions as compared with the electrolytic production of hydrogen using UK grid electricity. The effect of the future greening of the UK grid electricity mix was investigated by using a forecast UK grid mix for 2030, based on the projected pathways included in analysis by the UK Department for Energy and Climate Change (DECC) [16]. Hydrogen produced is utilized in a PEM fuel cell powered electric passenger vehicle. The fuel production and utilization pathways were compared with the reference scenarios of the use of petrol as a vehicle fuel, the production of hydrogen using conventional steam methane reforming followed by utilization in a PEM fuel cell vehicle, and the utilization of grid electricity in a battery powered electric vehicle.

Methods

Environmental burdens were quantified using a Life Cycle Assessment (LCA) approach undertaken in accordance with European guidance [17,18] using SimaPro v7.3 software (PRè Consultants b.v.). Whilst the renewable hydrogen production systems considered here are being trialled and researched at the Hydrogen Research Centre, University of South Wales, relatively little inventory data is available for individual components. As such, data has largely been sourced from literature as shown below. The Ecoinvent database (a widely used database of life cycle inventories) has also been utilized as indicated below.

Function and functional unit

The product system considered was the electrolytic manufacture of a compressed hydrogen vehicle fuel and its utilization in a fuel cell passenger vehicle. The function of the system was therefore to achieve the transportation of a passenger and the functional unit was 100 passenger km (100 pkm). This functional unit also allowed comparison between differing fuel and vehicle options.

System boundary

The processes considered in this study are shown in the system boundary diagram (Fig. 1). The major energy and material inputs as well as environmental emissions have been included for each sub process in the model. The aim of the study was to compare renewable hydrogen fuel with non renewable hydrogen, and to benchmark these against a liquid fossil fuel. A comparison with grid powered electrical vehicles using both current and future electric production mix was also included. Burdens associated with the decommissioning of the primary energy systems, service infrastructure or vehicles were not included due to their negligible impact compared with the energy and material flows associated with the production and operational phase of the systems [19].

Allocation procedures

It was assumed that hydrogen was the only product from the electrolytic conversion of water. Whilst the economic and environmental performance of electrolytic hydrogen is likely to be improved if the co-produced oxygen could also be utilized, this was not considered feasible at the small scale considered in this study. The oxygen produced was therefore included as an emission to atmosphere rather than a co-product and as such no allocation procedures were required.

LCIA methodology

Eco-indicator 99 H/A [20] was chosen as an appropriate impact assessment methodology as it concisely considers end point damage to relevant categories such as human health (including climate change), resources (including fossil fuels) and ecosystem quality. Following the calculation of damage factors for different impact categories, results were normalised at the