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Delving into sensible measures to enhance the environmental performance of biohydrogen: A quantitative approach based on process simulation, life cycle assessment and data envelopment analysis

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HIGHLIGHTS

- Combined life cycle assessment, data envelopment analysis and process simulation.
- Case study: hydrogen production via indirect gasification of grape pruning waste.
- Operational benchmarking at the biomass cultivation stage.
- Reductions of 45–73% in the consumption of operational inputs.
- Operational benchmarks significantly improve the life-cycle profile of biohydrogen.

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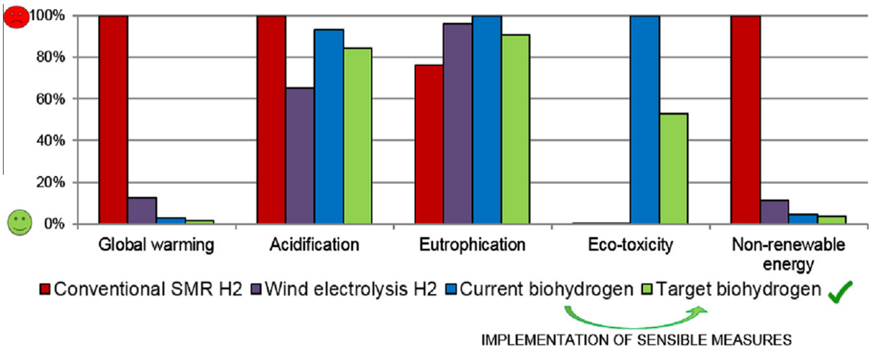
GRAPHICAL ABSTRACT



ABSTRACT

A novel approach is developed to evaluate quantitatively the influence of operational inefficiency in biomass production on the life-cycle performance of hydrogen from biomass gasification. Vine-growers and process simulation are used as key sources of inventory data. The life cycle assessment of biohydrogen according to current agricultural practices for biomass production is performed, as well as that of target biohydrogen according to agricultural practices optimised through data envelopment analysis. Only 20% of the vineyards assessed operate efficiently, and the benchmarked reduction percentages of operational inputs range from 45% to 73% in the average vineyard. The fulfilment of operational benchmarks avoiding irregular agricultural practices is concluded to improve significantly the environmental profile of biohydrogen (e.g., impact reductions above 40% for eco-toxicity and global warming). Finally, it is shown that this type of bioenergy system can be an excellent replacement for conventional hydrogen in terms of global warming and non-renewable energy demand.

1. Introduction

Energy plays a crucial role in economic and social development. Global primary energy consumption increased by 0.9% in 2014, reaching record consumption levels for every fuel type except for nuclear power (British Petroleum, 2015). Increasing energy consumption, along with growing concerns about climate change and national energy security, characterises the current energy context. Hence, scientists and governments worldwide focus on the search for solutions that promote the shift towards reliable and clean energy systems. Hydrogen energy systems are often presented as an effective solution due to the high energy content of hydrogen and their potentially favourable environmental

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performance (Dincer, 2012). However, the environmental suitability of hydrogen systems at a large scale is highly conditioned by the type of primary energy and conversion technology used for hydrogen generation (Serrano et al., 2012). Furthermore, from a sustainability perspective, the deployment of hydrogen infrastructure and the social acceptance of hydrogen are key barriers to be faced by this type of energy system.

Currently, hydrogen is mostly produced from fossil fuels, mainly via steam reforming of natural gas (Udomsirichakorn and Salam, 2014). Nevertheless, green hydrogen production is required in order to effectively mitigate global greenhouse gas emissions from a life-cycle standpoint. Dincer (2012) classified green hydrogen production methods according to the energy used to drive the process (electrical, thermal, biochemical, photonic, and combinations of these). Putting nuclear power aside, the green energy to drive the hydrogen production process (e.g., electrolytic and thermochemical processes) can be obtained from renewable resources (e.g., solar, wind, hydro and biomass energy) or it can be recovered energy (e.g., recovered industrial heat and landfill gas) (Dincer, 2012).

In particular, biomass from short-rotation plantations and waste biomass are seen as appropriate green energy sources in order to avoid the use of fossil fuels for hydrogen production. Key features of biomass include high annual global production, widespread availability and the development of advanced energy technologies for biomass conversion (Udomsirichakorn and Salam, 2014). The technologies available for biomass conversion into hydrogen-rich gas are generally classified into biological and thermochemical routes (Dincer, 2012; Udomsirichakorn and Salam, 2014), being the latter usually associated with economic and competitive advantages (Udomsirichakorn and Salam, 2014).

Gasification is an attractive thermochemical process for converting biomass into energy, with a promising performance in terms of global warming and energy security (Susmozas et al., 2013). It is a partial oxidation process at elevated temperature in which biomass is converted into gas in the presence of a gasifying agent (air, steam, oxygen, CO_2 or a mixture of these). The gas generated, called synthesis gas or (bio)syngas, consists mainly of CO, H_2, CO_2, CH_4, other light hydrocarbons, water and trace amounts of char, ash and tars (Susmozas et al., 2013). The use of pure steam as the gasifying agent favours the production of hydrogen-rich syngas.

Technologies such as gasification and resources such as biomass can therefore offer a pathway to sustainable hydrogen. The use of residual biomass may favour this path. However, waste biomass should not be understood as a feedstock free of environmental impact. Given the potential for a future market for biomass waste, it could be seen as a co-product from the cultivation stage with a certain (low) economic value. Following this perspective, among the different approaches to the estimation of the environmental profile of biomass waste (Boschiero et al., 2015), its calculation as a fraction of the environmental impacts of the whole cultivation stage based on economic allocation percentages would be preferred, rather than assuming residual biomass as a by-product without environmental burdens (European Commission, 2009).

Innovation and technological improvements may also facilitate the path towards sustainable hydrogen, although these improvements often involve high economic investments. Nevertheless, the sole implementation of enhanced technologies does not guarantee the environmental suitability of biohydrogen. In this respect, measures aimed at enhancing biomass production are expected to be of paramount importance (Susmozas et al., 2013). The influence of operational inefficiency in biomass production on the life-cycle performance of hydrogen has not yet been evaluated in a quantitative manner. The present work develops a novel quantitative approach to explore the relevance of current agricultural/agroforestry practices on the life-cycle profile of biohydrogen, identifying sensible (i.e., feasible and profitable) measures that enhance this profile. The novel methodological framework is used herein to prove numerically that sensible operational practices at the biomass cultivation stage lead to significantly improve the environmental performance of biohydrogen.

2. Methods

The hypothesis formulated in this study is that the implementation of currently feasible measures at the biomass cultivation stage leads to significantly improve the environmental profile of biohydrogen. The goal of this work is to validate this hypothesis through the quantitative analysis of an unfavourable case study: hydrogen production via indirect gasification of grape pruning waste. This is considered an unfavourable case study because of the use of residual biomass as feedstock. Assuming that the environmental profile of biomass waste is in proportion to its potential economic value, grape pruning waste is a biomass feedstock with relative low environmental impacts, e.g. in comparison with short-rotation plantations (Martín-Gamboa et al., 2015). Improvements in the performance of the cultivation stage would lead to enhance the environmental profile of both the main product of the agricultural system (grapes) and the residual biomass (grape pruning waste), thus improving the profile of the hydrogen produced from this biomass waste. The analytical challenge is to prove quantitatively that this final enhancement is significantly high, thereby validating the formulated hypothesis.

2.1. Definition of the case study

The case study involves hydrogen production through indirect gasification of grape pruning waste. Two main sections are considered: biomass cultivation and hydrogen production. The former includes the vineyards where the grape pruning waste is generated, while the latter includes the conversion of this biomass feedstock into hydrogen.

2.1.1. Biomass cultivation

The total area worldwide covered by vineyards amounts to 7.5 million ha, including the areas under vines not yet in production or harvested (International Organisation of Vine and Wine, 2015). Although the global surface area of vineyards has decreased in recent years, mainly due to the reduction of European vineyards, viticulture remains one of the most common activities in temperate regions due to adaptability and profitability advantages (Spinelli et al., 2014). Within the European Union (EU), vineyards are one of the most representative plantations of the Mediterranean region, with a vine-growing area of 3 million ha. In fact, EU is the world's leader in wine production, with almost half of the global vine-growing area and ca. 60% of the wine production by volume. Italy, France and Spain are the largest EU wine-producing countries, accounting for 80% of the production (International Organisation of Vine and Wine, 2015).

Spain has the largest vineyard area in the world (1.04 million ha in 2014) and an average annual production of 4 million m^3 of wine and grape juice (International Organisation of Vine and Wine, 2015). Because of this high production, the wine industry generates a substantial amount of waste. In particular, 6 million tonnes of grape pruning waste are generated annually in Spain. Traditionally, pruning residues are disposed by local vine-growers through open-air burning, thus releasing a variety of pollutants (Spinelli et al., 2014). However, this lignocellulosic waste can be used for energy purposes, thereby complementing the use of energy crops (Biagini et al., 2015).