Journal of Cleaner Production 175 (2018) 384–393

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Harmonising the cumulative energy demand of renewable hydrogen for robust comparative life-cycle studies

Antonio Valente [a, b], Diego Iribarren [a, *], Javier Dufour [a, b]

[a] Systems Analysis Unit, Instituto IMDEA Energía, 28935, Móstoles, Spain
[b] Chemical and Environmental Engineering Group, Rey Juan Carlos University, 28933, Móstoles, Spain

ARTICLE INFO

Article history:

Keywords:
Cumulative energy demand
Harmonisation
Life cycle assessment
Renewable hydrogen
Steam methane reforming

ABSTRACT

A significant number of case studies evaluating hydrogen through the Life Cycle Assessment (LCA) methodology are available in the scientific literature. However, inconsistencies in their methodological frameworks lead to potential misinterpretation concerns when it comes to comparing LCA results. In order to mitigate this risk, harmonisation protocols for life-cycle indicators arise as helpful tools. In this regard, a harmonisation protocol for the life-cycle global warming impact (GWP) of hydrogen has been recently developed. Taking this protocol as a starting point, this article expands the list of harmonised sustainability indicators of hydrogen by formulating a new protocol for the cumulative non-renewable energy demand (CED_{nr}) indicator. Furthermore, the protocol is applied to a sample of case studies of renewable hydrogen (harmonised CED_{nr} ranging from 3 to 184 MJ kg^{-1} H_2) as well as to a reference case study of conventional hydrogen produced via steam methane reforming (harmonised CED_{nr} of 201 MJ kg^{-1} H_2). The resultant library of harmonised CED_{nr} consistently complements that of harmonised carbon footprints of hydrogen, showing a high correlation between GWP and CED_{nr} ($R^2 = 0.91$). Overall, LCA harmonisation initiatives are found to mitigate misinterpretation concerns when comparing and ranking hydrogen energy systems both within the same technological category and between different technological categories (thermochemical, electrochemical, and biological).

1. Introduction

Hydrogen is expected to play a significant role in decarbonising and cleaning the energy sector. In this sense, hydrogen should involve a suitable environmental performance, which requires production from renewable power sources and feedstocks. A number of green hydrogen production methods are available and several authors have researched about their suitability under technical and environmental aspects (Dincer, 2015). Nevertheless, hydrogen is currently produced mainly from fossil resources, viz. through steam methane reforming (SMR) using natural gas as the feedstock. Moreover, its use is mainly associated with non-energy applications such as the production of fertilisers and metallurgical uses, in contrast to the use of hydrogen for mobility or residential applications (Nižetić et al., 2015).

Within this context, comprehensive analyses are required to check the actual suitability of the life-cycle profile of hydrogen production processes in terms of sustainability, i.e. under economic, environmental and social aspects. In particular, when focusing on the environmental dimension, the Life Cycle Assessment (LCA) methodology is an appropriate tool to comprehensively evaluate the potential impacts of product systems (ISO, 2006a). In fact, numerous LCA studies of hydrogen energy systems have already been carried out, most of them involving comparative studies and a wide range of different methodological choices. In this respect, according to the extensive review of LCA studies of hydrogen energy systems in Valente et al. (2017a), most of the studies apply cradle-to-gate system boundaries up to hydrogen production, reporting the life-cycle impacts of hydrogen (mainly, carbon footprint, energy consumption, and acidification) on an energy or mass basis (functional unit). Furthermore, when dealing with multifunctionality, system expansion is typically used.

When comparing LCA results from different case studies, differences in methodological choices may distort the findings, giving rise to potentially relevant misinterpretation concerns (Valente et al., 2017a). This is especially pertinent when comparing case

---

* Corresponding author.
E-mail address: diego.iribarren@imdea.org (D. Iribarren).

https://doi.org/10.1016/j.jclepro.2017.12.069
0959-6526/

studies coming from different works. For instance, opposite conclusions could be drawn when checking the suitability of a renewable hydrogen option with respect to conventional SMR hydrogen in terms of their carbon footprints (Valente et al., 2017b).

Hence, harmonisation initiatives for the mitigation of misinterpretation risks in LCA of hydrogen energy systems have been recently undertaken, focusing on both the formulation of a harmonisation protocol for the life-cycle global warming impact potential (GWP) of hydrogen and the initial building of a library of harmonised impacts (Valente et al., 2017b).

This article addresses the development and application of a robust protocol for the harmonisation of the cumulative energy demand (CED) of hydrogen. The relevance of this article is related to the potential major role of green hydrogen in a future clean energy system, as well as to the acknowledged need for checking its sustainability in terms not only of carbon footprint but also of other impact categories. The fact that only one harmonised life-cycle indicator (viz., GWP) is available to date strengthens the novelty of the study. In this respect, CED is an especially relevant life-cycle indicator of hydrogen energy systems, not only due to its suitability to understand the actual energy needs of product systems but also because it generally represents a link between environmental and technical performances (Huijbregts et al., 2006).

In particular, this article aims to formulate a protocol for the harmonisation of the cumulative non-renewable energy demand (CED_{nr}) of hydrogen production systems, as well as to apply the protocol to case studies of renewable hydrogen found in the scientific literature. In this sense, the two main outcomes of the study are the harmonisation protocol for CED_{nr} (Section 2.1) and the initial library of harmonised CED_{nr} (Section 3.1) for a sample of case studies of renewable hydrogen (Section 2.2). Therefore, the goal of this work is to answer the following research questions: (i) can the CED_{nr} of hydrogen energy systems be harmonised through a common protocol?; (ii) does the application of a harmonisation protocol mitigate misinterpretation risk when comparing hydrogen energy systems?; and (iii) do the harmonised CED_{nr} and GWP results show a good correlation as expected for energy systems?

2. Material and methods

The choice of CED_{nr} as the life-cycle indicator subject to harmonisation was due to several reasons. First, the number of available case studies of hydrogen energy systems including this indicator was considered to be appropriate for the formulation of a specific harmonisation protocol. In this regard, Valente et al. (2017a) found that many authors reported CED_{nr} in their LCA studies of hydrogen. The VDI method (VDI, 2012) was often used in these studies. Second, CED_{nr} is widely recognised as a practical screening indicator regarding not only the technical performance of product systems but also their environmental performance, being commonly linked to e.g. GWP and acidification (Huijbregts et al., 2006). In this respect, the assessment of CED_{nr} might help to cross-check both data correctness and technical feasibility of case studies (Hischier et al., 2010). Furthermore, when performing LCA of renewable energy systems, the evaluation of CED_{nr} enables analysts to verify the actual renewability of a system (García-Gusano et al., 2017). This facilitates the identification of energy systems that inappropriately claim to be renewable even though a significant amount of non-renewable energy is required along their supply chain (Pehnt, 2006).

2.1. Harmonisation protocol for CED_{nr}

The methodological framework for the harmonisation of CED_{nr} was consistently adapted from the protocol available for the harmonised carbon footprint of hydrogen (Valente et al., 2017b). Accordingly, trends in methodological choices in LCA of hydrogen (Valente et al., 2017a) as well as general and specific LCA guidelines were taken into account. On the one hand, general guidelines refer to LCA standards (ISO, 2006b). On the other hand, specific LCA recommendations for hydrogen energy systems refer to Lozanovski et al. (2011).

As the original protocol for GWP, the novel harmonisation protocol for CED_{nr} of hydrogen (Fig. 1) was divided into four sections. These sections deal with (i) attributional modelling approach, method and system boundaries, (ii) functional unit (FU), (iii) multifunctionality, and (iv) compression stage and capital goods. Since most of the choices and features of the protocol are common to those extensively reported in Valente et al. (2017b), only the key aspects and distinguishing features are addressed herein.

As shown in the first block of the protocol ("block 1" in Fig. 1), its applicability was limited to case studies in which the quantification of CED_{nr} included both fossil and nuclear CED. The rationale behind this decision was the prioritisation of the robustness of the protocol rather than the increased number of case studies.

The harmonised system boundaries and subsystems of a generic hydrogen energy system at the foreground level are shown in Fig. 2. Since hydrogen production is the key function of the system, the harmonised FU ("block 2" in Fig. 1) was set as 1 kg of hydrogen produced (Valente et al., 2017b). The definition of system boundaries followed a cradle-to-gate approach, i.e. from feedstock/driving energyproduction, through conversion, to hydrogen compression (Lozanovski et al., 2011).

Special attention was paid to those systems involving more than one function (e.g., co-production) along the stages included in the harmonised framework (Fig. 2). When multifunctionality arose in any of the subsystems, this was addressed using an approach selected according to the role of the product actually linked to hydrogen ("block 3" in Fig. 1). In this regard, if the hydrogen-oriented output represented the leading function of the subsystem, system expansion was used. Otherwise, an allocation approach based on economic values was followed (Valente et al., 2017b).

The final block of the protocol ("block 4" in Fig. 1) improves consistency in case-by-case comparisons by including capital goods and harmonising the hydrogen conditioning stage. The latter was done considering the hydrogen compression technique defined in Valente et al. (2017b): three-stage intercooled compression at 25 °C with 75% efficiency and 20 MPa as the final hydrogen pressure. Thus, comparisons between harmonised systems involved hydrogen with the same final conditions in terms of both temperature and pressure.

Default values (Tables 1–3) are provided in order to enhance the applicability of the CED_{nr} protocol. These values refer to electricity production (Table 1), compression energy (Table 2) and capital goods (Table 3) according to the specific needs identified for the sample of case studies presented in Section 2.2.

The default CED_{nr} values for power generation were estimated implementing inventory data in SimaPro 8 (Goedkoop et al., 2016). These inventory data involved foreground data from specific sources (detailed in Table 1) as well as background data from the ecoinvent database. Regarding the compression stage, the electricity demands in Table 2 were calculated according to Zhang et al. (2014) assuming for each technology an initial pressure based on literature data. Finally, the default CED_{nr} values for capital goods in Table 3 were based on data from the ecoinvent database (Frischknecht et al., 2007).

The main use of these default values by future LCA practitioners is expected to take place when harmonising other authors' studies. In this sense, when harmonising own LCA studies, more specific