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Life-cycle performance of hydrogen as an energy management solution in hydropower plants: A case study in Central Italy

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ABSTRACT

The suitability of hydrogen as an energy management solution in a run-of-river hydropower plant in Central Italy is evaluated from a life-cycle perspective. Hydrogen production at off-peak hours via electrolysis is considered, as well as potential hydrogen storage in metal hydrides followed by hydrogen use at peak hours for power generation using fuel cell technology. Hydropower generation and hydrogen production are identified as the subsystems contributing most to the nine evaluated impact categories (e.g., global warming, abiotic depletion and cumulative energy demand). The renewable hydrogen produced shows a more favourable life-cycle environmental and energy performance than conventional hydrogen generated via steam methane reforming. Furthermore, when enlarging the system with hydrogen use for power generation, the renewable electricity product shows a better life-cycle profile than conventional electricity for the Italian electrical grid. Overall, under life-cycle aspects, hydrogen is found to be a suitable energy solution in hydropower plants both as a hydrogen product itself (e.g., for transportation) and as a feedstock for subsequent power generation at peak hours.

Introduction

The continuous increase in primary energy demand and the decrease in the availability of fossil fuels have led to a situation of energy security concerns [1]. Moreover, the energy sector still depends mostly on fossil fuels, whose combustion gives rise to greenhouse gas (GHG) emissions [2]. Security and environmental concerns are key drivers for the research in clean energy systems.

Conventional renewables (e.g., wind and solar power) play a leading role in greening the energy sector. However, significant improvements (mainly regarding energy management) are still required in order to boost this type of renewable energy in the path towards a sustainable energy sector. In this respect, the discontinuous availability of the renewable

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resource (throughout the day and through the seasons) is among the main issues to be faced by systems based on wind and solar energy [3–6]. With regard to resource availability, hydropower energy is not affected by variations comparable to those of solar and wind power. Nevertheless, in run-of-river hydropower plants, in which an upstream reservoir is not available, energy storage is a key issue when it comes to managing the electricity surplus during periods of low demand (off-peak hours). This also applies to surplus electricity from wind farms and solar power plants.

Within this context, hydrogen is seen as a promising solution for energy storage in renewable energy systems. Green hydrogen production from renewables, the high energy content of hydrogen and the fact that the only by-product from its combustion is water make these systems highly interesting from a sustainability standpoint [7–9]. In this article, the suitability of hydrogen as an energy management solution in a run-of-river hydropower plant is assessed from a life-cycle perspective. Life Cycle Assessment (LCA) is a well-established methodology to evaluate the environmental aspects of a product system [10,11]. The LCA of a hydropower plant producing hydrogen at off-peak hours is carried out to give an insight into the actual suitability of hydrogen-based systems for both energy storage and subsequent hydrogen use for energy purposes.

Material and methods

The LCA methodology is used to compile and evaluate the inputs, outputs and potential environmental impacts associated with a product system through its life cycle. Four stages are involved in LCA studies [10,11]: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) interpretation.

In the first stage, the objectives and potential uses of the study are defined, as well as other key aspects such as the system boundaries, the functional unit (FU), assumptions and restrictions. The second stage focuses on data collection, requiring an inventory of the input and output data of the system under study.

The third stage comprises three mandatory steps: (i) selection of impact categories, indicators and characterisation models; (ii) classification, i.e. association of the inventory data with the selected impact categories; and (iii) characterisation, i.e. calculation of the results of each category indicator by converting the life cycle inventory elements to common units (using characterisation factors) and aggregating the converted results within the same impact category. Finally, in the interpretation stage, the results are summarised and discussed in order to identify relevant issues and provide conclusions, recommendations and information, thus supporting decision-making processes.

Goal and scope: the hydro-H_2 system

The goal of this work is to characterise the life-cycle environmental and energy performance of a renewable energy system (referred to as "hydro-H_2 system" hereinafter) consisting of a run-of-river hydropower plant with energy storage at off-peak hours in the form of hydrogen. Furthermore, the life-cycle profile of the hydrogen produced ("hydro-H_2") is compared with that of conventional (fossil-based) hydrogen generated via steam methane reforming ("SMR-H_2"). Finally, the suitability of using this renewable hydrogen for power generation at peak hours is also evaluated according to life-cycle criteria in comparison with conventional electricity from the grid.

A cradle-to-gate approach is followed for the LCA of the hydro-H_2 system, covering from the potential energy of the water input, through power generation at the run-of-river hydropower plant (real 7 MW plant in Central Italy [12]), to hydrogen production via electrolysis. Fig. 1 shows the main material and energy flows of the system, which is divided into two subsystems: hydropower generation (SS1) and hydrogen production (SS2). Capital goods are included within the system boundaries.

In LCA studies, the FU quantifies the function of the product system and provides a reference unit [10,11]. Because the key function of the system is to provide energy for commercialisation, the FU of this study is defined as 1 MWh of marketable energy provided by the overall system. This means that the case study is evaluated from a system perspective rather than from a (specific) product perspective.

The energy products of the hydro-H_2 system correspond with the arrows highlighted in bold in Fig. 1. They include electricity at peak and off-peak hours fed to the grid and hydrogen with 99.9 vol% purity. Electricity at both peak and off-peak hours is produced in the hydropower plant itself (SS1, see Hydropower-generation subsystem), while hydrogen is produced via electrolysis using surplus electricity from the hydropower plant (see Hydrogen-production subsystem). It should be noted that the number of electrolysers used for hydrogen production at off-peak hours is not the maximum, but a lower number adjusted to the amount of surplus electricity (i.e., non-marketable electricity produced at off-peak hours by the hydropower plant). Therefore, only a fraction of the electricity produced at off-peak hours (ca. one third of the annual working hours of the hydropower plant) is used for hydrogen production, while the remaining part is destined to the Italian electrical grid. It should also be noted that the oxygen stream coming from the electrolysers is assumed to be released to the atmosphere, and therefore it is not considered to be a by-product of the system [13].

Hydropower-generation subsystem

For the estimation of the average electricity production in the 7 MW hydropower plant (SS1), data on the flows of the river recorded by the closest hydrometric station to the plant are used [14]. The potential energy available is based on the duration of the river flows observed from January 2003 to November 2011 (personal communication with the Lazio Region Functional Centre) and the characteristic data available for the hydropower plant [12]. The main energy losses at the penstocks [15], the turbines [16] and the transformer [17] are also based on the technical information of the hydropower plant. Because the efficiency of the turbines and penstocks is a function of the water flow rate, the overall efficiency of the plant also varies with the river flow rate processed by the turbines. The integration of the curve of actual duration of the

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