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Modelling and control of hydrogen and energy flows in a network of green hydrogen refuelling stations powered by mixed renewable energy systems

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ABSTRACT

The planning of a hydrogen infrastructure with production facilities, distribution chains, and refuelling stations is a hard task. Difficulties may rise essentially in the choice of the optimal configurations. An innovative design of hydrogen network has been proposed in this paper. It consists of a network of green hydrogen refuelling stations (GHRSs) and several production nodes. The proposed model has been formulated as a mathematical programming, where the main decisions are the selection of GHRSs that are powered by the production nodes based on distance and population density criteria, as well the energy and hydrogen flows exchanged among the system components from the production nodes to the demand points. The approaches and methodologies developed can be taken as a support to decision makers, stakeholders and local authorities in the implementation of new hydrogen infrastructures. Optimal configurations have been reported taking into account the presence of an additional hydrogen industrial market demand and a connection with the electrical network. The main challenge that has been treated within the paper is the technical feasibility of the hydrogen supply chain, that is mainly driven by uncertain, but clean solar and wind energy resources. Using a Northern Italian case study, the clean hydrogen produced can be technically considered feasible to supply a network of hydrogen refuelling stations. Results show that the demands are satisfied for each time period and for the market penetration scenarios adopted.

1. Introduction

The global awareness concerning greenhouse gas (GHG) emissions, air pollution, fossil fuel depletion and others energy security issues [1,2] have led many governments and researchers around the world to develop secure and environmental friendly fuel. The current fossil fuel systems must be switched gradually to clean, affordable and reliable energy systems, thus to reach the global drivers for a sustainable vision of our future energy market. Among many alternative energy sources, hydrogen can be considered as an attractive solution to succeed the current carbon-based energy system.

The main benefits of hydrogen are even substantially considered by the fact that hydrogen can be manufactured

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from a number of primary energy sources, such as natural gas, nuclear, coal, biomass, wind and solar energy. Such diversity in production, obviously contributes significantly in diversifying the energy supply system and in ensuring the security of fuel supply. For transport applications, there will be an increasing requirement to use clean and low or zero emission fuels such as hydrogen [3]. In addition, hydrogen is the most abundant element on the earth, it is clean and has the highest specific energy content of all conventional fuels [4]. Hydrogen can contribute to a diversification of automotive fuel sources and supplies and can offer long-term solution being solely produced from renewable energies. The development of a hydrogen infrastructure for producing and delivering hydrogen appears as a key factor to achieve the hydrogen economy transition and its development. In fact, the modelling of hydrogen infrastructure is still a complex task, the main complexities rise from the significant uncertainties in demand, supply, economic and environmental impacts, and in the diversity of technologies available for production, storage and transportation. The key question is from which sources hydrogen can be produced in a sustainable manner [5]. The extent to which the hydrogen benefits will occur has a great dependency on the technologies involved. Many authors have agreed that renewable energy sources (RES), such as wind and solar are central for better transition to a long-term hydrogen economy.

In order to reach that goal, it is advantageous to use renewable energy for hydrogen generation. In fact, the resources for the operation of renewable energy systems are inexhaustible and practically free making. In addition, sustainable hydrogen production from electrolysis yields several advantages from a system point of view [6]. For instance, wind-powered water electrolysis ranks high in terms of technical and economical feasibility, having a great potential to become the first competitive technology to produce large amounts of renewable hydrogen in the future [7–11].

From the end users perspective, the use of hydrogen in fuel cell applications offers a number of advantages over existing fuels and other emerging competitors, especially in the transportation sector [12]. The fuel cell vehicles can be a long-term solution to the persisted environmental problems associated with transportation. The fuel cell vehicles would be less complex, have better fuel economy, lower GHG emissions, greater oil import reductions and would lead to a sustainable transportation system once renewable energy is used to produce hydrogen [13]. According to Doll et al. [14], the introduction of hydrogen coupled with the fuel cell vehicles could reduce significantly the emissions of CO_2, NO_x and SO_x.

The transition to a sustainable hydrogen economy faces paramount economic and technological barriers that must be overcome in order to ensure a successful transition. It is essential to study and analyse the interactions between different hydrogen infrastructure components in advance in order to set and build variety of options for the incorporation of this new economy. This will facilitate the management of hydrogen supply chain, and help decision makers to define adequate roadmaps for the hydrogen developement.

Many authors have detailed approaches and models for the development of the future hydrogen infrastructures. The approaches range from the examination of the supply chain as a whole [15–17] to the focus on a node of the infrastructure such as, production, storage or transportation [7,21–24]. In [18], Kuby et al. have developed a model able to locate the hydrogen stations that refuel maximum volume of vehicle fuel, this latter is measured both using the number of trips and vehicle miles travelled. Bersani et al. [19] have investigated the planning of a network of service stations of a given company within a competitive framework. They proposed a decision support system that can be considered to determine the optimal placement of service stations within a hydrogen economy. Nicholas et al. [20] have provided an analytical framework for locating hydrogen fuel stations assuming that the existing petrol infrastructure is strongly related to the needed hydrogen infrastructure of the future. In another study, Parker et al. [21] have assessed the economic and infrastructure requirements of the production of hydrogen from agricultural wastes, they concluded that the delivery price of bio-hydrogen is similar to the hydrogen produced from the natural gas. Joffe et al. [22] have developed a technical modelling of a hydrogen infrastructure. They investigated the operation of the system so to provide initial facility for refuelling hydrogen fuel cell buses in London city. Greiner et al. [9] have presented a simulation study of combined wind-H2 plant on a small Norwegian island. They include chronological simulations and economic calculations enabling the optimization of the components size. Their simulations include a grid-connected system and an isolated system with backup power generator. Dagdougui et al. [23] have introduced a dynamic decision model for the real time control of hybrid renewable energy production systems, which can be particularly suitable for autonomous systems.

General interest in a wind-hydrogen system has increased partly because the price of wind power has become competitive with traditional power generating sources in certain areas [24]. Wind-powered water electrolysis ranks high in terms of technical and economical feasibility, having a great potential to become the first competitive technology to produce large amounts of renewable hydrogen in the future [7]. Worldwide installations of wind turbine power have reached a value of 194.5 GW [25]. Studies carried out by Honnery and Moriarty [26] have evaluated the global potential of a coupled wind/hydrogen system, thus in order to estimate the future hydrogen production.

A challenging task that is worth to be deeply studied regards the feasibility to feed hydrogen demand points by an uncertain renewable supply, such as the case of hydrogen production from intermittent RES. The key question that needs to be addressed is the ability of the renewable energy system to meet the hydrogen fuel requirements (in amount and time).

In this paper, an attempt has been made to plan an innovative design of a hydrogen infrastructure. It consists of a network of GHRSs and several production nodes. The proposed model is formulated as a mathematical programming, where the main decisions are the selection of GHRSs that will be powered by each point of production based on distance and population density criteria, as well the energy