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## Review Article

# Hydrogen: Trends, production and characterization of the main process worldwide

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## ABSTRACT

There is a worldwide debate about which energies are more efficient and renewable energy systems. This discussion comprises hydrogen and fuel cells as potential emerging technologies. However, information about hydrogen technology remains somehow unknown to a broader public. Currently some technologies supporting hydrogen productive chain are not so competitive and this means a tight bottleneck. Expectation is that this would be the most promising innovation in a new energy system based on renewable sources. This paper reports the large range of existing processes and technological routes for the production of hydrogen in many countries. Thus, this work aims to show the current energy landscape, highlighting the hydrogen and the main characteristics of the technological routes for its production. The overview about the current situation and trends of Hydrogen Economy is presented. The prominent research on hydrogen technology, processes and their main characteristics are addressed as well. The uncertainties surrounding the implementation of hydrogen energy, based on renewable sources, require further studies regarding competitiveness.

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## Introduction

The growing energy demand causes more pollution and requires increase in energy efficiency [1]. Therefore, the emissions of greenhouse gases (GHG) and the global warming become important issues in science and global policy, accelerating the necessity for replacing fossil fuels with renewable energy sources [2,3]. Thus, energy systems are the main source of sulfur dioxide emissions (82% of total emissions) and a significant portion of carbon monoxide emissions (46% of total emissions) [4,5].

Countries with higher energy demand have high emissions of greenhouse gases (GHG), because the current economic development is based on intensive use of energy sources from fossil fuels [2]. According to the International Energy Agency (IEA), the energy sector will increase the CO<sub>2</sub> emissions from 50% in 2030 to 80% in 2050 [6]. This way, the environmental issues associated with the use of fossil fuels have been a concerning of the international community.

Furthermore, social and economic development indicators are directly related to high levels of per capita energy consumption [7]. Thus, modern society is characterized by a growing dependence on energy use [8,9].

Between 2000 and 2013, global energy demand grew 38% [10]. It is estimated that the world population will reach approximately 7.5 billion in 2025. Therefore, the global consumption of energy increased 50–60% compared to current consumption [11]. Environmental impacts, energy vulnerability and fossil fuels depletion led many governments to promote the use of alternative energy sources, nonpolluting and renewable [12,13]. Thus, the future of energy changed over the last decades [14,15]. The IEA reaffirmed many times the need of a revolution in the energy field, based on the implementation of low carbon technologies and encouraging governments to rethink the current energy model [12].

Hydrogen and fuel cells have been mentioned as an emerging potential technology [16] and an option for a transition in the long term to cleaner energy and transport systems [14,17]. The use of hydrogen as energy carrier and fuel cell as a technology transformed hydrogen into electricity, it was considered a break in the current energy system. Thus, the generated electricity can be used both for stationary and vehicular application [18–20], replacing the direct use of fossil fuels in the combustion engines. Many studies aim to develop energy sources to several applications, from vehicular –about 100 kW– to small mobile devices that requires few watts.

Hydrogen energy is considered a clean technology [21], the storage of hydrogen energy is an advantageous way to produce electricity using fuel cell [22]. To find an economic way to store hydrogen is the center of discussions about renewable energies [22–24]. Borohydride fuel cell have been studied

[22,25–27] as an alternative way to store hydrogen. Several authors [8,28–30] have reported that hydrogen is a key component to developing a clean and sustainable energy system, although it is necessary for its production technology to be made to be economically feasible [31].

In this sense, global initiatives promoted by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) searched actions to contribute with the development of hydrogen as energy carrier and the transition from the current energy model to the Hydrogen Economy - expression introduced by General Motors Co. in 1970 to name a new economy based on the use of hydrogen as an energy source [32]. Thus, governments have been funding development projects and studies on the hydrogen economy for local industrial use. As a result, the use of hydrogen enables the most efficient use of energy resources of local production chains [2].

There is not enough public dissemination of information about the hydrogen technology, its advantages and negative impacts affecting the social acceptance of this technology [8]. The study, analysis and comprehension of the transition possibilities for a new energy system can generate contributions to the development and consolidation of hydrogen energy, justifying the proposed efforts in this work. The existing processes and technological routes for the production of hydrogen reveal the importance of this review. This work aims to show the current energy overview highlighting the hydrogen and the main features of the technological routes for its production.

Research on hydrogen production technologies has been well documented; however they do not cover as much of the technologies currently known. More detailed studies are needed to further enhance the development of hydrogen economy [33].

This present review allows a better understanding of hydrogen production technologies and hydrogen conversion using fuel cells, giving a broad view about this subject. This paper has four sections: the first one is this introduction; the second section provides an overview about energy in the world and the importance of hydrogen energy; the third section presents the processes, technological routes and inputs, highlighting strengths, the weaknesses of them, fuel cells types and typical characteristics. Finally, the last section presents the final remarks.

## Energy overview in the world and the hydrogen potential for energy generation

The current world energy system is based on fossil fuels for stationary and vehicular energy generation [34,35]. Industry demands high energy consumption and the main energy

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