INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 9470–9481

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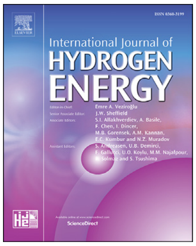

# Comparative risk assessment with focus on hydrogen and selected fuel cells: Application to Europe

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ARTICLE INFO

*Article history:*
Received 30 October 2017
Received in revised form
29 March 2018
Accepted 1 April 2018
Available online 22 April 2018

*Keywords:*
Hydrogen
Fuel cells
ENergy-related Severe Accident Database (ENSAD)
Risk assessment
Aggregated indicators

ABSTRACT

In this study, a first-of-its-kind comparative risk assessment is presented for accidents in the energy sector in EU28 with focus on hydrogen ($H_2$) and selected fuel cells, namely proton exchange membrane (PEM), phosphoric acid (PAFC), alkaline (AFC) and molten carbonate (MCFC) fuel cells. The analysis is based on PSI's well-established framework for comparative risk assessment, using available historical experience from its ENergy-related Severe Accident Database (ENSAD). For $H_2$, the technological risks are first identified and characterized to set up the so-called $H_2$ ENSAD, a subset of ENSAD including historical observations related only to $H_2$ accidents only. Afterwards risk indicators, namely fatality rate and maximum consequence, have been estimated for $H_2$ and selected fuel cells, and then compared to fossil fuels, hydro-power and selected new renewable technologies. $H_2$ and selected fuel cells showed fatality rates lower than natural gas, whereas maximum consequences were similar to other new renewables.

## Introduction

In our modern society, energy is one of the most important prerequisites for the production of goods and services, enabling sustainable industrial, social and economic development. However, the need to reduce green-house gas (GHG) emissions in order to limit global warming to at most 2 °C above pre-industrial levels, calls for a deep decarbonisation of the power sector [1]. Under a sustainable development perspective, technologies related to the energy carriers are thus requested to avoid environmental problems through harmful emissions or other impacts [2].

Hydrogen ($H_2$) is an energy carrier with the potential for a more sustainable supply. Although presently used extensively as a chemical feedstock [2], $H_2$ is considered to be on the rise as possible energy carrier in the future [3–5]. This is related to the fact that it is considered an environment-friendly fuel, since when used in a fuel cell or burned in an internal-combustion engine is mainly producing water vapour although nitrates have also been discovered [6]. Furthermore, it is a versatile energy carrier with potential for extensive use in electricity generation [1,7], for example in fuel cell systems, which are an important technology for converting $H_2$ to power and heat [8]. However, although intimately linked, fuel cells

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https://doi.org/10.1016/j.ijhydene.2018.04.004

can also be used with other fuels than $H_2$, such as for example natural gas [1].

The agreement on an hydrogen based economy between the European Union (EU) and the United States (US) in 2003 [9,10] marked the start of international and national efforts to develop safe and reliable technologies for hydrogen production, storage, transport and consumption. This has been well established in EU, where a variety of projects have been carried out through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU – http://www.fch.europa.eu). FCH JU is a public private partnership whose goals are to accelerate the development and deployment of fuel cells and hydrogen as energy carrier, and to launch them commercially by 2020, providing a relevant contribution to the transition to a low-carbon energy society.

One of the major requirements for commercial application of $H_2$ and its related technologies is that the safety and reliability of the required infrastructure is investigated, and that the associated risks are not significantly higher than that of existing fuel supplies, such as natural gas, etc. [11]. $H_2$ has already been used and safely handled for many years in several application areas (e.g. in aerospace technology, chemical processing, food and electronic industries). Furthermore, there have been an increasing number of regulations, standards and codes affecting design, installation, operation and maintenance of $H_2$ installations, which have been developed and implemented in the past decades to increase the safety and reliability of $H_2$ related infrastructures. For example, internationally, the International Organization for Standardization (ISO) introduced the Technical Committee TC 197 for hydrogen technologies in 1990 [12,13], while specifically in EU, directives like equipment for potentially explosive atmospheres (ATEX) or the pressure equipment (PED) have been developed in this context [14]. Nevertheless, hydrogen – as any other energy carrier – is not completely risk free, mainly due to its high flammability and the substantial amount of energy released if it burns or explodes. Furthermore, in comparison to current fossil energy carriers, it introduces different safety and regulatory issues that need to be understood and tackled. Generally, hydrogen-related accidents are not considered rare [9,15,16]. Therefore, $H_2$ is considered as a potentially unsafe fuel, if not handled with care [16]. As a consequence, it can possibly affect present and future hydrogen-related technologies, like fuel cells [17], power to gas [18], etc., in terms of accident risk in a full chain perspective.

In the past, several studies have focused on various risk and safety aspects of hydrogen and related technologies, such as, the risk and sustainability of hydrogen infrastructures [19], the analysis of hydrogen related accidents [9,15,16,20], the quantitative risk assessment for specific hydrogen related infrastructures [21–23], and hydrogen and fuel cells [24,25]. However, none of these specifically compared $H_2$ and hydrogen related technologies like fuel cells with other energy carriers (e.g., oil, coal, biomass, etc.).

Therefore, a comparative risk assessment of accidents for a broad range of energy technologies with focus on $H_2$ and its related technologies is of major interest, using quantitative risk indicators to evaluate their safety performance and to rank the systems under consideration. In fact, accident risks and their various consequences can have important implications on the environmental (e.g. land and water contamination), economic (e.g. property damage, business interruption) and social (e.g. human health impacts) dimensions of sustainability. Furthermore, risk assessment and the calculation of transparent and consistent risk indicators is an essential contribution to support stakeholders in complex decision-making processes to plan, design and establish supply chains that are economic, efficient, reliable, safe, secure, and sustainable. Ultimately a comprehensive approach is required that combines and evaluates all considerations using a systemic perspective to find broadly accepted solutions that best meet the often-conflicting objectives and expectations of different stakeholders (e.g. industry, investors, authorities, etc.).

The current study presents a first-of-its-kind comparative risk assessment of energy-related accidents in the European Union with a focus on $H_2$ and fuel cell systems. This analysis considers only these stationary type fuel cells: proton exchange membrane (PEM) [26], phosphoric acid (PAFC) [27], alkaline (AFC) [28] and molten carbonate (MCFC) [29] fuel cells. The selection has been based on the level of technology maturity and the present use or potential future use of them as stationary systems [1,2,24,30–33]. Furthermore, only stationary systems have been considered to build a reasonable comparison with other centralized and decentralized energy systems, such as fossil, hydro and new renewable technologies.

The comparative risk assessment presented here is based on PSI's well-established methodological framework. For fossil chains, and to a lesser extent for hydropower and wind, extensive historical experience is available in PSI's Energy-related Severe Accident Database (ENSAD) starting from 1970. In contrast, for the other new renewables a combination of available data, modelling and expert judgment is needed. Generally, full energy chains are considered, since accidents do not just take place during the actual production phase [34].

In this study, the so-called $H_2$ ENSAD, a subset of ENSAD including historical observations related to $H_2$ accidents only, has first been set up based on historical observations and an extensive literature review (Section Data). Afterwards risk indicators, namely fatality rate and maximum consequence, were estimated using an historical approach, similar to [34], for $H_2$ and selected fuel cell systems (Section Comparative Risk Assessment). For the latter, indicators have been estimated based on the used fuel only, since it has been shown to be the most significant source of accident risk for these systems [24]. Finally, the risk indicators for $H_2$ and the fuel cell systems have been compared against fossil fuel alternatives, hydropower and selected new renewables technologies adapted from Ref. [34] for the EU28 country group (Section Results & Discussion).

## Data

### The ENergy-related Severe Accident Database (ENSAD)

The ENergy-related Severe Accident Database (ENSAD) was first established in the 1990s at the Paul Scherrer Institute (PSI) to close the gap related to the lack of specific databases collecting energy-related accidents, since till then this information was mainly included in general industrial databases only [35]. ENSAD comprehensively collects information about