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Testing future hydrogen penetration at local scale through an optimisation tool

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ABSTRACT

The diffusion of smart energy systems at the local scale will lead to the implementation of innovative design, plans and applications mainly involving integrated energy infrastructures and distribution systems. In this framework, hydrogen will have the chance to play a major role but its penetration rate still represents a considerable uncertainty and needs to be investigated with special attention to show the real feasibility of a hydrogen economy advent.

The paper presents the results obtained analysing a set of scenarios applied to a comprehensive TIMES-based bottom-up energy model developed to describe and assess the energy systems of the single European countries and of macroareas of the rest of the world in an integrated approach. The modelling tool considers the hydrogen supply chain since its production stage (together with its storage and distribution) and evaluates – minimising the total system cost and over a mid-long time horizon – the penetration of the hydrogen-based end-use technologies.

The analysis shows that the residential and, above all, the transport sector may see a considerable diffusion of technologies supplied with hydrogen and especially for urban application, pushed by the upcoming stricter environmental constraints to the energy sector.

Introduction

During the last decades, hydrogen has been often identified as a promising fuel for future large scale applications in several fields. In the reality, up to now its penetration remains quite limited, even if several research activities on this topic are carried on. Internationally relevant studies and outlooks such as ETP2014 [1] point out that the penetration of hydrogen as a transport fuel may be slowed down by the unavailability of efficient storage devices. Most of the technologies are indeed already commercially viable and at a good stage of development as reported in the latest IEA roadmap in hydrogen and fuel cells [2]. The Roadmap also includes a status overview of the existing hydrogen based vehicles and of the whole transportation, distribution and retail chain. Although costs are still significantly higher than those of the respective fossil fuels based competitors, in the next years the situation could change, especially if environmental policies aiming to reduce significantly the role played by fossil fuels in a decarbonisation framework will be defined and adopted. Cantuarias-Villessuzanne et al. [3] evaluated a considerable shortening in the time horizon for profitability in the case of hydrogen fuelled buses in case carbon derived

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externalities due to other powertrains are internalised. Referring to the European Union, the Roadmap 2050 [6] sets as main targets a reduction by 80% compared to 1990 level for the greenhouse gas emissions by 2050 and a decarbonisation by 95% in the power sector. In order to make these targets achievable, a fuel shift to biomass, electrification and hydrogen is needed in the most relevant energy demand sectors, i.e. industry, transport and buildings. The penetration of hydrogen in the residential sector is mainly forecasted to take place thanks to Combined Heat & Power systems (CHP) [2] initially supplied via natural gas converted into hydrogen via internal reforming. Although technologies are available, several issues related to regulations, standards and grid connections can be reported and have to be solved while field tests are ongoing (*ene.field* in Europe [4] and *ene-farm* in Japan [5]).

Significant contribution in the long term is expected to come from electrification of cars and from hydrogen fuel cell vehicles in the transport sector; this will require, as a consequence, the development of specific infrastructures for both these commodities (electricity and hydrogen), a reduction in costs (reachable by means of technological improvements) and new regulations and emission standards for road transport [7].

According to these future goals, the aim of this paper is to investigate the possible role of hydrogen in the EU over a mid-long time horizon under different scenarios by using an optimisation energy modelling approach, focussing in particular on the effects of its penetration in the transport sector.

In the scientific literature, some studies applied different TIMES-based models and – more in general – optimisation approaches to forecasting scenario analyses involving hydrogen. Among these, the one carried on by Yang et al. [8] used the H2TIMES model to analyse the diffusion of hydrogen in California up to 2050, by describing in a modelling framework the infrastructures needed to supply hydrogen to eight Californian regions. A baseline run and several sensitivity scenarios were performed in order to assess the role of hydrogen under different constraints related to policies (like those imposing carbon intensity reduction targets and carbon capture and storage systems), availability of resources and technological development. The results showed the importance of the CCS and of the biomass availability as key elements to ensure low-cost and low-emission hydrogen.

Referring again to the Californian energy system, but moving to a smaller scale (i.e. urban), Stephens-Romero et al. [9] used a tool for energy planning defined STREET (Spatially and Temporally Resolved Energy and Environment Tool) to find the optimal configuration of the hydrogen infrastructures for the City of Irvine, assumed as case study. According to the authors' findings, this optimal planning could allow the penetration of hydrogen fuel cell vehicles, which could substitute ICE vehicles in a framework of long-term strategies aiming at ensuring the achievement of environmental (like emissions reduction and increase in air quality at urban level) and energy security targets. In particular, it was demonstrated that only eight hydrogen fuelling stations are needed to obtain services that can be compared to those offered by the existing gasoline infrastructure. Besides, pollutants, GHG emissions and use of water and energy can be lower than the ones related to the average park of gasoline vehicles, independently from the way through which hydrogen is produced (i.e. by means of renewable resources locally available or conventional resources like natural gas).

In another work, Strachan et al. [10] analysed the link between a GIS spatial description of hydrogen potential resources, infrastructures and demand with a MARKAL model of the UK energy system. By using this integrated approach, the authors explored the possible competitiveness of the hydrogen option in strong CO_2 reduction scenarios for the UK, especially in the transport sector.

Starting from the same UK MARKAL model (but in an improved version), Dodds et al. [11,12], investigated the potential future uses of the gas networks in the UK by taking into account a set of different options in a decarbonisation perspective, including the conversion of the networks to deliver hydrogen (e.g. hydrogen injection to the natural gas and bio-methane supply). The authors demonstrated that this last option could allow to reduce, in a mid-long time horizon, the overall cost of heating supply to UK buildings.

Dodds et al. [13] also analysed specifically the possible relevance of hydrogen in the heat production for buildings and industrial applications, focussing in particular on the benefits offered by fuel cells, which are considered a technology closer to the market in several countries. Furthermore, the study compared different regional and multi-regional models in order to verify if hydrogen chain is included or not. Among the considered models (US EPA 9R, Canada TIMES, Belgium TIMES, Norway TIMES, UK MARKAL, UKTM, ETSAP-TIAM, JRC-EU-TIMES), only the Canada TIMES, the UK MARKAL (which includes only fuel cells powered by natural gas), the UKTM (which includes both hydrogen boiler and fuel cell technologies) and the JRC-EU-TIMES (which includes a hydrogen burner and the hydrogen injection to the gas networks) take into account the hydrogen option for heat generation. However, the JRC-EU-TIMES model uses what seemed to the authors very high investment costs, that make the related technologies uneconomical. In general, this work underlines the importance of including hydrogen technologies for building and industrial heat production in all the energy models, in order to better describe long-term decarbonisation scenarios by taking into consideration all the possible alternatives that could be adopted.

Agnolucci et al. [14] described instead the SHIPMod model, a mixed-integer linear programming model able to find the optimal configuration of the hydrogen supply chains (also including CCS and storage systems) in the UK. This study highlighted that the model choice of technologies for hydrogen production and distribution and the related costs strongly depends on the demand value and on its spatial localisation.

As it can be noticed, all the studies previously mentioned mostly focused on the role played by hydrogen in future low-carbon scenarios at urban, regional or single country level. In comparison with these works, the present paper's goal is to put into evidence the impact that the penetration of hydrogen in local "decarbonised" energy systems (like urban and intercity transport sectors) can have at a wider scale, that is on the EU-28 energy system. This can be useful in order to