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Deployment of a hydrogen supply chain by multi-objective/multi-period optimisation at regional and national scales

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ABSTRACT

This study focuses on the development of a methodological framework for the design of a five-echelon hydrogen supply chain (HSC) (energy source, production, storage, transportation and fuelling station) considering the geographic level of implementation. The formulation based on mixed integer linear programming involves a multi-criteria approach where three objectives have to be optimised simultaneously, i.e., cost, global warming potential and safety risk. The objective is twofold: first, to test the robustness of the method proposed in De-Leon (2014) from a regional to a national geographic scale and, secondly, to examine the consistency of the results. A new phase of data collection and demand scenarios are performed to be adapted to the French case based on the analysis of roadmaps. In this case study, the ArcGIS® spatial tool is used to locate the supply chain elements before and after optimisation. The multi-objective optimisation approach by the ε-constraint method is applied, analysed and discussed. Finally, a comparison between the results of different geographic scale cases is carried out.

1. Introduction

Hydrogen produced from renewable sources and used in fuel cells both for mobile and stationary applications constitutes a very promising energy carrier in a context of sustainable development. A key point in the development of the hydrogen supply chain is the demonstration of feasibility of its infrastructure while many technical, economic and social obstacles must be overcome. Some strategic roadmaps were currently reported about the energy potentialities of hydrogen at European, national and regional levels. Their main objective is to evaluate some industrial, technological, environmental and social issues and to identify the main obstacles associated to the hydrogen economy. The literature review of recent dedicated scientific publications emphasises the need for the development of systemic studies in order to demonstrate the feasibility of the sector, to validate the technical and economic interest in the production and recovery of hydrogen produced from renewable sources. Such works involve the development of models based on economic scenarios for hydrogen deployment. In that context, this work only focuses on the study of hydrogen supply chain (HSC) for transport application, more precisely, the use of H_2 in fuel cell electric vehicles (FCEVs).

The HSC can be tackled with different levels (i.e. strategic, tactical and operational). This work focuses on the strategic approach that can take place considering different geographic scales according to the defined problem. Even if in some countries, a region or a state has noticeably taken a key role as a pilot state concerning the hydrogen economy, the future of the HSC obviously depends on the interconnection among

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big cities and countries. Intercontinental analysis seems now premature but a national study can be analysed with real constraints and data.

The H_2 Mobility roadmap (Williamson, 2010) reported that Germany and Great Britain have already introduced pilot projects for the use of FCEVs while study initiatives started in France in 2013. In this country, a regional case study for the Midi-Pyrénées region was recently conducted (De-Leon, 2014). One of the main questions arising from the Midi-Pyrénées case is whether or not the geographic segmentation that was adopted (i.e. regional scale) could be changed to ensure a more competitive cost without affecting environmental and safety criteria. A new geographic scale is thus considered in this paper in order to study the feasibility of large-scale hydrogen production in France.

France is the largest country in Western Europe and the third-largest in Europe as a whole with a total population of around 65.5 million (Insee, 2013). Transportation is a major contributor to greenhouse gas (GHG) emissions in France. In 2009, the final energy consumption due to transportation was 49.8 Mtoe and the associated GHG emissions resulted in 132 Mt CO_2-equiv. In general terms, the total emissions in France decreased (mainly due to electricity mix based on very low carbon emission technologies as nuclear and hydropower) between 1990 and 2009 but those associated to the transport sector increased in the same period (Direction, 2013). The French government adopted a Climate Plan in 2004 which requires a 75% reduction in GHG emissions by 2050 compared to current levels.

If the FCEV is able to gain an important market share, hydrogen availability must be guaranteed at an intercontinental supply chain. France has a strategic location because Spain, Andorra, Italy, Switzerland, Germany, Luxemburg and Belgium are all neighbouring countries. Besides, French hydrogen production was of 7 billion N m^3 in 2007 and there are 10 production plants already installed throughout the territory (Phyrenees, 2009). The most of hydrogen is produced onsite for captive uses for the chemical industry by steam methane reforming (SMR).

The remainder of this paper is organised as follows: Section 2 is devoted to a brief literature review to highlight the objectives of this work. The methodology aspects and formulation of the HSC problem followed in this work are presented in Section 3. Section 4 is dedicated to the solution strategy for applying multi-objective optimisation by mathematical programming and the use of a geographic tool for data treatment. The definition of the case study is presented in Section 5 with specific focus on parameters such as demand, energy sources, initial production plants and storage units, refuelling stations and roads. The multi-objective optimisation results for the national case are presented in Section 6 as well as the analysis and comparison of results for the regional and national scales. Finally, conclusions and perspectives are highlighted.

2. Literature review

Many studies use optimisation tools that could allow the generation of quantitative information when all the activities (nodes) of the supply chain are defined and integrated. Facility location problems have proven to be a fertile ground of operations research interested in modelling and design. In the case of a supply chain design, the network model assumes that demands arise, and facilities can be located, only on a network composed of nodes and links. In the mathematical formulation, mixed integer linear programming (MILP) formulations have been widely used.

2.1. Mono-objective optimisation

Mono-objective optimisation is still the most used approach considering an economic criterion. A largely used model is developed in Almansoori and Shah (June 2006): it determines the optimal design of a network (production, transportation and storage) for vehicle use where the network is demand-driven minimising the total daily cost. The model was applied to a Great Britain case study. The same authors extended the model in 2009 (Almansoori and Shah, Oct. 2009), to consider the availability of energy sources and their logistics, as well as the variation of hydrogen demand over a long-term planning horizon leading to phased infrastructure development as well as the possibility of selecting different scales of production and storage technologies. More recently, the technological diversity of the H_2 supply pathways together with the spatial-temporal characteristics is considered in (Murthy Konda et al., April 2011a) to optimise a large-scale HSC based on (Almansoori and Shah, June 2006) approach, including capacity expansion and pipeline features. An optimisation-based formulation is developed in Hugo et al. (Dec. 2005): it investigates different hydrogen pathways in Germany. The model identifies the optimal infrastructure in terms of both investment and environmental criteria for many alternatives of H_2 configurations. This model has been extended and considered as a basis for other works such as Li et al. (Li et al., Oct. 2008) for the case study in China. The development and use of a hydrogen infrastructure optimisation model using the H_2TIMES modelling framework to analyse hydrogen development in California to 2050 is described in Yang and Ogden (April 2013); in the same region, an economic model to assess several potential FCEV deployment rates is proposed in Brown et al. (April 2013). A multi-period MILP model (called SHIPMod) is presented in Agnolucci and McDowall (May 2013) presented: it optimises a HSC for hydrogen fuel demand scenarios in the UK, including the spatial arrangement of carbon capture and storage (CCS) units and the use of pipelines. This work concludes that assumptions about the level and spatial dispersion of hydrogen demand have a significant impact on costs and on the choice of hydrogen production technologies and distribution mechanisms.

2.2. Multi-period optimisation with different approaches on demand

All these models consider a deterministic demand but stochastic demand approaches are also available in the literature: Kim et al. (Sept. 2008) and Almansoori and Shah (2012) optimise the HSC finding the configuration that is the best for a given set of demand scenarios with known probabilities. The stochastic programming technique used is based on a two-stage stochastic linear programming approach with fixed recourse, also known as scenario analysis. More recently, an investigation (Liu et al., June 2012) focuses on the analysis of hydrogen demand from hydrogen FCEVs in Ontario, Canada for three potential demand scenarios (2015–2050). Dodds and McDowall (Feb. 2014) identified three key demand modelling decisions: the degree of car market segmentation, the imposition of market share constraints and the use of lumpy investments to represent infrastructure using the UK