INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 8881–8897

Available online at www.sciencedirect.com

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Review

Hydrogen supply chain architecture for bottom-up energy systems models. Part 1: Developing pathways☆

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ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form
19 March 2014
Accepted 23 March 2014
Available online 3 May 2014

Keywords:
Hydrogen energy systems
Energy systems modelling

ABSTRACT

The integration of hydrogen energy systems in the overall energy system is an important and complex subject for hydrogen supply chain management. The efficiency of the integration depends on finding optimum pathways for hydrogen supply. Accordingly, energy systems modelling methods and tools have been implemented to obtain the best configuration of hydrogen processes for a defined system. The appropriate representation of hydrogen technologies becomes an important stage for energy system modelling activities. This study, split in consecutive parts, has been conducted to analyse how representative hydrogen supply pathways can be integrated in energy systems modelling. The current paper, the first part of a larger study, presents stylised pathways of hydrogen supply chain options, derived on the basis of a detailed literature review. It aims at establishing a reference hydrogen energy system architecture for energy modelling tools. The subsequent papers of the study will discuss the techno-economic assumptions of the hydrogen supply chain components for energy modelling purposes.

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Introduction

Hydrogen is considered as one of the promising alternative fuels that can be utilized for reducing GHG emissions to achieve a more sustainable society with a better environmental footprint. Additionally, hydrogen energy technologies are also considered potentially viable enabler for a transition from the fossil energy age to a renewable energy age [1]. As hydrogen does not stay stable in nature in free form, it needs to be produced from various resources and then be delivered to appropriate locations via different pathways. A key question for hydrogen including energy system could be "from which source hydrogen can be produced in a sustainable manner?" However, this question needs to be complemented by a second question inquiring "how hydrogen will be delivered to

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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http://dx.doi.org/10.1016/j.ijhydene.2014.03.176

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end-use applications in a sustainable manner?” [2]. These two interrelated questions can lead to the investigation of an optimal hydrogen supply chain management.

The hydrogen supply chain comprises of consecutive steps. They begin with the transformation of natural resources to hydrogen and result after steps related to the distribution and conversion in fulfilling an energy related service demand. The hydrogen supply chain is a complex system itself. Furthermore, it is embedded in a larger system. Thus, it is not only affected by the interactions of its endogenous components but also affected by exogenous signals stemming from the larger system in which it is embedded [3]. How a future hydrogen supply chain could be influenced by its endogenous architecture and exogenous inputs in terms of energy-economic parameters has emerged as a key question for the design of international and national energy policy actions. As a result, optimising the hydrogen supply chain processes with the purpose of finding cost effective and sustainable strategies by harmonizing the entire system becomes an essential activity to design scenarios for the transition to future hydrogen economy. This activity can be assisted by the use of energy system models, which require detailed calculations and system analysis [4]. Accordingly, computerized quantitative tools and methodologies such as optimisation and simulation have been employed for the required calculations and analyses in the framework of energy systems modelling studies [5]. Several models have been employed for studying alternative scenarios for hydrogen supply chains. They can be categorized according to various dimensions [4]:

- The size of the defined systems: small-scale or large-scale,
- The purposes: general or specific purposes of energy models,
- The analytical approach: top-down or bottom-up,
- The mathematical approach,
- The underlying methodology,
- Data requirements.

This study aims at discussing the assumptions and alternative architectures for hydrogen supply chains for bottom-up energy models. It does so by reviewing the literature on bottom-up energy models and techno-economic analyses of hydrogen energy systems. In a subsequent step, our study proposes stylised hydrogen supply chains and their related techno-economic assumptions that can later be used in bottom-up energy models. Our study comprises of consecutive parts that present the pathways and techno-economic assumptions for representing the hydrogen supply chain in energy systems models. This paper, as the first part of our study, focuses on describing the hydrogen production and delivery pathways that are currently discussed in the literature. It covers the following three sections. The next chapter, titled Background and motivation, gives the literature review and provides information on the state of the art on modelling hydrogen supply chains in energy system models. On the basis of this literature review, the third chapter develops and proposes the description of alternative hydrogen supply chain architectures and describes in detail the hydrogen delivery pathways. The fourth chapter draws some conclusions on this first part of our study. The latter parts of the study will analyse the techno-economic assumptions for the developed hydrogen supply chain pathways, starting from hydrogen production. It will discuss in more detail techno-economic parameters such as the availability factor, lifespan, fixed maintenance and operational cost, investment cost, capacity and fuel efficiencies that are needed as inputs for hydrogen energy system models. All in all, these consecutive studies could be used as an introductory reference for bottom-up modelling activities of hydrogen energy systems.

Background and motivation

Energy systems modelling can be conducted with optimization techniques since a substantial number of modelling activities in energy systems has been tailored for finding optimal pathways within a multi-faceted environment during a planning process. Accordingly, optimization algorithms of various mathematical methods are used, such as linear programming, mixed integer programming, fuzzy sets, stochastic mathematical algorithms etc. [6,7]. The main characteristic of optimization models is that these models generally try to answer the question “how to”, instead of “what if” [4]. However, in addition to optimization models, simulation is another option used as an energy planning tool for observing the behaviour of the system under defined constraints and scenarios [8]. While simulation in modelling introduces the consequences of the actions, optimization gives results with quantified recommendations for a decision about a specific purpose [9]. Although their output can be represented by different indicators, optimization and simulation models are used in energy systems modelling separately or jointly according to the desired intention. In the following section we give an overview on two main categories of use, identified in the literature: (i) hydrogen in smaller scale energy system contexts, (ii) hydrogen in larger regional or global energy system models.

Hydrogen in smaller scale energy system contexts

Small-scale energy systems modelling studies, documented in the literature, have been implemented mostly for two purposes. One of the purposes is to obtain cost effective strategies for an energy resource allocation problem within limited dimensions for an industry [10–21]. The other is to investigate the feasibility of integrating renewable energy sources in energy systems [22–38].

In hydrogen based integrated energy system modelling studies, the role of renewable energy technologies is evaluated both for production and storage stages of hydrogen energy systems. For example, Venter and Pucher [39] improved a cost model for stationary bulk hydrogen storage in salt caverns, depleted natural gas reservoirs and liquid vessels. Zini and Tartarini [40] implemented a dynamic model to analyse the operation and performance of a wind-hydrogen system with carbon physiosorption storage. Feroldi and Zumoffen [41] generated a genetic algorithm based optimization method to find best strategies for hydrogen production system based on multiple renewable power sources and bioethanol. Vosen and

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