Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Planning sustainable hydrogen supply chain infrastructure with uncertain demand

Muhammad Dayhim [a,*], *Mohsen A. Jafari* [b], *Monica Mazurek* [c]

[a] *Center for Advanced Infrastructure and Transportation, Rutgers, The State University of New Jersey, 100 Brett Road, Piscataway, NJ 08854, USA*

[b] *Department of Industrial and System Engineering, Rutgers, The State University of New Jersey, 96 Frelinghuysen Road, Piscataway, NJ 08854, USA*

[c] *Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, 96 Frelinghuysen Road, Piscataway, NJ 08854, USA*

ARTICLE INFO

Article history:
Received 5 December 2013
Received in revised form
18 February 2014
Accepted 21 February 2014
Available online 25 March 2014

Keywords:
Hydrogen supply chain network
MILP
Spatially aggregated demand
Clean energy in New Jersey

ABSTRACT

This study introduces a multi-period optimization model taking into account the stochasticity and the effect of uncertainty in the hydrogen production, storage and usage in macro view (e.g. county level). The objective function includes minimization of total daily social cost of the hydrogen supply chain network with uncertain demand. There are several factors and key attributes, which influence consumer choice to buy a fuel cell vehicle. At the same time, consumer preference on the demand side is the most important factor in predicting changes in the auto market. A spatially aggregated demand model was developed to estimate the potential demand for fuel cell vehicles based on different household attributes such as income, education etc. These models were applied to evaluate the future hydrogen supply chain for State of New Jersey.

Introduction

Hydrogen has the great potential to become one of the major energy carrier in the future energy system especially for fuel cell vehicles. Building hydrogen infrastructure (production plants, storage facilities and delivery modes) is very expensive and needs significant investment with substantial risks [1]. This paper intends to address the problem of optimal planning of a sustainable regional infrastructure for hydrogen fuel supply chain network under uncertain demand during multiple time periods. The planning includes sizing and location of nodes from production to delivery of hydrogen as a fuel within the supply chain. The problem of planning also includes accurate estimation of demand for hydrogen-fueled vehicles and fuel consumption.

The model is used to establish and investigate a number of strategic decisions required to fulfill the customers' needs. These decisions include: the number, location, type and capacity of hydrogen production plants and storage facilities, delivery modes and the total production rate of hydrogen in each region, the determination of the total

* *Corresponding author.*
E-mail addresses: dayhim1361@yahoo.com (M. Dayhim), jafari@rci.rutgers.edu (M.A. Jafari), mmazurek@rci.rutgers.edu (M. Mazurek).
http://dx.doi.org/10.1016/j.ijhydene.2014.02.132

average inventory in each region, and the size and type of delivery flow with uncertain demand over a long time horizon. Taking these decisions into account, the model also minimizes total social costs of hydrogen supply chain network. The network described by the model is demand-driven, which means that the establishment of production plants, storage facilities and transportation links mainly depend on the demand structure. This is a stochastic multi-period model, formulated as a mixed integer linear programming with two stages. This work also includes spatially aggregated demand modeling to estimate the potential demand for those who are interested in purchasing Fuel Cell vehicles and eventually consume hydrogen as a fuel based on different household attributes.

Many researchers used different optimization techniques such as linear programming, stochastic programming, dynamic programming and multi-objective programming to design and model the hydrogen supply chain infrastructure [1]. Almansoori and Shah [2] have introduced a deterministic mathematical model with objective function on the basis of hydrogen supply chain including facility capital cost, transportation capital cost, facility operating cost and transportation operating cost. Later Almansoori and Shah [3,4] expanded their work to take into account uncertainty arising from long-term variation in hydrogen demand using a scenario-based approach in Great Britain. Their results show that the future hydrogen supply chain network is somewhat similar to the existing petroleum infrastructure in terms of production, distribution and storage. Kim et al. [5] developed a steady-state mixed integer Programming (MILP) model for hydrogen infrastructure under demand uncertainty in Republic of Korea. This work is the first stochastic approach for hydrogen infrastructure optimization. They used similar cost elements as Almansoori and Shah [2]. Kim and Moon [6] developed a multi-objective optimization model to minimize cost of the hydrogen supply chain network and maximize the network safety. The safety objective was treated in term of risk index calculated on the basis of region's population risk. Not many studies address risk based optimization of hydrogen supply chain [1].

Guillen-Gosalbez et al. [7] developed a deterministic and multi-period MILP framework for hydrogen supply chain network optimization considering cost and environmental impacts. The environmental impact was measures through the contribution to climate change occurred by hydrogen supply chain network operation. Sabio [8] developed a multi-scenario MILP optimization model to allow the control of variation of the economic performance of the hydrogen infrastructure in Spain. Konda et al. [9] developed a multi-period optimization framework based on a techno-economic analysis in Netherlands. Their results show that the transition toward a large scale Hydrogen based transport in economically feasible for any given demand scenario. Also Lin [21] developed a dynamic programming model to optimize the hydrogen transition based on social welfare maximization.

In order to capture the uncertainty in our study, a scenario-based approach from Almansoori and Shah [4] and Kim et al. [5] works was used. Kim et al. [5] didn't consider the time and the scenarios were limited to three levels. In our model addition to costs such as capital cost and operating costs which used by earlier works [2-9] also Emission, Energy consumption and risk costs were considered. This model helps decision makers to make a better decision regarding hydrogen infrastructure which considers all the cost categories such as Economy, Emission, Energy consumption and risk at the same time. Our model is cable of running many scenarios with different probabilities which can be defined by the user.

The earliest studies of aggregate vehicle demand (Dyckman [10]) evaluate the role of income, price, vehicle stocks and financial markets on per capita car ownership in the United States. Mokhtarian and Cao [11] present a thorough review of these and related works. Virtually all studies employ some measure of aggregate economic activity. Studies which use incomes include Dyckman [10], Tanner [12], Train [13], Manski [14], Dargay and Gately [15], Chung and Lee [16]. The works by Hicks [17] and Melendez and Milbrandt [18] focus on alternative fuel vehicles. Melendez and Milbrandt [18] developed a model which geographically optimizes locations for Hydrogen refueling stations. With the exception of Chung and Lee [16] each of these authors find a positive relationship between household income and automobile ownership (measured in many different ways). Other important variables included automobile stocks [10,14], average automobile price [10,14], and driving time, trips or distance [13,16]. Through these studies, a variety of variables were found and classified at aggregate level. These classes are: income-related, cost-related, land use-related, demographic characteristics.

Problem description

The problems addressed in this paper is to size and locate a sustainable hydrogen supply chain network under uncertain demand, and to detect the important factors that play major role in designing an optimal network design. The hydrogen supply chain (HSC) consists of hydrogen production plants, storage facilities and delivery modes. Each node in the network has its own costs, which are categorized by: Economy, Ecology, Energy and Risk. The capital cost and operating cost for each node are in economy cost category. The emission cost for each node is in ecology cost category and energy consumption cost for each node is in energy cost category. Each node has GHG emission cost. For instance Hydrogen, which is, produced from a zero emission power source such as solar produces zero emissions. But it still has emission in the production and delivery node (e.g. delivered by tanker truck).

In addition to the mentioned challenges the other challenge is how safe hydrogen is as a fuel and how a safe and feasible infrastructure can be developed. It is reasonable to determine the safety technological conditions and associated operating procedures for the realization of the hydrogen supply chain infrastructure at an early stage [19]. In this paper for each network node a risk cost is assumed which uses a quantitative risk assessment (QRA) method to calculate and evaluate risk quantitatively. QRA is a systematic methodology for the identification and quantification of a facility's risk contributors. A QRA can provide authorities and stakeholders