INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 7700–7716

Available online at www.sciencedirect.com

ScienceDirect

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

Mixed integer linear programing based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy

Azadeh Maroufmashat [a,b,c], *Michael Fowler* [b,*], *Sourena Sattari Khavas* [a,c,**], *Ali Elkamel* [b], *Ramin Roshandel* [a], *Amir Hajimiragha* [d]

[a] Sharif University of Technology, Department of Energy Engineering, Azadi Street, Tehran, Iran
[b] University of Waterloo, Department of Chemical Engineering, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada
[c] Sharif University of Technology, Sharif Energy Research Institute, Teymouri Blvd., Tarasht, Tehran, Iran
[d] General Electric (GE) Digital Energy, GridIQ Innovation Center, 650 Markland Street, Markham, Ontario, Canada

ARTICLE INFO

Article history:
Received 14 June 2015
Received in revised form
11 August 2015
Accepted 13 August 2015
Available online 7 September 2015

Keywords:
Hydrogen economy
Smart energy network
Mixed integer programming
Operational and design optimization
Electrolyser
Energy hub

ABSTRACT

The future of urban energy systems relies on the transition to “smart energy networks” which incorporate energy storage with renewable energy sources such as wind and solar. Hydrogen provides a desirable energy vector for both energy storage and exchange of energy between energy hubs within a smart energy network. This paper aims to develop a generic mathematical model for the optimal energy management of future communities where hydrogen is used as an energy vector. An energy hub is a novel concept that systematically and holistically considers the energy requirements of both mobility and stationary loads. In order to perform optimization studies, the minimization of capital cost of hydrogen refueling stations and operation and maintenance cost of all energy hubs within the network are considered. The modeling and optimization are undertaken and carried out in the General Algebraic Modeling Software (GAMS). The case study considers four energy hubs consisting of a commercial building, school, residential complex, as well as hydrogen refueling stations. The study investigates the optimal operation of different energy conversion and storage technologies in order to meet the demand of energy. The results showed that the optimum size of electrolyser and hydrogen tank for supplying the hydrogen demand in the energy hub network is two 290-kW electrolysers and four 30-kg tanks, respectively. The average daily strike price of electricity by which the electrolyser operates is $0.036 per kWh and will not operate when the average hourly Ontario electricity price is higher than $0.13 per kWh. The levelized cost of hydrogen produced by hydrogen refueling station is estimated to be $6.74 per kg. Moreover, the optimal operation of energy conversion and energy storage technologies within each hub and the optimal interaction

* *Corresponding author*. Tel.: +1 519 888 4567x33415; fax: +1 519 746 4979.
** *Corresponding author*. Department of Energy Engineering, Sharif University of Technology, Tehran, Iran. Tel.: +98 2166166106; fax: +98 2166166102.
E-mail addresses: mfowler@uwaterloo.ca (M. Fowler), sattari@sharif.ir (S. Sattari Khavas).
http://dx.doi.org/10.1016/j.ijhydene.2015.08.038

between energy hubs with in the network are also investigated. In addition, it is shown that distributed hydrogen generation is more preferable than H_2 delivery in environmental and economic comparison.

Introduction

The use of distributed generation is expanding with the increase in renewable energy generation and a move towards developing a 'smart energy network' [1]. Also, the energy demands of a community must be considered in a more holistic and comprehensive manner, thus electrical, heat and transportation demands must be taken into consideration in addition to the stationary electrical load. Mainly with the commercialization of hydrogen fuel cell vehicles starting in 2015, plug-in hybrid vehicles, and electric vehicles, transportation energy demand must be considered with an overall energy system. Communities and networks of facilities with distributed generation technologies present different energy flow problems. Serious consideration to the management of energy must be analyzed when using different energy sources such as natural gas, electricity, heat, and hydrogen. Energy vectors within a network can be exchanged and perform other key functions, such as energy arbitrage and energy storage. A distributed combined heat and power (CHP) system (i.e., a turbine operating on natural gas) can simultaneously produce electricity and heat, with an electrolyser operating within the network can satisfy the demands of both hydrogen transportation fleets and part of heat load. A key aspect to create an affordable and cleaner energy system is the development of an integrated, multi-node system with multiple energy vectors. In this system, electricity, fuel, heat, cooling, and transportation, optimally interact with one another at various levels; e.g., in a local district, city or region. This gives an opportunity to improve the technical, economic, and environmental performance of the system in comparison with traditional energy systems where different sectors are implemented independently. This improvement can take place at different stages, such as at the operational and the planning levels [2,3]. Therefore, an integrated study of energy systems is required to properly take into account energy conversion technologies and possible energy storage of the different energy carriers to reach a more efficient level of system operation.

Traditionally, energy resources such as natural gas and electricity have been used independently. However, in the recent years there is a growing appeal to supplement the isolated use of energy for an integrated form of energy usage to improve efficiency and reduce environmental impact. Energy integration is increasingly sought after particularly in the wake of two core challenges: the rise of energy demand and environmental concerns such a climate change [4]. The necessity of smart energy networks through the integration of different energy carriers including heat, electricity, hydrogen, as well as bio energy was discussed by Orecchini et al. [5]. The integration of natural gas and electric networks for optimal power flow for the best system operation was proposed by An et al. [6]. Syed et al. [7] developed a simulation model for the operational study of a fleet of plug-in fuel cell vehicles and a commercial building based on novel energy hub concept. The input energy flow of the proposed hub is electricity. Hydrogen and electricity are the energy output for the commercial building and vehicles in fleet. However, the optimization was not carried out in this work. Sharif et al. [8] presents a simulation model for an energy hub including natural gas and renewable energy as input carriers to the model. The aim of this work is to combine different energy generation technologies, which are evaluated in terms of the production of total energy, the unit cost of produced energy, and the amount of generated emissions. Maniyali et al. [9] presents an energy hub comprising of renewable energy, hydrogen storage facilities to supply hydrogen and electricity for different sectors such as transportation and industry for long term planning in comparison with the contemporary coal-based power generating facilities. However, the optimization and energy network was not carried out in these works.

The move towards a hydrogen economy, whereby hydrogen is used for transportation and utility-scale energy applications is of great deal of interest to both industry and society at a whole. Hydrogen is favored since it can be easily generated from renewable sources of energy as well as carbon free nuclear energy, and quickly refuels vehicles providing the extended range desired by consumers [10]. Moreover, hydrogen may act as an energy vector for applications related to transport reduces environmental issue such as greenhouse gas emission and urban pollution [11,12]. Salvi and Sabramanian reviewed the hydrogen based energy systems for the transportation sector. They discussed about the different methods of hydrogen production, its significance for the transportation systems, its safety concerns, and hydrogen vehicles [13]. Ajanovic did the economic feasibility study of usage of hydrogen based renewable energy for the transport sector in Austria [14]. Ball et al. developed a modeling approach in order to integrate hydrogen in to German energy systems [15]. In addition, hydrogen as an energy carrier is desired even from the outlook of a power grid management and competitive markets for its great energy storage potential and its cost difference between peak and low price hours, respectively [16]. To clarify, hydrogen can be produced through the low cost off-peak power and can be consumed by hydrogen vehicles or it can be stored and converted to electricity when the price of power is high [17]. However, there are still challenges to setting up the hydrogen economy in the fields of production, distribution, storage and consumption [18]. Given the many potential advantages of hydrogen as an