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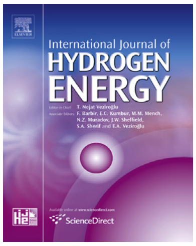

Development and environmental impact of hydrogen supply chain in Japan: Assessment by the CGE-LCA method in Japan with a discussion of the importance of biohydrogen

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ABSTRACT

Hydrogen is an attractive and clean source of energy with a high energy content and environmentally friendly production using green power. Hydrogen is therefore considered to be one of the future alternatives to fossil fuels that can limit the damage done by climate change. A dynamic GTAP model with LCA method is utilized herein in this investigation to forecast the development of the hydrogen supply chain and CO_2 emissions in Japan. The supply chain incorporates six hydrogen-related industries – biohydrogen, steam reforming, electrolysis, hydrogen fuel cell vehicles (HFCV), hydrogen fuel cells (HFC), and hydrogen fueling stations.

Baseline results reveal that the positive impacts on hydrogen application sectors (HFCV, HFC and HFS) are greater than hydrogen generation sectors (biohydrogen, steam reforming and electrolysis). Sensitivity analysis reveals that HFCV, HFC and biohydrogen are the three industries that are most sensitive to technology advance. Hydrogen-related industries will play a more important role if Japan shut down nuclear power plants or to meet the CO_2 mitigation target in response to the conclusions of COP 19. Biohydrogen has the potential gradually to become a major hydrogen-generating technology for future development of green economy.

Introduction

Climate change may cause various disasters, such as rising sea levels, acidification of oceans, extreme weather events and food shortages [1,2]. Various economic incentives, such as the clean development mechanism (CDM), carbon emission trading, the green climate fund, and green financing, may encourage the development of clean and low-carbon energy sources to support the green economy [3], green growth [4], and thereby to reduce the negative effects of climate change [4].

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Hydrogen is a clean, affordable, practically feasible energy carrier [5,6], combustible and abundant [7] which is widely regarded as a promising alternative to fossil fuels [8]. The use of renewable energy sources (RES) such as wave [9], solar [10], wind [11] or geothermal to generate clean hydrogen is developing and may support the production of hydrogen with low or even zero emissions [12,13]. Parra et al. [14] reveals the hydrogen generated by RES can achieve the decarbonization target for UK. To develop a hydrogen supply chain, which includes the production, delivery, storage, conversion and use of hydrogen, public education and outreach [15] are important [16]. Hydrogen delivery uses liquid organic hydrides as hydrogen carriers is a promising storage and delivery system [17] or use utilization of glass fiber pressure vessels at 200 K and 70 MPa [18]. Hydrogen storage capacity needs further improvement for using by vehicular applications [19] and for urban and industrial-complex area in large scale [20]. The major chicken-and-egg dilemma in the development of the hydrogen economy is whether to build the necessary infrastructure first, including hydrogen fueling stations (HFS) [21], or whether to develop hydrogen applications first, including hydrogen fuel cells (HFC) [22], hydrogen fuel cell vehicles (HFCV) [23] or hydrogen internal combustion vehicles [7,24]. Katikaneni et al. [25] perform feasibility analysis to reveal the on-site hydrogen generation using existing fueling station could support development of hydrogen production and applications [26]. This investigation discusses first three classes of hydrogen industries in the hydrogen supply and sales chain.

Hydrogen is typically produced by steaming reforming, electrolysis, a biological method or other approaches [27]. Through comparative assessment of hydrogen production from all sources, biomass gasification has the best energetic and exergetic efficiencies [28]. The generation of biohydrogen is a green process that uses biomass, wastewater, or sludge [29,30]. Biomass as a source of biohydrogen has more advantages and less impact to environment than fossil fuels [31,32]. The process is less energy-intensive than other generation processes and is technologically feasible. In a clean and green economy, biological and RES-electrolysis methods for generating hydrogen are more effective than steam reforming in mitigating CO_2 emissions. A new method names electrohydrogenesis which uses exoelectrogenic bacteria in microbial electrolysis cells to generate biohydrogen [33]. This investigation will identify the feasibility of the development of these hydrogen generation technologies.

Japan is one of most aggressive countries in developing a hydrogen economy, it plans to develop hydrogen highways for hydrogen-powered vehicles; to establish a hydrogen-powered society, including for example, hydrogen towns, and to promote micro combined heat and power (CHP) systems and HFCVs. Japan leads the number of patents and quality of HFCV research [34]. Since the Fukushima Daiichi Nuclear Disaster in 2011, Japan has required many alternative sources of energy to support economic growth and the quality of life of its citizens, especially as part of the government's program of “Abeconomics”, which is appearing to be effective in raising Japan's economy from its sorry position. A hydrogen-powered society can provide green jobs and help Japan to overcome the obstacles to meeting its global responsibility to mitigate CO_2 emissions. Developed countries such as Japan may face an increasing burden of mitigating CO_2 emissions and reducing their negative impact on the climate. Therefore, this investigation discusses the feasibility of Japan's developing hydrogen supply chains in all instances and a hydrogen economy.

Various economic models can be used to investigate hydrogen-related issues, such as the computable equilibrium model (CGE), linear programming (LP), and the input–output model (IO). The CGE model is suitable for evaluating the possible development of new energy, based on optimal behaviors of members in an economy with price adjustments, resources constraints, various production technologies and principles of market equilibrium. Evaluation of the impact of the development of a hydrogen economy requires a comprehensive economic energy model [5,6,8,27].

The dynamic GTAP model is a global CGE model [35] that was developed by Refs. [36], and is typically utilized to examine issues related to free trade. Lee [8] modified the dynamic GTAP model to incorporate the biohydrogen industry for the evaluation of a continent-wide roadmap to a hydrogen economy. The present investigation modifies and extends the model that was introduced, and utilizes a CGE, combined with the life cycle assessment (CGE-LCA) method that was developed by Refs. [37], to elucidate all the upstream and downstream industrial linkage effects and the life-cycle CO_2 emissions of the hydrogen supply chain. This study investigation uses a modified dynamic GTAP for hydrogen supply chain, combined with LCA to evaluate to the total CO_2 emissions associated with the development of a hydrogen supply chain in Japan. To the best of the author's knowledge, this investigation may be the first to use the dynamic GTAP-LCA method to evaluate the of a hydrogen supply chain.

This investigation contributes to the literature on economic evaluation of hydrogen supply chain and CGE-LCA method in four ways. First, this investigation incorporates complete) hydrogen-related supply chains (industries), including hydrogen fuel cells (HFC), hydrogen fuel cell vehicles (HFCV), hydrogen fueling stations (HFS), and three hydrogen-generating technologies – conventional steam reforming, electrolysis, and biological hydrogen. Little of the pertinent economic literature uses datasets with detailed, up-to-date cost and output data concerning the hydrogen supply chains. Second, the dynamic GTAP (Global Trade Analysis Project) model is modified by applying competition relations between biological, steam reforming and electrolysis technologies for generating hydrogen, and then having hydrogen compete with other secondary energies, such as electricity, gas manufacture and distribution (gas) and petroleum (refining). The model separates the energy substitutes into primary and secondary energy products, as did [8]. Third, the computable equilibrium model (CGE) is combined with the life cycle assessment (LCA) method that was developed by Ref. [37] to simulate the CO_2 emissions by the hydrogen industry under policy conditions. With respect to scenario design, the policies instituted by Japan following the Fukushima Daiichi nuclear disaster, and new CO_2 emission mitigation targets adopted in the Warsaw Climate Change Conference (19th Conference of Parties, COP 19), under the United Nations Framework Convention on Climate Change, are considered.