Evaluation of Sourcing Decision for Hydrogen Supply Chain

Subjects: Engineering, Industrial

Contributor: Kasin Ransikarbum , Wattana Chanthakhot , Tony Glimm , Jettarat Janmontree

The use of fossil fuels has caused many environmental issues, including greenhouse gas emissions and associated climate change. Several studies have focused on mitigating this problem. One dynamic direction for emerging sources of future renewable energy is the use of hydrogen energy.

hydrogen supply chain | multi-criteria decision analysis | analytic hierarchy process (AHP) | fuzzy analytic hierarchy process (FAHP) | data envelopment analysis (DEA)

1. Introduction

Renewable energy has gained worldwide interest due to increasing energy demand as well as a rising concerns over the environmental impact of traditional fuel consumption around the globe. Use of renewable energy in a production system reduces negative environmental impacts, and, therefore, controls climate change [1][2]. It is considered a type of energy that can be collected from natural resources and processes derived from a number of sources and forms, such as direct derivation from the sun and heat generation within the earth. Within the renewable energy definition are also electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, biofuels, and hydrogen derived from renewable resources. The trend towards renewable energy systems has been rapidly shown to be more efficient and economical, with the share of total energy consumption continuously increasing [3][4].

The environmental concerns related to energy production and consumption are globally increasing; these include Greenhouse Gas (GHG) emissions, air pollution, global warming, climate change, water pollution, and solid waste disposal [5]. The European Union (EU) has declared a number of goals one of which is reducing greenhouse gas emissions by about 80–95% by 2050. The Paris Agreement has further stipulated that all parties in the globe should strive to formulate long-term low GHG emission development strategies [6]. Thus far, many countries have taken a variety of actions through strategic policies aiming at meeting energy needs and environmental requirements more securely and sustainably, including the United States, the EU, Germany, China, and Thailand [7][8]. One of the most vigorous vectors for emerging sources of future renewable energy is the use of hydrogen energy.

According to the *Global Hydrogen Generation Market Size Report* [9], the global hydrogen generation market was valued at $129.85 billion in 2021 and is expected to expand at a compound annual growth rate of 6.4% from 2022 to 2030. The utilization of hydrogen will not only improve the sustainability of the renewable energy system but also overall system flexibility. Thus, hydrogen technology advancement from various energy sectors and effective logistics systems in the hydrogen supply chain network (HSCN) could help to increase operational flexibility and perform a pivotal function by linking diverse industrial sectors for future low-carbon energy systems [10]. The significant progress of hydrogen technologies and products has been realized in recent years especially for the usage of fuel cell electric vehicles (FCEV). Nonetheless, the insufficiency of existing infrastructure is one of the hurdles to boosting the hydrogen economy. Thus, an investigation of large-scale infrastructure based on a proper assessment of country-wide strategies is needed. Additionally, an assessment of sustainable hydrogen production technology along the HSCN is needed [11][12].

In Thailand, the growth of a number of environmentally friendly sectors such as biotechnology, biochemical, biopharmaceutical, and bioenergy has been fostered to support global and national bioeconomy plans [13]. In particular, the Thai government's initiatives and policies are to transition from the utilization of coal/natural gas sources of energy to biomass sources of renewable energy as part of the national renewable energy plan. That is, biomass from the first (e.g., corn, sugarcane, and starch) and the second (e.g., cellulosic materials, wood residue, waste biomass) generations of bioenergy are an on-going focus of the Thai government. A number of tax incentives for on-going projects of the Thai government to promote renewable energy have been reported, including support for farmers to grow fast-growing trees, the promotion of electricity manufacturing from garbage-derived energy, the promotion of projects associated with solar and wind energy, and the funding of research and development activities for research hubs focusing on bioenergy. Compared to the rising usage of biomass-based fuel energy in Thailand, hydrogen energy-based research in Thailand is still relatively new.

2. Evaluation of Sourcing Decision for Hydrogen Supply Chain Using an Integrated Multi-Criteria Decision Analysis (MCDA) Tool

The hydrogen economy is an economy that relies on hydrogen as the commercial energy that delivers a substantial portion of national energy and services. The concept of hydrogen energy is expected to become a reality when hydrogen production from various renewable energy sources can be economically obtained and used in an environmentally friendly manner. There are a number of leading countries in the globe that initiate policies and plans to boost the hydrogen economy. Based on the low-carbon hydrogen index ranking analyzed by Cornwall Insight [14], the top fifteen countries that are leaders in the hydrogen economy with a strong potential for production or consumption of hydrogen energy are Germany, followed by South Korea, Spain, Japan, United Kingdom, France, Canada, Chile, Netherlands, Australia, Portugal, Norway, United States, Italy, and Ireland.

For example, Germany has implemented an advanced hydrogen strategy. A countrywide hydrogen network to boost hydrogen infrastructure has been established by the German Ministry of Transport. In addition, regulations concerning the hydrogen network are provided to gradually build up a hydrogen infrastructure in the country. The Hydrogen Starter Network 2030 has been proposed as a part of the *Gas Network Development Plan 2020–2030* to support the core of the national hydrogen pipelines. According to a report from the Green Car Congress [15], Germany's Federal Ministry of Economics and the Federal Ministry of Transport have supported 62 large-scale hydrogen projects as a part of the national hydrogen strategy and of the joint European hydrogen project. In addition, the United States of America is one of the nations to conduct early research and adopt clean energy solutions for various sectors, such as power generation, manufacturing, and transportation. The USA's federal government provides study plans in accordance with the national hydrogen energy vision and a roadmap to support the development of hydrogen infrastructure in the country through a number of projects [9].

Infrastructure expansion is a key aspect for the development of HSCN. The HSCN typically begins at the energy source and ends at the fueling station, with various alternatives existing at each link of the infrastructure network. The produced hydrogen can also be distributed using a number of distribution channels and transportation modes depending on the physical forms of hydrogen as well as the energy demand profile. For example, while liquefied hydrogen can be transported in tankers via roads and railways, gaseous hydrogen may be distributed via pipelines in the network [16]. In addition, storage decisions are a vital function of the HSCN; they are also complex due to the dissimilar physical forms of hydrogen. Finally, the locational choice of the fueling station also depends on whether hydrogen will be delivered to the station or produced and stored on-site. It is thus imperative to analyze the context of HSCN not only from well-to-tank (i.e., from fuel production of the energy source to fuel supply) or tank-to-wheels (i.e., from fuel supply to the use of fuel in the vehicle) perspectives, but also from the perspective of well-to-wheels exploration.

The growth of a foreseeable hydrogen market inevitably requires complex analyses for the entire HSCN system in order to achieve optimal nationwide designs and plans. Challenges for complex HSCN thus depend on the interactions between different parts of the chain, which should be properly evaluated. That is, the interactions and flows among key stakeholders and activities of HSCN can be seen as one type of renewable-energy supply chain, but it is more challenging due to the complexity of the network itself and the various hydrogen production technologies that may complicate the evaluation of the network with respect to the commodity type and the distribution mode. A number of existing studies clearly point out that various aspects of the HSCN need to be further evaluated using advanced analytical models and proper decision levels for the analysis [17][18].

For example, existing analytical models developed in the area of HSCN rely typically on cost minimization. Thus, other criteria related to environmental (e.g., GHG emissions, waste reduction) and social requirements (e.g., poverty reduction potential, quality of life) are also needed for a sustainability analysis [19]. Moreover, decisions for logistics and supply chain management are typically divided into three levels depending on the types and periods of making decisions; these are strategic, tactical, and operational decision making. Strategic decisions for the HSCN in particular pertain to design and policy-related decisions on sourcing, technology types, type of storage, capacity level, locations, allocation and distribution between facilities, and transportation modes. Additionally, given that HSCN starts from various upstream energy sources that can be transformed in respective midstream and downstream processes, uncertainties become inevitably involved in a number of steps of the chain. Thus, the integration of uncertain aspects of real-life applications is also suggested by existing studies as an essential part of managerial decision making in order to increase competitiveness, efficiency, and responsiveness of the HSCN [20].

With respect to the sources of hydrogen supply in the upstream processes of the HSCN, various types of hydrogen technology exist. Different color codes are often used to indicate the origin of the hydrogen sources and technologies [21]. For example, grey hydrogen is created from natural gas using steam methane reformation (SMR) but without capturing the GHG made in the process. While grey hydrogen may emit GHGs that adversely affect environmental concerns, the blue-color coded hydrogen refers to hydrogen technologies that are capable of capturing carbon dioxide emissions during production and storage activities. The SMR, in particular, is a method of producing hydrogen from natural gas; currently, this is considered the cheapest source of industrial hydrogen. Meanwhile, green hydrogen involves the production of hydrogen using renewable energy, which has a clear advantage in achieving the extensive deployment of a low-carbon footprint in the energy system. In contrast to green hydrogen, the black coal in the hydrogen-making process is considered the most environmentally damaging.

Green hydrogen production, in particular, is specifically related to the electrolysis technique in which water and electricity from renewable energy sources, such as wind and solar, are mainly used. Although green hydrogen is considered a promising technology to achieve extensive deployment with low-carbon footprint in the energy system, the economic aspect of green hydrogen is still currently an expensive option. Grey and blue hydrogens cost around USD 1.00–1.80 per kilogram and USD 1.40–2.40 per kilogram, respectively. Meanwhile, green hydrogen costs approximately between USD 2.50 and USD 6.80 per kilogram. Thus, tradeoffs clearly exist among environmental and economic criteria in this regard [22]. Selecting hydrogen sources and technology types can be conceived as a type of MCDA problem concerned with multiple criteria and a number of finite alternatives.

Thus, the purpose of MCDA is to support decision makers where a unique optimal solution does not exist, and it is necessary to use decision makers' preferences to differentiate between solutions. The MCDA technique has evolved and has had many applications in the literature (e.g., [23][24][25]). Recent studies show that the trend in MCDA research is to integrate two or more tools to tackle the limitations of a particular, single method [26][27]. A number of literature review-type studies also provide directions for future tools using the MCDA technique (e.g., [28][29][30][31]). These studies similarly suggest that future applications include addressing more complex issues based on the integrated application of various techniques. Although applications in MCDA have been increasingly found in the literature, the selection problem for hydrogen sources and technology type is still relatively limited. Additionally, an application specifically for a case study in Thailand has not been found to date.

On the basis of the hydrogen source, the options have been categorized according to existing technology types. These technologies also depend on various criteria under consideration. For example, the SMR technology using natural gas as a source for hydrogen production is considered a mature and economical technology in current hydrogen generation. The process of coal gasification uses steam and oxygen to break the molecular bonds in coal to form a gaseous mixture of hydrogen and carbon dioxide. One of the drawbacks of producing hydrogen from coal and natural gas is the production of carbon dioxide during the reforming process, meaning that carbon capture will be an important operation for the environmentally benign utilization of these resources in the future. Meanwhile, biomass gasification uses a controlled process to convert biomass to hydrogen without combustion. The use of the biomass is another interesting pathway since biomass is not only an abundant resource but can also help to remove carbon dioxide from the atmosphere. Finally, there has been an increase in new electrolysis installations with the aim to produce hydrogen from water with the clear benefit of a zero-carbon emission technique. Regardless, most of the electrolysis projects are still relatively expensive and are limited to only some countries [31][32][33][34][35][36][37].

References

1. Elahi, E.; Khalid, Z.; Tauni, M.Z.; Zhang, H.; Lirong, X. Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk: A retrospective survey of rural Punjab, Pakistan. Technovation 2022, 117, 102255.
2. Elahi, E.; Khalid, Z.; Zhang, Z. Understanding farmers' intention and willingness to install renewable energy technology: A solution to reduce the environmental emissions of agriculture. Appl. Energy 2022, 309, 118459.
3. Farias, C.B.B.; Barreiros, R.C.S.; da Silva, M.F.; Casazza, A.A.; Converti, A.; Sarubbo, L.A. Use of Hydrogen as Fuel: A Trend of the 21st Century. Energies 2022, 15, 311.
4. Gawusu, S.; Zhang, X.; Jamatutu, S.A.; Ahmed, A.; Amadu, A.A.; Djam Miensah, E. The dynamics of green supply chain management within the framework of renewable energy. Int. J. Energy Res. 2022, 46, 684–711.
5. Levenda, A.M.; Behrsin, I.; Disano, F. Renewable energy for whom? A global systematic review of the environmental justice implications of renewable energy technologies. Energy Res. Soc. Sci. 2021, 71, 101837.
6. Mandley, S.J.; Daioglou, V.; Junginger, H.M.; van Vuuren, D.P.; Wicke, B. EU bioenergy development to 2050. Renew. Sustain. Energy Rev. 2020, 127, 109858.
7. Department of Alternative Energy Development and Efficiency (DEDE). Research and Development in the Field of Energy Conservation and Renewable Energy in Thailand. 2021. Available online: http://weben.dede.go.th/ (accessed on 1 May 2022).
8. Energy Tracker Asia. Southeast Asia Looks beyond Coal. 2022. Available online: https://energytracker.asia/ (accessed on 1 May 2022).
9. Global Hydrogen Generation Market Size Report. Grand View Research. 2022. Available online: https://www.grandviewresearch.com/ (accessed on 1 May 2022).
10. Körner, A.; Tam, C.; Bennett, S.; Gagné, J. Technology Roadmap-Hydrogen and Fuel Cells; International Energy Agency (IEA): Paris, France, 2015.
11. Ren, X.; Li, W.; Ding, S.; Dong, L. Sustainability assessment and decision making of hydrogen production technologies: A novel two-stage multi-criteria decision making method. Int. J. Hydrogen Energy 2020, 45, 34371–34384.

12. Talebian, H.; Herrera, O.E.; Mérida, W. Policy effectiveness on emissions and cost reduction for hydrogen supply chains: The case for British Columbia. Int. J. Hydrogen Energy 2021, 46, 998–1011.
13. Thailand Board of Investment (BOI). Thailand’s Bio Economy. 2022. Available online: https://www.boi.go.th/ (accessed on 1 May 2022).
14. Cornwall Insight. Low-Carbon Hydrogen Index. 2022. Available online: https://www.cornwall-insight.com/ (accessed on 1 May 2022).
15. Green Car Congress. 2021. Available online: https://www.greencarcongress.com/ (accessed on 1 May 2022).
16. Yoon, H.J.; Seo, S.K.; Lee, C.J. Multi-period optimization of hydrogen supply chain utilizing natural gas pipelines and byproduct hydrogen. Renew. Sustain. Energy Rev. 2022, 157, 112083.
17. Atashbar, N.Z.; Labadie, N.; Prins, C. Modelling and optimization of biomass supply chains: A review. Int. J. Prod. Res. 2018, 56, 3482–3506.
18. Ransikarbum, K.; Mason, S.J. A bi-objective optimisation of post-disaster relief distribution and short-term network restoration using hybrid NSGA-II algorithm. Int. J. Prod. Res. 2021, 60, 5769–5793.
19. Ransikarbum, K.; Pitakaso, R.; Kim, N.; Ma, J. Multicriteria decision analysis framework for part orientation analysis in additive manufacturing. J. Comput. Des. Eng. 2021, 8, 1141–1157.
20. Shah, S.A.A. Feasibility study of renewable energy sources for developing the hydrogen economy in Pakistan. Int. J. Hydrogen Energy 2020, 45, 15841–15854.
21. Van de Graaf, T.; Overland, I.; Scholten, D.; Westphal, K. The new oil? The geopolitics and international governance of hydrogen. Energy Res. Soc. Sci. 2020, 70, 101667.
22. Collins, L. A Wake-Up Call on Green Hydrogen: The Amount of Wind and Solar Needed Is Immense; Recharge: London, UK, 2020.
23. Chaiyaphan, C.; Ransikarbum, K. Criteria Analysis of Food Safety using the Analytic Hierarchy Process (AHP)—A Case study of Thailand’s Fresh Markets. In Proceedings of the 2019 Research, Invention, and Innovation Congress (RI2C 2019), Bangkok, Thailand, 11–13 December 2019; EDP Sciences: Les Ulis, Frace, 2020; Volume 141, p. 02001.
24. Ransikarbum, K.; Leksomboon, R. Analytic Hierarchy Process Approach for Healthcare Educational Media Selection: Additive Manufacturing Inspired Study. In Proceedings of the 2021 IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA), Chengdu, China, 23–26 April 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 154–158.
25. Laganà, I.R.; Colapinto, C. Multiple criteria decision-making in healthcare and pharmaceutical supply chain management: A state-of-the-art review and implications for future research. J. Multi-

Criteria Decis. Anal. 2022, 29, 122–134.

26. Goyal, P.; Kumar, D.; Kumar, V. Application of multicriteria decision analysis (MCDA) in the area of sustainability: A literature review. Int. J. Anal. Hierarchy Process 2020, 12, 720.
27. Chanthakhot, W.; Ransikarbum, K. Integrated IEW-TOPSIS and fire dynamics simulation for agent-based evacuation modeling in industrial safety. Safety 2021, 7, 47.
28. Dos Santos, P.H.; Neves, S.M.; Sant'Anna, D.O.; de Oliveira, C.H.; Carvalho, H.D. The analytic hierarchy process supporting decision making for sustainable development: An overview of applications. J. Clean. Prod. 2019, 212, 119–138.
29. Liu, Y.; Eckert, C.M.; Earl, C. A review of fuzzy AHP methods for decision-making with subjective judgements. Expert Syst. Appl. 2020, 161, 113738.
30. Yu, D.; He, X. A bibliometric study for DEA applied to energy efficiency: Trends and future challenges. Appl. Energy 2020, 268, 115048.
31. Yu, D.; Kou, G.; Xu, Z.; Shi, S. Analysis of collaboration evolution in AHP research: 1982–2018. Int. J. Inf. Technol. Decis. Mak. 2021, 20, 7–36.
32. Montignac, F.; Mousseau, V.; Bouyssou, D.; Aloulou, M.A.; Rousval, B.; Damart, S. An MCDA approach for evaluating hydrogen storage systems for future vehicles. In Evaluation and Decision Models with Multiple Criteria; Springer: Berlin/Heidelberg, Germany, 2015; pp. 501–532.
33. Acar, C.; Beskese, A.; Temur, G.T. Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP. Int. J. Hydrogen Energy 2018, 43, 18059–18076.
34. Xu, L.; Wang, Y.; Shah, S.A.A.; Zameer, H.; Solangi, Y.A.; Walasai, G.D.; Siyal, Z.A. Economic viability and environmental efficiency analysis of hydrogen production processes for the decarbonization of energy systems. Processes 2019, 7, 494.
35. Wulf, C.; Zapp, P.; Schreiber, A.; Kuckshinrichs, W. Setting thresholds to define indifferences and preferences in PROMETHEE for life cycle sustainability assessment of European hydrogen production. Sustainability 2021, 13, 7009.
36. Li, Z.; Tian, G.; El-Shafay, A.S. Statistical-analytical study on world development trend in offshore wind energy production capacity focusing on Great Britain with the aim of MCDA based offshore wind farm siting. J. Clean. Prod. 2022, 363, 132326.
37. Xuan, H.A.; Trinh, V.V.; Techato, K.; Phoungthong, K. Use of hybrid MCDM methods for site location of solar-powered hydrogen production plants in Uzbekistan. Sustain. Energy Technol. Assess. 2022, 52, 101979.