An Analysis of Production Sourcing Decision for Hydrogen Supply Chain using Analytic Hierarchy Process (AHP) technique: A Case Study in Thailand

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Abstract. Recently, renewable energy has been a worldwide promising interest due to an increasing energy demand as well as a mounting concern over the environmental impact of traditional fuel path. One of a vigorous vector for emerging source of the future renewable energy is the use of hydrogen energy. In this research, we evaluate a list of criteria and sourcing decision of hydrogen energy using a case study in Thailand. In particular, five selective criteria are evaluated: political acceptance, economic desire, social acceptance, resource potential, and environmental perception. In addition, four potential sources are assessed inclusive of natural gas, coal, biomass, and water. Next, the analytic hierarchy process technique is used to analyze weighted criteria as well as sourcing alternatives, given data from a group of selected experts. Our results reveal that political acceptance is considered the most important criterion, in which coal and natural gas are likely the foreseeable sources for hydrogen production in Thailand.

Keywords: Production Sourcing decision, Renewable energy, Hydrogen supply chain, Analytic hierarchy process, Multi-criteria decision analysis

Introduction and Motivation

Recently, renewable energy has been perceived as a promising alternative as a substitute for non-renewable fuels. This is due to an immersive energy demand these days as well as an increasing apprehension for the environmental effect around the world. The European Union goals, for instance, have been set with an aim to cut greenhouse gas emission [1]. Additionally, there are some requirements from the Paris Agreement that key parties around the globe should attempt to plan for long-term strategies for lowering Greenhouse Gas emission. Accordingly, a number of nations have taken a number of countermeasures through governmental policies in order to harmonize environmental requirements, energy needs, and society more sustainably [2-3]. One of a vigorous vector for emerging source of the future renewable energy is the use of hydrogen energy.

According to the International Energy Agency [4], the deployment of hydrogen can not only improve the sustainability of the renewable energy, but also the overall system flexibility. Thus, hydrogen technology advancement from various energy sectors and effective logistics system in the Hydrogen

Supply Chain Network (HSCN) could help to increase operational flexibility and perform a pivotal function by linking different industrial sectors for future low-carbon energy systems. 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 considered one of the hurdles to boost the hydrogen economy. Thus, an investigation of large-scale infrastructure based on the proper assessment of country-wide strategies is needed [5].

The governmental unit in Thailand, in particular, has initiated plans to move from coal utilization as well as natural gas towards the use of biomass, a significant source for renewable energy in Thailand, as a part of the renewable energy plan in Thailand. Biomass, in particular, can be obtained from various sources, such as those from the first generation (e.g., sugarcane, starch, and corn) and the second generation (e.g., waste biomass, wood residue). Both of these generations, in particular, are considered an on-going focus of the Thai government [6]. Additionally, tax incentives are also provided by the Thailand's government for a number of on-going projects, with an aim to promote the use of renewable energy. These projects include the support of the farmers, who grow fast-growing trees in various provincial zones, the advancement of the electricity production from garbage, the projects associated with wind and solar energy, as well as the Research and Development (R&D)-related projects for research activities for bioenergy [7]. Comparing to the rising usage of biomass-based fuel energy in Thailand, hydrogen-based research in Thailand is still relatively new.

In this research, we evaluate a list of important criteria and possible alternatives for production sources and methods of hydrogen energy using a case study in Thailand. In particular, five selective criteria are evaluated: political acceptance, economic desire, social acceptance, resource potential, and environmental perception. In addition, four potential sources are assessed inclusive of natural gas, coal, biomass, and water. Next, one of the Multi-Criteria Decision Analysis (MCDA) tools called Analytic Hierarchy Process (AHP) is used to investigate subjective opinions of a group of experts. The AHP technique, in particular, has been applied to a number of applications and has advantages due to its simplicity yet capability to aid decision makers in selecting the most valuable alternatives, while taking into account multiple, conflicting, decision criteria [8-11]. Thus, AHP is chosen in our study.

It is important to note that this current study is our on-going research with an ultimate aim to propose the mathematical model to analyze the hydrogen supply chain network using multiple-objective consideration. The outline of the paper is organized as follows. Section 2 further provides associated study in the literature and the proposed methodology. Next, Section 3 presents the Thailand case study and discussion for results. Finally, Section 4 presents conclusion and directions for future research.

Literature Review and Methodology

1.1. Hydrogen Supply Chain Network (HSCN)

The HSCN typically starts from the energy sources and ends at the fueling stations, in which various alternatives exist at each link of the infrastructure network. Concerning sources of hydrogen supply, conventional hydrogen production typically utilizes coal (i.e., coal gasification) and biomass (i.e., biomass gasification) as source for the production process. On the other hand, green hydrogen production is concerned with the electrolysis technique, in which water and electricity from renewable energy sources like wind and solar are used. The electrolysis process, in particular, is a promising technology to achieve an extensive deployment for low-carbon footprint in the energy system albeit currently an expensive option [12]. The produced hydrogen can be distributed using a number of modes depending on the physical forms of hydrogen. That is, liquefied hydrogen can be transported in tankers via roads and railways, whereas gaseous hydrogen may be distributed via pipelines.

In addition, storage decision is a vital function of the HSCN, which is also complex due to dissimilar physical forms of hydrogen. Finally, the locational choice of fueling station also depends on whether hydrogen will be delivered to the station or produced and stored on-site to serve FCEVs. It is thus imperative that an analysis in the context of HSCN is required from not only the 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) analysis, but also well-to-wheels exploration [13]. Figure 1 illustrates the flow of HSCN.

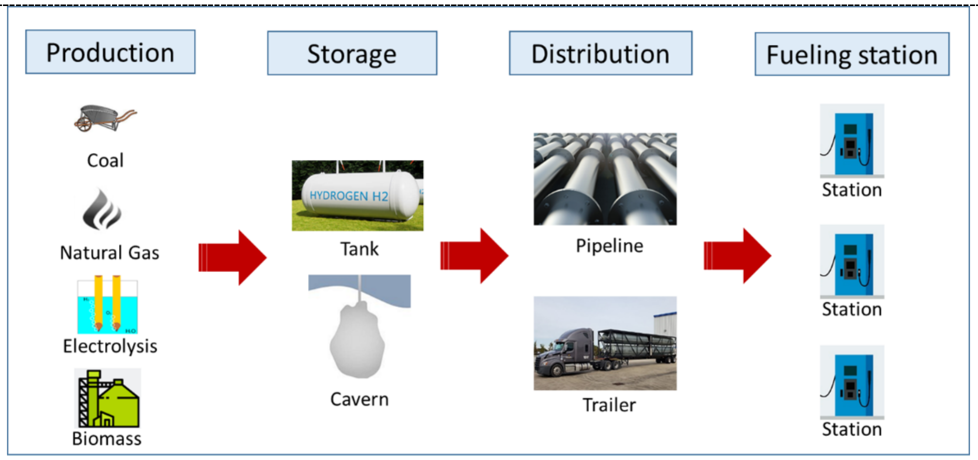

Figure 1. A structure of Hydrogen Supply Chain Network

1.2. Research Gaps in HSCN

The growth of a competitive market for hydrogen inevitably requires complex analyses for the whole system in order to achieve optimal design and plan nationwide. Challenges for the complex HSCN thus depend on the interactions between different parts of the chain, which should be properly evaluated. In addition, processes in the HSCN also involves various forms of the energy source, the production facility, modes of transportations, distribution and storage types, and fueling stations. Thus, the infrastructure of HSCN can be seen as one type of the renewable-energy supply chain, but is more challenging due to the complexity of the network itself and the on-going technologies that complicate the evaluation of the network. Some existing research gaps related to HSCN are next highlighted.

A number of researchers suggest that existing analytical models developed in the area of HSCN typically relies on the cost minimization. Thus, other criteria related to environmental (e.g., CO2 emissions, waste reduction) and social requirements (e.g., poverty reduction potential, quality of life) are also needed for the sustainable decision making [14]. The adoption of the Life Cycle Analysis (LCA) could also be considered incorporating several environmental indicators. Moreover, supply chain management is typically divided into three levels of decision makings – strategic, tactical, and operational. Strategic decisions, in particular for HSCN are pertaining to design and policy-related decisions on sourcing, capacity and type of storages, technologies, locations, allocation and distribution between facilities, transportation modes, etc., which are scarcely discussed in the literature [15].

Besides, similar to gasoline and natural gas, hydrogen can be dangerous comparative to other flammable fuel. Thus, risk assessment approaches for renewable energy and hydrogen infrastructures are also needed for further safety discussion. Additionally, HSCN starts from various energy sources that can be transformed to the downstream processes. Uncertainties are involved in a number of steps of the chain, in which the integration of uncertain aspects of real-life applications is essential for managerial decision makings in order to increase competitiveness, efficiency, and responsiveness of the market competition [16].

1.3. Analytic Hierarchy Process (AHP) and its Application

The AHP method is considered one of the well-known MCDA techniques that evaluates problems with qualitative data under various criteria and/or alternatives. The hierarchical structure of AHP normally starts from the Goal level, followed by the Criteria level, and the final level of Alternatives, respectively. In particular, AHP uses the pairwise-comparison practise to assess each pair of data. The comparison scale representing the level of importance for AHP method is typically in a range from 1 to 9, where increasing number implies higher relative importance [17]. That is, the AHP is an approach that incorporated and applied to approximate the magnitudes of criteria as well as alternatives of interest. We next briefly introduce the AHP methodology as follows.

The methodology for AHP is separated into the following nine steps.

2.3.1 Step 1. The number of pairwise comparisons for AHP will depend on the number of associated criteria as illustrated in Equation (1), where n is the number of factors of interest.

2.3.2 Step 2. A matrix table called decision matrix for both criteria and alternatives will be constructed as illustrated in Equation (2), where a_{ij} is the comparison of criteria i and j.

$$n(n-1)/2 \tag{1}$$

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & a_{ji} = 1/a_{ij} & 1 & \dots \\ a_{n1} & \dots & \dots & 1 \end{bmatrix} \tag{2}$$

2.3.3 Step 3. A decision matrix will be normalized called normalized decision matrix by dividing each obtained decision value from the first step with the sum of each matrix column.

2.3.4 Step 4. The Eigenvector is next computed based on the criteria weights as well various alternatives (if any) as presented in Equation (3).

2.3.5 Step 5. The maximum Eigenvalue can be computed based on the Eigen vector obtained earlier, represented using $\lambda_{\max}$ notation, where p is the local priority vector.

$$A \cdot p = \lambda_{\max} \cdot p \tag{3}$$

2.3.6 Step 6. The Consistency Index *(CI)* can next be computed as illustrated in Equation (4).

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

2.3.7 Step 7. The Random Consistency Index table *(RI)* is next examined, in which the appropriate value will be chosen based on the size of the matrix under evaluation as shown in Table 1.

Table 1. The RI values for the AHP method

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.3.8 Step 8. The Consistency Ratio *(CR)* of the matrix can then be calculated as shown in Equation (5).

$$CR = \frac{CI}{RI} \tag{5}$$

2.3.9 Step 9. Finally, the ranking of each alternative (if any) will be computed as shown in Equation (6), where w_j is the weighted value of each criterion j; l_{ij} is the local score of particular alternative i compared to j; and g_i is the global score of each alternative i of interest.

$$g_i = \sum_j w_j l_{ij} \tag{6}$$

1.4. Data Collection and Analysis Plan

In this study, we collect data from a group of decision makers (i.e., experts), in which qualifications are justified. In particular, subjective opinion and qualitative judgements are obtained during data collection process. Then, collected data will be verified and analyzed using the above AHP method.

Case Study, Results, and Discussion

1.5. Case Study of Hydrogen Sourcing Decision

We next discuss detailed data relevant to the criteria and alternatives relevant to the case study of Hydrogen sourcing decision of the HSCN. Initially, five criteria are chosen based on the literature review (e.g., [18-20]). In addition, four alternatives for Hydrogen production/sourcing are discussed. Finally, a group decision making based on nine chosen experts are elaborated. We initially illustrate the evaluated AHP hierarchy as shown in Figure 2, in which level 0 implies the goal, level 1 shows a list of assessed criteria, and level 2 presents associated alternatives.

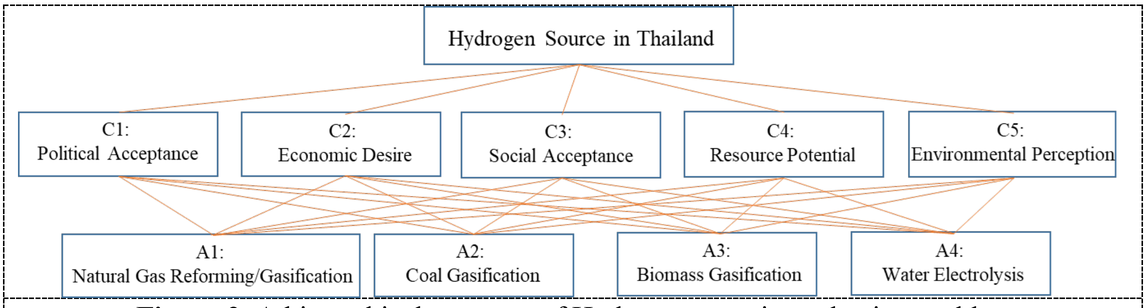

Figure 2. A hierarchical structure of Hydrogen sourcing selection problem

3.1.1 Decision Criteria

- *C1-Political acceptance*: The first criterion is defined as a conformity with Thailand energy policy, regulation from the government, etc.
- *C2-Economic desire*: The second criterion concerns with economic benefit and investment worthiness by taking into account relevant Thailand economic growth.
- *C3-Social acceptance*: The third criterion is factor related to the acceptance or resistance perspective of the society both at the local and at the national level.
- *C4-Resource potential*: The fourth criterion is related to the availability and sufficiency of the source of raw materials with respect to Thailand.
- *C5-Environmental perception*: The fifth criterion is based on importance of environmental concerns, waste generation, pollution effect, and a capability for environmental management.

3.1.2 Sourcing Alternatives

- *A1-Natural Gas Reforming/Gasification:* The first alternative is to use synthesis gas, which is a mixture of carbon monoxide, hydrogen, as well as carbon dioxide created by reacting natural gas with high-temperature steam process. Currently, the process of reforming low-cost natural gas can be currently seen to provide hydrogen for FCEVs worldwide.
- *A2-Coal Gasification*: The process of coal gasification uses oxygen and steam in order to break molecular bonds in coal and to form a gaseous mixture of carbon monoxide and hydrogen. It is possible that carbon dioxide and other polluted substances may be detached from gas using the coal gasification process.
- *A3-Biomass Gasification*: The biomass gasification process uses a controlled operation, which involves steam, heat, and oxygen, to convert from biomass to hydrogen and other products without combustion. Currently, key challenges to the biomass gasification method are noted for availability of biomass feedstock as well as costs associated with capital equipment.
- *A4-Water Electrolysis*: The electrolysis is the process of using electricity to split water into oxygen and hydrogen. This method is considered a leading hydrogen production pathway to achieve the goal of zero greenhouse gas emissions. Regardless, some challenges are noted for

capital cost of the electrolyzer unit as well as energy-efficiency improvement to convert from electricity to hydrogen over an inclusive range of operating procedures and conditions.

3.1.3 Group Analysis for Experts. Next, a group of decision makers who are qualified as experts are interviewed and asked to give judgmental decisions. In particular, these experts are chosen based on background, experience, and publication record in the field. That is, 9 representative experts are chosen, in which 5 of them are from academic institutes and 4 of them are from governmental units and companies. These experts also have experienced in energy-related research and practices for more than 5 years. Next, collected data and input are analyzed using a group decision making technique based on the AHP methodology [21].

1.6. Results and Discussion

We next discuss analyzed results. Initially, the mathematical aggregation is performed at the pairwise comparison matrix of each decision maker/expert using geometric mean approach. Then, criteria and alternative weights are evaluated and synthesized for a group decision making. We note that the geometric mean procedure is a well-known technique for a group decision making in AHP due to its capability to lessen rank reversal issue in AHP [21]. In particular, Table 2 illustrates analyzed group decision-making results for each alternative with respect to each criterion.

Clearly, there are some trade-offs among these alternatives. For example, the coal gasification option (i.e., A2) is considered the most superior option in terms of political acceptance, economic desire, and resource potential criteria (i.e., the highest relative weight of 0.44, 0.35, and 0.34 for C1, C2, and C4 criteria, respectively). On the other hand, the natural gas reforming/gasification (i.e., A1) is perceived as the best option for social-acceptance condition. Finally, the water electrolysis option (i.e., A4) is found to be best suited with respect to an environmental perception (i.e., C5). The biomass gasification (i.e., A3) is perceived as challenges due partly to the underneath process and future stability.

Table 2. Analyzed group decision making for alternative weights for each criterion

Criteria	Alternatives	Relative Weights
C1	A1	0.16
	A2	**0.44**
	A3	0.20
	A4	0.20
C2	*A1*	0.23
	A2	**0.35**
	A3	0.20
	A4	0.22
C3	A1	**0.46**
	A2	0.07
	A3	0.16
	A4	0.30
C4	A1	0.29
	A2	**0.34**
	A3	0.25
	A4	0.13
C5	A1	0.30
	A2	0.11
	A3	0.22
	A4	**0.36**

Next, the results from group decision making are obtained for both criteria weight and alternatives as shown in Figure 3. In particular, the highest-weighted criterion is C1 (Political acceptance) followed by C3 (Social acceptance), C2 (Economic desire), C4 (Resource potential), and C5 (Environmental perception), respectively. Additionally, a ranking list for relevant alternatives for hydrogen source and production is found to be A2 (Coal Gasification), followed by A1 (Natural Gas Reforming/Gasification), A4 (Water Electrolysis), and A3 (Biomass Gasification), respectively.

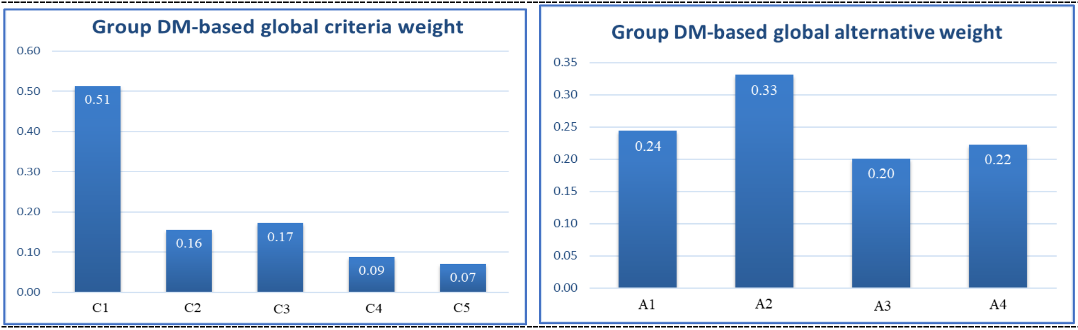

Figure 3. Global (left) criteria weight and (right) alternative weight

Political acceptance is clearly the most influential criterion especially for Thailand, in which a direction from government policy plays a key role for renewable energy plan. In addition, both Economic desire and Social acceptance criteria are approximately equally important. Finally, both perspectives for Resource potential and Environmental perception criteria are found to be as important but at a lesser degree compared to both Economic desire and Social acceptance criteria. With regard to the alternative list, both Coal and Natural Gas Reforming/Gasification alternatives are the most favourable alternatives. This is expected given that Thailand can potentially move to an initial state of the so-called grey hydrogen first. Moreover, both Water Electrolysis and Biomass Gasification are potentially promising options for hydrogen production but at a lesser degree. There are also some remarks from a group of experts concerning a scarcity of water resource as well as a society perception towards hydrogen energy. In addition, the economies of scale for the use of biomass for the hydrogen energy source still requires further attention.

Conclusion and Future Research

In conclusion, we explore the perceptions of selecting alternative sources for hydrogen production, one of the key global renewable energy, using a case study in Thailand. A list of vital criteria deemed important for choosing production sources of hydrogen energy inclusive of natural gas reforming/gasification, coal gasification, biomass gasification, and water electrolysis are assessed. Our analysis using the Analytic Hierarchy Process (AHP) techniques reveals perception of key experts, in which a ranking list of both criteria and alternatives can be obtained for future analysis of hydrogen source-related decision of Hydrogen Supply Chain Network (HSCN) development.

We further briefly note the limitations of our study. For example, it would be interesting to also discuss and explore sub-criteria relevant to each main criterion for practical implication (e.g., [22]). In addition, our plan for the future research is to further analyze relative efficiency (e.g., [23-24]) among hydrogen-source alternatives and compare against the ranking list optioned in this study. Additionally, various aspects between the context of hydrogen sources and supply chain network between Thailand and Germany will be assessed, as representatives between developing and developed countries. The future research will also focus on model development and analysis of supply chain aspects using mathematical model (e.g., [25]).

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