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Hydrogen supply chain uncertainty: A systematic literature review#

Xing Lu[1, 2*], Anja Fischer [1], Mona Wappler [2]

1 TU Dortmund University, Dortmund, 44227, Germany

2 Rhine-Waal University of Applied Sciences, Kamp-Lintfort, 47475, Germany
(Corresponding Author: xing.lu@tu-dortmund.de)

ABSTRACT

This paper seeks to identify the uncertainty factors in the hydrogen supply chain that affect supply chain costs through a systematic review of the existing literature from 2019 to 2023. 45 uncertainty factors are identified, which can be divided into two categories based on their impact scope. The factors in the first group impact the whole hydrogen supply chain, while the parameters in the second group affect one or several specific sectors in the supply chain. Hydrogen demands, electricity prices, and the capital expenditure of the electrolyzer are the most considered uncertainty factors in the existing literature. Additionally, it turns out that the current research on hydrogen supply chain uncertainty mainly focuses on the factors that affect the whole supply chain and the sector production, while the sectors of storage and transportation have received less attention in the current research.

Keywords: hydrogen supply chain, uncertainty, systematic literature review

1. INTRODUCTION

The implementation and integration of hydrogen into the current energy system are being investigated to address climate change concerns, thereby enabling the decarbonization targets of various countries [1]. To do so, optimal design and construction of cost-effective and stable hydrogen supply chains, encompassing production, conditioning, storage, transport, transloading (terminal), reconditioning, and consumption play a significant role. As the hydrogen economy is still emerging, there are plenty of uncertain sources associated with the supply chain that affect the hydrogen supply chain costs and have to be considered during the decision-making process by the political makers, investors, designers, and planners.

The term "supply chain uncertainty" refers to the uncertainties (including the risks) that can occur at any point within the supply chain. These are often caused by a lack of information or understanding about the supply chain, its environment, or processing capacities [2]. The issues of uncertainty can have positive or negative impacts on the supply chain [3]. For example, the investment costs of electrolyzer or liquefaction facilities for liquefied hydrogen may decrease due to future technological development, thereby benefiting the hydrogen supply chain with lower costs and accelerating the industrialization of the hydrogen economy. According to Simangunsong et al. [3], the general supply chain uncertainty sources can be divided into three groups:

1) the uncertainty sources that come from the specific supply chain sectors (section-specific). This group encompasses product characteristics (for example, product life cycle and specification), manufacturing process, control/chaos/response uncertainty, decision complexity, organization/behavioral issues, and information system or IT complexity;

2) the uncertainty sources that arise from some of the hydrogen supply chain sectors (internal supply chain) and. For this group, sources such as customer demand, supplier, order forecast horizon and chain configuration, infrastructure, and facilities are relevant;

3) external uncertainty factors from outside the hydrogen supply chain. These include environmental factors such as government policy, competitor behavior, macroeconomic changes, and disasters.

Hydrogen supply chains have been studied for many years; therefore, it is necessary to summarize the uncertainties within them. To the best of our knowledge, there is still a significant gap in the research. Therefore, we conducted a systematic literature review to provide transparency regarding the current state-of-the-art and to identify scientific gaps in the research on hydrogen supply chain uncertainty sources.

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2. MATERIAL AND METHODS

In this section, we introduce the methodology of the systematic literature review utilized for this paper.

The literature review is conducted by using the guideline from Kraus et al. [4]. To cover a holistic references paper, the keywords “hydrogen” AND “Supply Chain” AND “logistic” OR “distribution” OR “transport” OR “distribution” in the topic were searched from the database Web of Science and Scopus. A specific set of inclusion and exclusion criteria are developed and utilized to collect the relevant papers. We only consider peer-reviewed articles published between 2019 and 2023 in journals ranking SJR Q1 and Q2 in the research fields “energy,” “chemical engineering, “and “Business, Management, and Accounting” to ensure the quality of the database. Furthermore, only papers written in English are considered because of the issue of understanding. Lastly, the relevant papers should focus on 1) the hydrogen supply chain, including hydrogen production, storage, and transport; 2) the uncertainty sources in the supply chain. As a result, 68 papers were identified as the ultimate sample for the review. After the comprehensive review of the sample, 48 papers were then reviewed thoroughly with the target uncertainty factors.

3. RESULTS AND DISCUSSION

In this section, we present the hydrogen supply chain uncertainty factors identified in the referenced literature. We categorize these factors into distinct uncertainty groups based on their scope of impact, highlighting the analysis within various supply chain sectors and the evaluation of the tools employed to address hydrogen supply chain uncertainties.

Through a comprehensive analysis, 45 uncertainty factors for the hydrogen supply chain were identified in the referenced papers. These factors were categorized based on their impact in two groups. The uncertainty factors in Group 1 affect supply chain decisions within the internal section only, while the factors in Group 2 can influence decisions throughout the entire hydrogen supply chain, including the parameters arising from the internal supply chain and the environment.

Four factors of the 45 identified uncertainty sources are observed to influence the entire supply chain. Hydrogen demand, originating from the internal supply chain, is considered the most uncertain factor in the sample. The hydrogen supply chain should meet end-user demands efficiently and cost-effectively. In designing, planning, and optimizing the hydrogen supply chain, hydrogen demand is one of the most significant parameters. However, as the hydrogen market is still emerging, accurately forecasting future hydrogen demand is challenging. Therefore, hydrogen demand uncertainty has been addressed in many studies to improve the accuracy of the hydrogen supply chain design and assessment, ensuring the capacity of hydrogen facilities and supply within a cost-effective network. Additionally, factors such as carbon pricing and the version for CO_2 emission, which are influenced by government policies, are often considered uncertainty sources for the hydrogen supply chain, particularly for clean or green hydrogen. Since hydrogen is considered one of the most promising energy carriers for achieving decarbonization targets, it is vital to evaluate the impact of CO_2 on the design and construction of hydrogen supply chain networks to ensure these goals are met. In some cases, carbon prices play a decisive role in determining whether the hydrogen supply chain is cost-effective, particularly for truck transport pathways [5]. This is because transportation trucks are still expected to use traditional fuels, resulting in high CO_2 emissions during their operations. Therefore, it is significant to assess the uncertainty in CO_2 aspects, including emission targets and prices.

The final uncertainty sources identified impacting the entire supply chain (group 1) are the capital recovery factors, such as the weighted average cost of Capital (WACC) and discount rate. Hydrogen projects are generally expected to be constructed over several decades. The WACC that leverages the required cost on the net present value can impact hydrogen costs significantly, particularly for infrastructure with high investment costs, such as production and conversion plants, underground storage facilities, and hydrogen pipelines. Consequently, it is important to evaluate the financial recovery factors for hydrogen supply chain infrastructures, as they may affect investment decisions made by supply chain stakeholders, including governments and investors. Table 1 lists the identified uncertainty factors in the sample, including their descriptions, corresponding groups, impact scopes, and main sources. In the sample, the tool scenario analysis is primarily used to address the uncertainty factors in group 1 since this tool can effectively deal with uncertainties arising from unexpected changes in the external environment [6]. Because of the unpredictable characteristics of the hydrogen economy and the challenges of precision long-term future forecasts at the time decisions are made, this tool suits the effective planning and design of the hydrogen supply chain. In

General, several scenarios are defined to evaluate the uncertainty factors, in which each scenario depicts one possible future state. For instance, the hydrogen demands are assumed to be 0, 25%, 50%, 75%, and 100% penetration rates of FCEVs in many cases in the reference papers [7–10], while the scenarios for financial discovery factors range from 0 to 10% [8,11,12]. Each scenario in this analysis depicts one possible future state. The scenarios together highlight the importance and potential consequence of the accessed uncertainty factors.

Forty-one identified factors impact specific supply chain sectors. The uncertainty sources in the hydrogen production section have received the most attention in the reference papers, with 13 factors mentioned 43 times. Following hydrogen demand, the electricity price for electrolysis and electrolyzers' capital expenditure (CapEx) are the most considered uncertainty factors. The electricity price for electrolysis can significantly impact the dynamics of hydrogen production, storage, and transmission systems. During off-peak electricity price periods, hydrogen production plans may increase their production volume. When hydrogen demand is low, this increases the volume of hydrogen stored and transported within the supply chain, which can be utilized during periods of low renewable resource availability. Consequently, the electricity price can noticeably affect investment decisions regarding hydrogen infrastructure, especially the production assets for electrolysis. Since the electrolyzer technology is still not commercially or technologically mature, the CapEx of electrolyzers is expected to decrease through more mature series production concepts, while efficiency may increase via technological optimization. These considerations necessitate including these two factors as uncertainties when evaluating hydrogen production costs.

For the conversion and reconversion section, the primary focus of uncertainty evaluation is on the CapEx of the conversion and reconversion equipment, such as de-/hydrogenation and liquefaction, conversion efficiency, and the raw materials for Liquid Organic Hydrogen Carriers (LOHC). Similar to the production section, the technologies for conversion and reconversion are not yet technologically or commercially mature. As a result, the CapEx of the equipment and its efficiency are expected to remain unstable. Additionally, the raw material costs for LOHC are considered a high uncertainty source for the LOHC hydrogen supply chain, as this section is still developing [11].

In the transportation sector, transportation distance is the most studied uncertainty factor, as it may significantly impact the hydrogen transportation network and its associated costs. Other factors evaluated in the reference papers include fuel price, operational expenditure of trailers, and trailer capacity, primarily concerning the truck transport system. However, other modes of transport, such as pipelines and ships, are not evaluated.

Notably, the hydrogen storage section has received little attention, with only the storage cycle length, CapEx of salt caverns, and the boil-off rate of liquefied hydrogen being researched once each. Given that large-scale hydrogen transportation and storage are critical challenges in the hydrogen supply chain, more research in these areas from a holistic perspective is necessary to enable effective planning and construction of the hydrogen supply chain [13].

The uncertainty factors impacting specific supply chain sectors are primarily addressed using sensitivity analysis. This method is mainly used to identify critical uncertainty factors and risk sources or to prioritize additional data collection in real situations or mathematical models with more parameters [14]. In the reference papers, sensitivity analysis is primarily used in hydrogen supply chain design studies involving operations research mathematical models. These studies evaluate factors such as the CapEx of equipment for hydrogen production, conversion, and storage, energy prices, and transportation distances. Through this approach, key uncertainty factors in the hydrogen supply chain, such as energy (electricity) prices, carbon prices, and equipment CapEx, are identified.

4. CONCLUSIONS AND NEXT STEPS

We conducted a systematic literature review to identify the uncertainty factors considered in research from 2019 to 2023. As a result, 45 uncertainty sources were identified in the sample. Among these, hydrogen demand, which belongs to the environmental aspect, is highlighted as the most studied uncertainty factor, given its critical role in hydrogen deployment. For hydrogen sector-specific uncertainty sources, the investment cost and efficiency of hydrogen equipment and facilities are the main uncertainty sources considered in the referenced literature. This is because the hydrogen market and technology are expected to develop rapidly in terms of technology, production process, production efficiency, and the corresponding supply chain. Additionally, material prices and availability (e.g., biomass, natural gas, water, and LOHC) are other identified uncertainty sources. The electricity price for electrolysis and the CapEx of electrolyzers are following hydrogen demand mainly studied in the samples, which come from the production sector.

Table 1: Summary of identified uncertainty factors

Sources	Description	Group	RT[viii]	SCM	P[vii]	Co[vi]	Tr[v]	St[iv]	Te[iii]	Rc[ii]	Rf[i]	Sources
Hydrogen demand	The hydrogen consumption for a given time unit	Supply chain (SC) - internal	20	x								[7,9,10,15–27]
Electricity price for electrolysis	The price of electricity needs to be paid during the electrolysis	Section specific	12		x							[11,24,28–32]
CapEx of electrolyzer	Investment cost of the green hydrogen production equipment electrolyzer	Section specific	10		x							[28,29,31]
Carbon prices	An instrument of carbon penalty that captures the external costs of greenhouse gas (GHG) emissions	SC environ-mental	6	x								[28,32–36]
Distance	The transport distance between the production and the storage facilities or from the storage facilities to consumers	Section specific	5				x					[16,29,37,38]
Capital recovery factor	A constant rate to determine the present value of a series of investments over the equipment or project depreciation time	SC environ-mental	4	x								[8,11]
Electrolyzer efficiency	The efficiency with which the electrolyzer converts electricity into hydrogen.	Section specific	4		x							[18,28,39]
CO_2 Emission targets	The goal of the greenhouse gas in a given period	SC environ-mental	3	x								[40–42]

Table 1: Summary of identified uncertainty factors (continue)

Sources	Description	Group	RT	SCM	P	Co	Tr	St	Te	Rc	Rf	Sources
CapEx of refueling station	Investment cost of refueling station	Section specific	2								x	[5]
Share of renewable energy supply	The portion of renewable energy supply in gross final energy consumption	Section specific	1	x								[8]
CapEx and OpEx in the whole SC	Investment cost and operational cost for all the equipment and facilities in the supply chain	Section specific	1	x								[39]
Water availability	The water available for hydrogen production	Section specific	1		x							[38]
Installed capacity of electrolyzers	The capacity of electrolyzers	Section specific	1		x							[43]
Raw material water prices for electrolyzer	The price of the water for electrolysis	Section specific	1		x							[31]
OpEx of electrolyzer	The operational cost of the electrolyzer	Section specific	1		x							[44]
Raw material biomass price	The price of biomass for hydrogen production	Section specific	1		x							[45]
Operating hours of the electrolyzer	The operating hours of the electrolyzer in a given time	Section specific	1		x							[39]
Raw material prices	The raw material prices for LOHC	Section specific	1			x						[11]
Purification OpEx VRA	The variable operational cost for the purification	Section specific	1			x						[12]
Construction cost-sharing model of pipeline	Who will pay the construction cost for the pipeline	Section specific	1				x					[46]
Charter rate for ships	The rental cost of ships in the time unit	Section specific	1				x					[28]
Attribution of pipeline to the total LCA	The attribution of the pipeline construction to the LCA of 1 MJ of hydrogen consumed by an FCEV pickup truck	Section specific	1				x					[47]
CapEx of trailer	Investment cost of the truck trailer	Section specific	1				x					[33]

Table 1: Summary of identified uncertainty factors (continue)

Sources	Description	Group	RT	SCM	P	Co	Tr	St	Te	Rc	Rf	Source
Capacity of trailer	The net capacity OF the truck trailer	Section specific	1				x					[48]
Highway speed	The limited highway speed	Section specific	1				x					[48]
Depreciation period of trucks	The number of years to allocate the cost of the truck	Section specific	1				x					[48]
Utilization of trucks	The operating hours of the truck in each time unit	Section specific	1				x					[48]
Driver salary	The driver's salary in each time unit	Section specific	1				x					[48]
Fuel consumption	The volume of fuel required for trucks	Section specific	1				x					[48]
Storage cycle length	The average number of days or months required to turn over the storage capacity	Section specific	1					x				[17]
Boil-off rate	The self-discharge rate of LH_2	Section specific	1					x				[49]
CapEx of cavern	Investment cost of the salt cavern	Section specific	1					x				[45]
CapEx of ship terminals	Investment cost of the terminal for seaway	Section specific	1						x			[29]
Raw material degradation	The degradation rate of the raw material for LOHC	Section specific	1							x		[11]
Heat sources for dehydrogenation	The heat sources, such as traditional heat or hydrogen, for dehydrogenation	Section specific	1							x		[49]
Learning rates of PSA	For hydrogen natural gas mixture	Section specific	1							x		[34]
Scaling factor	Cost reduction or increasing rate by scaling up or down the facilities capacity	Section specific	1								x	[8]
Number of refueling station	The total number of hydrogen stations built over the planning horizon	Section specific	1								x	[50]

Several research gaps have been identified from the sample. The uncertainty factors are mainly focused on the entire hydrogen supply chain or the production sector. Storage, transportation, and seaway terminals have received less attention in current research. This gap should be addressed in future research, as efficient and cost-effective storage, transport, and terminal operations are expected to be key success factors for hydrogen deployment. Furthermore, the identified uncertainty sources primarily include equipment specifications, life cycles, or hydrogen demand. Other potential uncertainty factors, such as the availability of facilities, organizational or behavioral issues, and external parameters like political changes, incentives, or funding to support hydrogen deployment, are not considered in the reference papers. Evaluating these factors may facilitate a more accurate decision-making process and outcomes for hydrogen deployment, thereby enabling the effective development of the hydrogen economy.

As the next steps, we will evaluate the details and effects of the identified uncertainty factors on the hydrogen supply chain, aiming to identify the decisive uncertainty factor(s) based on current research. This effort aims to offer greater transparency of the uncertainty factors and to identify research gaps in more detail.

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[i] Refueling station
[ii] Recondition
[iii] Terminal
[iv] Storage
[v] Transportation
[vi] Condition
[vii] Production
[viii] Research time