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Economic Assessment of Green Hydrogen Infrastructure: A Case Study in China

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Renewable energy infrastructure struggles with location and long-distance transportation challenges. To address this, the use of hydrogen as an energy carrier has gained prominence. However, large-scale hydrogen transport poses difficulties. This study investigates converting hydrogen into more stable and transportable carriers, methanol and ammonia, with the aim of developing a sustainable green hydrogen supply chain. A versatile multi-period mixed integer linear programming (MILP) model is proposed for an optimal economic assessment. Using data from China, the model identifies key nodes, quantities of photovoltaic panels, and wind turbines required. The results favor wind power, accounting for 72 % of total installations. Despite renewable energy abundance in northwest China, long-distance transportation costs make other regions more economically viable. The total annual cost of creating a green hydrogen supply chain to meet demand from 35 large enterprises is estimated at approximately 9.96 billion USD, providing useful insights for policymakers and industry stakeholders.

1. Introduction

Fossil fuel depletion and pollution have accelerated the adoption of renewable energy to meet rising energy demand. The U.S. Energy Information Administration (2021) reports that renewable energy accounted for 12 % of total consumption in the United States, with 60 % being utilized in the electric power sector. However, most renewable energy infrastructures, such as solar and wind power plant, are located in sparsely populated areas. As the World Bank Group (2020) reported, 93 % of the global population lives in countries with an average daily photovoltaic (PV) power potential between 3.0 and 5.0 kWh/kWp. However, the populations are spare for the areas with higher solar radiation (between 5.0 and 6.2 kWh/kWp). Transporting electric energy over long distances through power cables is challenging and expensive. Significant voltage drops and obstacles make it infeasible to transport renewable electricity, particularly from sources like wind and solar energy.

Various approaches have been explored to address these challenges, including grid integration, energy storage solutions (Behabtu et al., 2020), and the use of hydrogen as a promising energy carrier due to its high energy density and versatility (Van Hoecke et al., 2021). Recently, hydrogen production plants integrated with renewable energy systems are progressively being industrialized. Sinopec (Xinhua, 2021) invested in a mega-scale PV power project for green hydrogen production in western China, which is expected to reduce CO_2 emissions by approximately 485,000 t/y. Nevertheless, large-scale liquefied hydrogen transportation below -253 °C via pipeline is challenging, as it requires avoiding all environmental or geo-human factors along the pipeline route. Hydrogen liquefaction is an energy-intensive process consuming roughly 30 % of the energy contained in hydrogen (Restelli et al., 2023), which complicates shipping large quantities of hydrogen in liquid form.

To address these challenges, researchers have proposed converting hydrogen into methanol (MeOH) or ammonia (NH_3) as a promising method for long-distance hydrogen transportation (Blanco et al., 2023). These chemical carriers are more physically stable and relatively less expensive to transport than hydrogen. The mature synthesis technology for MeOH and NH_3 renders power-to-methanol and power-to-ammonia conversion economically viable and environmentally beneficial.

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Green hydrogen production from renewable energy sources has emerged as a promising solution to mitigate the negative environmental impact of fossil fuels. However, the large-scale deployment of green hydrogen necessitates developing an efficient and reliable supply chain to transport and distribute hydrogen from production sites to end users. This requires complex decision-making processes that consider factors such as production and consumption site locations, transportation modes, storage options, and infrastructure investments. Additionally, integrating green hydrogen into existing energy systems demands careful examination of technical, economic, and environmental aspects to ensure sustainability and competitiveness, an area not extensively covered in the existing literature.

In the field of green hydrogen supply chain, numerous researchers have already conducted various studies focusing on different aspects of the problem. For instance, Sgarbossa et al. (2023) assessed the potential of a renewable hydrogen supply chain, analyzing the optimal locations for the production, storage, and distribution of hydrogen. While their work provides valuable insights into the spatial aspects of hydrogen production and transportation, it does not specifically address the challenges associated with integrating renewable energy systems with hydrogen carriers. Crandall et al. (2023) conducted a techno-economic assessment of green hydrogen carrier chains, identifying formic acid as the most cost-effective carrier. While their study provides valuable insights into green hydrogen carrier selection, the research focuses on optimizing the entire green hydrogen supply chain for a more comprehensive analysis.

This study builds upon these previous works and extends the analysis to include a comprehensive and general approach that investigates the economic viability of renewable energy systems utilizing MeOH and NH_3 as hydrogen carriers. The proposed multi-period mixed integer linear programming (MILP) model is versatile and can be adapted to various contexts, making it a valuable tool for stakeholders in the energy industry seeking to optimize the deployment of technologies and logistics in green hydrogen supply chains.

2. Methodology

Figure 1 presents a schematic summarizing the scope of this work. The goal of this project is to develop a green hydrogen transportation supply chain that utilizes renewable energy sources such as solar and wind power. The process involves converting renewable energy to electricity using a conversion technology and then using water electrolysis to produce green hydrogen. To ensure its availability for future use, excess hydrogen is stored in a hydrogen storage tank. Subsequently, the hydrogen is transported through various modes of transportation to technology providers who leverage mature conversion technologies to transform it into candidate hydrogen carriers, such as MeOH and NH_3. Finally, the converted products are transported to fulfill the demand of various end-users.

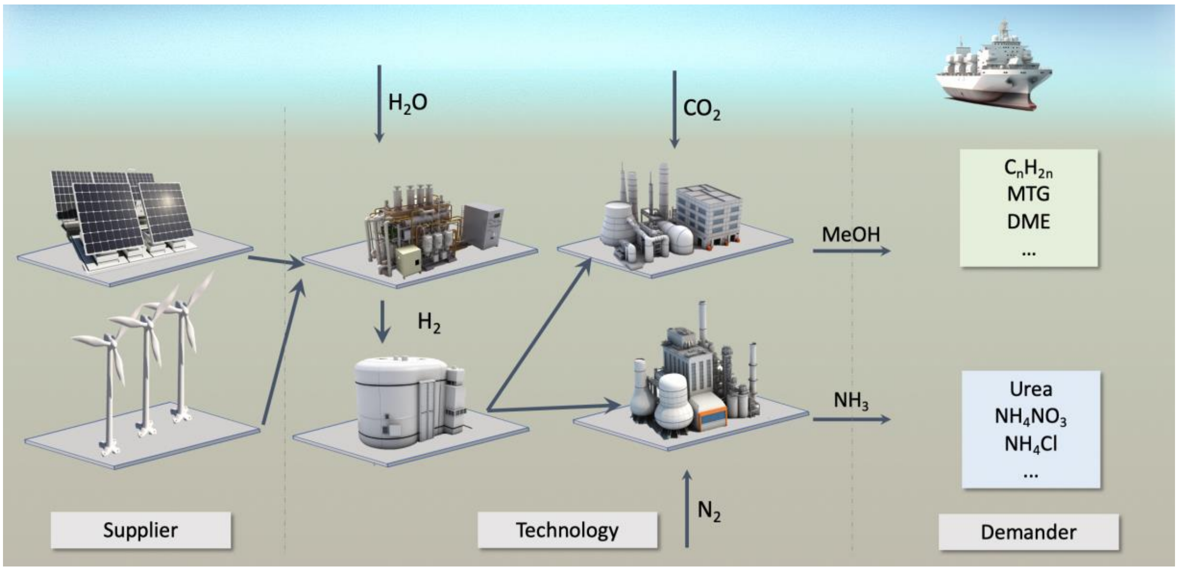


Figure 1: Schematic diagram of the proposed green hydrogen supply chain

The supply chain methodology employed in this work is based on the research of Ma et al. (2022). To optimize the entire supply chain, the first step involves establishing a MILP model with the objective of achieving the least annualized cost. This model encompasses the supply scheme, demanding scheme, transportation scheme, and investment scheme of the infrastructure. Once the model is in place, 1 y practical data is deployed for a case study in China. Various candidate suppliers and technology providers are defined as potential sources to meet downstream demand. After evaluating the economic benefits of each potential candidate, an informed decision is made regarding which nodes to select, as well as the number of PV panels and wind turbines that are ready to be installed. The results of the optimization process provide valuable insights for policymakers and industry stakeholders, guiding them in making strategic decisions on infrastructure investments, technology adoption, and supply chain management to promote a sustainable and efficient green hydrogen supply chain.

3. Mathematical model

3.1 Objective function

The objective is to establish an environmentally friendly supply chain for transporting hydrogen fuel, using green production methods. To achieve this, a range of elements have been considered, including a set of nodes (N), suppliers (S), conversion technologies (C), demanders (D), scales (SC), products (P), hydrogen storage levels (L), and time periods (T).

The objective function is to minimize the total annualized cost (tac) of the green hydrogen transportation supply chain. The model for the integrated supply chain takes into account the following components of the cost: (1) supply cost, (2) operation cost of hydrogen generation and hydrogen carrier synthesis process, (3) investment cost of PV panels, wind turbines, MeOH, and NH_3 synthesis facilities, (4) transportation cost, and (5) hydrogen storage cost.

The supply cost is the aggregate cost of all raw material supplies, such as CO_2, and is represented by Eq(1). In this equation, $s_{i,p,t}$ denotes the supply flow of product p in node i at the time of t, while C_s^p represents the corresponding supply cost of the target product.

$$supcost = \sum_{i \in S} s_{i,p,t} * C_s^p \tag{1}$$

The annual operation cost includes renewable electricity generation cost, water electrolysis cost, MeOH synthesis cost, and NH_3 synthesis cost. The definition of annual operation cost is given in Eq(2). The variable $x_{i,p_{ref},c,t}$ denotes the quantity of reference product p at node i that is available for conversion through technology c at time t. Each technology is associated with a specific reference product (usually the reactant). $OPEX_c$ is the operational cost of conversion technology c.

$$opcost = -\sum_{i \in D} \sum_{c \in C} \sum_{t \in T} x_{i,p_{ref},c,t} * OPEX_c \tag{2}$$

The total capital cost equals the total installation costs for PV panels, wind turbines, PEM electrolyzer, MeOH synthesis, and NH_3 synthesis facilities, as shown in Eq(3). The notation $z_{i,c,sc}$ denotes the number of facilities installed for technology c at node i in scale sc. This study prepares two different scales for each technology. $CAPEX_c^{SC}$ represents the capital cost of the infrastructure technology c at scale sc.

$$capcost = \sum_{i \in N} \sum_{t \in T} \sum_{sc \in SC} z_{i,c,sc} * CAPEX_c^{SC} \tag{3}$$

Eq(4) shows that the transportation cost is determined by several factors, such as the distance between two nodes, the amount of product flow, and the transportation mode used. $Distance_{i,j}$ is calculated based on the geographic locations of two nodes. $f_{i,j,p,t}$ represents the flow of product p from node i to j at time period t, while C_m^p represents the unit transportation cost of product p by the transportation mode m.

$$transcost = \sum_{i \in N} \sum_{j \in N} \sum_{p \in P} \sum_{t \in T} Distance_{i,j} * f_{i,j,p,t} * C_m^p \tag{4}$$

The storage cost is calculated by multiplying the capacity of the hydrogen storage tank with the unit price, as shown in Eq(5), where $capacity_i$ is the storage capacity at inventory i. C_{store}^i is the corresponding unit price.

$$storecost = \sum_{i \in L} capacity_i * C_{store}^i \tag{5}$$

From Eq(6), it can be inferred that the total cost is the sum of all the costs mentioned above, where af represents the annualized factor.

$$tac = supcost + opcost + af * capcost + transcost + storecost \tag{6}$$

3.2 Constraints

The mass balance of the product p in node i at time period t is given by:

$$s_{i,p,t} + p_{i,p,t} + release_{i,p,t} + \sum_{j \in N} f_{j,i,p,t} = \sum_{j \in N} f_{i,j,p,t} + d_{i,p,t} + store_{i,p,t} \quad \forall i \in N, p \in P, t \in T \tag{7}$$

Where $S_{i,p,t}$ denotes the supply flow of product p in node i at the time of t, while $d_{i,p,t}$ is the demand.

For each supplier side, the planned supply does not exceed the suppliers' maximum capacity. For instance, as in Eq(8), when the product is solar electricity, the power generated at node i under time t does not exceed the maximum theoretical power generation capacity of n photovoltaic panels.

$$s_{i,p,t} \leq n_{i,p,t} * \bar{s}_{i,p,t} \quad \forall i \in N, t \in T, p = solar_{electricity} \text{ } or \text{ } wind_{electricity} \tag{8}$$

For each technology provider side, the modular constraint on the size of equipment is shown on Eq(9). This formula indicates that the material produced or passed by the equipment is upper bounded by the sum of the maximum capacity owned by the technology c equipment.

$$x_{i,p_{ref},c,t} \leq \sum_{sc \in SC} z_{i,c,sc} * size_{sc} \quad \forall i \in N, c \in C, t \in T \tag{9}$$

For each demander side, the planned demand of the target product p at time t must be above its minimum requirement from demander in node i, as shown in Eq(10).

$$d_{n,p,t} \geq \underline{d}_{n,p,t} \quad \forall n \in N, p \in P, t \in T \tag{10}$$

For each hydrogen storage side, the inventory level $l_{i,p,t}$ cannot exceed the maximum hydrogen storage capacity.

$$l_{i,p,t} \leq \bar{l}_{i,p,t} \quad \forall i \in N, p \in P, t \in T \tag{11}$$

4. Results and discussion

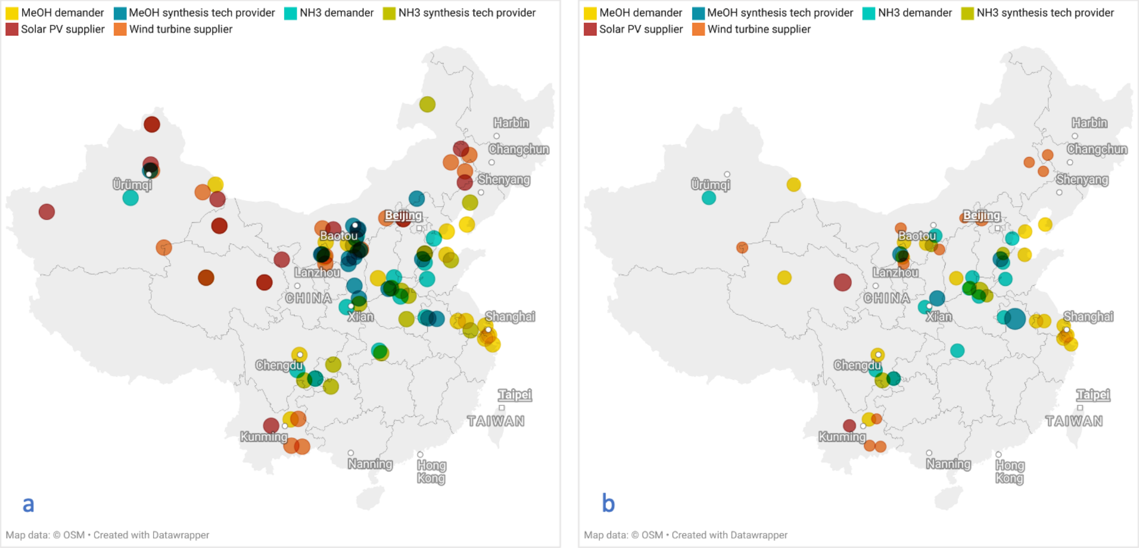
To demonstrate the efficacy of the proposed model, a large-scale refined product supply chain in China is used as a case study. The supply chain comprises 31 power suppliers, consisting of 13 solar energy suppliers and 18 wind suppliers, as well as 35 technology providers, with 20 dedicated to MeOH and 15 to NH_3. Additionally, there are 34 product demanders, with 20 for MeOH and 14 for NH_3. Figure 2a displays the distribution of the aforementioned 100 nodes across various locations in China.

On the supplier side, the 210 PECVD (210-size 66-chip version) photovoltaic panels from Tongwei Solar (2023) are utilized, while the wind power generation component deploys GW175 Smart Wind Turbine Platform from Goldwind (2023). The parameters of the two power generation methods are listed in Table 1. On the demander side, MeOH manufacturers require a total annual production of 5,438 kt, while NH_3 demanders need 7,696 kt. The discount rate is set at 8 %, and the lifetime is 20 y. For the technology provider side, it is assumed that suppliers can directly purchase and utilize raw materials for the production of MeOH or NH_3.

Table 1: General information of solar and wind power generation system

Item	PV panels	Wind turbine
Brand	Tongwei solar	Goldwind
Model	210 PECVD	GW175-8.0 MW
Module power	690 W	8.0 MW
CAPEX (USD/kW)	281	361.75
OPEX	3 % of CAPEX	3 % of CAPEX

The potential of utilizing green hydrogen energy in order to synthesize hydrogen energy carriers and meet the minimum downstream requirements was investigated. The findings indicate that at least 126 million MWh of renewable electricity would need to be generated annually, which would then be converted into a total of 2.48 Mt of green hydrogen. The results from the MILP model suggest that the optimal supply chain would require a total of 24,840,000 photovoltaic panels and 7,861 wind turbines to be installed across various nodes. Upon optimization, the number of nodes was reduced from 65 (excluding demanders) to 24, as illustrated in Figure 2b. A key observation from the optimized supply chain model is the preference for wind energy installations, which make up 72 % of the total installations, compared to only 15 % for solar bases. This can be attributed to the relatively low cost associated with wind power generation.



Map data: © OSM • Created with Datawrapper

Figure 2: Spatial distribution of (a) planned nodes and (b) optimized nodes

The findings indicate that 21 % of MeOH synthesis plants and 33 % of NH_3 synthesis plants are planned to be operational. Notably, the majority of manufacturers and demanders are located in central and eastern China. Despite the abundance of renewable resources in the Northwest region, the additional costs related to distance make it an unsuitable supplier in this particular case.

The calculated minimum total annualized cost for the optimized supply chain comes out to be approximately 9.96 billion USD. This figure highlights the financial implications of transitioning to a green hydrogen-based energy system, which is an important consideration for policymakers and stakeholders. The results of this study can be used to inform decisions regarding the optimal distribution of renewable energy resources and the development of hydrogen energy carriers to support a more sustainable energy future.

5. Conclusions

This paper examines the economic advantages of incorporating green hydrogen, MeOH, and NH_3 into the refined product market competition. To determine the optimal supply scheme, transportation scheme, and demand scheme for both MeOH and NH_3, a MILP model for a single-cycle supply chain is established, with the objective of minimizing the cost. The key findings are as follows:

(1) The entire process of synthesizing green hydrogen from renewable energy and meeting the demand for MeOH and NH_3 from 35 large enterprises will cost approximately 9.96 billion USD/y.

(2) Wind power proves to be more economically advantageous than solar power, with 72 % of the planned installations utilizing wind energy compared to only 15 % for solar energy bases. This can be attributed to the relatively low cost of wind power generation.

(3) Despite the abundance of renewable energy resources in northwest China, the added cost of long-distance transportation makes it less economical compared to other regions. The optimal supply chain scenario shows that only 24 out of 65 nodes, excluding demanders, remain after optimization, with manufacturers and demanders mostly located in central and eastern China.

In future studies, a comprehensive approach should assess the integrated supply chain's benefits, considering both economic and environmental aspects. This includes optimizing fuel types based on environmental impact, conducting detailed infrastructure investment analyses incorporating environmental factors, and coordinating multiple transportation modes for reduced emissions and improved sustainability. This holistic perspective can guide the development of a more sustainable and efficient green hydrogen supply chain.

Nomenclature

af – annualized factor, -
C – set of conversion technologies, -
capacity – storage capacity, t
capcost – capital cost, USD
CAPEX – capital cost, USD
d – demand related flows, t/h
D – a set of demanders, -
distance – distance between two nodes, km
f – transportation flows, t/h
I – inventory level parameters, t/h
L – set of hydrogen storage levels, -
MeOH – methanol

n – number of solar panels or wind turbines, -
N – a set of nodes, -
NH_3 – ammonia
OPEX – operational cost, USD
opcost – annual operation cost, USD
P – a set of products, -
PV – photovoltaic
p_{ref} – production related flows, t/h
s – supply related flows, t/h
S – a set of suppliers, -
SC – a set of scales, -
$size_{sc}$ – maximum capacity, t
supcost – supply cost, USD
storecost – storage cost, USD
T – a set of time periods, -
tac – total annualized cost, USD
transcost – transportation cost, USD
x – quantity of product flow, t/h
z – number of facilities installed, -

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