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Profitability assessment of electro-fuel supply from hybrid energy systems#

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ABSTRACT

Electrolytic hydrogen plays a significant role in the decarbonization of hard-to-abate sectors. This paper evaluates the profitability of hydrogen, ammonia and methanol supply from hybrid energy systems, including wind power, solar PV power, and the utility grid. Based on the IEA hydrogen project database, ten representative locations are selected as production sites, and the levelized production costs are evaluated based on the optimization of installed capacity and operation strategy. The results indicate that the mass-based levelized cost of hydrogen across all sites ranges from 20 to 26.6 CNY/kg, which is significantly higher than that of ammonia (5.6-7.1 CNY/kg) and methanol (6.6-8.2 CNY/kg). Aksu exhibits the lowest levelized cost for all fuel options among various production sites, as it has the lowest electricity tariffs. However, with the transportation cost included, Aksu has the highest landed costs for almost all trading spots, as Aksu is far away from all trading spots. In contrast, Ulanqab presents the lowest landed costs for all trading locations, due to the coupling effects of low production costs and short transport distances. Furthermore, all hydrogen pathways, except for Zhangzhou-Zhengzhou, present lower landed costs than the trading price, whereas all ammonia and methanol pathways are not profitable due to their extremely low trading prices.

Keywords: renewable energy, hydrogen, electro-fuels, profitability, energy system optimization.

NONMENCLATURE

Abbreviations	
CAPEX	Capital expenditure
LCOF	Levelized cost of fuel
NPC	Net present cost
WACC	Weight average capital of costs

1. INTRODUCTION

Renewable energy technologies, especially wind power and solar photovoltaic (PV) power, are essential for replacing fossil fuels and achieving energy decarbonization [1]. However, the intermittency and volatility of wind and solar energy resources pose challenges to the stable and reliable operation of power systems [2].

A solution to alleviating the volatility is to integrate renewable energy systems with energy storage technologies, such as battery, pumped hydro storage, Carnot battery, and hydrogen storage [3]. Energy storage technologies can store surplus renewable energy and discharge power during renewable shortage periods, thus balancing the supply-demand mismatch. He et al. [4] investigated the techno-economic performance of various energy storage options in hybrid renewable energy systems, and the results indicated that large-scale Carnot battery achieved the best cost-effectiveness. Furthermore, He et al. [5] studied the performance of hybrid energy storage systems for renewable energy applications, with results showing that a hybrid electrical-thermal energy storage system achieved the lowest costs through coordinated operation. Nevertheless, the cost of large-scale electrical energy storage systems remains significantly high, and practical energy storage projects tailored for renewable energy plants are still very limited.

Another solution is to convert volatile renewable energy into hydrogen via the flexible operation of electrolyzer. Compared to electricity, hydrogen is more cost-effective to store, particularly when underground caverns are available. Pan et al. [6] evaluated the cost competitiveness of electrolytic hydrogen across China, and the results showed that the levelized cost of hydrogen ranged from 31.5 to 46.8 CNY/kg.

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Furthermore, renewable energy systems for hydrogen and electricity cogeneration are also promising, in which curtailed renewable energy can be used to flexibly produce hydrogen. He et al. [7] proposed a novel hybrid renewable energy system configuration for constant electricity supply and flexible hydrogen production. The findings of this work revealed that using curtailed energy for hydrogen production is profitable in regions with abundant wind resources.

Hydrogen is also essential for decarbonizing hard-to-abate sectors, such as long-distance transportation, refineries, and chemical industries, which are difficult to directly electrify [8]. Furthermore, hydrogen can be further converted into electro-fuels such as ammonia and methanol, which have higher volumetric energy density and lower transmission costs than hydrogen [9]. To understand the techno-economic feasibility of electro-fuels, Fasihi et al. [10] investigated the global potential of green ammonia production based on hybrid renewable energy systems. The results showed that the levelized cost of green ammonia was 440-630 EUR/tonne in 2020, which was expected to become cost-competitive by 2030. Fasihi et al. [11] also explored the potential of methanol production based on renewable energy, and the results indicated that the levelized cost of methanol was 1200-1500 EUR/MWh at the best sites in 2020, which could fall within market prices by 2040.

These research works have made significant contributions to the assessment of electro-fuels in current and future scenarios. However, there is still a lack of studies focusing on the techno-economic assessment of real-world projects. To address this knowledge gap, this work focuses on the realistic projects that either in operation or under construction, based on the IEA hydrogen projects database [12], and aims to evaluate and compare the economic performance of various fuel options. First, the production costs at various sites are evaluated based on energy system optimization. Subsequently, the profitability of various pathways is assessed by comparing the trading prices with landed costs, which include both production and transportation costs.

2. METHODOLOGY

2.1 System configuration

The system configuration of electro-fuel supply pathways is shown in Figure 1. Based on hybrid energy sources, including wind power, solar PV power, and the utility grid, the electrolyzer can operate reliably and flexibly to minimize production costs. Subsequently, hydrogen can either be directly transported to end-users via compressed hydrogen pipelines, or be reacted with nitrogen or carbon dioxide to produce ammonia or methanol, which is then transported to end-users in trading spots. The benefit of converting hydrogen to ammonia/methanol is to reduce transportation costs, while it will incur higher energy consumption and additional synthesis costs.

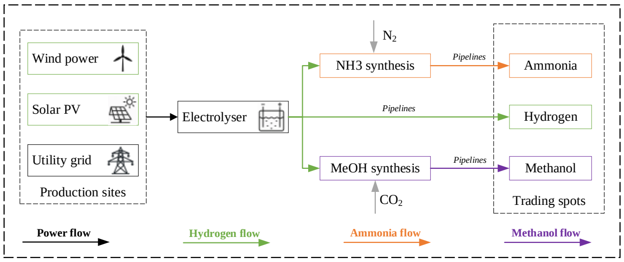


Fig. 1 System configuration

2.2 Cost evaluation models

The levelized production costs of various fuel options are evaluated based on the optimization of the installed capacities of wind power and solar PV power, as well as the operation strategies of electrolyzer and electro-fuel synthesis units, considering the constraints associated with energy balance and annual total production. The optimization models are formulated as:

$$F_{\mathrm{obj}} = \min LCOF\left(C_{\mathrm{WP}}, C_{\mathrm{PV}}, C_{\mathrm{EL}}, C_{\mathrm{H2F}}, P_{\mathrm{WP}}(t), P_{\mathrm{PV}}(t), P_{\mathrm{grid}}(t), P_{\mathrm{EL}}(t), P_{\mathrm{H2F}}(t)\right) \tag{1}$$

$$LCOF = \frac{NPC_{\mathrm{total}}}{\sum_{n=1}^{N_{\mathrm{life}}} M_{\mathrm{fuel}} \Big/ (1+WACC)^{n-1}} \tag{2}$$

$$P_{\mathrm{WP}}(t) + P_{\mathrm{PV}}(t) + P_{\mathrm{grid}}(t) = P_{\mathrm{EL}}(t) + P_{\mathrm{H2F}}(t) \tag{3}$$

$$\frac{\sum_{t=1}^{T} P_{\mathrm{EL}}(t)}{\eta_{\mathrm{EL}}} \geq M_{\mathrm{H_2}}, \quad \frac{\sum_{t=1}^{T} P_{\mathrm{H2F}}(t)}{\eta_{\mathrm{H2F}}} \geq M_{\mathrm{fuel}} \tag{4}$$

where, F_{obj} is the objective function, which aims to minimize the levelized cost of fuel production ($LCOF$), C_{WP}, C_{PV}, C_{P2H} and C_{H2X} are the installed capacity of wind, solar PV, electrolyzer and hydrogen-to-fuel (H2F) synthesis units, $P_{\mathrm{WP}}(t)$, $P_{\mathrm{PV}}(t)$, $P_{\mathrm{grid}}(t)$, $P_{\mathrm{EL}}(t)$ and $P_{\mathrm{H2F}}(t)$ are the hourly power output of wind, solar PV and grid, as well as the hourly power input to the electrolyzer and synthesis unit, NPC_{total} is the total net present cost of all system components, including capital expenditure, operation expenditure, replacement expenditure and salvage value, N_{life} is the project lifetime, $WACC$ is the weighted average cost of capital, M_{H2} and M_{fuel} are the annual hydrogen and electro-fuel production, η_{EL} and η_{H2F} are the specific power consumption of electrolyzer and electro-fuel synthesis units, respectively.

2.3 Techno-economic parameters

Table 1 Techno-economic parameters

Components	Efficiency	CAPEX	OPEX	Lifetime
Unit	kWh/kg, kWh/(kg/h)	CNY/kW, CNY/(kg/h), CNY/kg	-	years
Wind power		9070	2.0%	20
Solar PV power		4500	1.7%	25
Electrolyzer	53.8	4780	2.6%	20
Compressor	0.99	46320	3.0%	20
Air separation	0.20	11220	3.0%	30
Haber Bosch	0.53	50250	2.0%	25
Methanol synthesis	0.31	24780	4.0%	20
Hydrogen tank		3520	2.0%	20
Ammonia tank		5.7	4.0%	30
Methanol tank		0.7	4.0%	30

The techno-economic parameters for various electro-fuel pathways are summarized in Table 1. These data represent the baseline scenario derived from an extensive literature review. Additionally, the system design lifetime is assumed to be 20 years, and the WACC is taken as 7.5%.

3. RESULTS & DISCUSSION

3.1 Boundary conditions

Figure 2 presents the production sites and trading spots of hydrogen, ammonia, and methanol, in which the production sites are sourced from IEA hydrogen project database [12] and the trading spots are based on publicly available trading price data [13-15]. The large-scale hydrogen projects are primarily located in northeast China and offshore areas, due to abundant wind resources and land availability. The hourly output of wind power and solar PV power of various locations are directly sourced from Renewable.ninja [16]. The annual electricity tariffs in each location are collected from the open-source data of the State Grid [17].

Figure 3 shows the renewable energy potential in various production sites, including the annual capacity factor of onshore wind power and solar PV power. The wind power potential exhibits significant regional differences, where Ulanqab, Tongliao, and Songyuan have obviously higher wind capacity factors (>40%) than other sites. In contrast, the solar PV potential is more uniformly distributed across all sites, with capacity factors consistently around 20%.

Figure 4 illustrates the average electricity tariffs of the utility grid across various production sites. Aksu, Alxa, Ulanqab, and Yingchuan demonstrate lower electricity tariffs at 0.3-0.4 CNY/kWh, while the electricity tariffs for the remaining sites are ~0.6 CNY/kWh. Notably, the electricity tariffs for each site follow a peak-valley profile, enabling price arbitrage via flexible operation.

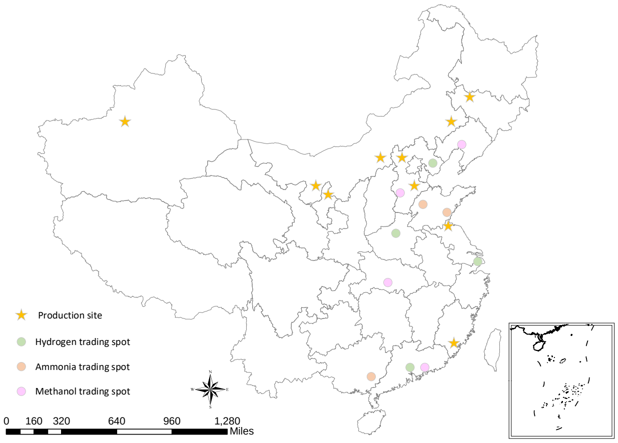


Fig. 2 Production sites and trading spots

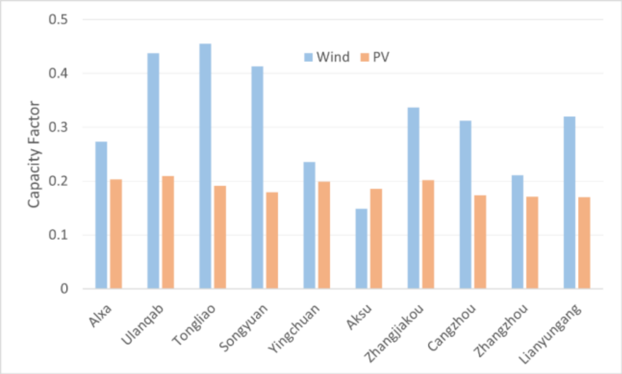


Fig. 3 Renewable energy potential

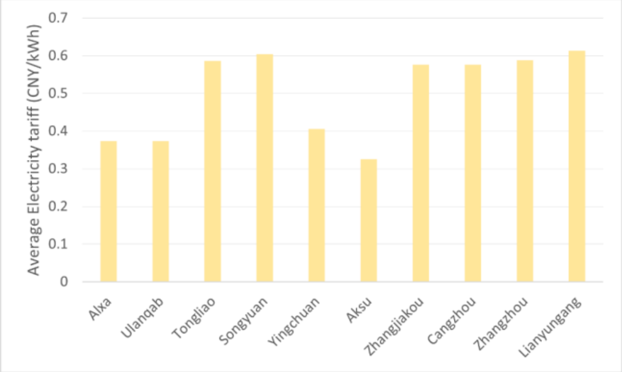


Fig. 4 Average electricity tariffs

3.2 Production costs

Figure 5 presents the optimal levelized production costs of hydrogen, ammonia, and methanol across various locations. The mass-based levelized cost of hydrogen across all sites ranges from 20 to 26.6 CNY/kg, significantly higher than that of ammonia (5.6-7.1 CNY/kg) and methanol (6.6-8.2 CNY/kg). In contrast, the energy-based levelized cost of hydrogen ranges from 600 CNY/MWh to 800 CNY/MWh, which is much lower than that of ammonia (1090-1380 CNY/MWh) and methanol

(1190-1490 CNY/MWh), due to the higher lower heating value of hydrogen.

Regarding the regional comparison, Aksu exhibits the lowest levelized cost for all fuel options, primarily due to its lowest electricity tariffs. However, the wind potential of Aksu is significantly lower than other production sites, indicating that the electricity tariffs outweigh the wind potential and become the dominant factor of economic performance. Ulanqab holds the second lowest levelized cost thanks to relatively low electricity tariffs and high wind potential. Tongliao with the highest wind potential ranks the third place of cost-effectiveness. In contrast, Zhangzhou with almost the highest electricity tariffs and lowest wind/solar potentials presents the highest production costs. Notably, the regional differences do not change the ranking of various fuel options.

To further understand the regional differences, the cost and energy breakdowns of hydrogen production across various sites are shown in Figure 6 and Figure 7, respectively. The costs for electricity accounts for the largest proportion of the total costs, followed by electrolyzer. Other components including water source, hydrogen compressor and buffer storage tank, contribute only a minor proportion.

Regarding the energy mix, the hydrogen production in Aksu, with the lowest levelized costs, is fully supplied by the utility grid, as installing wind and solar PV plants here is not cost-effective compared to purchasing electricity directly from the utility grid. Similarly, Alxa, Yingchuan and Zhangzhou with low wind potential, are supplied by the mix of solar PV power and the utility grid. In contrast, Ulanqab, Tongliao and Songyuan rely primarily on wind power, due to their favourable wind resources.

3.3 Profitability analysis

The profitability of various fuel options depends on the production costs, transportation costs and the market prices in trading locations. Figure 8, Figure 9, and Figure 10 present the landed costs of hydrogen, ammonia, and methanol from production sites to various trading locations, respectively, including production and transportation costs.

All hydrogen pathways, except for the Zhangzhou-Zhengzhou route, present lower landed costs than the trading price, indicating the practical profitability of hydrogen trade. Ulanqab presents the lowest landed costs among all trading locations, due to the combined advantages of relatively lower production costs and shorter transport distances. In contrast, Aksu has basically the highest landed costs for all trading spots despite its lowest production cost, due to its remote location relative to all trading spots. Furthermore, Guangzhou as the trading spot is also not attractive, since Guangzhou is geographically distant from most production sites. Therefore, the optimal siting of hydrogen production should consider not only the resource potential and electricity tariffs, but also proximity to major trading spots.

All ammonia and methanol pathways are currently not profitable due to the extremely low trading prices. These low prices are because the ammonia and methanol markets are dominated by grey technologies

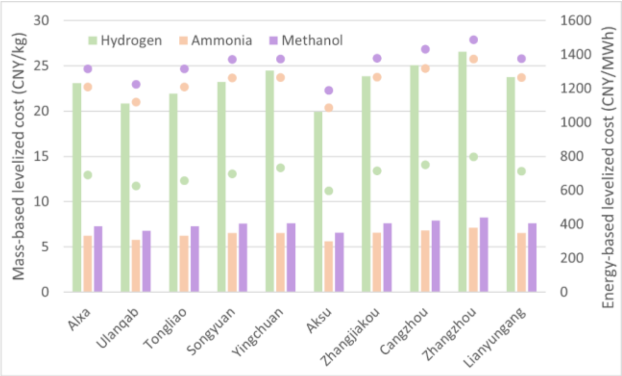


Fig. 5 Levelized cost of various fuels

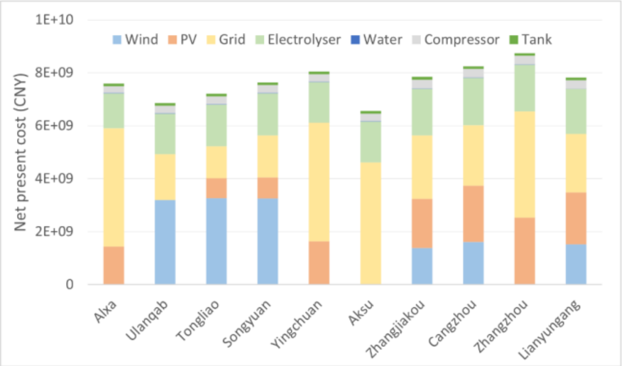


Fig. 6 Cost breakdown of hydrogen production

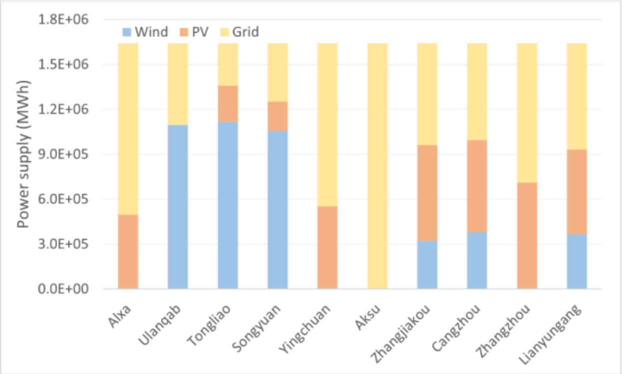
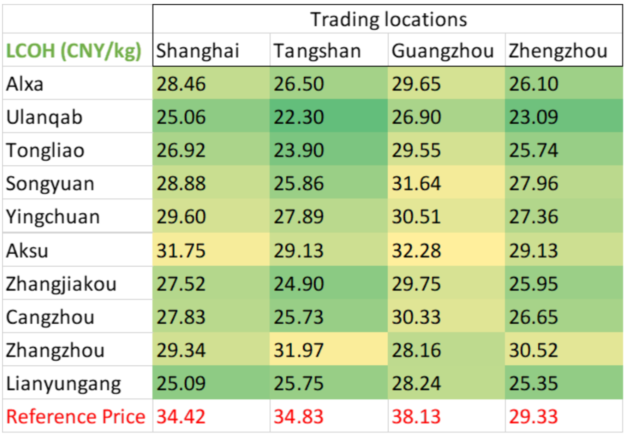


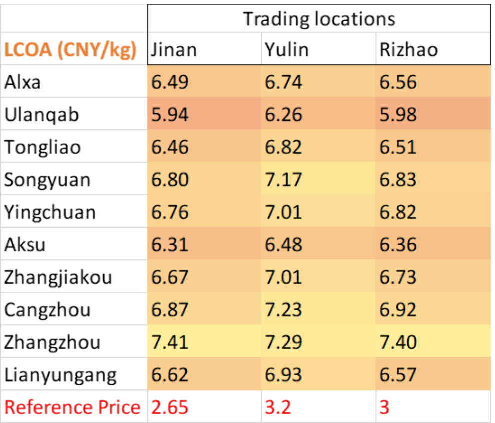
Fig. 7 Energy breakdown of hydrogen production

using fossil fuels, while the green ammonia and methanol markets are not emerging. Therefore, the development of green electro-fuel markets is essential for the large-scale production and application of electro-fuels, thereby supporting the clean energy transition in hard-to-abate sectors.



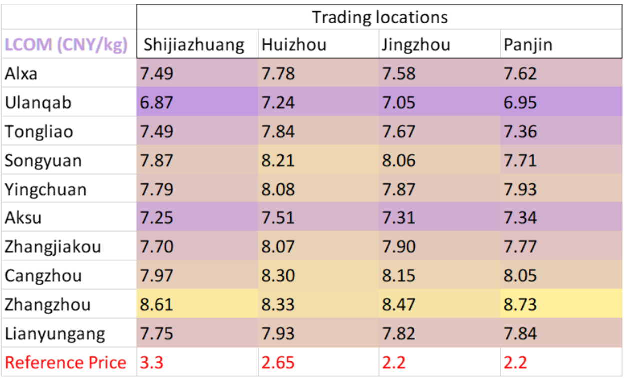
	Trading locations			
LCOH (CNY/kg)	Shanghai	Tangshan	Guangzhou	Zhengzhou
Alxa	28.46	26.50	29.65	26.10
Ulanqab	25.06	22.30	26.90	23.09
Tongliao	26.92	23.90	29.55	25.74
Songyuan	28.88	25.86	31.64	27.96
Yingchuan	29.60	27.89	30.51	27.36
Aksu	31.75	29.13	32.28	29.13
Zhangjiakou	27.52	24.90	29.75	25.95
Cangzhou	27.83	25.73	30.33	26.65
Zhangzhou	29.34	31.97	28.16	30.52
Lianyungang	25.09	25.75	28.24	25.35
Reference Price	34.42	34.83	38.13	29.33

Fig. 8 Levelized landed costs of hydrogen versus market prices of green hydrogen



	Trading locations		
LCOA (CNY/kg)	Jinan	Yulin	Rizhao
Alxa	6.49	6.74	6.56
Ulanqab	5.94	6.26	5.98
Tongliao	6.46	6.82	6.51
Songyuan	6.80	7.17	6.83
Yingchuan	6.76	7.01	6.82
Aksu	6.31	6.48	6.36
Zhangjiakou	6.67	7.01	6.73
Cangzhou	6.87	7.23	6.92
Zhangzhou	7.41	7.29	7.40
Lianyungang	6.62	6.93	6.57
Reference Price	2.65	3.2	3

Fig. 9 Levelized landed costs of ammonia versus market prices of fossil-based ammonia



	Trading locations			
LCOM (CNY/kg)	Shijiazhuang	Huizhou	Jingzhou	Panjin
Alxa	7.49	7.78	7.58	7.62
Ulanqab	6.87	7.24	7.05	6.95
Tongliao	7.49	7.84	7.67	7.36
Songyuan	7.87	8.21	8.06	7.71
Yingchuan	7.79	8.08	7.87	7.93
Aksu	7.25	7.51	7.31	7.34
Zhangjiakou	7.70	8.07	7.90	7.77
Cangzhou	7.97	8.30	8.15	8.05
Zhangzhou	8.61	8.33	8.47	8.73
Lianyungang	7.75	7.93	7.82	7.84
Reference Price	3.3	2.65	2.2	2.2

Fig. 10 Levelized landed costs of methanol versus market prices of fossil-based methanol

4. CONCLUSIONS

This paper evaluates the profitability of hydrogen, ammonia and methanol supply chains powered by hybrid energy systems, including wind power, solar PV power, and the utility grid. Based on the IEA hydrogen project database, ten representative locations are selected as the electro-fuel production sites, and the levelized production costs are evaluated based on the optimization of installed capacity and operation strategy. The results indicate that the mass-based levelized cost of hydrogen across all sites is 20-26.6 CNY/kg, which is significantly higher than that of ammonia (5.6-7.1 CNY/kg) and methanol (6.6-8.2 CNY/kg). Aksu exhibits the lowest levelized cost for all fuel options among various production sites, as Aksu has the lowest electricity tariffs. However, with the transportation cost included, Aksu incurs the highest landed costs for all trading spots, owing to its remote location. In contrast, Ulanqab presents the lowest landed costs for all trading locations, due to the combined effects of low production costs and short transport distances. Furthermore, all hydrogen pathways, except for the Zhangzhou-Zhengzhou route, present lower landed costs than the trading price, whereas all ammonia and methanol pathways are not profitable due to their extremely low trading prices, highlighting the critical role of developing mature markets for green fuel trade.

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