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Navigating China's Hydrogen Transition: Multi-tier Strategic Insights and Roadmap for Sustainable Development

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Hydrogen, as an energy carrier, is seen as a prominent candidate for the deep decarbonization of hard-to-abate sectors. Realizing the vision of a low-carbon hydrogen economy requires a complex transition pathway based on international collaboration, national efforts, and project practices. First, this paper aims to provide a comprehensive, multi-tier review of hydrogen development. The results indicated that an increasing number of countries are formulating ambitious hydrogen strategies. However, in China, the world's most important market for hydrogen, national-level strategic guidance remains insufficient. At the same time, provincial government plans far exceed the conservative national targets, resulting in significant project activity. China's initial position is advantageous due to its capabilities in electrolyzer manufacturing capacity, cost-efficient supply chains, and effective project implementation. To address the mismatch between top-down coordination and bottom-up development, the objective of this paper is to propose an enhanced roadmap for China using a hydrogen-adapted Energy-Sustainability-Governance-Operation (H-ESGO) framework. This framework aligns quantitative targets with key actions over a long-term horizon, providing a balanced techno-centric perspective on scaling hydrogen supply chains and system integration synergies. For China, the findings show a roadmap to overcome strategic shortcomings by taking immediate action with decentralized hydrogen production. This is significant for guiding future policy and practical steps towards a low-carbon hydrogen economy.

1. Introduction

2023 turned out to be the hottest year in recorded history, underscoring the accelerated pace of global warming. To mitigate climate change, the burning of fossil fuels must be phase out and greenhouse gas (GHG) emissions drastically limited. Decarbonizing the global energy system includes electrification powered by renewables and energy savings efforts. For hard-to-abate sectors (HTA), more radical changes—known as deep decarbonization—need to be made. Here, hydrogen, as an energy carrier, presents an alternative pathway beyond its traditional role as a chemical feedstock. These new applications of hydrogen in HTA sectors are in the industry (e.g., chemicals, iron and steel, and other heavy industries), transportation (e.g., aviation, marine, heavy-duty road transport) and power generation. For these new uses, green hydrogen, produced via water electrolysis powered by renewables, should be prioritized. This method emits only water vapor, leaving no harmful residues in the air. The global potential for hydrogen economies varies, with estimates ranging from 4 % to 11 % (Riemer et al., 2022), or even up to 22 % (HC, 2021), of total final energy consumption (TFEC) by 2050. Some scenarios of these studies also underscore a possibility to continue the status quo, so that a significant hydrogen economy might never develop. Historically, the economic feasibility of green hydrogen has been a significant barrier. The concept of a hydrogen economy first emerged in the 1970s, in response to the oil crisis, but projects have consistently struggled with economic viability, and none have yielded significant profits for decades. What has changed is the expansion of the energy dilemma from a dual focus on affordability and reliability to a trilemma that includes sustainability (WEC, 2022). Consequently, the imperative to reduce GHG emissions requires the global adoption of new clean technologies despite high transition costs. Over time, economic barriers may become manageable, particularly in HTA sectors where electrification is not an option. Beyond its role in decarbonization, hydrogen energy is gaining traction as a means to enhance energy independence and security in various countries.

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International commitment to net-zero targets was solidified with the Paris Agreement in 2015. To achieve the treaty's objectives, countries formulated nationally determined contributions. Currently, more specific strategic plans are being published to provide detailed pathways for energy transitions. Among these are hydrogen strategies. To stimulate investment across the hydrogen supply chain (HSC), political assurance through long-term hydrogen development plans is essential for energy companies and investors. With this commitment, a full-scale hydrogen economy can be unlocked, so current challenges associated with unprofitable production and distribution can be overcome in the long run. However, unfavourable unit economics and the need for substantial initial investments in hydrogen production capacity and infrastructure pose significant financial challenges. Clear strategic plans are imperative to set ambitious goals, build capabilities, and initiate large-scale hydrogen adoption. This paper contributes by reviewing hydrogen strategies using a multi-tier approach. This funnel method contextualizes vast amounts of existing data and information. The paper proposes a new roadmap to derive strategic policy recommendations aimed at promoting hydrogen development in China.

2. Multi-tier review of hydrogen

The methodology for this section follows a multi-tier review approach considering global, national and project-level. Based on the review, a mismatch for China's development towards a hydrogen economy was identified.

2.1 Global hydrogen perspective

The review of global hydrogen perspectives is divided into two parts. First, the current status quo is presented, as depicted in Figure 1. Hydrogen supply is almost exclusively based on fossil fuels as a primary energy source. The dominant production technologies include steam methane reforming (SMR) at 62 %, coal gasification (CG) at 21 %, and by-product hydrogen at 16 % (IEA, 2023a). Combined with carbon capture, utilization, and storage (CCUS), SMR and CG can produce blue hydrogen. In contrast, green hydrogen is produced via water electrolysis using renewable electricity, with the predominant technology being alkaline (ALK) and proton exchange membrane (PEM). Despite the potential, there is no significant production of blue or green hydrogen. In 2022, global hydrogen production amounted to 94.8 Mt with an average emission intensity of 12-13 kg CO_2e per kgH_2 (IEA, 2023a). Given that hydrogen primarily produced onsite and not yet a globally traded commodity, there is no large-scale infrastructure in place for transporting hydrogen over long distances. Current hydrogen demand occurs in refining (44.2 %) and industrial applications (55.8 %). In refining, hydrogen acts as a catalyst that stimulates chemical reactions. For industrial applications, hydrogen is predominantly consumed in the production of ammonia and methanol. This overview highlights the current fossil-fuel dependency of hydrogen production and sectors where hydrogen is mostly utilized, setting the stage for discussing its future development.

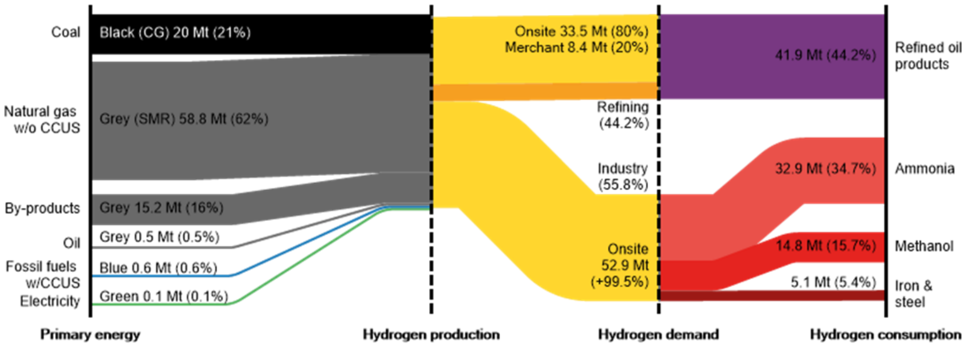

Figure 1: Global hydrogen production by technology and sector-specific consumption in 2022 (IEA, 2023a)

For the second part, outlooks project a wide range for global hydrogen demand by 2050. High-end scenarios show ambition to achieve carbon neutrality, while low-end scenarios indicate no substantial progress.
According to IEA's (2023a) Net Zero Emissions scenario, hydrogen demand by 2030 could reach 150 Mt and 400 Mt by 2050, with sector-specific breakdowns: Oil refining 10 Mt, chemicals 70 Mt, iron and steel 49 Mt, other industries 21 Mt, aviation and marine fuel 116 Mt, road transport 61 Mt, power generation 75 Mt. This demand mix highlights hydrogen's potential in new applications as a reducing agent, transport fuel, and power storage medium. IRENA (2023) projects 613 Mt by 2050, with 25 % of demand met by international trade, 55 % transported as pure hydrogen via retrofitted natural gas pipelines, and 45 % shipped as ammonia. The Hydrogen Council (2021) predicts hydrogen reaching 22 % of TFEC by 2050, totaling 660 Mt annually. McKinsey's report (Gulli et al., 2023) outlines scenarios from 125 to 585 Mt by 2050, with clean production estimates of 73 % to 100 %. Reports from WEC (2021) and Fraunhofer (Riemer et al., 2022) synthesize various sources to provide comprehensive projections ranging from 150 to 600 Mt and 116 to 458 Mt. The IPCC's (2018) scenarios, aiming

to limit global warming to 1.5 °C, have a median of around 125 Mt for 2050, with high estimates reaching 230 Mt, still comparatively low. These wide-ranging estimates imply significant uncertainties, underscoring the need for political commitment and strategic guidance in the form of hydrogen strategies.

2.2 National hydrogen strategies

According to CGEP's National Hydrogen Strategies and Roadmap Tracker (Corbeau and Kaswiyanto, 2024), 60 countries have published official government documents on hydrogen strategies and roadmaps. A comparison shows there is no one-size-fits-all solution for developing hydrogen economies. For the purpose of this paper the hydrogen strategies of the four largest economies by GDP are summarized in the following.

China's first Hydrogen Industry Development Plan (NDRC, 2022) was published in March 2022 and follows three essential guiding principles: diversify end use, improve storage and transport, and focus on low-carbon sources. China's hydrogen strategy defines short-term quantitative targets for 2025, which are 100 to 200 kt/y of green hydrogen production and 50,000 fuel cell electric vehicles on the road. Mid-term, the strategy defines qualitative targets for 2030 to build a relatively complete hydrogen industry supporting the carbon emission peak and for 2035 to build a comprehensive hydrogen industry supporting the energy transition. An additional 21 provincial strategies are published that exceed the conservative national targets in terms of production capacity.

The US National Clean Hydrogen Strategy and Roadmap (US DoE, 2023) released in June 2023 is a strong commitment towards hydrogen. Hydrogen is seen as an opportunity to contribute to national decarbonization goals across multiple sectors of the economy. The government document presents a strategic framework for achieving large-scale production and use of clean hydrogen by examining different scenarios for 2030, 2040, and 2050. It also states the need for collaboration in order to accelerate market lift-off. The hydrogen strategy establishes concrete targets, market-driven metrics, and tangible actions to measure success. It is strongly supported by the Inflation Reduction Act, which foresees significant subsidies for low-carbon hydrogen.

The German Nationale Wasserstoffstrategie (BMWK, 2023) of June 2020 positions hydrogen as an essential pillar for sector coupling in a zero-carbon future energy system. The initiative Made in Germany refers to an export-driven focus on hydrogen technology for the HSC, aiming at technology leadership to strengthen domestic industrial production. Due to energy import dependencies and renewable resource limitations in Germany, another approach is Shipping the Sunshine, that underscores import needs. Domestic hydrogen production is used for grid balancing. Both ideas envision a systemic approach for international hydrogen value chains. Hence, an emphasis is put on partnerships for hydrogen trade, starting with pilots in Australia and Africa.

Japan's Basic Hydrogen Strategy (METI, 2023), was revised with more ambitions in June 2023 as a reaction to hydrogen investments by the US and EU. Japan sets out targets to boost annual hydrogen supply from about 2 Mt today to 12 Mt by 2040 and 20 Mt by 2050. To achieve this, USD 107 billion is planned to be invested in hydrogen supply in the public and private sectors over the next 15 y. Japan faces a resource endowment, leading to a similar strategic focus as Germany. Technological leadership is pursued by setting standards and the goal to win a 10 % global market share by 2030 for local electrolyzer manufacturers. Supply chains in cooperation with Australia, the Middle East, and other Asian countries are planned to be established.

2.3 Project-level hydrogen development

To depict the status quo in terms of project-level hydrogen development, IEA's Hydrogen Production and Infrastructure Projects Database (2023b) is analyzed. The database includes all projects commissioned worldwide since 2000, as well as projects in planning or under construction. The scope of the covered projects is appropriate, as it includes initiatives aimed at producing hydrogen for energy and climate change mitigation. In contrast, conventional hydrogen production projects are excluded from this analysis, as they do not represent the transformative changes required to develop a low-carbon hydrogen economy. For hydrogen infrastructure projects, all projects related to pipelines, underground storage facilities, and import or export terminals are included in the analysis because the developed infrastructure supports the hydrogen economy regardless.

Table 1 presents hydrogen production projects from 2019 to 2024 for the previously highlighted countries, along with planned projects starting in 2025. Notably, China, the US, and Germany exhibit high project activity, while Japan lags behind. China's cumulative installed electrical capacity for these projects stands out at 3.0 GW, nearly double that of the US, Germany, and Japan combined. China's capacity translates to an annual hydrogen production output of approximately 600 kt for 2024, significantly surpassing China's national development target of 100 to 200 kt for 2025. This discrepancy between China's lagging national hydrogen strategy and its high project activity is unique. The lack of strategic planning is further evidenced by the planned hydrogen production capacity from 2025 onwards. The US is notable for its planned projects, amounting to 55 GW of electrical capacity, whereas China and Germany have similar planned capacities of 25.6 GW and 21.2 GW. When compared to the size of each country's energy system, measured by total primary energy consumption—159.4 EJ for China and 12.3 EJ for Germany in 2022 (EI, 2023)—there is a factor of 13 difference. This disparity reflects Germany's highly ambitious hydrogen strategy in contrast to China's more cautious approach.

Table 1: Project-level hydrogen development country comparison (IEA, 2023b)

Country	# of projects since 2019 (planned)	Installed until 2024 [MW_{el}; kt H_2/y]	Planned from 2025 [MW_{el}; kt H_2/y]	Fossil w/CCUS [$MtCO_2$/y]	Infrastructure
CHN	46 (30)	3,017; 564	25,588; 4,433	4.5 operational	400 km East-West H_2 pipeline 100 to 500 ktH_2/y H_2 by 2030
USA	48 (91)	750; 140	55,160; 15,466	5.7 operational; 46.8 planned	370 km Hydrogen City - South Texas; 41.0 ktH_2/y storage
JPN	15 (6)	22; 4	16; 91	0.1 demo (decommissioned)	Hy Touch Kobe for importing 150 kt liquefied hydrogen
GER	58 (83)	888; 150	21,176; 4,074	1.8 planned	26 pipeline projects with 2,684.7 km new, 3,874.3 km repurposed

In terms of technology deployment, the main commercially available electrolyzers, ALK and PEM, are considered. China has a cumulative annual hydrogen production of 115.1 kt from ALK and 68.3 kt from PEM, resulting in an ALK-to-PEM ratio of 1.7 to 1. This contrasts with the US, which has a ratio of 1 to 7.6, and Germany, with a ratio of 1 to 1.7. China's focus on ALK electrolyzers is due to their cost-performance advantage compared to the more efficient PEM technology. Additionally, 55 % of the projects considered have a dedicated renewable electricity source. Regarding blue hydrogen production from fossil fuels with CCUS, only China and the US have operational plants, with 4.5 and 5.7 $MtCO_2$/y. For infrastructure, Germany has the most ambitious pipeline projects planned, reflecting the government's 2023 announcement (BMWK, 2023) of significant investments in a core hydrogen network.

3. H-ESGO roadmap for China

For national-level hydrogen development, a new approach is proposed, using H-ESGO dimensions and technology road mapping. H-ESGO dimensions are based on a conceptual framework that explains the iterative dynamic process of energy transitions, known as Energy-Sustainability-Governance-Operation (ESGO) (Zhang et al., 2022). In the following each H-ESGO dimension is introduced and then applied to China.

3.1 Methodology: Aligning hydrogen adapted ESGO with technology road mapping

Hydrogen serves as a chemical feedstock and energy carrier, forming a subsystem of the energy system. The physical hydrogen flow from production to end use is known as the hydrogen supply chain (HSC), divided into a supply-infrastructure-demand chain. The annual hydrogen output is a key indicator for target formulation.

An energy system supplies energy services to end users through technologies and infrastructure for acquisition, conversion, storage, transportation, distribution, and use. These processes are illustrated by energy and material balances. For H-ESGO, hydrogen's role in the energy system, such as using surplus electricity for grid balancing, is considered. Hydrogen integration is measured by its share in the TFEC.

Sustainability addresses the natural resource and ecological constraints on continuous energy services, including international influences from energy imports and exports. It encompasses challenges like energy poverty, climate change, energy security, and pollution. In this context, hydrogen's carbon emission reduction potential (CERP) is discussed in section 3.2 as an indicator for target formulation.

Governance is the process in which multi-level bodies of communities rely on specific agendas and mechanisms to mediate differences on energy development issues and formulate resolutions, plans, and policy texts. It can be briefly described by energy strategy topics and related plans and involves a series of agreements on current trends, vision goals, or mission measures. Existing hydrogen strategies are covered by this dimension.

Operations cover conventional and innovative behaviors in energy systems, such as consumption, production, transportation, construction, transformation, and decommissioning. Economic networks and financial flows measure these activities. For hydrogen, the levelized cost of hydrogen (LCOH) is key. Social factors like attitudes, transition costs, safety, and risk management are harder to quantify.

To integrate H-ESGO dimensions into a strategic plan, technology road mapping is used. The strategy involves analyzing and deciding in the present about future opportunities, involving risk-taking and innovation. An effective technology roadmap addresses: Where are we now? Where do we want to go? How can we get there? This involves understanding the status quo, setting targets, and defining key actions. The goal is to build a roadmap for transitioning to a hydrogen economy, with short-, mid-, and long-term actions and targets aligned with H-ESGO dimensions. Five guiding principles enable development across all dimensions toward a comprehensive hydrogen economy.

3.2 Applying H-ESGO to improve China's hydrogen development plan

China is ready to become a major player in the global hydrogen economy, with strong capabilities to manufacture and export hydrogen technology, as well as to become a prosumer or import hydrogen as needed. However, there is a notable mismatch between strategic planning and actual project activities. Despite renewable energy abundance in northwest China, long-distance transportation costs for hydrogen make other regions closer to the demand more economically viable. To address this, China should prioritize a rapid rollout of decentralized hydrogen production, supported by swift project implementation, minimizing infrastructure investment barriers and promoting technology openness. Technological risks within hydrogen pipeline transport due to material degradation that potentially can lead to releases are avoided. Developing a robust HSC requires substantial investment dependent on economic viability. High utilization rates are needed to achieve cost-efficient unit economics for hydrogen. The diversified demand-side development aims to stabilize the consumption of new applications and mitigate uncertainties. Subsequently, the HSC can scale up with large-scale, centralized hydrogen production, leveraging pipeline networks to connect supply and demand efficiently and reduce unit economics. Global hydrogen trade must be considered if exporting countries achieve low LCOH or if China faces domestic production constraints. Key impact factors on delivered LCOH include electrolyzer selection, transportation distance, and electricity price.

Currently, hydrogen serves as an industrial feedstock. To reduce carbon emissions, a transition away from coal-based hydrogen production is recommended, with low electricity costs being crucial. Over time, hydrogen will transition from a chemical feedstock to an energy carrier, fully integrating into the energy system and supporting its transition. Given China's geography, where renewable energy potential in the Northwest contrasts with demand in the Southeast, hydrogen can bridge this gap for grid balancing.

China's status as a global manufacturing powerhouse positions it well to produce cost-effective technology, with substantial hydrogen demand potential from heavy industry. For example, using zero-carbon hydrogen for green steelmaking in China can reduce life-cycle emissions by more than 60 % (Ren et al., 2023). Considering the carbon intensity of coal gasification with 21.7 $kgCO_2e$ per kg of hydrogen (Li et al., 2022), the CERP effect is even higher. With zero carbon electrolysis, life-cycle GHG emissions below 1 $kgCO_2e$ per kg green hydrogen (HC, 2021) are achievable. This study considers 20 kgCO2e per kg of hydrogen as CERP.

Political guidance is crucial. Establishing a regulatory framework for hydrogen energy, including targets, standards, incentives, and carbon pricing, is strongly recommended. China's financial strength can support this transition, ensuring energy independence and security, complemented by international collaboration to globalize the HSC. A subsidy-driven approach is designed to overcome initial cost barriers. By leveraging its manufacturing strengths, China can become an export hub, pushing innovation and market competitiveness.

For the purpose of this research, a simplified target development in China was applied, as seen in Figure 2. Orientating the hydrogen share of TFEC with gradual adoption.

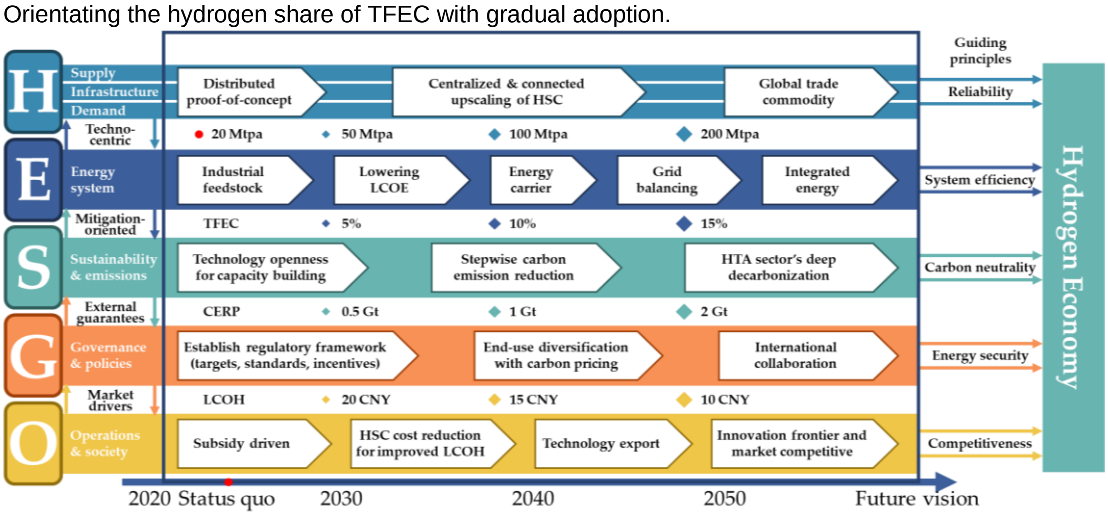

Figure 2: Hydrogen adapted ESGO Roadmap proposed for improved hydrogen strategy in China

3.3 Policy recommendations

Two main policy recommendations can be derived from the previous multi-tier review and the formulated H-ESGO roadmap. First, the national hydrogen development plan of China should be enhanced with long-term quantitative targets aimed at supporting carbon neutrality by 2060. These unified targets will provide a clear direction for government bodies, industries, and investors, ensuring that hydrogen development efforts are strategically aligned. This alignment will reduce uncertainty for all stakeholders and facilitate coordination across various provincial and local governments, mitigating the fragmented and inefficient approaches currently observed. The establishment of clear targets will boost investor confidence, leading to improved financial planning and a more efficient allocation of resources towards hydrogen projects. Secondly, it is recommended to take immediate action with decentralized hydrogen production to capitalize on existing capabilities and circumvent infrastructure investment barriers. This approach will accelerate the overall rollout of hydrogen energy and offer adaptability in the evolving market. Due to the lower initial capital investment, upfront risks are minimized. Producing hydrogen closer to the point of use enhances accessibility while reducing the need for extensive transportation and distribution infrastructure, which is time-consuming to build and incurs energy losses during long-distance transportation. This practical and flexible pathway leverages innovation in technology and business models, fostering a rapidly advancing transition process.

4. Conclusions

The multi-tier review was used to find key issues of China’s hydrogen development. The global hydrogen perspective highlights the uncertainty of hydrogen development, which makes strong strategic planning a necessity. For China, a discrepancy between high project activity with 3.0 GW installed capacity and weak strategic planning with 25.6 GW planned capacity was established. With a long-term political commitment, China’s already agile project activity could be unlocked to new levels. An improved hydrogen development plan for China was proposed, integrating H-ESGO dimensions into a roadmap. From this, two main policy recommendations were derived, which are practical steps towards a low-carbon hydrogen economy. First, improving the hydrogen development plan with long-term quantitative targets in order to reduce uncertainty for involved stakeholders. Secondly, taking immediate action with a decentralized hydrogen production to avoid infrastructure investment barriers and capitalize on existing capabilities. Guiding policymakers to adopt a leading role for hydrogen is crucial for achieving cost-effective deep decarbonization across hard-to-abate industries.

Limitations of this study are within the target development and the complex connections of key actions within the H-ESGO roadmap and deserve more research attention. A separate risk analysis linked to the H-ESGO dimension considering technological aspects along the HSC as well as economic, environmental, and social considerations is a valid extension of this work. The roadmap for China might also be subject to iterations due to dynamic market or international policy changes. Implications of the newly developed hydrogen adaptation of ESGO dimension to a strategic roadmap are transferring this system thinking approach to other promising energy sources, raw materials or low-carbon transition technologies. This ESGO roadmap adaptation is also possible for biomass (B-ESGO), metals (M-ESGO), or energy storage (ES-ESGO).

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