ENVIRONMENT AND NATURAL RESOURCES PROGRAM

Mission Hydrogen

Accelerating the Transition to a Low Carbon Economy

Edited by
Nicola De Blasio

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ISPI
ITALIAN INSTITUTE FOR INTERNATIONAL POLITICAL STUDIES

REPORT
OCTOBER 2021

Environment and Natural Resources Program
Belfer Center for Science and International Affairs
Harvard Kennedy School
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About the Program

The Environment and Natural Resources Program's mandate is to conduct policy-relevant research at the regional, national, international, and global level, and through its outreach initiatives to make its products available to decision-makers, scholars, and interested citizens.

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About the Author/Editor

Dr. Nicola De Blasio is a Senior Fellow leading Belfer Center research on energy technology innovation and the transition to a low-carbon economy. With more than 25 years of global experience in the energy sector, Dr. De Blasio is an expert in navigating the challenges of strategic development and technology innovation toward sustainable commercial success, at scale. This coupled with his insight on the impact of an institution's development and innovation activities on other facets of business strategy, such as environmental, social, operational, geopolitical, and governmental factors. Dr. De Blasio spent 18 years at Eni, one of the world's leading energy companies, most recently as Vice President and Head of R&D International Development. Prior to joining Harvard, Dr. De Blasio was Senior Research Scholar in the faculty of SIPA at Columbia University and Program Director Technology and Innovation at the Center on Global Energy Policy, where he was also Director of Strategic Partnerships. Dr. De Blasio holds a degree in Chemical Engineering from the Politecnico of Milan University with a thesis in industrial catalysis. He specialized at St. Andrews University, Scotland and then at Eni Corporate University, where he focused on energy economics. He is author of the book Value of Innovation, and has extensively published and lectured on energy, innovation, project evaluation and catalysis.

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1 Photo by Shizuo Kambayashi/AP

Executive Summary

To accelerate the global transition to a low-carbon economy, all energy systems must be actively decarbonized. While hydrogen has been a staple in the energy and chemical industries for decades, clean hydrogen – defined as hydrogen produced from water electrolysis with zero-carbon electricity – has captured increasing political and business momentum as a versatile and sustainable energy carrier in the future carbon-free energy puzzle. But taking full advantage of this potential will require a coordinated effort between the public and private sectors focused on scaling technologies, reducing costs, deploying enabling infrastructure, and defining appropriate policies and market structures. Only in this way can we avoid replicating the system-wide inefficiencies of the past that have characterized regional approaches to deploying new energy infrastructure.

Key findings include:

- Clean hydrogen could play a significant role in an accelerated transition to a low carbon economy, particularly for hard-to-abate sectors, and offers a path toward meeting national and international climate and pollution goals while avoiding reliance on imported fuels.
- The two key challenges to clean hydrogen adoption and use at scale are currently its cost and limited infrastructure availability. Public concerns around safety might also present additional challenges to deployment.
- From a market perspective, clean hydrogen, like natural gas, will initially flourish in regional markets with the corresponding potential for geopolitical conflicts.

- A country's role in clean hydrogen markets will depend not only on its ability to produce and distribute renewable hydrogen cost-competitively and at scale, but also on its policy choices. Nations will likely assume specific roles in future clean hydrogen markets, which can be classified into five groups: export champions, water constrained producers, major importers, self-sufficient producers or regional exporters, and infrastructure constrained producers. For example, our analysis on China (Section 4) suggests that Beijing still has a long way to go before a hydrogen society could reach fruition, but if the country were to replicate the success it has had with other clean technologies (like solar PV) China could significantly lower production costs and accelerate adoption around the world, while emerging as a renewable hydrogen superpower.

- Clean hydrogen can help address renewable energy intermittency and curtailment issues and open new avenues for developing clean technology manufactured goods for both domestic and export markets, thus providing substantial additional benefits to local economies.

- In the mobility sector, hydrogen can complement existing efforts to electrify road and rail transportation, especially in long-distance and heavy-duty sectors, and provide a scalable option for decarbonizing shipping and aviation.

- Blockchain can greatly accelerate the transition to a low-carbon economy as technology and policy pathways to decarbonization will need to rely on processes that accurately measure and record emissions and green molecules across global markets characterized by limited transparency, uneven standards, different regulatory regimes, and trust issues. Addressing these challenges will require managing large volumes of multi-party transactions, which need to be settled quickly, securely, and inexpensively. These processes can be aided greatly by blockchain.

Based on these findings, we recommend the following set of actions:

- The G20 should institute a "Technology 20" official engagement group that brings together leading global stakeholders from the private and public sectors across entire value chains to serve as a technology sandbox and provide technology and policy recommendations to accelerate innovation cycles. The case of hydrogen highlights how adopting new clean technologies can offer unique opportunities to accelerate the transition to a low-carbon economy. Still, deployment at scale faces significant challenges that neither the private nor public sector can address alone.

- Governments pursuing clean hydrogen should increase investments in innovation, convene stakeholders across value chains, and foster collaboration in addressing first-mover risks, strategic barriers, and opportunities.

- Nations and regions that wish to adopt clean hydrogen at scale should prioritize detailed analysis and planning now since the effects of policy choices made today will be felt decades in the future. As our research highlights, nations will need to carefully consider their role in future clean hydrogen markets from a geopolitical and market perspective. It will also be critical to identify infrastructure bottlenecks and address financial gaps in specific markets and applications. For example, building a pipeline network to deliver hydrogen to homeowners who have yet to install hydrogen-fueled stoves and heating systems would be financially disastrous. Hence, synchronizing infrastructure investments with growth in supply and demand will be essential but challenging.

- Addressing the price gap between clean and fossil-based hydrogen will require active policy interventions. Such policies could include measures to incentivize the value and use of clean hydrogen, such as implementing clean hydrogen standards and carbon pricing.

- Stakeholders must be appropriately credited for investing in the current premium required to produce carbon-free hydrogen. This will require concerted efforts to identify design principles, best practices, and standards for robust blockchain platforms that achieve shared agreement among key stakeholders (including mandating clean blockchains) and to educate stakeholders about blockchain technology and its value proposition.
- Nations and regions should implement market-aligning policies, together with production and safety standards, to accelerate clean hydrogen adoption and enable transnational trade.

Clean hydrogen offers a unique opportunity to accelerate the global transition to a low-carbon economy, but deployment at scale faces important challenges. We believe that only a deeper understanding of the underlying dynamics will allow policymakers, investors, and other stakeholders to better navigate the challenges and opportunities of a low-carbon economy without falling into the traps and inefficiencies of the past. Stakeholders need to thoroughly assess clean hydrogen's economic, environmental, and geopolitical implications, develop strategies to address them, and define long-term implementation plans – and it is essential to do so now.

1. Introduction

Hydrogen and energy have a long-shared history. Despite past false starts, hydrogen is capturing unprecedented political and commercial momentum as a versatile, sustainable energy carrier that could serve as the "missing link" in global decarbonization efforts. Clean hydrogen produced from zero-carbon energy sources such as renewable and nuclear power through a process known as water electrolysis appears ever more likely to play a prominent role in the global transition to a low-carbon economy. While pathways to the energy transition are visible in the power sector, all other carbon-emitting sectors must also find ways to substantially reduce emissions. As governments and corporations become increasingly committed to addressing climate change, they are placing greater emphasis on the deep decarbonization of all energy-intensive sectors; particularly in sectors where electricity is not the preferred energy carrier and emissions are "hard-to-abate." Examples include iron and steel production, high-temperature industrial heat, aviation, shipping, long-distance road transportation, and heating for buildings; areas where the required dual transition – shifting to electricity as the preferred energy delivery system while decarbonizing electricity production – may not work. Due to its versatility, hydrogen could play this role and serve as a "link" between emitting sectors.

It is important to note that to reap clean hydrogen's full environmental benefits, hydrogen must be produced from zero-carbon sources. While hydrogen burns cleanly as fuel at its point of use, hydrogen produced from fossil fuels simply relocates emissions from one site to another.

At the same time, the adoption of clean hydrogen at scale will depend on more than its environmental benefits; economic, policy, technological, and safety factors must also be addressed. Two key elements will determine hydrogen's rate of global growth: the competitiveness of production costs and the deployment of enabling infrastructure at scale.

Today, green hydrogen (produced from renewable electricity by water electrolysis) costs two to three times as much as hydrogen produced from fossil fuels; however, innovation, economies of scale, and carbon pricing policies can improve its economic viability.

One of hydrogen key benefits is that it can provide carbon-free energy in multiple sectors – transport, heating, industry, and electricity generation. But this advantage also creates uncertainties. The infrastructure needed in an economy in which hydrogen is primarily used as a transport fuel is very different from one in which its primary value is as a heating fuel.

No major hydrogen pipeline networks exist today, and no liquified hydrogen ships are in commercial operation. Here is a true chicken and egg problem. If there is no infrastructure to move hydrogen, will investments in supply and demand happen at the pace needed to meet national decarbonization targets? This challenge raises an even more pressing question: what should the respective roles of the public and private sectors be in deploying enabling infrastructure at scale?

Clean hydrogen can be used in both stationary and mobility applications. As a readily dispatchable means of storing energy, hydrogen can help address growing intermittency and curtailment challenges associated with expanded renewable energy capacity. It can serve as a fuel in stationary systems for buildings, backup power, distributed generation, or for high-temperature industrial heat. In mobility applications, hydrogen could become an essential energy carrier for sustainable transportation. Whether by powering fuel-cell electric vehicles such as hydrogen cars, trucks, and trains or as a feedstock for synthetic fuels for ships and planes, hydrogen can complement ongoing efforts to electrify road and rail transportation and provide a scalable option to decarbonize shipping and aviation sectors.

Since clean hydrogen has the potential to become an essential piece in the carbon-free energy puzzle, it is also relevant to explore its geopolitical implications as it enables policymakers to navigate a new energy world. Key variables to consider are technology, infrastructure, environment, finance, global markets, and geopolitics. Focusing on renewable hydrogen, our work described in Section 3 developed a methodology to frame these variables, address the challenges they cause as well as the potential opportunities they present. If hydrogen is adopted at scale, future market dynamics will likely resemble today's regional natural gas markets – creating the potential for similar geopolitical dynamics.

Indeed, countries are likely to assume specific roles in future renewable hydrogen systems based on their resource endowment and infrastructure potential. As a result, future geopolitical realities of resource-poor countries in Europe and Southeast Asia might look very similar to the present realities, as energy import dependency might continue. We may also witness an emergence of new export champions, such as Australia and North Africa.

What are the general principles of how renewable hydrogen may reshape the structure of global energy markets? What are the likely geopolitical consequences such changes would cause? A deeper understanding of these nascent dynamics will allow policymakers and investors to better navigate the challenges and maximize the opportunities that decarbonization will bring, without falling into the inefficient behaviors of the past.

The remainder of this report is structured as follows: Section 2 gives an overview of the colors of hydrogen. Section 3 draws the geopolitical and market map for renewable hydrogen. Section 4 provides a deep dive on China and its potential to become a renewable hydrogen superpower. Section 5 outlines the market and geopolitical implication of renewable hydrogen adoption for the European Union. Section 6 addresses the infrastructure challenge. Section 7 analyzes the potential role of renewable hydrogen in the transport sector. Section 8 addresses the role of blockchain technology and Section 9 provides an overall conclusion and recommendations.

2. **The Hydrogen Rainbow**

A rainbow of colors dominates almost every conversation on the transition to a low-carbon economy: green, grey, blue, turquoise, pink, yellow, orange – an ever-increasing palette to describe the same colorless, odorless, and highly combustible molecule, hydrogen. The only difference is the chemical process used to produce it.

Hydrogen is the most abundant element in the solar system, but on Earth it naturally occurs only in its compound form. Therefore, it must be produced from molecules that contain it, such as water or hydrocarbons, through specific processes, including thermo-chemical conversion, biochemical conversion, or water electrolysis.

Annual global hydrogen production today stands at about 75 million tons (Mt) or 10 exajoules (EJ)[1] and comes almost entirely from natural gas (steam gas reforming) and coal (coal gasification)[2]. China is by far the world's largest hydrogen producer: its 24 Mt per year represents almost a third of the world's production; however, most of China's hydrogen is produced from coal, accounting for 5% of the nation's total coal consumption.[3] [4]

Although hydrogen burns cleanly as a fuel at its point of use, producing it from fossil fuels without carbon capture simply relocates emissions. Hence, to reap hydrogen's full environmental benefits, it must be produced from zero-carbon electricity through water electrolysis, an electrochemical process that splits water into hydrogen and oxygen. Currently, however, water electrolysis accounts for less than 0.1% of global hydrogen production.[5]

Hydrogen is mainly used in oil refining and the production of ammonia, fertilizers, methanol, and steel. Yet, with a growing emphasis on its decarbonization potential across sectors, hydrogen demand is projected to increase considerably in the coming decades. Estimates on annual global

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1 IEA (2020), "Energy Technology Perspectives 2020."

2 IEA (2019), "The Future of Hydrogen. Seizing today's opportunities." Report prepared for the G20, Japan.

3 Brasington, L. (2019), "Hydrogen in China." Cleantech Group https://www.cleantech.com/hydrogen-in-china/, accessed June 2021.

4 World Coal Association (2019), "Coal" https://www.worldcoal.org/coal , accessed June 2021.

5 IEA (2019), "The Future of Hydrogen. Seizing today's opportunities." Report prepared for the G20, Japan.

demand by 2050 vary significantly among scenarios. The 2017 Hydrogen Council study estimates demand at approximately 78 EJ or around 14% of projected total global energy demand. Studies by Bloomberg-NEF (2019), DNV (2018), and IEA (2020) are more conservative, with estimates between 5 and 40 EJ.[6] Overall two factors will determine hydrogen's rate of global growth: competitiveness of production costs and deployment of enabling infrastructure at scale.[7]

The colors of hydrogen are crucial for the energy transition because each production pathway generates different amounts of greenhouse gas emissions and results in different production costs. Today, renewable (or green) hydrogen is two to three times more expensive than hydrogen produced from fossil fuels.[8] However, thanks to innovation, economies of scale, and carbon pricing policies, these costs are expected to decrease over time.

Furthermore, the world's dependence on grey hydrogen has a high carbon cost. A shift to blue hydrogen would reduce carbon emissions by half.[9] Although fossil fuel plants utilizing Carbon Capture and Storage (CCS) are well-suited to mitigate emissions, only the adoption of green hydrogen at scale, with its zero-carbon impact, would fully address emissions concerns associated with the production and consumption of hydrogen.

The following section on the colors of hydrogen offers a detailed description of each production pathway, including cost valuations provided by Goldman Sachs[10] and emissions estimates provided by IEA.[11]

6 De Blasio, N. (2021) "The Role of Clean Hydrogen for a Sustainable Mobility." Harvard Kennedy School's Belfer Center, August 2021. https://www.belfercenter.org/publication/role-clean-hydrogen-sustainable-mobility.

7 Ibid.

8 IRENA (2020), "Making Green Hydrogen a Cost – Competitive Climate Solution." https://www.irena.org/newsroom/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution, accessed April 2021.

9 IEA (2019), "The Future of Hydrogen. Seizing today's opportunities." Report prepared for the G20, Japan.

10 Goldman Sachs (2020), "Green Hydrogen: The next transformational driver of the Utilities industry, accessed June 2021. https://www.goldmansachs.com/insights/pages/gs-research/green-hydrogen/report.pdf

11 IEA (2019), "The Future of Hydrogen. Seizing today's opportunities." Report prepared for the G20, Japan.

2a. **The Colors of Hydrogen**

Black or brown hydrogen refers to hydrogen produced by coal gasification. The black and brown colors sometimes indicate the coal type: bituminous (black) and lignite (brown). This process generates significant CO_2 emissions (19 tCO_2/tH_2).

Blue hydrogen refers to hydrogen produced mainly from natural gas by steam gas reforming, paired with carbon capture and storage (CCS). Blue hydrogen has a much lower carbon intensity than grey hydrogen, with estimates ranging from 1 to 4 tCO_2/tH_2. Although the use of CCS increases costs, blue hydrogen currently remains the cheapest "clean" alternative to grey hydrogen; blue hydrogen cost estimates range from € 1.1 to 1.6 per kg.

Green or renewable hydrogen refers to hydrogen produced from renewable energy sources like wind and solar through a process known as water electrolysis, where an electrolyzer splits water molecules into oxygen and hydrogen. There are no CO_2 emissions generated during the production process. Today, green hydrogen costs are significantly more than those of grey hydrogen, with estimates ranging from € 2.3 to 4.1 per kg. It accounts for less than 0.1% of the world's hydrogen production.

Grey hydrogen refers to hydrogen produced from fossil fuels mainly by steam gas reforming or coal gasification. It generates significant CO_2 emissions, between 10-19 tons of CO_2 per ton of H_2 (tCO_2/tH_2)[12] and costs between € 0.7 to 1.1 per kg. Currently, over 95% of the world's hydrogen consumption is grey hydrogen.[13]

12 10 tons of CO_2 per ton of H_2 (tCO_2/tH_2) from natural gas, 12 tCO_2/tH_2 from oil products, and 19 tCO_2/tH_2 from coal.

13 Rapier, R. (2020), "Estimating the Carbon Footprint of Hydrogen Production." Forbes https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/?sh=605c40b924bd, accessed September 2021.

Orange hydrogen refers to emerging processes to produce hydrogen using plastic waste as a feedstock. Orange hydrogen may offer a solution to both the clean energy problem and issues surrounding disposal of plastic waste. Currently, orange hydrogen remains in the early development stage, with various technologies and production processes, including pyrolysis, microwave catalysis, and photo-reforming under evaluation.

Pink hydrogen refers to hydrogen produced by water electrolysis powered using nuclear power, a clean, but non-renewable source of energy. It does not generate CO_2 emissions.

Purple hydrogen refers to hydrogen produced by water electrolysis using both nuclear power and heat.

Red hydrogen refers to hydrogen produced by high-temperature catalytic splitting of water using the heat and steam generated from nuclear plants. The process requires much less electricity than traditional electrolysis.

Turquoise hydrogen refers to hydrogen produced from natural gas under a process known as methane pyrolysis, in which natural gas is decomposed into hydrogen and solid carbon at high temperatures. Currently, turquoise hydrogen remains in the early development stage.

Yellow hydrogen refers to green hydrogen produced from solar energy. It does not generate CO_2 emissions. Estimates suggest that yellow hydrogen may become the cheapest form of renewable hydrogen in the medium term, with current cost estimates of around € 2.3 per kg

3. The Geopolitics of Renewable Hydrogen

Nicola De Blasio & Fridolin Pflugmann

The transition to low-carbon energy will likely shake up the geopolitical status quo that has governed global energy systems for over a century. Policymakers need to rethink the role their country could play in a new energy world.

Renewables are widely perceived as an opportunity to shatter the hegemony of fossil fuel-rich states and democratize the energy landscape. Virtually all countries have access to some renewable resources (especially solar and wind power) and could thus substitute foreign supply with local resources. Our research shows, however, that the role countries are likely to assume in decarbonized energy systems will be based not only on their resource endowment but also on their policy choices.

Renewable hydrogen is enjoying growing political and business momentum as a versatile and sustainable energy carrier with the potential to play a key role in the global transition to a low-carbon economy; and it is often described as the 'missing link' in global decarbonization. This is even more true for energy intensive sectors where emissions are hard to abate and electrification is not the preferred solution – such as steel production, high-temperature industrial heat, shipping, aviation and heat for buildings. But making renewable hydrogen a significant part of the world's future energy mix will require defining new and innovative national and international policies while developing appropriate market structures aimed at spurring innovation along value chains, scaling technologies while significantly reducing costs, and deploying enabling infrastructure at scale. Success is possible, but this transformational effort will require close coordination between policy, technology, capital, and society to avoid falling into the traps and inefficiencies of the past.

Renewable hydrogen can be used for both mobility and stationary applications. As a sustainable mobility energy carrier, it can power fuel-cell electric vehicles or be the base for synthetic fuels. In stationary applications, it can be used to store renewable energy, both at utility scale or off-grid, hence providing backup to buffer renewable energy sources' intermittency and serve as a carbon-free heating source.

From a geopolitical perspective, whether future renewable hydrogen energy systems will be as concentrated as today's oil and gas supply or as decentralized as renewables is strongly related to future market structures, technology, and enabling infrastructure availability.

The role a country could play in renewable hydrogen markets will depend on its ability to produce and distribute renewable hydrogen cost competitively and at scale. Since the production of renewable hydrogen through electrolysis requires both renewable energy and freshwater resources, to analyze a country's renewable hydrogen potential, we consider three parameters: (1) renewable energy resource endowment; (2) renewable freshwater resource endowment; and (3) infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation, and distribution infrastructure.

Our research shows that countries will likely assume specific roles in future renewable hydrogen systems and can be aggregated in five groups. Countries with large renewable and freshwater resource endowments, as well as high infrastructure potential, such as Australia and Morocco, are well positioned to emerge as "export champions" thanks to their superior cost positions and access to large import markets (Group 1). Group 2 countries have abundant renewable energy resources, but limited freshwater resources, which decreases their likelihood of becoming major green hydrogen exporters. Countries in Group 3 will need to import renewable hydrogen due to their limited renewables potential and/or land availability. Most countries in this group – including Japan and parts of the EU – are already dependent on energy imports today. Hence, energy dependencies of these countries might perpetuate into the future as well. Countries in Group 4 have the renewable and freshwater resource potential to satisfy their local renewable hydrogen demand through domestic production. While these countries are potentially self-sufficient, they may still complement domestic production with imports due to cost considerations. Hence, nations in Group 4 are typically faced with a make-or-buy decision. Finally, countries in Group 5 have vast access to renewable resources but are unlikely to be able to build the required infrastructure at scale. The larger the landmass, the more complex and costly it is to deploy a cohesive national infrastructure, hence, a likely alternative for these countries is hydrogen production at smaller off-grid sites.

A detailed country classification is depicted below.

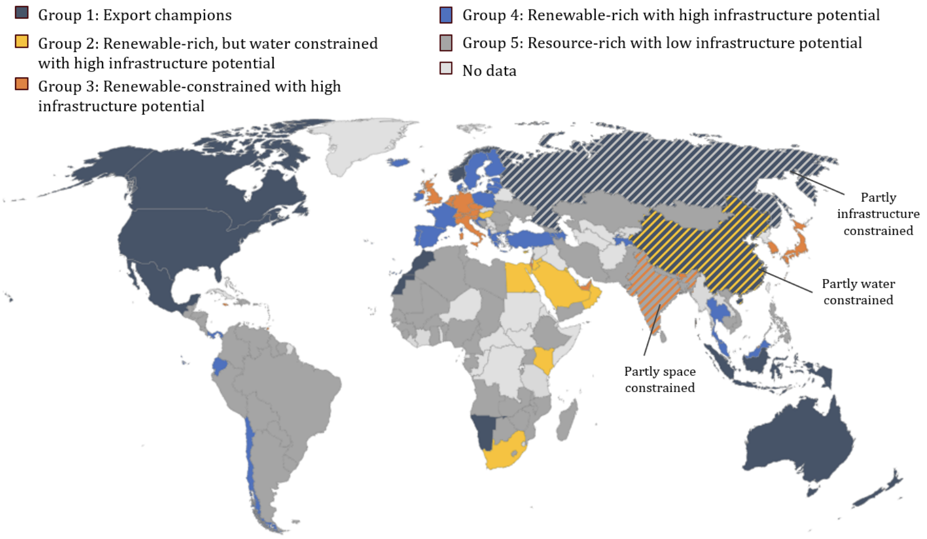

Figure 1. The global renewable hydrogen map (authors' elaboration)

The results illustrate how a global transition to low-carbon technologies may not change the geopolitical position of importing countries, with their reliance on foreign fossil fuels being simply replaced by dependence on foreign renewable energy supplies. Future geopolitical realities of resource-poor countries in Europe and Southeast Asia might therefore be very similar to today's and energy import dependencies continue. At the same time, the Middle East is almost certain to play a less prominent role in future renewable hydrogen markets than in today's oil markets. As a result, international political interest in the region could dwindle and shift to regions like North Africa.

From a policy perspective, "export champions" should define policies to trigger innovation and infrastructure investments, thus paving the way for a dominant positioning in future markets. However, sustaining high renewable deployment rates will be key to achieve the needed scale. On the other hand, importing countries would benefit from enhanced cooperation with exporting nations to establish international standards for renewable hydrogen. In order to increase their energy security, governments of importing countries will also need to define long-term hydrogen strategies, including options to diversify supply. The potential impact of interruptions in hydrogen supply depends on how global the market will develop. If liquefaction and shipping over thousands of kilometers were to become cost-competitive, interruptions of supply in one part of the world could have impact on global prices. However, we believe that hydrogen, similar to natural gas, will initially flourish as regional markets.

Policymakers, investors, and other stakeholders need to assess the economic, environmental, and geopolitical implications of renewable hydrogen and examine possible courses of action. A deeper understanding of these nascent dynamics is needed, so that policy makers and investors can better navigate the challenges and opportunities of a low carbon economy to avoid the traps and inefficiencies of the past.

This Section is based on the report: "Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World" published by the Harvard Kennedy School's Belfer Center for Science and International Affairs in March 2020.

4. China: The Renewable Hydrogen Superpower?

Nicola De Blasio & Fridolin Pflugmann

President Xi Jinping's pledge during the 2020 United Nations General Assembly, that China would reach peak carbon dioxide emissions by 2030 and achieve carbon neutrality before 2060, is a significant step in the fight against climate change. Since China is the world's top contributor of greenhouse gases, there is no doubt that Beijing needs to be front and center of any effort to curb global emissions.

In 2019, China accounted for almost 30% of global emissions, about twice as much as the second largest emitter, the United States.[14] But while U.S. emissions have been on an overall decline since 2007,[15] China's have increased, raising concerns over whether Beijing can deliver on its targets. This reality should not distract from the fact that China is also the world's top developer of renewables and other clean energy technologies. For example, China was the world's largest installer of photovoltaics (PV) by 2013 and, in fewer than two years, also became the global leader in solar module manufacturing. At the same time, China leveraged its industrial might and economies of scale to drive down modules' costs – which, by the end of 2018, were 90% lower than only ten years before.

In this context, renewable hydrogen could significantly accelerate China's transition to a low-carbon economy, increasing the likelihood of meeting its carbon neutrality goal. Renewable hydrogen offers significant advantages for China. It can help Beijing meet its climate and pollution goals – at a time when coal continues to dominate – while avoiding increased reliance on imported fuels. As a readily dispatchable means of

14 Statista (2021), "Carbon dioxide emissions in 2009 and 2019 by country" https://www.statista.com/statistics/270499/co2-emissions-in-selected-countries/, accessed April 2021.

15 EIA (2021), "U.S. Energy-Related Carbon Dioxide Emissions" https://www.eia.gov/environment/emissions/carbon/, accessed April 2021.

storing energy, hydrogen can help address intermittency and curtailment issues as renewable energy increases its share of China's energy mix. As a sustainable mobility energy carrier, it can power fuel-cell electric vehicles or be the base for synthetic fuels. Finally, renewable hydrogen can open new avenues for developing clean technology manufactured goods for both internal and export markets.

Today, most of China's hydrogen is produced from coal via 1,000 gasifiers, accounting for 5% of the country's total coal consumption. Hydrogen costs vary significantly as a function of production technology and prices of fossil fuels and electricity. Production from coal remains the lowest cost option: about 30% cheaper than hydrogen from natural gas. Therefore, reducing the carbon footprint of coal-based hydrogen will be critical in a low-carbon economy. In the medium term, coal-based hydrogen with carbon capture, utilization and storage will likely remain China's lowest-cost clean hydrogen production pathway. Hence, the underlying question is whether Beijing will prioritize cost considerations or put its full industrial might behind the development and deployment of renewable hydrogen.

In March 2019, the Chinese government took a significant step forward by announcing measures to promote the construction of hydrogen facilities for new energy vehicles. Wan Gang, who is known as China's "father of the electric car", called for China to "look into establishing a hydrogen society" and "move further toward fuel cells."[16] Given that Gang made a similar call two decades ago on vehicle electrification, which played a key role in China's current battery electric vehicles market dominance, close attention is warranted.

This broad vision on hydrogen has also been underpinned by significant investments at the provincial level aimed at spurring adoption of renewable hydrogen. In 2020, Guangdong province released a "New Energy Industry Fostering Plan" to promote "clean energy-based" hydrogen production. Hebei province is now home to four high-priority renewable power-to-gas

16 Bloomberg (2019), "Wan Gang, China's father of electric cars, thinks hydrogen is the future" https://www.bloomberg.com/news/articles/2019-06-12/china-s-father-of-electric-cars-thinks-hydrogen-is-the-future, accessed April 2021.

projects and Baicheng city (located in Jilin province) intends to establish a hydrogen hub based on wind energy, supported by local renewables majors such a SPIC and Goldwind.[17] These are just a few examples. Looking forward, in order for renewable hydrogen to become a significant part of China's low-carbon energy mix, Beijing will need to define new and innovative policies while developing appropriate market structures aimed at spurring innovation along the value chains, scale technologies while significantly reducing costs, and deploy enabling infrastructure at scale. A comprehensive Chinese hydrogen strategy needs to tie together all aspects of the hydrogen value chain, ranging from research, production, storage, and transmission, to end uses.

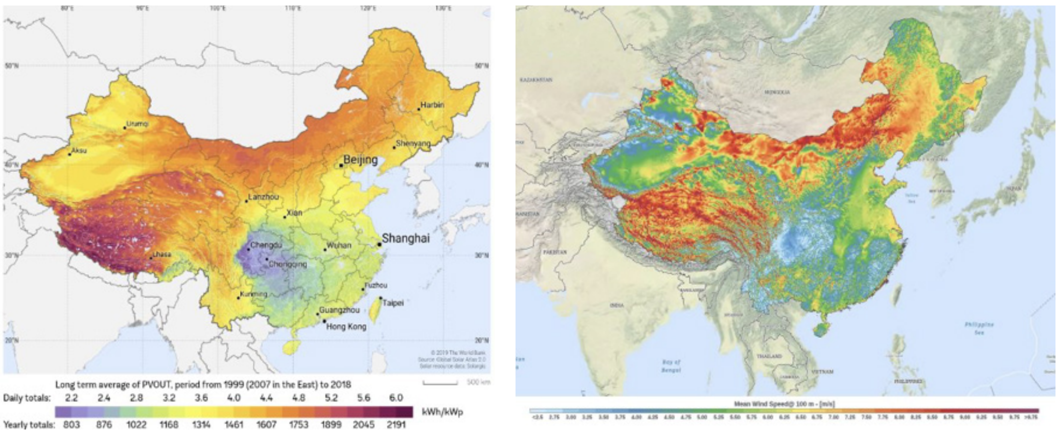

Figure 2. China's annual solar and wind potential (Global Atlas 2021)

A key barrier to renewable hydrogen adoption at scale is the geographical distribution of required renewable energy and freshwater resources. On one hand, while China's largest renewable potential is inland (see Figure 1), the key industrial and urban demand centers are located on the East coast. Similarly, while China as a whole is not water-constrained, freshwater availability varies greatly among regions. Water scarcity is already a serious issue in some areas, especially impacting the urban centers and industrial zones of the North. Eleven provinces are already water-constrained: Beijing, Gansu, Hebei, Henan, Jiangsu, Liaoning, Ningxia, Shandong, Shanghai, Shanxi, and Tianjin. And seven more are at risk of becoming

17 Energy Iceberg (2020), "China's Green Hydrogen Effort in 2020: Gearing Up for Commercialization" https://energyiceberg.com/china-renewable-green-hydrogen/, accessed April 2021.

water-constrained: Anhui, Chongqing, Guangdong, Hubei, Inner Mongolia, Jilin, and Shaanxi.[18]

At a national level, renewable hydrogen could be most efficiently and effectively produced in the Southwestern region. This region has rich renewable resources and less constrained water resources, but is far from China's economic heartland, thus requiring significant infrastructure investments to connect supply with demand, potentially making regional imports from neighboring countries more attractive. Furthermore, if water scarcity issues are addressed, China could become a renewable hydrogen export champion, supplying international markets in Southeast Asia and beyond.

From a geopolitical perspective, renewable hydrogen could become a key part of the Belt and Road Initiative, symbolizing China's technological prowess while increasing export opportunities and potentially enhancing Beijing's status as a leader in the global fight against climate change.

China still has a long way to go before a hydrogen society reaches fruition, but if Beijing were to replicate the success it has had with other clean technologies like solar PV, it could significantly lower costs and accelerate adoption around the world, while emerging as a renewable hydrogen superpower.

This Section is based on the report "Is China's Hydrogen Economy Coming? A Game-Changing Opportunity" published by the Harvard Kennedy School's Belfer Center for Science and International Affairs in July 2020.

18 China Water Risk Project (2020), "Who is running dry?" http://www.chinawaterrisk.org/the-big-picture/whos-running-dry/, accessed April 2021.

5. The European Union at a Crossroads: Unlocking Renewable Hydrogen's Potential

Nicola De Blasio & Alejandro Nuñez-Jimenez

European countries are at a crossroads on their path to carbon neutrality. Today, they are at the forefront of the global clean hydrogen race but going forward they would be better served by collaborating instead of working alone.

Overall, the European Union (EU) is highly competitive in clean technologies manufacturing and thus well-positioned to benefit from the emergence of global hydrogen markets. But a narrow focus on short-term cost considerations could drive member states to implement national roadmaps with little or no coordination among themselves and hence little or no chance of competing globally.

As a bloc, the EU has pledged to reach carbon neutrality by 2050. Clean hydrogen is a cornerstone of this transformational effort; accordingly, in July 2020, the EU adopted its hydrogen strategy with the ambition of deploying open and competitive clean hydrogen markets for all energy sectors and segments by 2050.[19]

Success hinges around implementing a cohesive long-term strategy to address a fundamental question and its associated challenges: where could the EU source competitive and secure renewable hydrogen supplies?

As Section 3 shows, all countries have access to renewable resources (such as solar or wind), to different degrees, and could produce some renewable hydrogen locally. However, while resource-rich countries, such as Spain, could evolve into regional exporters, no EU member state has the potential to become a global export champion. At the same time, North African

19 European Commission (2020), 'A hydrogen strategy for a climate-neutral Europe', COM(2020) 301 final, 8 July 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

countries, such as Morocco, are well-situated to act as key suppliers to the EU. Furthermore, imports from resource-rich regions like North America could help to address security of supply concerns.[20]

Today, EU hydrogen demand stands at 7.8 million tons per year (Mt/yr), equivalent to about 10% of global demand. Germany and the Netherlands are the largest consumers, accounting for over a third of EU demand, followed by Poland, Spain, Italy, Belgium, and France, which consume about 0.5 Mt/yr each.[21] According to available projections, as hydrogen use grows across all economic sectors, EU hydrogen demand could reach 76 Mt/yr by 2050.

But while the EU strategy sets clear targets on electrolyzer deployment by 2030, it provides very few details on how the bloc could meet demand – and at what cost – by 2050.

Reference Scenarios

We explain how the EU could meet its overall renewable hydrogen demand through the lenses of three reference scenarios, each focusing on a key strategic variable: energy independence, cost optimization, and energy security.

- **Hydrogen Independence:** the EU prioritizes energy independence to develop an internal, self-sufficient renewable hydrogen market.
- **Regional Imports:** the EU prioritizes cost optimization by complementing the lowest-cost internal production with imports from neighboring export champions (Morocco and Norway) and renewable-rich countries (Iceland and Egypt).
- **Long-distance Imports:** the EU prioritizes energy security and cost optimization by combining long-distance imports from export champions (Australia and the United States) with regional imports and internal production.

20 Pflugmann, F., and De Blasio, N. (2020) "Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World." Harvard Kennedy School's Belfer Center for Science and International Affairs. March 2020. https://www.belfercenter.org/sites/default/files/files/publication/Geopolitical%20and%20Market%20Implications%20of%20Renewable%20Hydrogen.pdf

21 Fuel Cell and Hydrogen Observatory (FCHO) (2020), 'Hydrogen molecule market', FCHO Reports, https://www.fchobservatory.eu/sites/default/files/reports/Chapter_2_Hydrogen_Molecule_Market_070920.pdf

Each scenario analysis consists of three steps. First, overall renewable hydrogen potentials are calculated for each country (based on renewables, freshwater and land availability, infrastructure potential, and competing demand for renewable electricity). Second, each country's production cost curves are computed (based on local renewable electricity and electrolyzers costs). Trade optimizations are then carried out (based on production cost curves and transportation costs).

Our analysis highlights how all three scenarios are viable pathways to meet the projected EU renewable hydrogen demand. Still, the overall market and geopolitical implications are significantly different in terms of the above key strategic variables and in terms of enabling infrastructure investment allocations.

Under the Hydrogen Independence scenario, renewable hydrogen trade between member states would account for almost 70% (52 Mt/yr) of EU demand.[22] From an infrastructure perspective, pipelines from the Iberian Peninsula (Spain, Portugal), the Baltic states (Estonia, Latvia, Lithuania), and Denmark will need to be built across the continent to resource-constrained member states, in combination with imports terminals for shipments from Ireland (Figure 3).

Imports could reduce the cost of meeting demand by up to 12%, thanks to the significantly lower production costs attainable outside the EU. Under the Regional Imports scenario, renewable hydrogen imports to the EU account for as much as 83% (63 Mt/yr) of demand, mainly from neighboring export champions (Morocco, Norway) and renewable-rich countries (Iceland, Egypt). From an infrastructure perspective, regional partners will have to develop internal production at scale, and overall investments in transportation infrastructure will increase by around 40%. At the same time, prioritization purely on cost could result in the EU relying on imports from Morocco for as much as 40% of demand.

22 Taking into consideration only renewable hydrogen potentials, without any cost optimization considerations, needed trades between member states to meet "production gaps" would account for only 30%.

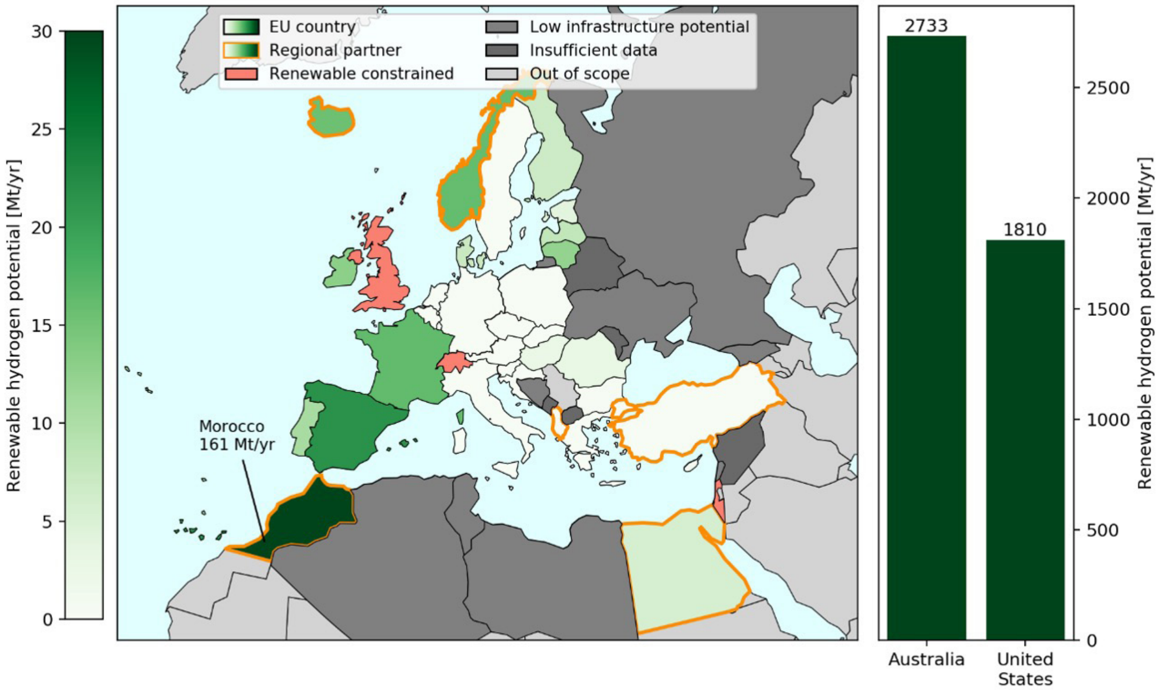

Figure 3. Renewable hydrogen potentials (authors' analysis)

To avoid replicating past patterns of energy dependence and security risk, the EU could diversify supplies by leveraging imports from long-distance export champions without increasing total supply costs. Under the Long Distance Imports scenario, Australian imports are not cost competitive due to the significantly higher transportation costs. At the same time, shipments of renewable hydrogen, as ammonia, from the United States can partly displace imports from Morocco and limit EU dependence on any single producer to 20% of overall demand.

Conclusions and recommendations

In the end, today's policy choices will determine which scenario will unfold, but policymakers need to carefully evaluate alternative requirements and competing needs.

Overall renewable hydrogen adoption at scale in the EU will require policymakers to:

- Lower market risk and remove commercialization barriers to achieve the required economies of scale.
- Define clear policies to stimulate strong renewable energy sources growth, particularly in member states that can become regional exporters.
- Fund innovation and pilot projects to accelerate progress towards cost-competitive renewable hydrogen technologies.
- Coordinate enabling infrastructure development and deployment across the continent.
- Harmonize standards and regulations, including certificates of origin, to ensure renewable hydrogen flows seamlessly across borders.

Implementation of the Regional Imports or Long Distance Imports scenario(s) will also require the definition of:

- Long-term contracts and direct investments to help reduce market risk for producers.
- Transparent regulations and long-term investments in enabling infrastructure to send strong signals to investors in producing nations and trigger production-capacity investments.
- International standards for renewable hydrogen production, transportation, and use.

Renewable hydrogen offers a unique opportunity to accelerate the EU's transition to a low-carbon economy. Still, deployment at scale faces important challenges that neither the private nor the public sectors can address alone. Only by working together can the EU become a global leader in renewable hydrogen innovation and simultaneously contribute to its climate and energy security goals, a stronger economy, and a more integrated union.

6. Hydrogen Deployment at Scale: The Infrastructure Challenge

Nicola De Blasio, Fridolin Pflugmann & Henry Lee

Clean hydrogen is experiencing unprecedented momentum as confidence in its ability to accelerate decarbonization efforts across multiple sectors is rising. New projects are announced almost every week. For example, international developer – Intercontinental Energy – plans to build a plant in Oman that will produce almost 2 million tons of clean hydrogen and 10 million tons of clean ammonia.[23] Dozens of other large-scale projects and several hundred smaller ones are already in the planning stage. Similarly, on the demand side, hydrogen is gaining support from customers. Prominent off-takers such as oil majors like Shell and bp, steelmakers like ThyssenKrupp, and world-leading ammonia producers like Yara are working on making a clean hydrogen economy a reality.

Despite the optimism surrounding clean hydrogen, key uncertainties remain. One of hydrogen's attractions is that it can provide carbon-free energy in multiple sectors – transport, heating, industry, and electricity generation. But this advantage also creates uncertainties. The infrastructure needed in an economy in which hydrogen is primarily used as a transport fuel is very different from one in which its primary value is as a heating fuel. Today no major hydrogen pipeline networks exist,[24] and no liquified hydrogen ships are in commercial operation. There is a true chicken and egg problem. If there is no infrastructure to move hydrogen, will investments in supply and demand happen at the pace needed to meet national decarbonization targets? This challenge raises an even more pressing question: what should be the respective roles of the public and private sectors in deploying enabling infrastructure at scale?

23 The Guardian (2021), "Oman plans to build the world's largest green hydrogen plant" https://www.theguardian.com/world/2021/may/27/oman-plans-to-build-worlds-largest-green-hydrogen-plant, accessed June 2021.

24 Except for limited regional pipeline systems in the United States and Europe owned by merchant producers serving captive markets.

While market economics must be the driving force behind production and demand decisions, regulatory incentives will play a pivotal role in both shaping and deploying enabling infrastructure at scale. Realizing hydrogen's full potential will require careful policy consideration to address competing needs. It is essential to plan for the future now, since the effects of policy choices made today will be felt decades in the future. For example, building a pipeline network to deliver hydrogen to homeowners who have yet to install hydrogen-fueled stoves and heating systems would be financially disastrous. Hence, synchronizing infrastructure investments with growth in supply and demand will be essential but will be very challenging.

An ongoing debate is how hydrogen will be delivered to demand centers, or in other words, what will be the preferred energy carrier. One option would be to generate carbon-free power and transmit it to residential, commercial, and industrial users. The electricity would then be used to produce hydrogen directly onsite. This approach eliminates hydrogen transmission costs at the expense of overburdening power grids already constrained by the need to transport increasing shares of renewable energy. Another option would be to pipe hydrogen directly to customers. While not impacting power grids, this approach requires upgrading existing natural gas pipelines to allow for increasing shares of hydrogen or building new hydrogen dedicated infrastructure.[25] Each of these options would cost billions, and each would face significant risks in the form of uncertain markets, operations, and regulatory regimes.

Countries without existing natural gas networks will need to invest in new hydrogen pipelines or upgrade their power grids. The most viable solution will depend on the required volumes and the geographical distribution of production and demand sites. In extreme synthesis, pipelines are usually the most cost-efficient solution when volumes are large, and many demand centers are located along the pipeline route.

Admittedly, the use of natural gas infrastructure could significantly lower the overall cost of transporting hydrogen, both in terms of reduced

25 Unless new technologies, such as membranes able to separate natural gas from hydrogen, will become available in the near future.

investment in pipeline infrastructure and avoided investment in the expansion of the electricity grid. Still, a careful case-by-case evaluation of the technical and economic feasibility of competing options and of the overall value chains implications of a transition from natural gas to hydrogen will be needed.

In the early stages, hydrogen could be blended at low percentages with natural gas in existing networks, in most cases without the need for any upgrades. However, even this approach comes with challenges and costs due to the regional nature of natural gas systems. While some networks and uses can manage higher hydrogen shares, others can only deal with limited percentages. Furthermore, from a market perspective, countries have different blending limits, significantly hindering cross-border trade opportunities. In later stages, either new infrastructure or the widespread conversion of existing gas networks and end uses (industrial, commercial. and residential) to pure hydrogen would be required.

But herein lies the ultimate challenge of operationally managing the final step in this conversion process. It is a never-addressed point that reiterates the importance of solid policy guidance for a hydrogen economy to fully take off: the conversion to pure hydrogen would require all end uses in the distribution zone – including residential appliances – to be ready almost overnight. How this process should work from an operational point of view is unclear. What is clear, though, is that the public and private sectors will need to coordinate their activities at the planning, financing, and implementation stages.

From a global market perspective, governments will need to proactively synchronize national regulatory regimes so that hydrogen can flow between countries. Within countries, regulators and policymakers will need to address key challenges, such as:

- how to define the regulatory regime, ownership, and sharing of enabling infrastructure
- how to incentivize customers to install new uses, compensate for rendering existing equipment worthless, and handle conflicts of stakeholders not cooperating in the transition
- how to synchronize demand ramp-up, production build-out, and infrastructure availability, especially given that natural gas demand might not decline complementary to hydrogen rise
- how to ensure uninterrupted energy supply to end-users, particularly residential consumers, during the transition process

To stimulate the needed investments from the private sector, policymakers and regulators will need to create a leveled playing field with clear market structures and regulations, recognizing the pros and cons of all alternatives and a concerted effort to synchronize investments in supply, demand, and infrastructure. Only in this way can we avoid replicating the system-wide inefficiencies which characterized regional approaches to the deployment of new energy infrastructure.

7. The Future of Sustainable Mobility: The Role of Clean Hydrogen

Nicola De Blasio, Charles Hua & Alejandro Nunez-Jimenez

The transportation sector is the second-largest source of CO_2 emissions, after electricity and heat generation, accounting for about 25% of global emissions.[26] However, it is also one of the most challenging to decarbonize due to its distributed nature and the advantages of fossil fuels in terms of high energy densities, ease of transportation, and storage. Moreover, the degree of difficulty in decarbonizing varies significantly across the sector, making the challenge even more daunting.

So far, emissions reduction strategies have focused on improving vehicle and system-wide efficiencies, mode switching, and electrification. The latter is proving relatively easy for smaller vehicles that travel shorter distances and carry lighter loads. However, sector-wide decarbonization pathways will require a transition to low-carbon fuels and the deployment of enabling infrastructure to support innovation at scale.

Renewable hydrogen holds promise in sustainable mobility applications, whether by powering fuel-cell electric vehicles (FCEVs) like cars, trucks, and trains or as a feedstock for synthetic fuels for ships and airplanes. Fuel cells convert hydrogen-rich fuels into electricity through a chemical reaction. FCEVs use a fuel cell, rather than a battery, to power electric motors, and operate near-silently and produce no tailpipe emissions.

Hydrogen-powered vehicles offer key advantages, including shorter refueling times, longer ranges, and a lower material footprint compared to lithium battery-powered alternatives. However, high costs of ownership and a lack of enabling infrastructure are key challenges that must be addressed through policy support, technological innovation, and financial investment.

26 IEA (2021), "Data and statistics" https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=CO2%20emissions&indicator=CO2BySector, accessed May 2021.

Hydrogen can complement existing efforts to electrify road and rail transportation and provide a scalable option for decarbonizing shipping and aviation. Figure 1 summarizes the mobility segments for which battery electric vehicles (BEVs), FCEVs, and vehicles running on bio-or hydrogen-based synthetic fuels are most applicable.

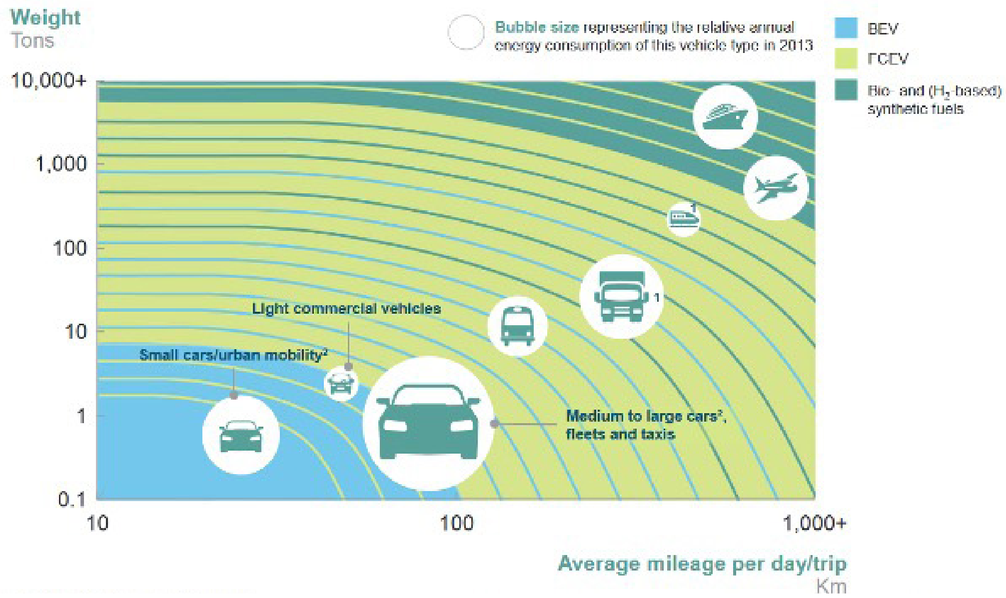

Figure 4. Hydrogen applications in the mobility sector. Source: Hydrogen Council (2017)

Road Transportation

Motor vehicles account for about 20% of global CO_2 emissions from energy and 75% of transportation-specific emissions.[27] Renewable hydrogen competitiveness will depend on overall costs of ownership and the availability of refueling infrastructure. Short refueling times, lower added weight for stored energy, and zero tailpipe emissions are key advantages. Fuel cells also show promise thanks to their lower material footprint compared to lithium batteries. Long-distance and heavy-duty vehicles offer the greatest potential, but investments are required to lower the delivered price of hydrogen. Captive fleets, such as taxis, buses, and trucks, can help overcome the challenges of low utilization of refueling stations and spearhead the adoption of hydrogen.

Rail

Rail is one of the most energy-efficient and clean transport modes. Trains carry 9% of global motorized passengers and 7% of freight but account for only 3% of energy demand and 1% of CO_2 emissions for the overall transportation sector.[28] Renewable hydrogen-powered trains could be most competitive in rail freight and rural/regional lines where long distances and low network utilization do not justify the high costs associated with track electrification. Hydrogen trains also hold promise due to flexible bi-mode operations, allowing them to run on electrified and conventional lines alike. However, innovation in compressing and storing hydrogen will be needed to improve economics and scalability.

27 IEA (2019), "Transport sector CO_2 emissions by mode in the Sustainable Development Scenario, 2000-2030" https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030, accessed May 2021.

28 Ibid.

Shipping

Despite being one of the most efficient forms of freight transport, shipping remains a challenge for decarbonization efforts. The sector accounts for about 3% of global and 11% of transportation related CO_2 emissions and has an industry goal of reducing emissions by 50% by 2050 from 2008 levels.[29] Renewable hydrogen and ammonia can overcome the limitations of battery ships. However, high costs compared to fossil fuels, the challenge of cargo volume loss due to fuel storage (in terms of energy content parity, while batteries require 64 times more volume than marine diesel oil, hydrogen and ammonia only require 8 and 3 times more, respectively)[30], and the deployment of global refueling networks need to be addressed.

Aviation

In 2019, aviation accounted for around 3% of global energy-related CO_2 emissions and 12% of transportation sector emissions.[31] Compared to road transportation, this seemingly small number should not be dismissed, though, since the overall contribution to global warming is significantly higher due to emissions other than CO_2, like nitrogen oxides and soot. Although the pandemic has caused the most extensive retrenchment in aviation history, it also provides a unique opportunity for the sector to restructure itself towards a low-carbon future. Drop-in synthetic liquid fuels provide an attractive decarbonization option at the expense of higher energy consumption and potentially higher costs. Direct hydrogen use also shows promise, but the sector will need to borrow technologies developed for the automotive and space industries and apply them to commercial aircraft operations while achieving similar or better safety targets. Due to the very long aircraft development and certification lead times, these challenges demand urgent answers from both industry leaders and policymakers.

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29 International Maritime Organization (2018), "UN body adopts climate change strategy for shipping" https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx, accessed May 2021.

30 ETH Zurich (2019), "Towards Net-Zero: Innovating for a Carbon-Free Future of Shipping in the North and Baltic Sea" https://fe8dce75-4c2a-415b-bfe4-e52bf945c03f.filesusr.com/ugd/0a94a7_0980799eb-ca344158b897f9040872d36.pdf, accessed May 2021.

31 Air Transport Action Group, https://www.atag.org/, accessed June 2021.

Conclusions

Before renewable hydrogen can truly become a game-changer in the transportation sector, significant barriers, mainly related to storage, infrastructure, and costs, will need to be addressed.

From an innovation perspective, it will be crucial to reduce costs and improve performance. Technological challenges around weight and hydrogen storage need solutions, particularly in the maritime and aviation sectors.

From a policy perspective, renewable hydrogen adoption at scale will require governments to:

- Establish a role for hydrogen in long-term domestic and international energy strategies, considering geopolitical and market implications.
- Implement policy support in the form of low-carbon targets and carbon pricing measures to stimulate commercial demand for clean hydrogen.
- Address investment risks, especially for first movers, such as targeted and time-limited loans and guarantees.
- Focus on new hydrogen applications, clean hydrogen supply, and infrastructure projects.
- Support research and development efforts and public-private partnerships to accelerate innovation cycles.
- Harmonize standards and eliminate unnecessary regulatory barriers while developing certification systems and regulations for carbon-free hydrogen supply.

To date, technological factors, economic considerations, and consumer choices have hindered the adoption of hydrogen at scale in the transportation sector. New geopolitical forces such as the challenges of sustainable development and climate change are reshaping the playing field. Stakeholders around the world must decide their role in the transition to a decarbonized transportation sector.

This chapter is based on the paper "The Role of Clean Hydrogen for a Sustainable Mobility"" published by the Italian Institute for International Political Studies (ISPI) and McKinsey in July 2021 as part of the report "The Global Quest for Sustainability – The Role of Green Infrastructure in a Post-Pandemic World."

8. The Role of Blockchain in Renewable Hydrogen Value Chains

Nicola De Blasio & Charles Hua

A rainbow of colors currently dominates almost every conversation on the transition to a low-carbon economy: green, grey, blue, turquoise, pink, yellow[32] – an ever-increasing palette to describe the same colorless, odorless, and highly combustible molecule, hydrogen. The only difference is the chemical process used to produce it.

The colors of hydrogen are crucial for the energy transition because each production pathway generates different amounts of greenhouse gas emissions. For example, while grey hydrogen, produced from fossil fuels, yields up to 20 tons of carbon dioxide per ton of hydrogen, green hydrogen, produced from renewable energy sources like solar and wind, yields no emissions. Furthermore, although these colors all refer to the same molecule, production costs differ: green hydrogen remains substantially more costly today.

With aggressive development and deployment of electrolyzers and other hydrogen technologies at scale, green hydrogen could become cost-competitive with blue hydrogen, produced from natural gas with carbon capture, by 2030 in many countries.[33] Overall, the rate at which green hydrogen costs decrease will also depend on government policies and incentives, such as carbon pricing and tax credits.

Therein lies a critical challenge for the successful transition to a low-carbon economy. As energy systems increasingly evolve from centralized to decentralized, from "grey" to "green," stakeholders will need to efficiently account for and track emissions and green molecules in a transparent,

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32 The colors of hydrogen correspond to different production pathways. Green hydrogen is produced from renewable energy by water electrolysis, grey from fossil fuels, blue from natural gas with carbon capture and sequestration (CCS), turquoise from natural gas pyrolysis, pink from nuclear, and yellow from solar.

33 IRENA (2020), "Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal" International Renewable Energy Agency, Abu Dhabi.

secure, and standardized way, and must be able to do so along value chains from production to consumption.

Tracking emissions and green molecules along value chains

Stakeholders must be appropriately credited for investing in the current premium required to produce carbon-free hydrogen. Therefore, the ability to verify a hydrogen molecule's origin from clean energy sources amidst a dynamic energy landscape presents both a sizable challenge and a tremendous opportunity. Addressing this dilemma will require managing large volumes of multi-party transactions, which need to be settled quickly, securely, and inexpensively.

Today, the origin of a commodity is certified through certificates of origin. However, the certification process can be complex, requiring many intermediaries that add time, labor, and cost burdens. Furthermore, concerns over whether commodities are accurately counted and traded pose challenges to scalability. Innovative technologies like blockchain could significantly simplify carbon accounting and green certification processes.

A blockchain is a shared, decentralized, and immutable digital ledger that securely stores transactions and enables the automated execution of "smart contracts"[34] among parties without a central authority or intermediaries.[35] At its core, the technology consists of a distributed network of independent computers, or nodes, that manages the blockchain; the nodes receive new transactions, review their legitimacy based on consensus protocols, and integrate them into a chain.

Blockchain technology is already demonstrating its innovation potential in the financial sector, thanks to its unique structural advantages of trust, efficiency, control, and security. These properties make blockchain well-suited to optimize processes, enable novel business solutions,

34 Smart contracts are programs stored on a blockchain that run when predetermined conditions are met. They are typically used to automate the execution of an agreement so that all participants can be immediately certain of the outcome, without any intermediary's involvement or time loss. They can also automate a workflow, triggering the next action when specific conditions are met.

35 Swan, M. (2015), "Blockchain: Blueprint for a new economy" O'Reilly Media Inc.

and promote greater access to services for a broader range of users by significantly reducing costs. However, significant challenges need to be addressed to foster adoption, such as interoperability between blockchain networks, trust among users, and energy consumption.

Many trends driving profound changes in the energy sector can also benefit from and further unlock blockchain's full potential. Pilot applications are emerging in many developed and developing countries. For example, US-based Brooklyn Microgrid runs a community energy market within a microgrid[36] where members can buy and sell energy from each other using smart contracts on a blockchain.[37]

Overall, the increased adoption of distributed generation, energy storage, and smart devices, together with the need to track emissions and green molecules along value chains, creates new complexities and challenges for energy markets designed for centralized control. Indeed, blockchain technology can help policymakers and regulators address concerns over measurement, certification, and tracking.

Conclusions and Policy Recommendations

As technology and policy pathways to decarbonization will need to rely on processes that accurately measure and record emissions and green molecules across global markets characterized by limited transparency, uneven standards, different regulatory regimes, and trust issues, blockchain can greatly accelerate the transition to a low-carbon economy. But significant barriers to adoption remain, including policy, regulatory, and technological hurdles.

Due to the substantial public and national security interests ingrained in the energy sector, policymakers and regulators will need to fully assess all opportunities and challenges, including the integrity of information on a blockchain, rules of access, transparency issues, and privacy requirements.

36 A small network of electricity users with local sources of supply that is usually attached to a centralized national grid but is also able to function independently.

37 Brooklyn Microgrid, https://www.brooklyn.energy/, accessed October 2021.

Furthermore, blockchain's full potential will not be realized until a critical mass of users embraces the technology.

Going forward, adoption at scale will require a concerted approach to:

- Convene stakeholders across the value chain and foster collaboration in addressing first-mover risks, strategic barriers, and opportunities.
- Educate stakeholders about blockchain technology and its value proposition, as many still have limited understanding or misconceptions about its true potential (for example, conflating the concepts of blockchain and cryptocurrency). Address stakeholder concerns associated with transparency of transactions and cybersecurity risks.
- Develop a stable regulatory framework for users and adopters and structured markets and incentives to support key players, particularly utilities, in adopting blockchain and investing in digital infrastructure.
- Identify design principles, best practices, and standards for robust blockchain platforms that achieve shared agreement among key stakeholders (including mandating reasonable energy consumption levels associated with blockchain adoption).
- Support research and development efforts and pursue pilot and demonstration projects.

As governments and corporations increasingly prioritize green hydrogen in the energy transition, and as new policy, business, and regulatory models for a rapidly changing energy sector are developed, blockchain is poised to play a prominent role in supporting these strategies. If blockchain succeeds in disrupting the energy industry, stakeholders throughout the energy value chain will reap substantial benefits for years to come.

9. Conclusions and Recommendations

Clean hydrogen could play a significant role in the global transition to a low carbon economy, particularly for hard-to-abate sectors. It offers a path toward meeting national and international climate and pollution goals while avoiding reliance on imported fuels. It can help to address renewable energy intermittency and curtailment issues. And it can open new avenues for developing clean technology manufactured goods[38] for both internal and export markets, thus providing substantial additional benefits to local economies.

At the same time, key challenges to adoption and use at scale need to be addressed, including higher production costs compared to fossil fuel-based hydrogen and the limited infrastructure availability. One of clean hydrogen's main attractions is that it can provide carbon-free energy in multiple sectors – transport, heating, industry, and electricity generation. But this advantage also creates uncertainties. What future hydrogen value chains will develop is a function of the specific application being pursued. For example, as discussed, the infrastructure needed in an economy in which hydrogen is primarily used as a transport fuel is very different from one in which its primary use is as a heating fuel. Public concerns around safety might also present additional challenges to deployment.

From a geopolitical perspective, renewables are often perceived as an opportunity to reduce the hegemony of fossil fuel-rich states and democratize the energy landscape. Virtually all countries have access to some renewable energy resources and could therefore substitute foreign supplies with local resources. Our research shows, however, that the role countries are likely to assume in decarbonized energy systems will be based not only on their resource endowment but also on their policy choices. Since the production of renewable hydrogen through electrolysis requires both renewable energy and freshwater resources, we consider three

38 Clean technology manufacturing aims at minimizing the energy and environmental impacts of the production, use, and disposal of goods, ranging from commodities such as metals and chemicals to final-use products such as airplanes and wind turbine blades, through the use of clean energy and the development of new materials and process technologies.

parameters in analyzing a country's renewable hydrogen potential: (1) renewable energy resource endowment; (2) renewable freshwater resource endowment; and (3) infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation, and distribution infrastructure.[39] On the basis of these variables, countries can be grouped into five archetypes: export champions, water constrained producers, major importers, self-sufficient producers or regional exporters, and infrastructure constrained producers. These archetypes allow us to draw the global renewable hydrogen map (see Figure 1) and help elucidate the geopolitical implications of renewable hydrogen adoption at scale. From a global market perspective, clean hydrogen, if adopted at scale (like natural gas), will initially flourish in regional markets with the corresponding potential for geopolitical conflicts.

Our analysis of China, for example, shows that the country still has a long way to go before a hydrogen society could reach fruition, but if China were to replicate the success it has had with other clean technologies like solar PV, and at the same time address its regional water scarcity issues it could significantly lower production costs and accelerate adoption around the world, while emerging as a renewable hydrogen superpower.

Looking at specific applications, our research on the future of sustainable mobility shows how hydrogen can complement existing efforts to electrify road and rail transportation, especially for long-distance and heavy-duty sectors, and provide a scalable option for decarbonizing shipping and aviation. Figure 4 summarizes the sectors for which battery electric vehicles, fuel cell electric vehicles, and vehicles running on bio-or hydrogen-based synthetic fuels are most applicable. From an innovation perspective, technological challenges around weight and hydrogen storage will need solutions, especially for the maritime and aviation sectors.

39 It should be noted that the evaluation of a country's infrastructure potential includes considerations on financial variables (e.g., access to capital markets, credit rating, cost of capital) and political stability. The lack of these enabling factors would significantly hamper a country's ability to develop infrastructure even today; hence, they are indirectly accounted for in our evaluation.

Finally, from a value chain perspective, blockchain can greatly accelerate the transition to a low-carbon economy as technology and policy pathways to decarbonization will need to rely on processes that accurately measure and record emissions and green molecules across global markets characterized by limited transparency, uneven standards, different regulatory regimes, and trust issues. Addressing these challenges will require managing large volumes of multi-party transactions, which need to be settled quickly, securely, and inexpensively – processes that can aided significantly by blockchain.

Taking full advantage of clean hydrogen's potential will require a coordinated effort between the public and private sectors focused on scaling technologies, reducing costs, deploying enabling infrastructure, and defining appropriate policies and market structures. This is the only way to avoid replicating the system-wide inefficiencies of the past that have characterized regional approaches to deploying new energy infrastructure.

To accelerate the global transition to a low-carbon economy and clean hydrogen adoption at scale, we recommend the following set of actions:

- The G20 should institute a "Technology 20" official engagement group that brings together leading global stakeholders from the private and public sectors across entire value chains to serve as a technology sandbox and provide technology and policy recommendations to accelerate innovation cycles. The case of hydrogen highlights how adopting new clean technologies can offer unique opportunities to accelerate the transition to a low-carbon economy. Still, deployment at scale faces significant challenges that neither the private nor the public sectors can address alone.
- Governments pursuing clean hydrogen should increase investments in innovation, convene stakeholders across value chains, and foster collaboration in addressing first-mover risks, strategic barriers, and opportunities.

- Countries and regions that wish to adopt clean hydrogen at scale should prioritize detailed analysis and planning now, since the effects of policy choices made today will be felt decades in the future. As our research highlights, nations will need to carefully consider their role in future clean hydrogen markets from a geopolitical and market perspective. It will also be critical to identify infrastructure bottlenecks and address financial gaps in specific markets and applications. For example, building a pipeline network to deliver hydrogen to homeowners who have yet to install hydrogen-fueled stoves and heating systems would be financially disastrous. Hence, synchronizing infrastructure investments with growth in supply and demand will be essential but challenging.
- Addressing the price gap between clean and fossil fuels-based hydrogen will require active policy interventions. Such policies could include measures to incentivize the value and use of clean hydrogen, such as implementing clean hydrogen standards and carbon pricing.
- Stakeholders must be appropriately credited for investing in the current premium required to produce carbon-free hydrogen. This will require concerted efforts to identify design principles, best practices, and standards for robust blockchain platforms that achieve shared agreement among key stakeholders (including mandating clean blockchains) and to educate stakeholders about blockchain technology and its value proposition.
- Countries and regions should implement market-aligning policies, along with production and safety standards, to accelerate clean hydrogen adoption and enable transnational trade.

Stakeholders need to thoroughly assess clean hydrogen's economic, environmental, and geopolitical implications, develop strategies to address them, and define long-term implementation plans. It is essential to do so now.

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