August 9, 2022
Chairman Ryan Bizzarro
PA House Democratic Policy Committee

Submitted via email to jseip@pahouse.net

Re: Comments on the House Democratic Policy Committee Hearing: Developing a Hydrogen Hub

---

Clean Air Task Force (CATF) welcomes the opportunity to provide comments to the Pennsylvania (PA) House Democratic Policy Committee regarding the development of a hydrogen hub in Western PA.

CATF is a global nonprofit organization working to safeguard against the worst impacts of climate change by catalyzing the rapid development and deployment of low-carbon energy and other climate-protecting technologies. With 25 years of internationally recognized expertise on climate policy and a fierce commitment to exploring all potential solutions, CATF is a pragmatic, non-ideological advocacy group with the bold ideas needed to address climate change. CATF has offices in Boston, Washington D.C., and Brussels, with staff working virtually around the world.

CATF's global carbon management and zero-carbon fuels teams consist of technology and policy analysts with expertise on carbon dioxide capture, transport, removal, and storage, zero-carbon fuels production and use, and lawyers familiar with federal and state regulation of these activities. The team's expertise stems from regular contact with carbon management and zero-carbon fuels project developers, investors, innovators, regulators, policy advocates and modelers. CATF specializes in analyzing the effect of various regulatory and policy options, in order to discern the most cost- and climate-effective means to scale up key technologies like carbon capture, transport, removal, and carbon storage, in addition to hydrogen, to achieve midcentury decarbonization goals.

I. Introduction

Pennsylvania has an opportunity to be a first-mover in developing an end-to-end decarbonization hub that links hydrogen, carbon capture and storage, renewables, and other clean energy infrastructure. Pennsylvania's path to economy-wide decarbonization will require a strategy for deploying a broad suite of clean energy and carbon mitigation technologies to achieve deep decarbonization and public health goals at least cost.[1] Low-emissions hydrogen (i.e., hydrogen produced using methods with significant lifecycle greenhouse gas emissions reductions compared to conventional hydrogen production, also referred to as "clean hydrogen") will play a critical role in affordably achieving economy-wide decarbonization in Pennsylvania by midcentury while meeting the Appalachian region's energy needs. While electrification and buildout of zero-emissions electricity can and will decarbonize much of the economy, more than 80% of final energy use in the U.S. comes from fuels. Some hard-to-abate sectors (e.g., heavy-duty transportation and ironmaking) will require zero-carbon fuels, namely hydrogen and ammonia, to reach full decarbonization. Carbon capture will play an important role in the Commonwealth for generating zero-carbon fuels and mitigating point source emissions from hard-to-abate industrial facilities (e.g., cement production).

As is being discussed in this hearing, a clean hydrogen hub could be developed in western PA that contributes to decarbonizing the Appalachian region. Clean hydrogen hubs are regional networks consisting of the production, end-use, and connective infrastructure needed to produce, transport, store, and use clean hydrogen in a functional regional market.[2] An abundance of natural gas, the high density of industrial fuel use, and some associated infrastructure already in place in Western PA make it potentially well-suited for a clean hydrogen hub.

II. What Makes for a Good Clean Hydrogen Hub?

Pennsylvania has an important opportunity to support the development of a state-of-the-art clean hydrogen hub. A robust strategy will be required to ensure the effective and equitable deployment of hydrogen and the related infrastructure. CATF recommends that government leaders, hub developers, and other stakeholders (in any region considering hydrogen hub development) take the steps below to ensure that hydrogen hub development is clean, equitable, and sustainable.[3]

---

[1] https://www.vibrantcleanenergy.com/wp-content/uploads/2021/10/US-Econ-Decarb_CCSA.pdf See also: Net Zero America Project Report (https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf) and Decarb America "Pathways to Net-Zero Emissions (https://decarbamerica.org/report/pathways-to-net-zero-emissions/)

[2] See the Department of Energy's Regional Clean Hydrogen Hubs program for more information: https://www.energy.gov/bil/regional-clean-hydrogen-hubs.

[3] See CATF "What makes for a good clean hydrogen hub" (https://www.catf.us/2022/06/what-makes-good-clean-hydrogen-hub/).

1) Minimize the greenhouse gas intensity of hydrogen production to the greatest extent practicable, regardless of how the hydrogen is produced. For example, hydrogen producers that use natural gas with carbon capture must source natural gas from producers with strong systems in place for detecting and eliminating methane venting, flaring, and leakage from gas production and transport infrastructure, maximize carbon capture and storage rates, and minimize CO_2 emissions from the production process or use of grid electricity.

2) Maximize climate impact with end-use sectors that are most likely to need hydrogen to decarbonize. A well-functioning hydrogen hub is likely to need multiple long-term off-takers (i.e., consumers), ideally coming from sectors like heavy transportation, heavy industry, or the power sector (for providing long-term storage as load-balancing) which will need zero-carbon fuels to fully decarbonize.

3) Commit to meaningful community engagement and a focus on environmental justice and a just transition, including instituting structures and avenues for meaningful community engagement, creating local and sustained jobs that meet prevailing wages and support local workforce development, and conducting and reporting on comprehensive community environmental health assessments.

4) Deliver near-term environmental benefits for the communities living in the hydrogen hub region by ensuring that projects deliver benefits across multiple environmental indicators, which will benefit both the environment and public health. For example, hydrogen hubs can prioritize transitioning medium- or heavy-duty diesel trucks to hydrogen fuel cell electric vehicle trucks to directly improve local air quality.

III. Carbon Capture and Storage Opportunities and Challenges

Carbon capture and storage is a diverse suite of technologies to capture, transport, and permanently store carbon dioxide that would otherwise be emitted to the atmosphere by industrial facilities. Carbon capture and storage will play an integral role in the development of a hydrogen hub in Pennsylvania by providing a means to produce blue hydrogen and to decarbonize point source emissions from hard-to-abate industrial facilities. While not all industrial facilities are well-suited for carbon capture, 57 facilities in Pennsylvania have CO_2 emissions above the current Internal Revenue Service (IRS) threshold for receiving 45Q tax credits, totaling nearly 90 million metric tons per year of CO_2 that can receive a tax credit for being permanently sequestered.

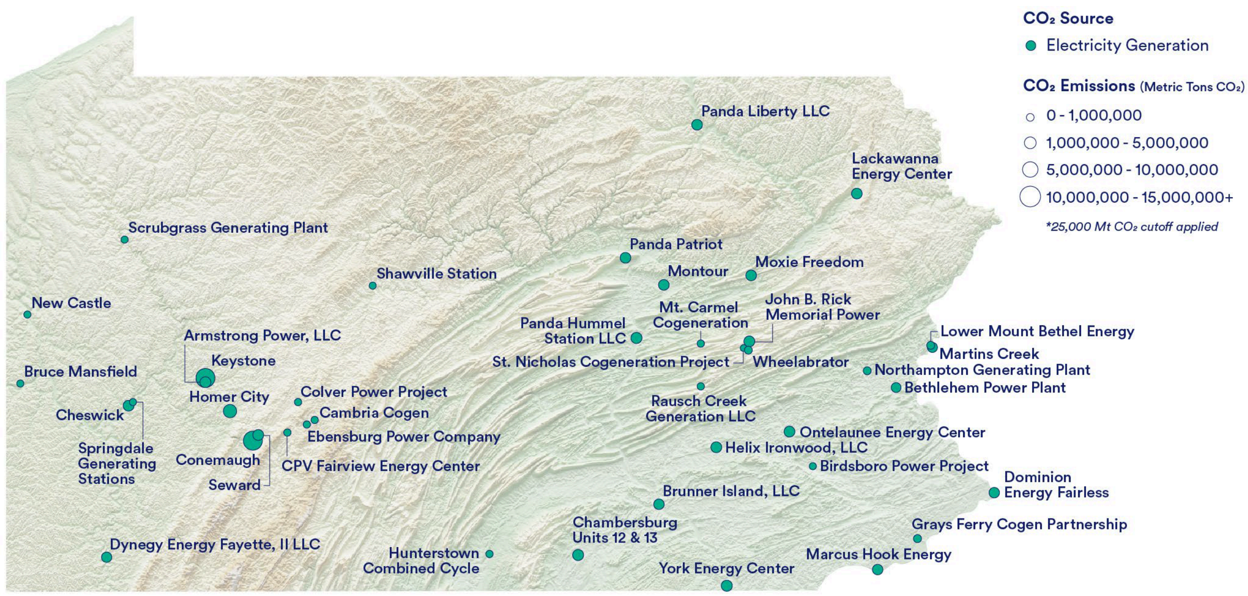


Figure 1: Pennsylvania emissions sources with CO_2 emissions above 500,000 metric tons per year, which is above the IRS threshold for receiving a 45Q tax credit: Electricity generation.

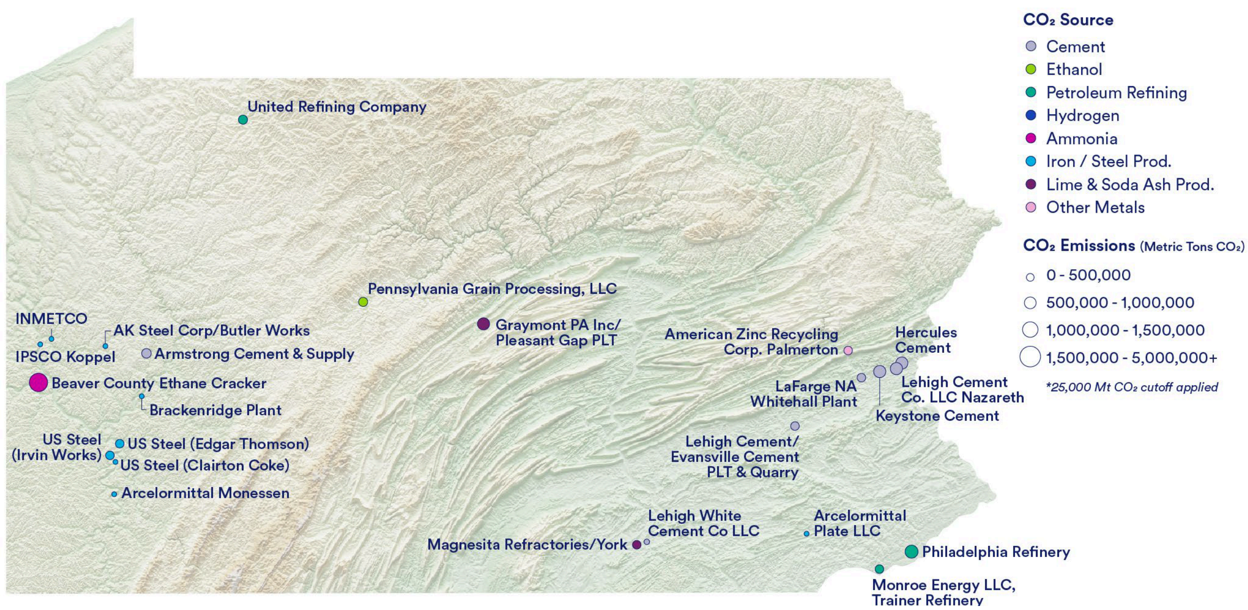


Figure 2: Pennsylvania emissions sources with CO_2 emissions above 100,000 metric tons per year, which is above the IRS threshold for receiving a 45Q tax credit: Other industrial facilities

With the need for carbon capture comes the need for geologic storage. In a typical carbon capture and storage system, carbon is captured at the point of emission, transported to a storage site, and injected deep underground for permanent storage. Fortunately, much of PA is situated in the Appalachian Basin, which hosts many deep sedimentary rocks that could be suitable for geologic carbon storage. Most of the geologic storage potential in the Commonwealth is in the western and northern portions of the state. The uneven distribution of geologic storage potential in PA means that in many cases, CO_2 pipelines will likely be required to transport CO_2 from where it is captured to where it can be stored. Additional storage opportunities may exist in adjacent states like Ohio and West Virginia, suggesting that regional state coordination may be beneficial.

Figure 3: Stylized relationship between CO_2 emission sources and potential storage capacity for the Lockport and Knox geologic formations combined.

While high-level estimates by the Department of Energy's (DOE) National Energy & Technology Laboratory (NETL) suggest enormous storage potential in Pennsylvania (over 17 billion metric tons)[4], the realistic commercial-scale storage potential is likely smaller. Pennsylvania's commercial-scale storage potential must be verified to support carbon capture and sequestration deployment. Despite the long history of oil and gas production in the Commonwealth, subsurface data required for a commercial carbon storage capacity assessment is not yet readily or publicly available for deep saline formations.

This can and must be remedied with additional geologic characterization work across Pennsylvania. To accelerate carbon capture and storage deployment, Pennsylvania lawmakers should consider directing funds toward geologic characterization efforts, which may include drilling exploratory characterization wells. Identifying and verifying storage sites capable of storing commercial-scale quantities of CO_2 is critical for advancing the development of a clean hydrogen hub in the region.

IV. Policy Needs to Advance Hub Development

Supportive state policy and regulatory frameworks for a clean hydrogen hub with associated carbon capture are crucial for advancing a hydrogen hub in Pennsylvania. Developing a clean hydrogen hub requires significant coordination between state agencies, permitting authorities, industry, and communities.

Policy priorities for developing a clean hydrogen hub include:

- Production and/or investment tax credits to support deployment of low-emissions hydrogen at the state-level;
- Further research on potential regulatory tools or frameworks for transportation and storage of hydrogen, particularly for hydrogen pipelines;
- Further research and development on best practices for minimizing hydrogen leakage throughout the hydrogen value chain (i.e., all the way from hydrogen production through transportation, storage, and eventual end-use systems), both to ensure safety and to minimize any climate impacts of leaked hydrogen;
- State-level financial support for development of new hydrogen end-use sectors (e.g., contracts for differences, state funding to match federal hubs funding, or other policy tools to defray the cost differentials between low-emissions hydrogen and incumbent fuels); and

---

[4] https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf

- Public sector support for environmental justice, equity, and just transition efforts to ensure that communities are meaningfully involved in the process and that the benefits are directed towards the local economy and workforce.

Policy and regulatory priorities for carbon capture and storage include:

- Considering whether there would be benefits to applying to the Environmental Protection Agency (EPA) for primary enforcement authority (i.e., primacy for Class VI wells under EPA's Underground Injection Control program) in collaboration with communities and stakeholders;
- Geologic characterization efforts;
- Pore space ownership clarification;
- CO_2 pipeline regulations;
- Considering establishing state carbon emission standards for industrial sources, including power plants and hydrogen production, based on the availability of carbon capture and sequestration; and
- Public outreach and engagement.

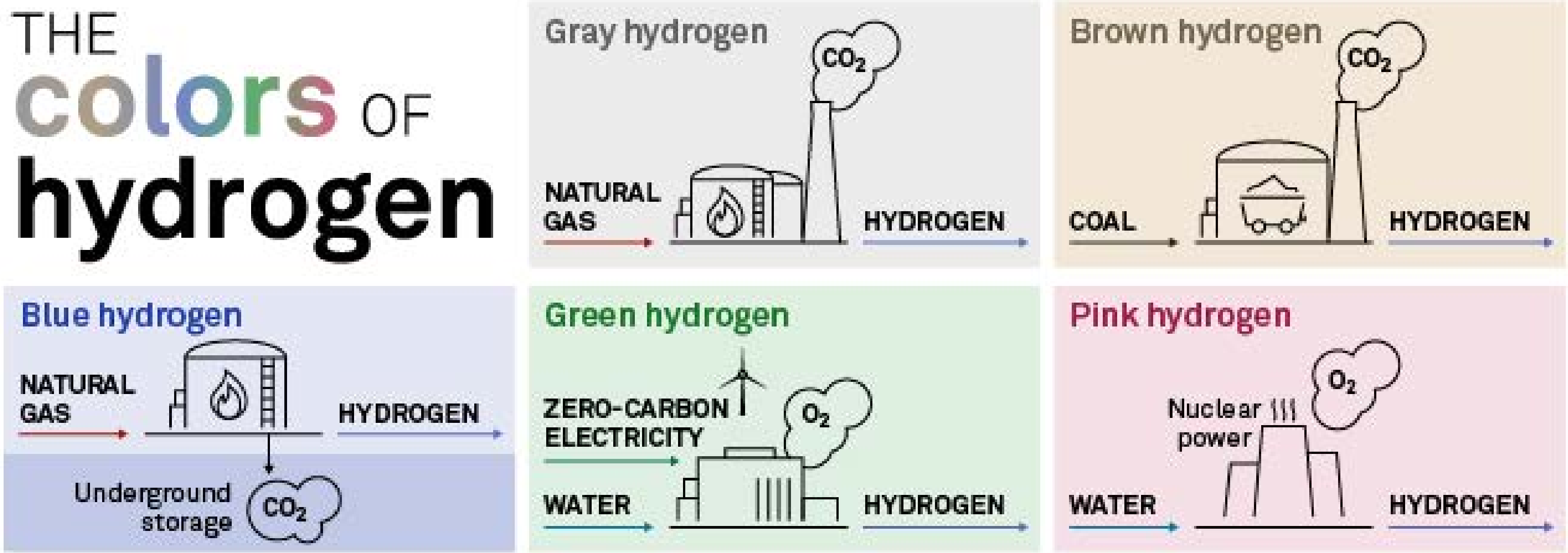
Pennsylvania is well-positioned to be a potential first-mover in developing a regional clean hydrogen hub. Successful hub development will require a well-coordinated strategy and supportive state policy and regulatory frameworks to ensure that the hydrogen hub is beneficial to both climate and public health and that it is equitable. We encourage Pennsylvania to be visionary and bold.

Respectfully submitted,

Clean Air Task Force

Contact

If you would like to connect with CATF directly, please reach out to CATF's U.S. State Policy and Advocacy Manager, Angela Seligman, by email: aseligman@catf.us or phone: 314.922.5293.



As of July 26, 2022.
Design credit: Cat VanVliet
Source: S&P Global Commodity Insights

WORLD ENERGY COUNCIL

WORLD ENERGY INSIGHTS: WORKING PAPER

REGIONAL INSIGHTS INTO LOW-CARBON HYDROGEN SCALE UP

In collaboration with PwC and EPRI

ABOUT

WORLD ENERGY COUNCIL

The World Energy Council has been at the heart of global, regional and national energy debates for nearly a century, developing new thinking and driving effective action around the world to achieve the benefits of sustainable energy for all.

Comprised of over 3,000 member organisations in nearly 90 countries, drawn from governments, private and state corporations, academia and new and wider system shapers stakeholders, the Council is the world's first and only truly global member-based energy network.

The Council works dynamically across the whole energy sector as a global energy transitions platform, pulling together intelligent leadership to catalyse and inform the world's energy policy dialogue, create impact and drive practical action.

The Council does not advocate for any country, company, technology or source of energy. The World Energy Council remains thoroughly committed to the challenge of being both impartial and impactful.

To learn more visit www.worldenergy.org
Published by the World Energy Council April 2022

World Energy Council
Registered in England and Wales No. 4184478
VAT Reg. No. GB 123 3802 48

Registered Office
62–64 Cornhill
London EC3V 3NH
United Kingdom

THE WORLD ENERGY INSIGHTS

These World Energy Insights on hydrogen are part of a series of publications by the World Energy Council focused on Innovation. They were developed in collaboration with the Electric Power Research Institute (EPRI) and PwC.

EPRI and Gas Technology Institute (GTI) have created the Low-Carbon Resources Initiative (LCRI) to address the challenges and gaps in achieving deep carbon reductions across the energy economy. LCRI is focused on the value chain of alternative energy carriers and low-carbon fuels—such as hydrogen, ammonia, biofuels (including renewable natural gas), and synthetic fuels—and research, development, and demonstration to enable their production, storage, delivery, and use across the energy economy. These energy carriers/fuels are needed to enable affordable pathways to economy-wide decarbonization by mid-century. This five-year, global collaborative will identify and accelerate fundamental development of promising technologies; demonstrate and assess the performance of key technologies and processes, identifying pathways to possible improvements; and inform key stakeholders and the public about technology options and potential pathways to a low-carbon future.

PwC is a network of firms in 155 countries with over 284,000 people committed to delivering quality in assurance, advisory and tax services, including more than 20,000 professionals engaged in the energy, utilities and resources sectors. With its global strategy, The New Equation, PwC is responding to the challenges shaping the world today, with a focus on building trust and delivering sustained outcomes that create value for organisations, their stakeholders and broader society. Climate change is one of the world's most pressing problems, and PwC has committed to reach net zero greenhouse gas emissions by 2030 and is working with organisations to accelerate their own climate-based transformation. PwC and the World Energy Council have a common goal of promoting energy transition and sustainability by engaging with policymakers and leading industry players. Our shared view is that energy transition and sustainability are achieved through the interaction of robust policy frameworks and a strong, competitive energy industry. Learn more about PwC

In a fast-paced era of disruptive changes, these insights aim to facilitate strategic sharing of knowledge between the Council's members and the other energy stakeholders and policy shapers and contribute to a global dialogue on hydrogen's role in energy transitions. These insights build upon earlier work by the Council, notably the release of the "Hydrogen on the Horizon" series in July and September 2021, and involved regional in-depth conversations with 180+ high-level experts from 67 countries, reflecting 82% of the global Total Primary Energy Supply – TPES (2019 data, U.S. EIA) and 89% of global GDP (2020 data, WB).

The analysis and forecasts available in this publication and any associated references do not reflect the military conflict occurring in Ukraine. Although we acknowledge that the situation in Ukraine and the resulting disruptions in energy markets will greatly affect the future of low-carbon hydrogen, this release is based on analysis prior to the February 2022 events.

PAGES

TABLE OF CONTENTS

EXECUTIVE SUMMARY 04

INTRODUCTION 13

INSIGHTS ON HYDROGEN SUPPLY CHAINS DEVELOPMENT 14

Low-carbon hydrogen: a global commodity in the future?

Low-carbon hydrogen price developments

REGIONAL INSIGHTS 19

Context
Africa
Asia-Pacific
Europe
Latin America and the Caribbean
Middle East & Gulf States
North America

ENABLERS FOR LOW-CARBON HYDROGEN MARKET RAMP-UP 34

ANNEX 1: REGIONAL DASHBOARDS 39

Africa
Asia-Pacific
Europe
Latin America and the Caribbean
Middle East & Gulf States
North America

ANNEX 2: LIST OF LOW-CARBON HYDROGEN VALLEYS 51

REFERENCES 53

ACKNOWLEDGMENT 54

EXECUTIVE SUMMARY

TAKEAWAYS

- Low-carbon hydrogen can play a significant role by 2040 across the world, to support countries' efforts to achieve the Paris Agreement goals whilst contributing to the diversity and security of their energy portfolios. This would require significant global trade flows of hydrogen and hydrogen-based fuels.

- The momentum is continuing to grow worldwide, but differences are seen between regions – based on differing market activities and opportunities.

- Moving from "whether" to "how" to develop low-carbon hydrogen highlights significant uncertainties, which need to be addressed if hydrogen is to reach its full potential. Can the challenges in various supply chain options be overcome? Can hydrogen play a role in tackling climate change in the short term? Can bankable projects emerge and the gap between engineers and financers be bridged? Can the stability of supply of the main low-carbon hydrogen production sources be guaranteed?

- Enabling low-carbon hydrogen at scale would notably require greater coordination and cooperation between stakeholders worldwide, to better mobilise public and private finance, and to shift the focus to end-users and people: by moving from production cost to end-use price, developing Guarantees of Origin schemes with sustainability requirements, developing a global monitoring and reporting tool on low-carbon hydrogen projects and better considering social impacts alongside economic opportunities.

By 2040, low-carbon hydrogen[1] could play a significant role in energy systems and energy transitions across the world. In the context of energy transition, it serves to support countries' efforts to achieve the Paris Agreement goals whilst contributing to the diversity and security of their energy portfolios.

The World Energy Council, in collaboration with EPRI and PwC, aims to provide new and critical insights to facilitate strategic sharing of knowledge between the Council's members and the other energy stakeholders and policy shapers, and contribute to a global dialogue on hydrogen's potential role in energy systems and in energy transitions. Following the release of the "Hydrogen on the Horizon" series in July and September 2021, the World Energy Council, EPRI and PwC, led a series of regional deep dives to better understand regional differences into low-carbon hydrogen development. These regional deep dives helped uncover the regional richness, differing dynamics for low-carbon hydrogen uptake and distinctive challenges and opportunities. These "regional paths" also provided new insights into the global scaling up of low-carbon hydrogen in the coming years, and its potential role in achieving the Sustainable Development Goals.

These news findings are synthesised in these World Energy Insights on Hydrogen.

Note on the Military Conflict in Ukraine
The analysis and forecasts available in this publication and any associated references do not reflect the military conflict occurring in Ukraine. Although we acknowledge that the situation in Ukraine and the resulting disruptions in energy markets will greatly affect the future of low-carbon hydrogen, this release is based on analysis prior to the February 2022 events.

[1] *"Low-carbon hydrogen" in this briefing encompasses all hydrogen production technologies and sources resulting in low carbon emissions: from renewable energy sources, nuclear, fossils combined with CCUS, etc.*

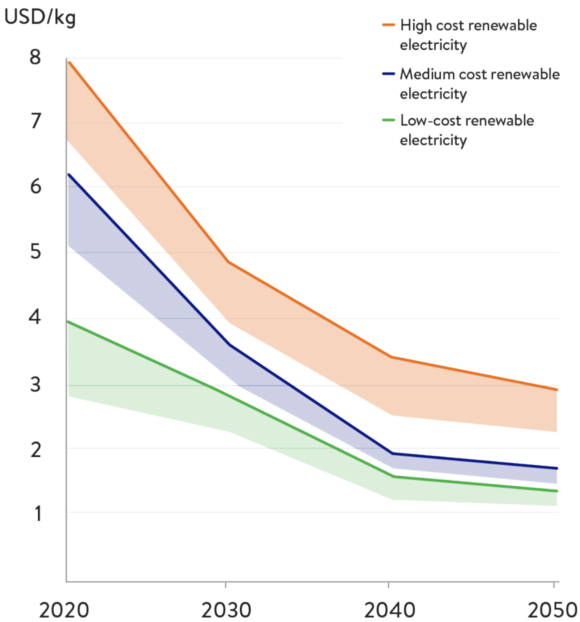
POTENTIAL FOR A SIGNIFICANT ROLE BY 2040

Building upon early technology deployment taking place today, by 2040 the demand for low-carbon hydrogen may exceed the current demand for fossil-based hydrogen today. In addition to replacing existing fossil-based hydrogen uses, low-carbon hydrogen opens opportunities for applications in new end-uses in a decarbonising world: moving from pilot projects to deployment at scale in sectors such as medium- and heavy-duty land transport, petrochemicals, iron and steel, rail, maritime shipping, and aviation. In some parts of the world, low-carbon hydrogen, pure or blended with natural gas, could also take off as a fuel for power generation, for industrial processes and for heating buildings.

The extent to which low-carbon hydrogen fulfils its potential depends heavily on the evolution of its key production technologies. Low-carbon hydrogen use could come from electrolysis (using renewable or nuclear generated electricity) or from fossil fuels with CCUS. The relative economics will depend largely on the resources available locally or on the lowest cost import option when local supply cannot fulfil local demand. The most cost-effective low-carbon hydrogen technology and transport method will vary in each region and could change over time as the cost of low-carbon hydrogen from renewable electricity is expected to fall relative to the cost of low-carbon hydrogen from fossil fuels. (Figures I & II)

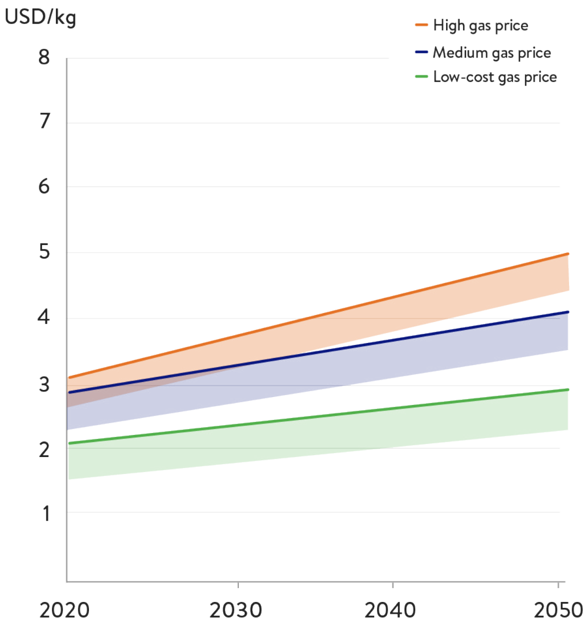
The high cost of transporting hydrogen means that most hydrogen will be consumed in the country or region where it is produced. The two largest energy markets, China and the USA, are likely to be more or less self-sufficient in hydrogen. Nevertheless, there is potential for significant global trade flows in hydrogen and hydrogen-based fuels / chemicals to develop by 2030 if sufficient regional and global cooperation emerge in the near future (Figure III).

Figure I. Projected cost by 2050 of low-carbon hydrogen from renewable electricity



Source: World Energy Council

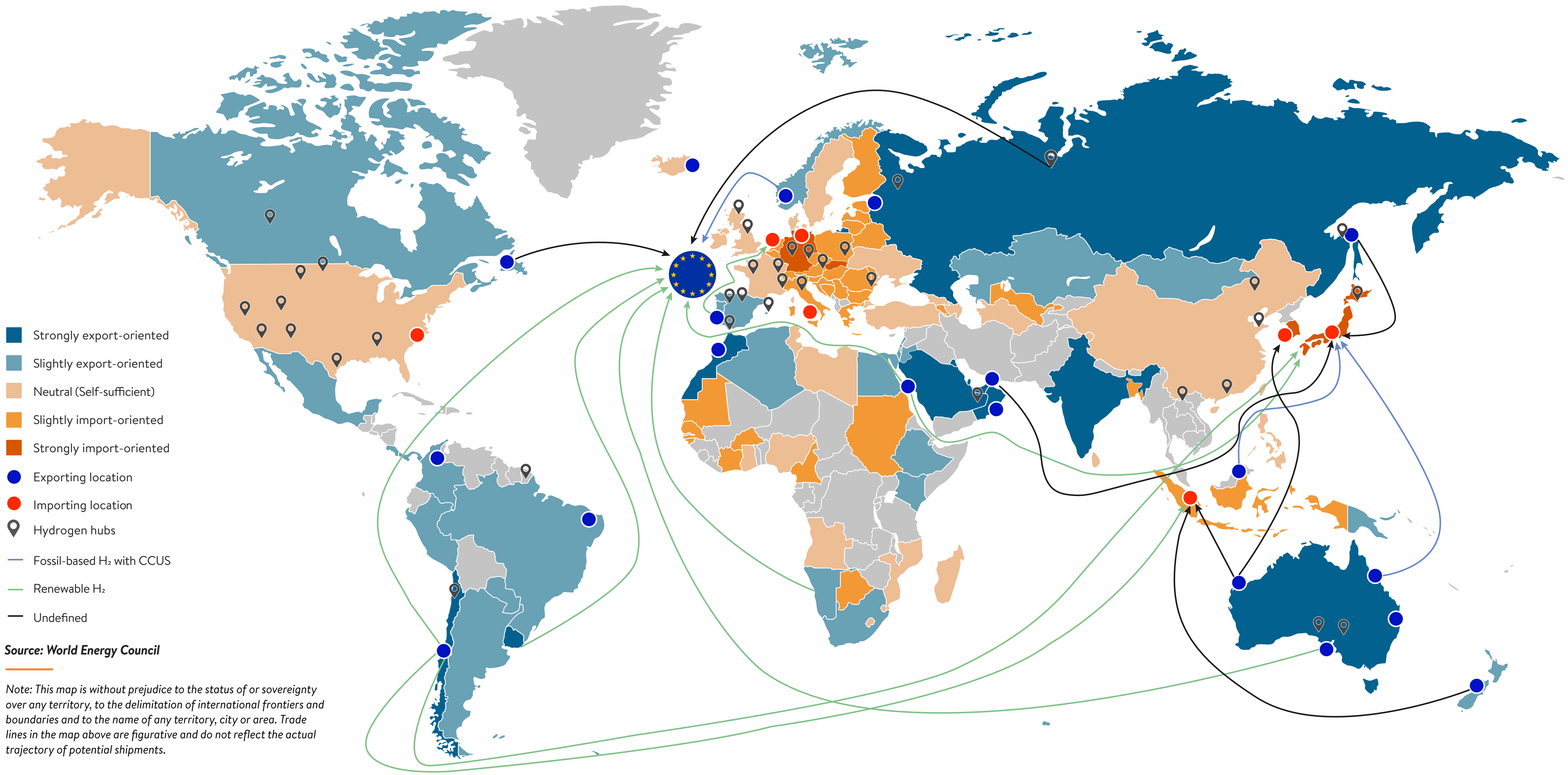
Figure II. Projected cost by 2050 of low-carbon hydrogen from natural gas with CCUS



Source: World Energy Council

The trade map highlights the potential for two major importing hubs, one centred around North Europe and the other around Japan and South Korea. The major exporting regions divide into those based on an abundance of cheap fossil fuels and CCUS opportunities (Australia, Canada, Middle East, and Russia), and those based on abundant renewable resources (Africa, Latin America, and Middle East).

Figure III. Map of potential low-carbon hydrogen import-export dynamics in 2040



Source: World Energy Council

Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Trade lines in the map above are figurative and do not reflect the actual trajectory of potential shipments.

METHODOLOGY

The map of low-carbon hydrogen import-export dynamics in 2040 is based on multiple external sources and internal modifications. There are 5 country categories: Strongly export oriented, Slightly export oriented, Neutral (self-sufficient), Slightly import oriented, Strongly import oriented. Each country's assessment was based on energy experts' expectations for the respective countries' positioning in the global hydrogen trade by the year 2040. This was based on national hydrogen strategies, projects that have already been announced, and market trends, which together made it possible to estimate future trade routes.

The energy experts were identified within the Council's and PwC's experts' communities in the different regions. 80+ experts' responses were aggregated and synthesised to assign a score to each country's status. The final position in the import/export spectrum is based on the average score obtained amongst experts, subject to a minimum number of responses is achieved per country to ensure robustness of the score and taking into account the standard deviation of the responses for each country to reflect the uncertainty level (in case responses for a single country varied widely). Countries with high standard deviation scores were reviewed by the Council's team and an informed final score and status assigned accordingly.

Moreover, the map pinpoints major exporting and importing centres, along with the associated trade routes, and the classification of the commodity traded (low-carbon hydrogen with CCUS, renewable hydrogen, undefined, etc.). Major exporting and importing centres have been identified, and the routes are based on selected planned or announced international hydrogen trade projects or on bilateral partnerships that envisage future trading perspectives, which were identified using the World Energy Council's own sources, IEA - Global Hydrogen Review 2021, IRENA - Geopolitics of the Energy Transformation: The Hydrogen Factor 2022, and the Council's own assessment of publicly available trade projects and official partnership agreements and Memoranda of Understanding. For simplification purposes, trade routes connected to the EU flag symbolises trade with one or multiple EU countries. For bilateral partnerships outside the scope of any trade activities of low-carbon hydrogen fuels/derivatives, please refer to Figure 13.

Finally, the map also shows the major hydrogen hubs/valleys where most low-carbon hydrogen investments/activities are occurring Details are listed in Annex 2: List of low-carbon hydrogen valleys.

GROWING MOMENTUM FOR LOW-CARBON HYDROGEN

Interest in low-carbon hydrogen continues to grow rapidly, with 22 countries having published and established a national strategy (including 11 strategies since January 2021), more than 400 low-carbon hydrogen projects have been announced to date (IEA, 2021), and increasing interest from investors and financial institutions. The cost of low-carbon hydrogen production technologies is decreasing across the globe, with low-carbon hydrogen produced from renewable energy reaching parity with hydrogen produced from fossil fuels in locations where current gas prices are high.

The current military conflict in Ukraine has brought up the issue of security of supply back to the top of political agendas. Low-carbon hydrogen using renewable resources or nuclear electricity could occupy an increasing place in energy plans to support the diversification of supply and suppliers. In the short term, this could translate in more projects in renewable energy and nuclear, increasing support for R&D in alternative fuels and energy carriers, and additional bilateral partnerships being developed across countries for the potential future trade of low-carbon hydrogen. As for hydrogen derived from natural gas with CCUS, uncertainties are emerging in regard to its role in the short term due to the current volatility in natural gas supply stability and price.

While the momentum for low-carbon hydrogen is growing worldwide, e**ach region is taking a different route in deploying low-carbon hydrogen, and differing paths will remain to accommodate the specificities of each region, country, and city.** Differences in low-carbon hydrogen uptake across regions will exist due to differences in market opportunities and stakeholders' priority actions. Hydrogen's versatility makes it relevant in many countries, but applications and supply chains development should be tailored to each specific context. As regional similarities and potential synergies arise, **increasing regional cooperation should be seen on hydrogen development.** (Table I below)

RESOLVING THE UNCERTAINTIES

Moving from "whether" to "how" to develop low-carbon hydrogen highlights significant uncertainties, which need to be addressed if hydrogen is to reach its full potential.

- *Can the challenges in various supply chain options be overcome?* The low-carbon hydrogen supply chain is composed of a variety of production sources, transport and storage technologies, and potential end-uses. In addition, all hydrogen-related technologies and applications will evolve with time, with increasing options and potential paths available to each country, depending on their individual context. The plurality of options and the high evolving technological landscape in the nascent global low-carbon hydrogen market creates additional difficulty for decisions makers as to which solutions to invest in along the value chain. Moreover, the development of a national colour-blind hydrogen strategy can increase long-term visibility for project developers and facilitate the emergence of cross-country cooperation along the supply chain.

- *Can hydrogen play a role in tackling climate change in the short term?* **The timeline for low-carbon hydrogen project development is not sufficiently aligned with the need to address climate change.** There is an urgent need to develop infrastructure and increase volumes of both supply and demand - including replacing current fossil-based hydrogen - to achieve material low-carbon hydrogen penetration by 2030 for hydrogen to play a role in reaching Paris Agreement goals. However, infrastructure development at scale will struggle to be ready in time, particularly if there is no existing gas infrastructure which can be repurposed. Therefore, priority should be given to "quick win" projects, pilot projects and hubs, and projects that are integrated along the value chain in order to solve the chicken-and-egg problem between hydrogen supply and demand.

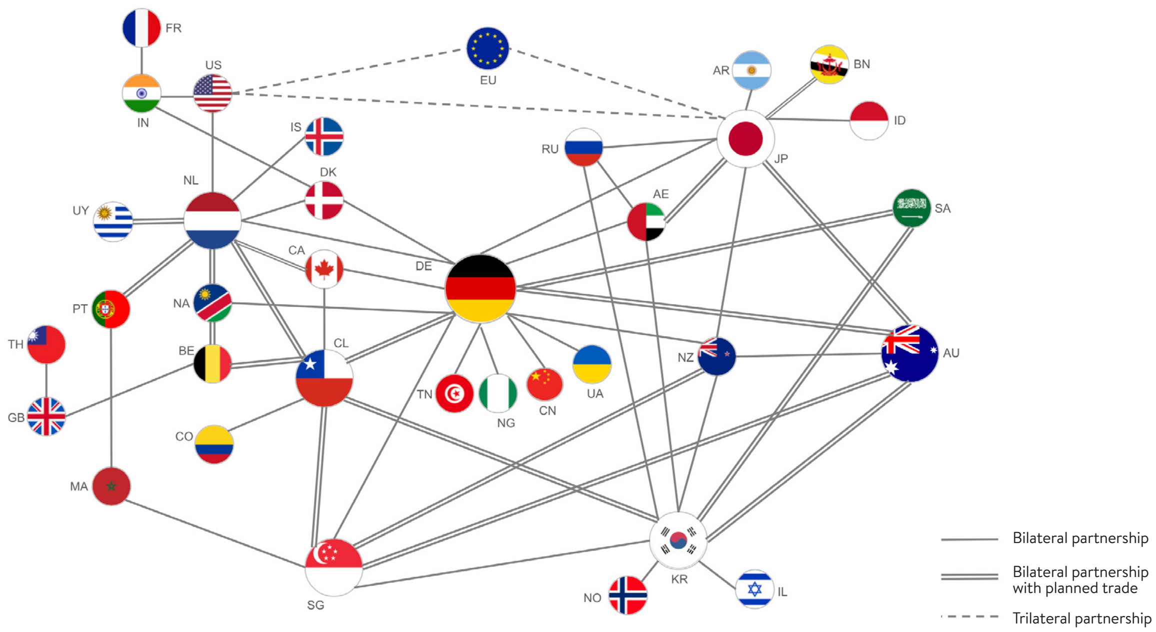
- *Can bankable projects emerge and the gap between engineers and financers be bridged?* **There is a gap between what technology providers could deploy and what bankers will finance.** What steps can be taken to ensure that new business models work, and that low-carbon hydrogen becomes competitive with alternative existing solutions? Globally, a shift in investment budgets towards green investments can be observed, joined by pandemic recovery funds across the world focused on sustainable investments. This sustainable finance and ESG movement can help governments attract financing to further develop hydrogen projects. However, without government support in de-risking the projects, they still face a financing problem.

- *Can the stability of supply of the main low-carbon hydrogen production sources be guaranteed?* Renewable hydrogen relies heavily on the supply of electricity from renewable resources that are at the mercy of weather fluctuations. Extreme weather events can significantly impact the supply of renewable energy, which could then create challenges and uncertainty with the **stability of renewable hydrogen supply.** Low-carbon hydrogen derived from fossil-fuels with CCUS also may have uncertainty of supply due to uncertainties in the supply of natural gas and/or to major fluctuations in its price.

ENABLING SCALE

For low-carbon hydrogen to develop at scale, key enablers have been identified with the energy community at the global, regional, and national level. Scaling up would first require greater coordination between stakeholders at the global level in the immediate term to help the market develop and better match supply and demand. In that context, bilateral partnerships between countries are continuing to develop and increasing include the trade of low-carbon hydrogen (Figure IV). Strong and coordinated climate action is particularly fundamental in driving low-carbon hydrogen interest – and with the appropriate policies in place, low-carbon hydrogen could achieve its true potential and help to achieve the long-term goals of the Paris Agreement. Mobilising public and private financing is also crucial at the global, regional, and national levels to de-risk investments, increase the number and volume of projects, and support infrastructure development. At the national level, one of the most critical enablers of hydrogen development is having a well-defined national strategy which includes: plans for market development and targets to provide long term visibility; regulatory priorities to unlock low-carbon hydrogen potential, notably adapting legislation to allow for clean molecules to be part of the energy mix; economic and financial mandates and incentives, including carbon pricing, blending quotas, and low-carbon fuel credits. National support for the development of hydrogen hubs is also key to facilitate the creation of local demand and supply in concert.

Figure IV. State of play of bilateral partnerships



Source: World Energy Council

In particular, there is an **urgent need to shift the focus onto the usefulness of energy for people, and to look at low-carbon hydrogen demand and the end-users.**

Firstly, **focus must be shifted to look at the low-carbon hydrogen end-user price.** Increase in low-carbon hydrogen demand is cost sensitive. The focus of the conversation should move from hydrogen production cost to final price for end users and include transport cost (challenging as there are many components, with some very difficult to estimate, such as transport infrastructure, local permitting, etc.), storage costs, profit margin, and provisioning costs at the final point of consumption. These costs may be much larger than the cost of hydrogen production itself and the end objective to make hydrogen competitive in the low-carbon future is not production at the lowest cost, but supply at the lowest price for the greatest benefit of societies and the environment.

Secondly, additional support should be focused on the end-users. More support on the demand-side is needed, targeting end-users that will consume hydrogen in their application. This can be achieved by **providing supply transparency and guarantees for the buyer.** In particular, experts unanimously called for **guarantees of origin and global sustainability requirements** to help the hydrogen market develop. Global cooperation on the topic needs to start today if clean hydrogen development is going to help achieve the goals of the Paris Agreement. However, it should be noted that a globally harmonised mechanism poses the risk of establishing a deliberately simplified or less ambitious framework (i.e., agreeing on the lowest common denominator) and may require a longer time frame to be adopted, which might be incompatible with short-term cross-country trade plans. Current regulatory uncertainty on low-carbon hydrogen (e.g., lack of harmonised definitions of hydrogen production methods, carbon intensity rules, etc.) is delaying investment and ramp-up of industrial-scale projects. National and regional initiatives are advancing on this topic, but unilaterally, which can create barriers for global trade. Experts are therefore calling for an international, recognized institution to lead a global effort to standardize these definitions. Additionally, providing more support to end-users entails **encouraging the switch to low-carbon alternatives through incentives and other policy tools** (e.g., carbon price, Carbon Contracts for Difference (CCFDs), Carbon Border Adjustment Mechanism (CBAM), or quotas). Finally, supporting end-users requires **reducing uncertainty to de-risk investment.** While current prices and safety concerns hinder hydrogen scale-up, in the short term, Memoranda of Understanding, partnerships, and long-term contracts are shaping the market and providing visibility for risks takers. As the market develops, more flexibility and competitiveness can emerge.

Thirdly, **low-carbon hydrogen development should consider social impacts alongside economic opportunities.** More emphasis is needed on ensuring local low-carbon hydrogen demand is met first in applications where it makes economic sense compared to alternatives, particularly in countries with significant existing consumption of hydrogen or export ambitions. Developing low-carbon hydrogen usage downstream requires its own transport, infrastructure, and storage facilities, which can create new skills and jobs opportunities, particularly in countries with abundant renewable energy resources, due to hydrogen's versatility. This can enable the respective societies to capture more value linked to low-carbon hydrogen economy developments. A key success factor for low-carbon hydrogen uptake relates to the social licence and the resulting necessity to provide more education for the public around its role in abating climate change and the role it could play in energy systems in respect to increasing equity and justice. Training and outreach will be needed to increase hydrogen literacy within the general population, and to improve the existing skillset across the industry. In that respect, the development of **a global monitoring and reporting tool on low-carbon hydrogen projects** would help awareness and literacy efforts amongst the general public, in addition to tracking progress over time and supporting decision making.

Table I. Regional Insights

	AFRICA	ASIA-PACIFIC	EUROPE	LAC	MEGS	NORTH AMERICA
	A huge potential but little infrastructure: how does Africa enable an export market as well as grow a domestic one?	**Mainstreaming low-carbon hydrogen and its derivatives and capturing related economic opportunities**	**A high ambition to decarbonise as fast as possible, while increasing security of supply and tackling the flexibility issue**	**Increasing self-sufficiency and developing new regional cooperation**	**Low-carbon hydrogen driven by Circular Carbon Economy and sustaining energy export**	**Increasing self-sufficiency and developing new regional cooperation**
SDGS	2 Zero Hunger; 7 Affordable and Clean Energy; 8 Decent Work and Economic Growth	8 Decent Work and Economic Growth; 9 Industry, Innovation and Infrastructure; 13 Climate Action	7 Affordable and Clean Energy; 12 Responsible Consumption and Production; 13 Climate Action	2 Zero Hunger; 9 Industry, Innovation and Infrastructure; 12 Responsible Consumption and Production	7 Affordable and Clean Energy; 9 Industry, Innovation and Infrastructure; 12 Responsible Consumption and Production	9 Industry, Innovation and Infrastructure; 11 Sustainable Cities and Communities; 13 Climate Action
Market activities / opportunities	**End-use priorities:** 1- Energy access, 2- Agriculture, 3-Export, 4- Industry **Low-carbon hydrogen production sources:** 1- Renewable hydrogen, 2- Natural hydrogen, 3- Hydrogen from natural gas with CCUS	**End-use priorities:** 1- Industry, 2- Mobility, 3- Power generation **Low-carbon hydrogen production sources:** 1- "Carbon-free" hydrogen (i.e., low-carbon; no prejudice of the type of hydrogen - renewable hydrogen, low-carbon hydrogen from natural gas and coal with CCUS)	**End-use priorities:** 1- Industry, 2- Mobility **Low-carbon hydrogen production sources:** 1- Renewable hydrogen, 2- Hydrogen from natural gas with CCUS, 3- Hydrogen from other sources (nuclear, waste, biogenic methane, methane pyrolysis, etc.)	**End-use priorities:** 1- Industry, 2- Mobility, 3- Agriculture, 4- Export (H2 & products using H2) **Low-carbon hydrogen production sources:** 1- renewable hydrogen, 2- hydrogen from all locally available fossil fuels with CCUS	**End-use priorities:** 1- Export, 2- Industry **Low-carbon hydrogen production sources:** 1- hydrogen from all locally available fossil fuels with CCUS, 2- renewable hydrogen	**End-use priorities:** 1- Industry, 2- Mobility, 3- Agriculture, 4- Export (H2 & products using H2) **Low-carbon hydrogen production sources:** 1- renewable hydrogen, 2- hydrogen from all locally available fossil fuels with CCUS
Regional paths	Developing low-carbon hydrogen could help Africa in tackling issues of **energy access, energy independence, food security and local employment** Africa has **sizeable renewable energy resources** to develop low-carbon hydrogen production & important **mineral resources** to be part of the value chain of energy transition technologies However, there are **many challenges to overcome:** some countries' concrete ability to take advantage of the hydrogen economy is limited by the lack of infrastructure and general awareness, political and economic challenges, and lack of demand security, as well as water stress **North Africa** has more favourable conditions - Morocco, Algeria and Egypt in particular could be first movers and exporters of hydrogen and its derivatives In the early stage of hydrogen development, there are opportunities to unlock in the hydrogen innovation space that could position African countries as technology-setters, not takers	Asia-Pacific region **at the epicentre of the movement towards a "hydrogen economy"** - Japan, South Korea and Australia released a strategy first **Integrated approach to low-carbon hydrogen-based fuels** that can support decarbonisation efforts across a multitude of applications and sustain economic growth via innovation and new technologies for export Interest increasing in other countries; although the overarching plans are yet to be released, inc. from key players **China and India** In the early stage of low-carbon hydrogen uptake: **defining priorities between fuels** could facilitate the scale up and more regional and global cooperation is needed to **tackle the obstacles to global trade development** (e.g., lack of harmonised definition of hydrogen sources, updating maritime regulations, etc.)	Impulse given by Germany - now Europe is **at the forefront of hydrogen development worldwide** The EU plans to rely heavily on low-carbon hydrogen to support its decarbonisation ambitions, with high targets for imports (from North Africa, Latin America, Gulf States, etc.) **Several challenges in the EU** - More dissonant voices: e.g., on blending; on which low-carbon production sources, pure hydrogen vs. intermediate steps (e.g., power to methane, ammonia, liquid fuels), etc. - Developing harmonised standards and streamlining regulations is key for low-carbon hydrogen ramp up **Timeline gap between the ambitious climate agenda and hydrogen infrastructure implementation:** very large infrastructure projects (notably for import) operational after 2030. In the meantime, within Europe, on-site projects and hydrogen hubs are developing, and off-site electrolysers in regions with high renewable energy capacities could supply part of the European demand	Wide interest to develop hydrogen production and use, **focusing mainly on hydrogen from renewable energy,** but considering all resources available on the continent Developing **local demand is the primary objective** to help decarbonise the economy **Chile is the early mover** and gave the impulse on hydrogen in the continent, which is now very dynamic; momentum is picking up and **regional cooperation is increasing** The continent is attracting **increased attention from potential importing markets** (e.g., Netherlands, Australia, Japan) Cooperation could increase to **attract more foreign investment** and install the LAC region in the global hydrogen market	Momentum in MEGS is driven by the **energy incumbents,** in addition to the region's Circular Carbon Economy agenda Investments are being implemented with the end goal of **sustaining energy exports** to existing markets in Europe and Asia Existing **vast oil and gas assets**, coupled with excellent **natural resources** for renewable energy production, are making the production of low-carbon hydrogen in the region among the most competitive in the world **Saudi Arabia, the UAE, and Oman** are driving the momentum for low carbon hydrogen Aspirations to become an **export hub** of low-carbon hydrogen and its derivatives **Foreign laws** and regulations can create **policy obstacles** that might hinder these goals, particularly regulations related to potential exports	Momentum is emerging in Canada and in specific states within the US. Goal is to increase and enhance **overall resiliency** of the energy systems over the coming decades **High technology readiness** is pushing the domestic market to pick up end-use applications particularly in the transport sector **Developed regulations and incentives** targeting clean mobility are pushing further the use of low-carbon hydrogen in the transport sector **Export ambitions** of low-carbon hydrogen and its derivatives are also emerging, especially as the region is an existing energy net exporter **Priority** is on the **creation of hubs** where supply and demand are located in the same place
Key Enablers	Regional & subregional cooperation, & cooperation with importing markets to develop African hydrogen technologies and to create a shared vision for hydrogen Gap assessments for human capital and infrastructure development Developing domestic demand in the transport, industry and agriculture sectors	Increasing bilateral and multilateral cooperation to progress the low-carbon hydrogen global supply chain and hydrogen trade Integrated approach to energy policies & mainstreaming hydrogen and its derivatives in many aspects of energy systems Supporting hydrogen-related technologies and increased use in mobility	Eliminating regulatory obstacles in the European Union (and misalignment between Member States) More support mechanisms for the production-side and switch incentives for the demand-side (e.g., CCFDs or quotas) Supporting the development of international trade More coordinated hydrogen diplomacy action in the EU	Regional cooperation to increase visibility for the continent and attract external investments Better identifying and building on each country's individual strengths for an integrated low-carbon hydrogen supply chain	Increasing regional collaboration and learning from previous failed attempts Developing local ecosystems and end-use applications in the local market as opposed to primarily creating an export hydrogen industry Finance subsidies and support mechanisms to enhance the bankability of large pilot projects	Scaling and reducing the cost of hydrogen transport and distribution Funding support for R&D andpilot and demonstration projects Creating hubs centres to help derisk future projects

SDGs legend

Out of the 17 sustainable development goals (SDGs), scaling up low-carbon hydrogen in the different regions could particularly help achieve the following:

- *2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture*
- *7: Ensure access to affordable, reliable, sustainable and modern energy for all*
- *8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all*
- *9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*
- *11: Make cities and human settlements inclusive, safe, resilient and sustainable*
- *12: Ensure sustainable consumption and production patterns*
- *13: Take urgent action to combat climate change and its impacts*

INTRODUCTION

The World Energy Council, in collaboration with EPRI and PwC, aims to provide a better understanding of hydrogen development worldwide for the energy community, building on the expertise and experience of its global network. In this context, we published the “Hydrogen on the Horizon” series, including an Innovation Insights Briefing in July 2021 and 3 working papers in September 2021, seeking to start a multi-stakeholder community dialogue at the global, regional, and national levels on hydrogen’s role in energy transitions.

This work had identified the following 4 areas for further discussion:

- Significant diverging paths are emerging across countries and regions, as national hydrogen strategies reveal varying attitudes towards hydrogen’s role in energy transitions. This signals a need to embrace diversity – eliminating a one-size-fits-all mindset – and enable differing technologies and use cases to be explored.

- Confusion over ‘colours’ is stifling innovation, with over-simplification and colour prejudice risking the premature exclusion of some technology routes that could potentially be more cost- and carbon-effective. There is a need for further dialogue which looks beyond colour to also explore carbon equivalence.

- Demand-centric hydrogen perspectives are needed to advance the Humanising Energy agenda. The current hydrogen conversation focuses heavily on supply, ignoring the role of hydrogen users. Discussions must explore what’s needed to trigger hydrogen demand, with a specific focus on the development of hydrogen infrastructure and a global supply chain for hydrogen and hydrogen value-added products.

- The hydrogen economy could stimulate job creation and economic growth, potentially helping to fulfil ‘build forward together’ ambitions post-COVID-19. Several national hydrogen strategies highlight jobs as an important driver of hydrogen development, with opportunities to reskill the existing workforce and upskill a new workforce.

These new World Energy Insights on Hydrogen follow the “Hydrogen on the Horizon” series and are the result of the implementation of this multi-stakeholder community dialogue. Building on insights gathered within the Council’s energy+ community, notably via high-level invitation-only regional workshops, these new World Energy Insights aim to dive deeper into the concrete developments of low-carbon hydrogen worldwide, looking at the differing routes taken in each region, their “hydrogen path”, and to highlight short term enablers for low-carbon hydrogen to play its potential role in energy transitions and in energy systems by 2040.

INSIGHTS ON HYDROGEN SUPPLY CHAINS DEVELOPMENT

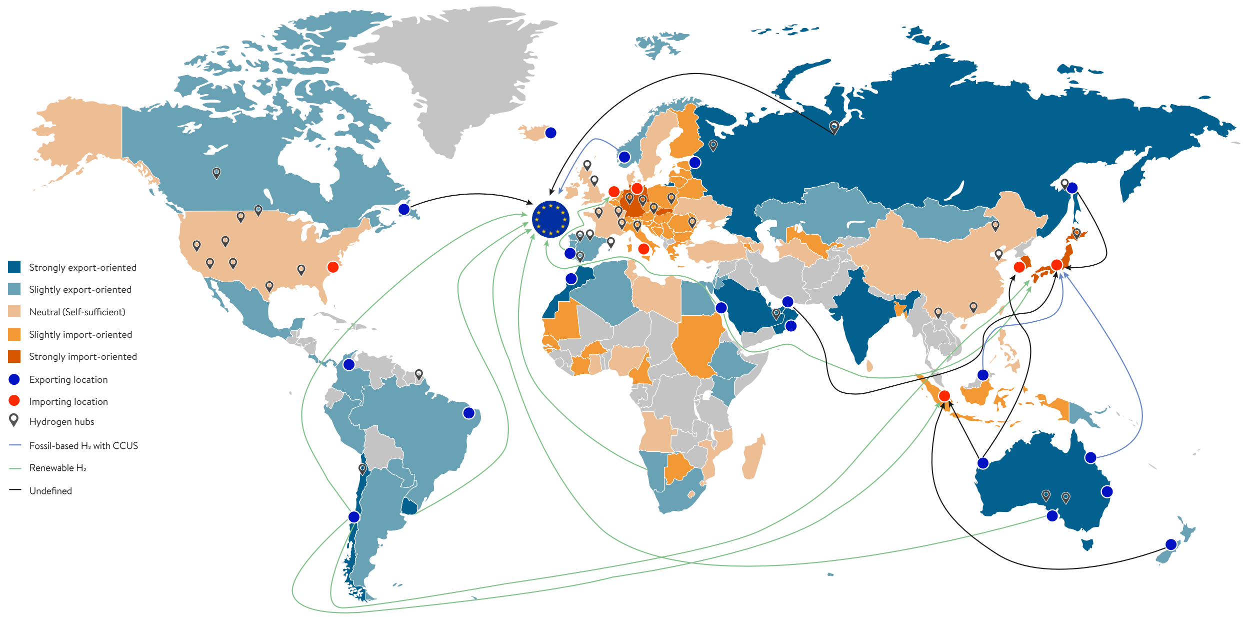
LOW-CARBON HYDROGEN: A GLOBAL COMMODITY IN THE FUTURE?

With low-carbon and in particular renewable hydrogen momentum picking up significantly since 2019 in line with decarbonisation targets, hydrogen trade is swiftly emerging throughout the world. This is evidenced by the large number of bilateral agreements between governments and joint projects between companies that are shaping the market at a rapid pace. Like all other commodities, the trade in low-carbon and in particular renewable hydrogen is being shaped by supply and demand and supported by net-zero focused emission abatement policies. Countries with excellent renewable resources, nuclear electricity and/or with significant fossil fuel resources and Carbon Capture Utilisation and Storage (CCUS) capacities will be supplying the demand markets, mainly in Europe and Asia.

The demand for low-carbon hydrogen, however, is difficult to forecast, as it depends on many different factors, notably climate policies, end-user price competitiveness, electricity market prices, and the future use of natural gas and the development of carbon prices. In principle, the development of low-carbon hydrogen demand will also depend on production, transport and storage technologies' cost development and the end-users' willingness to pay, as this has a decisive influence on competitiveness and thus on use. Experts agree that the 2020s decade will be crucial to achieving the Paris Agreement's targets. This decade should show important developments of low-carbon hydrogen infrastructure at scale, as volumes increase, and prices are expected to diminish. During this decade, policy support and incentives are needed in order to balance the demand and supply gap and justify the investments in infrastructure and new applications.

According to the World Energy Council's map below, most of Europe will be import oriented from 2030 onwards, and therefore is currently shaping partnerships with most exporting countries in the form of bilateral agreements. For example, Latin America is shaping up its export potential, being led by Chile, with several partnerships with European countries. North Africa and Europe are also working together on exporting renewable hydrogen, mainly through existing pipeline networks from Morocco and Algeria. In the Middle East, shipments of low-carbon ammonia derived from fossil-fuel hydrogen with CCUS technology have already been exported from Saudi Arabia and UAE to Japan, with more partnerships with Asian countries being developed to export from UAE and Oman to the Asian markets as well as from Saudi Arabia to Europe. Finally, Australia is fiercely competing on the export market, with many announced projects and partnerships with Japan and South Korea already under way, including a new custom-built hydrogen tanker "Suiso Frontier" transporting liquid hydrogen from Australia to Japan. Low-carbon hydrogen uptake and trade is likely to benefit from current favourable conditions using "transferable" models from other sectors, such as existing incentives and laws for renewable energy, existing industry and infrastructure for hydrogen derived from fossil fuels, and the infrastructure for the global trade of various raw materials and chemicals.

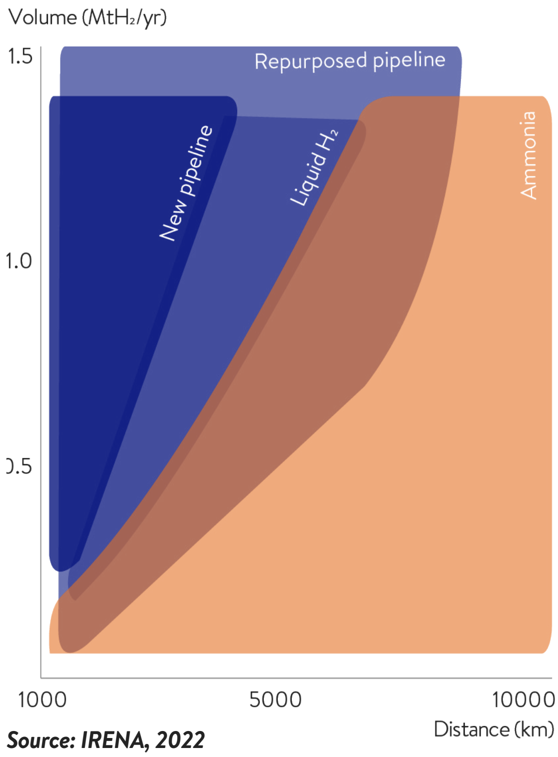
Figure 1. Map of potential low-carbon hydrogen import-export dynamics in 2040



Source: World Energy Council

However, low-carbon hydrogen development comes with its own major challenges.

Figure 2. Cost efficiency of transport options when considering volume and distance



Source: IRENA, 2022

First, it faces challenges in terms of transport, regardless of the type of carrier used (see more on regional takes on hydrogen transport in the section on Regional insights). According to IRENA, the most economical option for long distance transport (>4000 km) is via ships. Several options for seaborne transport are being explored. Hydrogen liquefaction is one option; however, it is energy intensive since it requires a temperature of -253°C (compared to -160 °C for LNG). Another option is converting it to ammonia and reconverting it back to hydrogen after transport (except if ammonia is the end-use being traded for applications in combustion engines or in gas turbines). It is the most promising, although still energy intensive and costly because of the conversion/reconversion and purification processes. Liquid Organic Hydrogen Carriers (LOHC) are also an option being explored; however, the process is reported to be costly and energy intensive (for cost comparison, please refer to Figure 5). For medium distances (<4000 km), new dedicated hydrogen pipelines, or using the existing natural gas pipelines which might be repurposed for pure hydrogen transport (technical constraints apply in terms of percentage blending and material compatibility of the existing network with hydrogen) are the most cost-effective way to transport high volumes from supply clusters to the demand clusters. Figure 2 highlights the cost efficiency of several transport options. Finally, for short distance and low volumes (local transportation), hydrogen can be distributed compressed or liquefied by trucks in storage tanks (i.e., distribution to Hydrogen Refuelling Stations (HRS)). To bridge the gap until low-carbon hydrogen transport costs reduce, which is likely with an increase of traded volumes and technology improvements, some countries are prioritising the creation of hydrogen valleys or hubs, where supply and demand are located in the same regional cluster. These hubs are mostly located near concentrated industrial activities, or near ports which can become major import/export hubs.

At the same time, international trade of technologies needed to produce low-carbon hydrogen, in particular of electrolysers and the materials used to manufacture them (i.e., steel, nickel, platinum, iridium, etc.), is increasing, and should be given more attention going forward, especially in a post covid crisis world where localisation of production of technologies comes back at the forefront of the agenda. On another note, most electrolysers are still being manufactured in work processes that involve little to no automation due to the current low level of market demand, which is preventing manufacturers from making the necessary investments to streamline the production process. This is adding to the cost and time needed to deploy electrolysers at scale (Mayyas, Ruth, Pivovar, Bender, & Wipke, 2018).

Finally, the development of policy support for low-carbon hydrogen, at this nascent stage, is still disparate and uncoordinated. The limited number of structured initiatives regionally and globally, the plurality of tools and experimental policies developed to support hydrogen – and lack of sufficient implementation time to get feedback –, combined with the diverging regulations and standards, can create complexity and obstacles for global trade (e.g., differences in low-carbon or renewable hydrogen qualifications and eligibility for support instruments). More obstacles are identified in the safety space (e.g., standards missing for new applications) and in human capital (e.g., skills availability), which need to be tackled more proactively, especially if potential solutions can give rise to new and more business opportunities, which would make the hydrogen agenda more attractive than challenging.

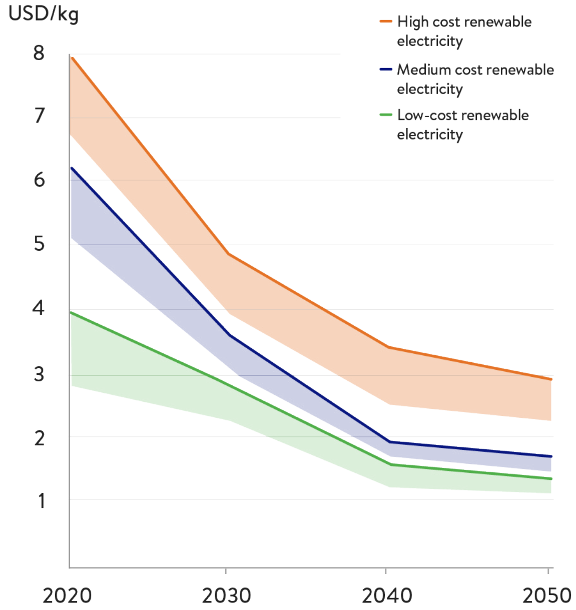
To face these challenges, cooperation is crucial between all actors involved in the supply chain. Increased cooperation is called upon and driven by many actors, and collective enablers are emerging to reduce barriers to global trade (see in the section on Enablers for low-carbon hydrogen market ramp-up).

LOW-CARBON HYDROGEN PRICE DEVELOPMENTS

The cost of low-carbon hydrogen is one of the most decisive factors influencing its competitiveness and thus increased use. In addition, the costs of the different processes for hydrogen production differ, therefore influencing which production method is chosen and how much CO_2 is emitted. Currently, producing hydrogen via SMR with CCUS is often a low-cost option, mainly driven by the comparatively low-cost prices of natural gas over the last decade. However, in regions of the world that are currently importing natural gas and have very favourable conditions of renewable electricity, producing hydrogen via electrolysis with renewable electricity can already be competitive today. In the future, the price of natural gas is expected to rise, making it increasingly expensive to produce hydrogen using SMR with CCUS. The cost of low-carbon hydrogen from renewable electricity, on the other hand, should decrease, as both the prices for renewable electricity and the electrolysis technologies will continue to fall, due notably to the realisation of economies of scale, technological developments and learning effects. Under this respect, however, we must also consider that the growing share of intermittent renewable sources in the power production mix will most likely increase network fees and balancing costs, reducing the scope of cost decrease for grid-connected electrolysers. In some countries, governmental action is supporting this trend by developing financial incentives, implementing quotas, and other economic support tools focused on renewable hydrogen only. To manage the scale up of supply, renewable hydrogen projects should go hand-in-hand with the development of significant renewable energy capacities able to operate the electrolysers.

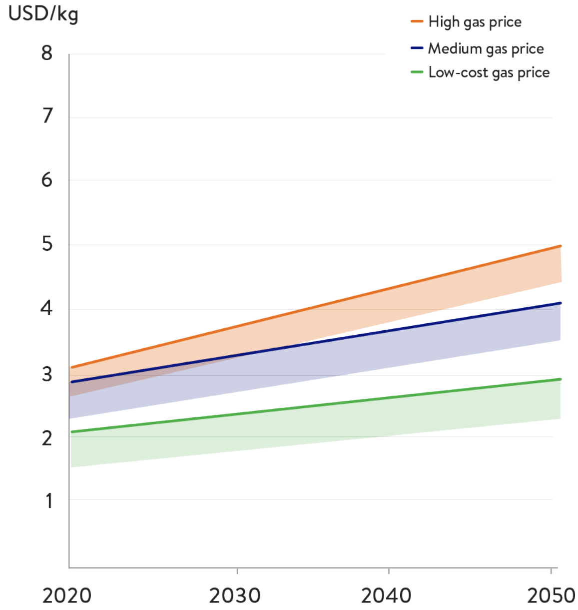
The continuous decrease in renewable hydrogen cost (Figure 3) will lead to a situation where in 2050 it will be cheaper to produce low-carbon hydrogen using SMR with CCUS only in few regions with continued low gas prices, low availability of renewable electricity and good access to CO_2 storage sites. In most of the other regions around the world, the production of low-carbon hydrogen using renewable electricity is estimated to become the most cost-effective.

Figure 3. Projected cost by 2050 of low-carbon hydrogen from renewable electricity



Source: World Energy Council

Figure 4. Projected cost by 2050 of low-carbon hydrogen from natural gas with CCUS



Source: World Energy Council

METHODOLOGY

The figure 3 of projected cost for low-carbon hydrogen from renewable electricity is based on a forecast of renewable electricity price development (Fasihi & Breyer, 2020), combined with a PwC data tool which includes CAPEX and OPEX costs of electrolysers. The methodology also considered the scale learning effects of electrolysers technologies. 3 scenarios are used, each considering different prices of renewable electricity:

- **Low cost:** 34 USD/MWh in 2020, decreasing to 11 USD/MWh in 2050;
- **Medium cost:** 40-45 USD/MWh in 2020, decreasing to 17 USD/MWh in 2050;
- **High cost:** 50-62 USD/MWh in 2020, decreasing to 23-45USD/MWh in 2050.

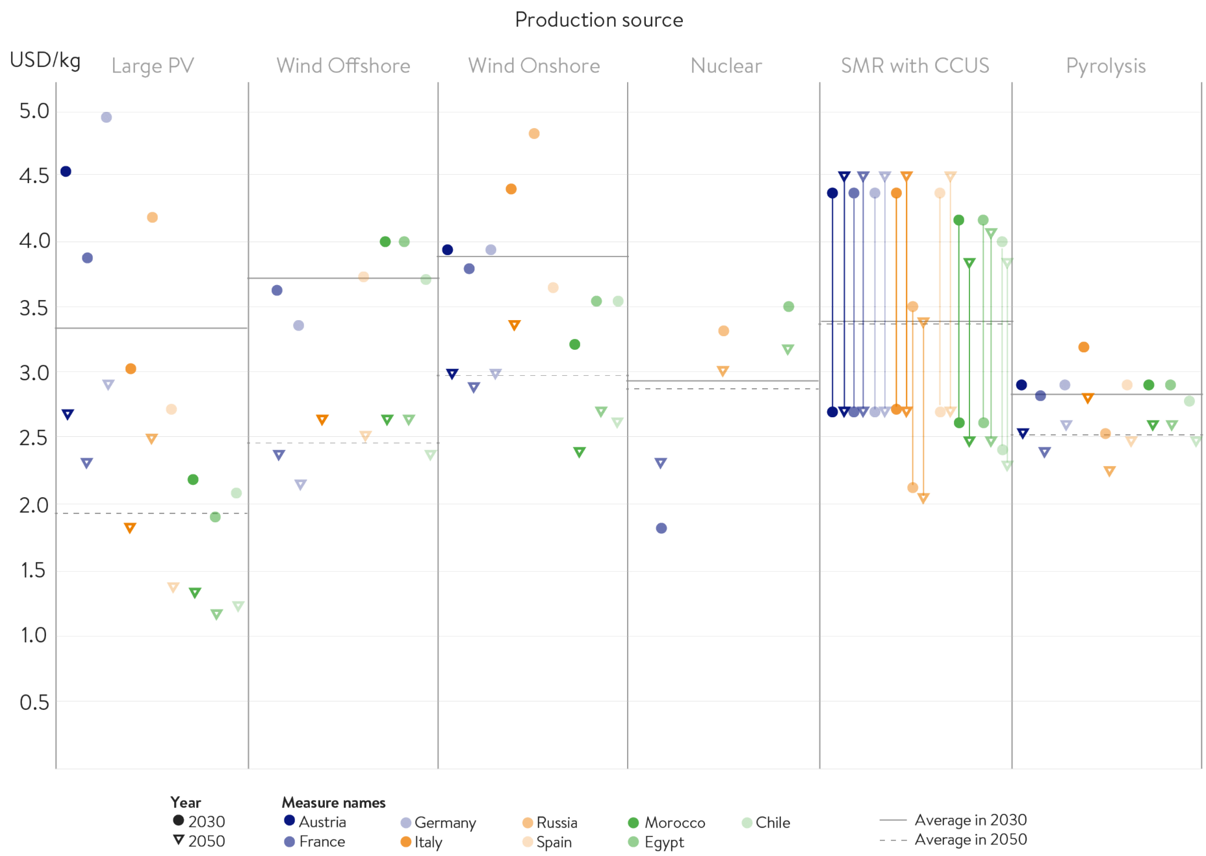
METHODOLOGY

The figure 4 of projected cost for low-carbon hydrogen from fossil fuels with CCUS is based on 4 case studies developed by EPRI and Wood. The case studies explore two main types of SMR processes: SMR with post-combustion CO_2 capture, and SMR with advanced technology configuration, while achieving in both processes a 90% of CO_2 capture. The hydrogen production capacities that were explored (50,000 kg/day and 300,000 kg/day) are showcased with the 2-lines for each gas price range.

Moreover, 3 natural gas price development scenarios were used (not tied to any particular region, acknowledging sub-regional disparities):

- **Low cost:** 17 USD/MWh in 2020, increasing to 34 USD/MWh in 2050;
- **Medium cost:** 34 USD/MWh in 2020, increasing to 68 USD/MWh in 2050;
- **High cost:** 45 USD/MWh in 2020, increasing to 90 USD/MWh in 2050

Figure 5. Production Cost (USD/kg) per technology for select countries (by 2030 and 2050)



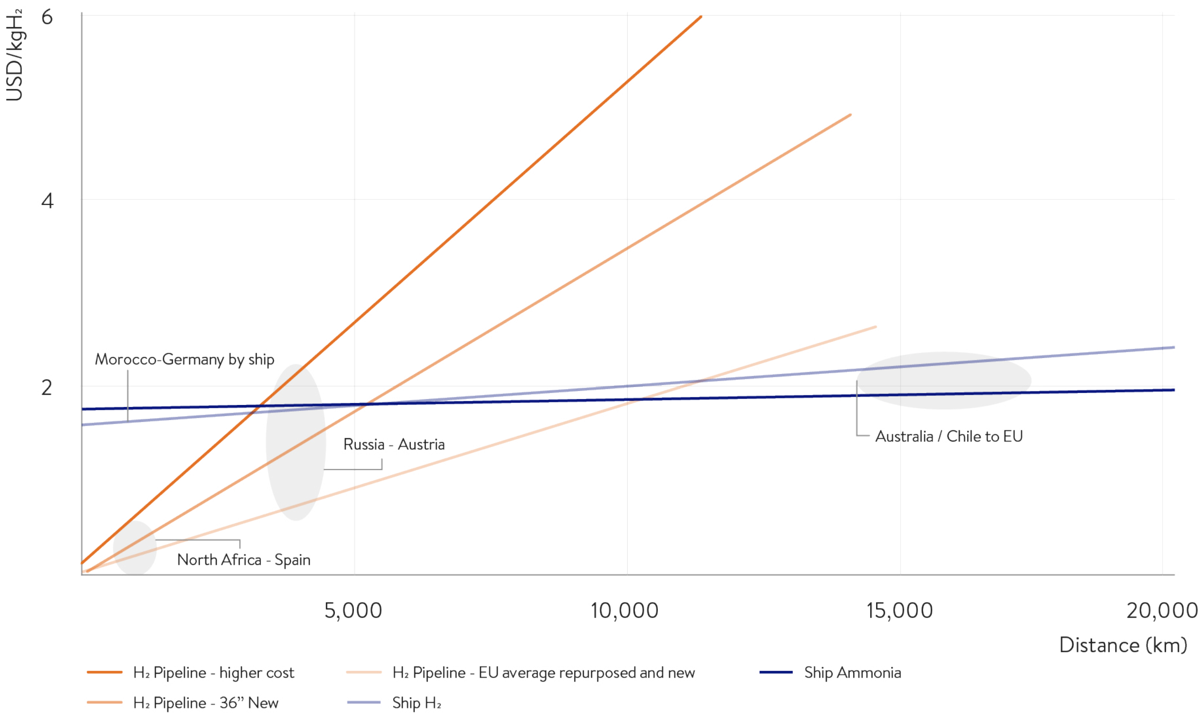
Source: World Energy Council

METHODOLOGY

Based on the data from the WEC Europe study on hydrogen imports (Word Energy Council - Europe, 2021). Excludes transportation costs. All calculations are based on average investment costs (~ 400 USD/kW in 2050) and not the cheapest available (160 USD/kW) to reflect the average cost of production. Gas prices were revised and estimated as a range by PwC and the World Energy Council for both European and North African countries due to it's volatility. For more information on assumptions, please refer to WEC Europe study on hydrogen imports (Word Energy Council - Europe, 2021).

While low-carbon hydrogen production costs are set to decrease rather rapidly, making the commodity and its derivatives increasingly competitive compared to alternative fuels, the market price – ultimately paid by consumers – remains a significant barrier to low-carbon hydrogen uptake. According to the National Renewable Energy Laboratory (NREL), the average retail price of hydrogen in the transportation sector was around 16.51 USD/kg between Q4 2018 and Q3 2019 in the USA. In order to reach parity with gasoline, 1 kg of hydrogen should sell for 2.5 times a gallon of gasoline – hence to match a 3.20 USD/gallon retail price, hydrogen should sell at 8 USD/kg (Baronas, 2019). The hydrogen debate should shift from production cost across the various technologies to the final price for end-users in order to include the additional costs such as transport and storage costs, as well as the profit margin. Low-carbon hydrogen's transport costs are particularly challenging to estimate, as they include many components, and should acknowledge transport infrastructure development in this early phase of the trade development. As long-distance transport of low-carbon hydrogen is needed in the future to supply the main demand centres, more emphasis should be put on better assessing transport costs across different methods and distances. As technologies develop in this area, all possible solutions remain explored to suit each country's particular context.

Figure 6. Comparison of hydrogen transport options over various distances



Source: World Energy Council, based on data from the World Energy Council - Europe, 2021

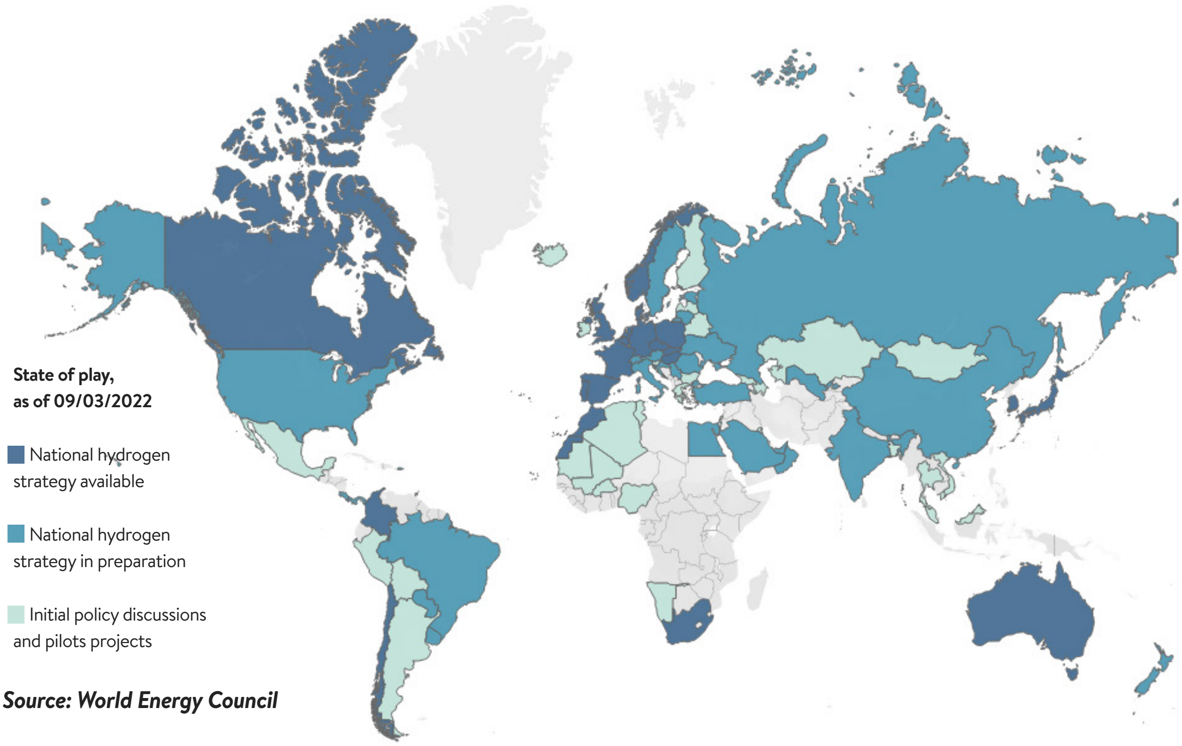
Besides the cost projection, the stability of supply and volume availability of low-carbon hydrogen can affect the retail price significantly. For instance, intermittency in the production of renewable energy because of weather fluctuations can directly impact the supply of low-carbon hydrogen to end-users, and therefore increase volatility around the retail price, if hydrogen storage is not available. A similar case on the uncertainty of supply can be made for low-carbon hydrogen derived from fossil-fuels with CCUS since a disruption in the supply of natural gas, or a major fluctuation in its price, can also cause major uncertainties on the stability of supply of low-carbon hydrogen.

CONTEXT

REGIONAL INSIGHTS

Local interest in low-carbon hydrogen uptake is continuing to grow around the world. As of 09/03/2022, 21 countries and the European Union have released a national hydrogen strategy, 27 have a national strategy in preparation, and initial policy discussions and pilot projects are seen in at least 34 additional countries. In the last year, the most public support for low-carbon hydrogen development continues to be seen in Europe, however the momentum is also growing in Latin America and the Caribbean, Africa and the Middle East and Gulf States, where additional countries are developing plans for low-carbon hydrogen uptake. Potential key low-carbon hydrogen players in terms of volumes, such as China, India, Russian Federation, and the United States of America are planning to release their national hydrogen strategies shortly.

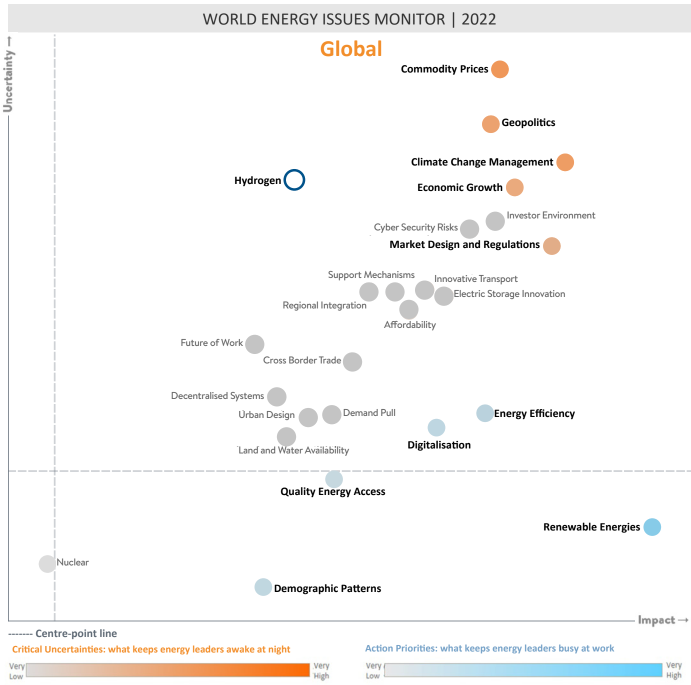
Figure 7. Overview map of the countries activities towards developing a hydrogen strategy



Source: World Energy Council

Figure 8. World Energy Issues Monitor 2022 - Global map with Hydrogen

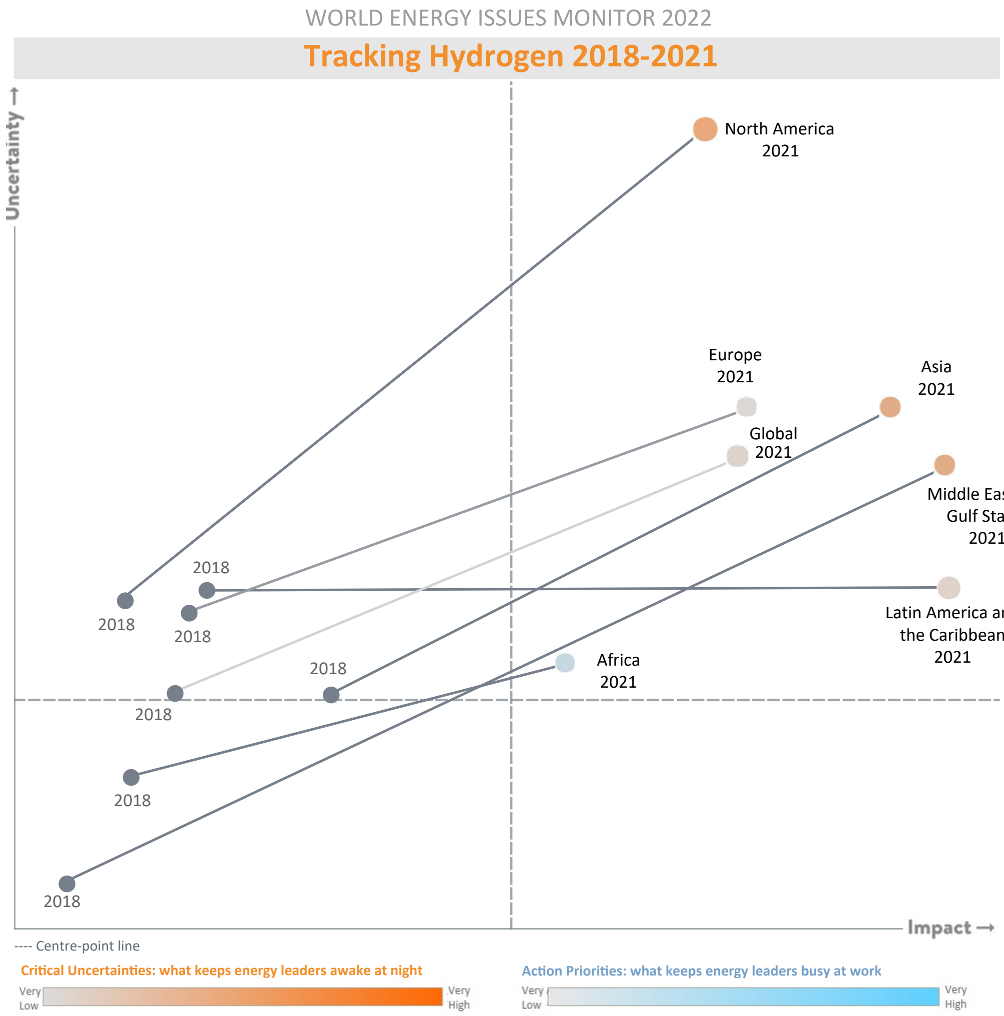
Source: World Energy Council



WORLD ENERGY COUNCIL IN COLLABORATION WITH EPRI AND PWC

Hydrogen positioning in the World Energy Issues Monitor[2] has evolved dramatically in the last 4 years. Experts across all the regions consider that the topic is increasingly critical and impactful for energy systems and energy transitions. Uncertainty around hydrogen is particularly high: 1st uncertainty out of the 25 issues for North America, 3rd uncertainty in Europe, 4th uncertainty in the Middle East and Gulf States, and 5th in Asia. However, hydrogen is still overall perceived with limited impact in 2022, which prevents the issue from being seen as a critical uncertainty in all regions but Asia, and as an action priority in all regions. The high level of uncertainty still places hydrogen high on leaders' issues to track.

Figure 9. Regional tracking of Hydrogen in the World Energy Issues Monitor between 2018 and 2021



Source: World Energy Council

[2] *The World Energy Issues Monitor tracks energy leaders' perspectives on the issues affecting the sector. By asking policy makers, CEOs and leading industry experts to assess the level of impact and uncertainty they attribute to preidentified energy transition issues, the Monitor provides a unique overview of a) the Action Priorities or areas where countries are acting pragmatically to progress in their energy transition; and b) the Critical Uncertainties or issues that are in the energy leaders' radar as areas of concern, and how these have evolved overtime.*

AFRICA

LOW-CARBON HYDROGEN DEMAND PERSPECTIVES

Hydrogen development shows great potential for African countries in the long term. Various domestic end-uses have been identified, particularly for the agricultural sector, the development of energy access, and to strengthen the reliability and resilience of the electricity system. In terms of agriculture, locally produced low-carbon hydrogen could play an important role in increasing the use of nitrogenous fertilisers, and in turn improve food security. Early mover Morocco could notably help further supply low-carbon hydrogen and ammonia for fertilisers to Sub-Saharan countries, as low-carbon hydrogen would help to localise ammonia production in the respective countries, improving local added value and reducing supply chain and carbon footprint. Looking at energy access, combined with further electrification on the continent, hydrogen could be used as a vector and act as standby capacity and for long-term storage, particularly in remote areas. Some African countries could also explore the development of renewable hydrogen production for electricity storage in thefuture; however, the process of producing hydrogen for storage currently has a low round-trip efficiency compared to other storage technologies (S&P Global Market Intelligence, 2021). Nevertheless, economic challenges, particularly for Africa, currently make alternative solutions (e.g., battery, pumped-storage hydroelectricity) more cost-efficient. It can also act as long-term storage capacity for hydropower energy, which fluctuates between seasons and across different years. Hydrogen also shows potential in the energy sector to stabilise the grid, notably for peak energy use and backup power for the telecom industry (radio masts), and in many other business sectors with high energy consumption and high-power reliability requirements (e.g., hospitals, hotels, supermarkets, shopping malls, offices, and data centres), where ammonia fuelled fuel cell systems could replace mostly imported diesel generators. Moreover, low-carbon hydrogen can increase renewable electricity market growth potential substantially and broaden the reach of renewable solutions. In addition, North Africa currently has the most potential for power generation using low-carbon hydrogen from fossils with CCUS, due to existing gas power plant infrastructure. Finally, low-carbon hydrogen use could support the continent's path to net-zero, notably in industry (iron and steel industry in South Africa, Egypt, Algeria, Morocco, or Mauritania; refineries in Egypt, Libya, Algeria, Nigeria and South Africa; methanol), and mobility (as part of a mix of technologies – fuel cells, electric vehicles, biofuels sectors; in public transports as highlighted by South Africa). The development of local production capacity could reduce imports (fertilisers, diesel for isolated areas, energy for heavy transport in mines, etc.) and contribute to strengthening the energy and economic independence of the African countries.

Another economic advantage could come from exports. North Africa is currently better positioned for exports, mainly looking at the European market, while most other African countries can only consider low-carbon hydrogen export in the long term. On this topic, there are lessons to learn from previous initiatives across the Mediterranean, like the Mediterranean solar plan and Desertec, which failed notably due to lack of some institutional, political, and financial drivers. It is necessaryfor African countries to develop local low-carbon hydrogen uses, before or at the same time as exploring exportopportunities, in order to increase value creation domestically. Export activities are seen as an opportunity to foster thedevelopment of infrastructures and other capacities for local demand uptake, but the lack of infrastructure hinders most African countries' perspectives in the coming decade. In addition, with minerals being critical to the development ofthe renewable energy infrastructure and providing an important diversification option to existing mineral supply chains, Africa with its abundant mineral resources offers an excellent option to be part of the value chain of energy transitiontechnologies. For instance, South Africa holds 90% of known platinum group metals (PGMs) reserves worldwide, which arecritical materials used in certain types of electrolysers as well as in fuel cells, and will therefore play an important role in the worldwide uptake of renewable hydrogen.

SUPPLY CHAINS

Production sources

African countries have overall a tremendous potential to produce low-carbon hydrogen, with an abundance of renewable energy sources and very interesting capacity factors. However, significant capacity building is required to unlock this potential, and water stress in certain areas can hinder production capability. Most countries are looking to develop renewable hydrogen production, using solar and wind (e.g., Egypt, Kenya with the Turkana wind farm, or Angola), hydro (e.g., in Ethiopia, the Congo River in DRC) and geothermal (notably in Ethiopia, Kenya which will soon have 140 MWh capacity in geothermal, Uganda, Tanzania, and Rwanda – however less likely due to its high cost). Namibia willsoon be home to one of the largest renewable hydrogen projects on the African continent, with electricity generatedfrom solar and wind power plants in the Tsau/Khaeb National Park. From an export perspective, renewable hydrogenproduction could be favoured to suit the European Union market. In addition, some countries could exploit their naturalgas resources (Algeria, Nigeria, Mozambique, Egypt, Tanzania) to produce low-carbon hydrogen, while Mali is opening theway to the extraction and production of naturally occurring geological hydrogen found in underground deposits (often referred to as "white hydrogen"), being the first country in the world to produce electricity from natural hydrogen with its pilot project in Boukarebougou.

In terms of cost competitiveness, the cost of renewable hydrogen is decreasing (see the section on Insights on hydrogen supply chains developments) and moving towards a par with conventional hydrogen in some places (South Africa, Namibia, Northern African countries). In the short term, access to water suitable for electrolysers may require upstream investments to desalinate water in parts of the continent, which may require additional investment particularly in water-stressed areas and improvement of a suitable technology. By 2050, most African countries are expected to be able to produce low-carbon hydrogen at 1 USD/kg, which would then make it a competitive fuel for local consumption in Africa.

Transport and Storage

Africa faces significant challenges in terms of access to energy, lack of resilient infrastructure, and inadequate technological and skills capacities. The lack of infrastructure to transport energy across one country in various parts of Africa is one of the main barriers to the rapid adoption of low-carbon hydrogen. This also impacts the continent's capacity for hydrogen storage.

The development of production for export could attract investments in infrastructure development (e.g., pipelines, shipping). These investments would also need to benefit the development of low-carbon hydrogen uses domestically in order to increase value creation in each country. In the short and medium terms, North African countries are best positioned to benefit from export activities to Europe, using the existing infrastructure. Low-carbon hydrogen and derivatives such as ammonia for fertilisers could be favoured in the short term, with Morocco having already laid its ambition for both products. Besides Europe, shipping routes could also support export to Asian importing markets. Potential synergies could be explored at the sub-regional level with the development of the 5 Power Pools, namely the Southern African Power Pool (SAPP), Eastern Africa Power Pool (EAPP), Central African Power Pool (CAPP), West African Power Pool (WAPP) and North African Power Pool (NAPP), the sub-regional multi-stakeholder institutions that coordinate cross-border power trade and grid interconnection among African nations.

Looking at the global supply chain development, many bilateral partnerships are emerging between African countries and future net-importing countries in Europe and Asia. Few bilateral or multilateral cooperation initiatives have been flagged so far between African countries on the theme of transport and storage of hydrogen, which could benefit more the development of local uses.

ENABLERS FOR LOW-CARBON HYDROGEN RAMP UP

Africa may not be ready to produce and use hydrogen at scale, however in this decade infrastructure and other capacities can be built up and appropriate policies and regulations developed to promote low-carbon hydrogen production and consumption. In this context, the development of pilot projects with innovation and technology transfer and subsidies support to test the business models before scaling up is key. In addition, developing regional cooperation is seen as a priority in the region. Therefore, identifying the required cooperation and coordination frameworks with all the concerned parties is seen as a priority, and notably between African universities and research centres to team up in the study of hydrogen, and reduce dependency on technologies from outside the region. In the African context, the sub-regional level could also be relevant in developing cooperation (Sub-Saharan Africa, Maghreb, East Africa, etc.).

Experts have identified priority actions for hydrogen ramp up in Africa. These are challenging structural tasks, that require significant reforms. The appropriate organisation or group of stakeholders to lead the implementation of these actions are yet to be determined. These actions include: 1- Making an inventory: identifying the role of hydrogen in the energy transition process and conducting gaps assessment of human capital deficit in Africa and gaps assessment of infrastructure requirements. 2- Developing a regional roadmap setting out the African countries' vision for the development and scaling up of a hydrogen economy. This roadmap should take a 'whole-system approach' to developing the hydrogen economy, setting out how governments and industries need to coordinate and deliver activity across the supply chain, detailing the supporting policies and their timeline and review process. 3- Reforming the Industrial Strategies to set out a vision of how Africa can turn low-carbon hydrogen into a viable solution to decarbonise different sectors over time. 4- Increasing hydrogen literacy with awareness-raising, education, and demonstration initiatives, to develop buy-in.

Across the continent, a priority area for investment relates to research and development and training, focusing efforts on reducing low-carbon hydrogen cost, notably its transport and storage, but also looking at production technologies, for instance exploring alternative materials in cathodes to take account of available inventory (e.g., nickel).

Finally, looking at exporting opportunities, it is crucial for hydrogen development in Africa to better capture the value associated with export. Priority measures to ensure the success of the export-import model can be implemented jointly in institutional, political, and financial areas. African players call for incentives from the global level and importing markets (e.g., quotas, reduction of taxes on African hydrogen exports, carbon prices at both international and national levels), as well as importers' investment plan in Africa not only focusing on security of supply but also on benefitting Africa (e.g., programmes for technology transfer, building facilities to manufacture electrolysers, training of workforce, etc.). In that context, Africa could notably build on the strong ties with Europe to help to realise the Paris Agreement targets and the African Union's Agenda 2063. In this regard, the recommendations of the Africa–Europe High Level Platform on Sustainable Energy Investments (Africa–Europe High–Level Platform for Sustainable Energy Investments in Africa, 2019) should particularly be considered.

ASIA-PACIFIC

LOW-CARBON HYDROGEN DEMAND PERSPECTIVES

There are strong differences within the Asia-Pacific region as to what are the short-term priority end-uses for low-carbon hydrogen. The lack of clear application priorities illustrates the region's overall approach to hydrogen, driven by South Korea and Japan's visions for a "hydrogen economy" by 2050. Low-carbon hydrogen can first support the decarbonisation of existing industrial hydrogen applications, for instance regarding ammonia and methanol production, the iron and steel industry and refining applications, as emphasised in Australia, New Zealand, Singapore, China, Japan and India. The switch from hydrogen derived from fossil fuels to low-carbon hydrogen in the industry shows tremendous potential in the region – e.g., replacing hydrogen from fossil fuels in for instance China, which is currently the world's largest hydrogen user in the refining and chemical industries. At the same time, many countries are broadening the scope of low-carbon hydrogen applications in other hard-to-abate sectors, such as the mobility sector. Singapore, China, South Korea and Japan have put an emphasis on hydrogen use in light passenger vehicles, buses and taxis, while Australia focuses on heavy-duty transport, such as heavy trucks, mining machinery, and buses. Asia-Pacific is the region where the FCEV market is currently advancing the most rapidly, with South Korea, China and Japan being in the top 4 largest markets for FCEVs today. In terms of transport, low-carbon hydrogen use in the maritime sector is a priority for Singapore for instance, and R&D initiatives are seen in the shipping sector particularly in Australia and Japan.

Moreover, low-carbon hydrogen use is being explored to diversify energy fuels. Its use is therefore considered for power generation in Australia, Singapore, Japan, Hong Kong, and South Korea, and blending in the gas network in Australia, New Zealand, Hong Kong, or Singapore for city gas. While it does not appear to be an area of focus in most regions at this stage, hydrogen use in building heating is high on the Japanese and South Korean agendas, while Australia is testing the blending of low-carbon hydrogen in existing residential gas appliances.

Finally, low-carbon hydrogen uptake could benefit economic growth. Considering the huge potential volume of demand for low-carbon hydrogen in Asia-Pacific, export is the priority end-use for Australia's low-carbon hydrogen production, which could support cost reduction and in turn increase internal use, as well as for New Zealand to a lesser extent. India could also consider low-carbon hydrogen export to its neighbours, after meeting internal demand. Domestic use in India could support the achievement of air quality targets in the mobility and industry sectors and could also support the country's population growth by serving its agricultural needs with ammonia for fertilisers and infrastructure developments with low-carbon steel. In addition, Asia-Pacific countries could also become exporters of hydrogen-related technologies, with fuel cell technology manufacturing taking place in countries like South Korea, China, and Japan.

SUPPLY CHAINS

Production sources

The Asia-Pacific region focuses on "carbon-free" hydrogen (i.e., low-carbon hydrogen), exploring different production methods and energy sources. India, Australia and parts of Southeast Asia possess tremendous solar resources, while New Zealand is one of the windiest countries in the world and has large onshore and offshore wind potential, as well as geothermal potential. Low-carbon hydrogen used in the Asia-Pacific region could also be derived from natural gas with CCUS, and coal with CCUS – the latter being continuously used by China and Australia who are amongst the few countries in the world considering this technology in the long term. In addition to differing technology routes, views differ across countries regarding the role that hydrogen produced from non-renewable sources with CCUS should play in the mix, and for how long. New Zealand is already focusing on producing and using only hydrogen from renewable energy sources, as new gas exploration permits are not being issues in the country, outside the Taranaki region. Some countries plan to rely on low-carbon hydrogen from natural gas with

CCUS, alongside hydrogen from renewable sources during the ramp up period, such as Singapore which plans to switch to renewable hydrogen only in the future, and South Korea which has set a target of using 70% of renewable hydrogen by 2040. On the contrary, Japan treats hydrogen from renewables and from natural gas with CCUS equally, preferring to refer to “carbon-free” hydrogen, and China plans to use all resources available in its territory to produce hydrogen (i.e., renewable energy, natural gas and coal with CCUS).

In that context, the dilemma between supporting low-carbon hydrogen or its derivative ammonia in the infrastructure ramp up phase has been particularly highlighted in the Asia-Pacific region. While some experts argue that both supply chains can develop in parallel, others consider that only one can reasonably be explored for the scale up phase due to the massive investments required. Some consider that ammonia should be a first step, due to its existing supply chain and its properties making it easier to transport, while others consider that low-carbon hydrogen can be produced in bigger volumes in the short time.

Similar to other regions, cost reduction of low-carbon hydrogen and its derivates is the priority. Asia-Pacific countries are putting an emphasis on reducing the cost of transport and CCUS technologies, notably via developing financial support mechanisms and R&D efforts to develop new technologies. Shifting the conversation from production cost to final price for end-users is particularly crucial in Asia-Pacific, where the biggest future demand centres are at a significant distance from hydrogen production places. Projected future net-importer Japan is expected to be procuring 300,000 tons of low-carbon hydrogen annually at the price of ~USD 2.89/kg[3] from 2030, and South Korea is targeting a low-carbon hydrogen supply in 2040 of 5.26 million tons/year at the price of ~USD 2.49/kg.

Transport and Storage

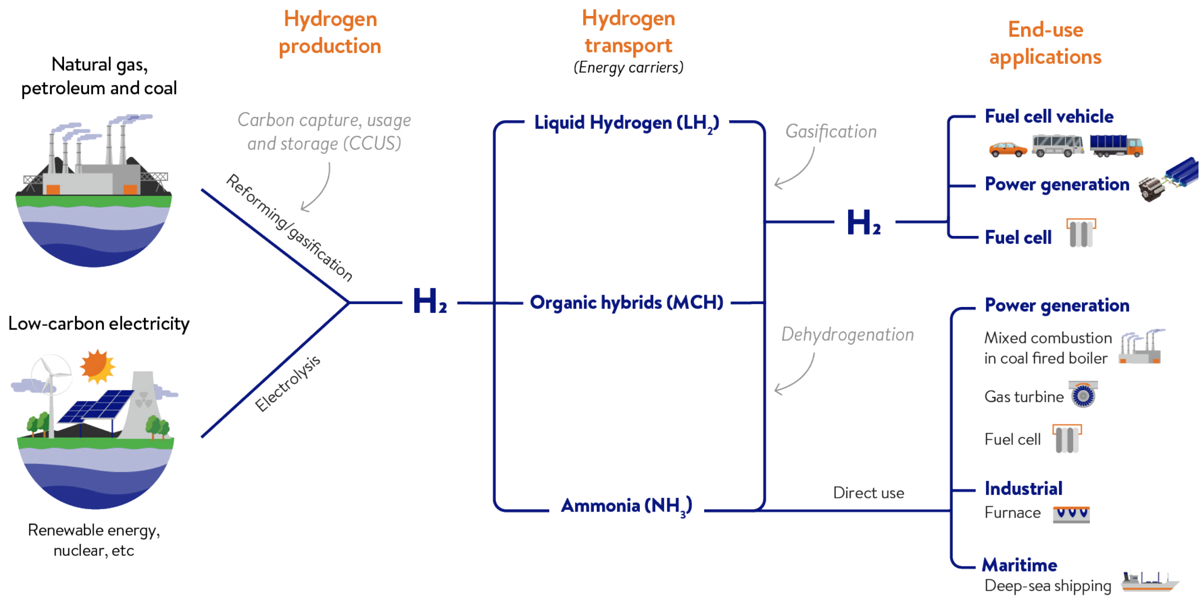
The shaping of the low-carbon hydrogen supply chain is already underway in the Asia-Pacific region, with Japan, South Korea and Australia having been the first countries worldwide to release a dedicated national hydrogen strategy. Japan and South Korea are already identified as future significant net-importers for low-carbon hydrogen, while Australia and New Zealand have positioned themselves on the exporting side. China and India, with massive expectations for internal demand in the mid-term, combined with significant available energy resources, could aim to become self-sufficient, if the appropriate additional capacity is built. Identified future net-importers and exporters are developing inter-country cooperation along the supply chain to remove obstacles for off-takers and secure the first volumes of supply. Many Memoranda of Understanding have already been signed by future high demand countries with partners in the region, as well as with outside countries, for instance between Japan and Argentina, South Korea and Russia, or Singapore and Chile. Singapore is also exploring potential cooperation with its neighbours Malaysia and Indonesia for potential renewable hydrogen projects there, for export to the Singaporean market.

Long distance transport of low-carbon hydrogen is crucial to the development of a hydrogen economy in the Asia-Pacific region. Future net-importing countries such as Japan and South Korea are at the forefront of the exploration and testing of various hydrogen energy carriers. At this stage, there is no consensus over the preferred hydrogen carrier, between ammonia, liquid hydrogen, methylcyclohexane (MCH), or low-carbon hydrogen embodied into finished products. Ammonia appears to be leading in the short term, due to its cost, the infrastructure readiness and direct combustion in energy systems. For instance, the power industry in Japan is planning to start the commercial use of fuel ammonia by mix combustion in coal power plants in 2027. However, all potential carriers are being considered as related infrastructure, transport and storage technologies, and prices evolve over time.

Within each country, various transport methods are being explored to accommodate their geographical specificities and end-uses. New Zealand is transporting its current hydrogen production via trucks with liquid tankers or tube trailers and is also exploring transport in the country via blending from 2030 onwards and via dedicated pipelines. Blending is also considered by India, which is developing its gas grid infrastructure. South Korea has a project to build Asia’s largest hydrogen liquefaction plan to supply its transport sector with low-carbon hydrogen. Meanwhile, China is facing challenges to transporting hydrogen internally between production plants located in West China and demand centres in Eastern China, notably due to a constrained and congested electricity grid.

[3] Exchange rates applied: 1 JPY = 0.0086 USD; 1 KRW = 0.00083 USD.

Figure 10. Hydrogen supply chain



Source: World Energy Council

ENABLERS FOR LOW-CARBON HYDROGEN RAMP UP

The Asia-Pacific region with its future big demand centres is at the forefront of the development of a global low-carbon hydrogen market, alongside Europe. Consequently, the region is one of the most active in terms of building cross-countries cooperation to progress the hydrogen supply chain, within the region and worldwide. This cooperation is seen bilaterally, notably via the development of bilateral partnerships and signing of MoUs, but also multilaterally, taking a leading role in associations such as the Clean Fuel Ammonia Association or in intergovernmental initiatives like the Hydrogen Energy Ministerial Meeting. Multilateral cooperation could be further enhanced in the region. Many experts in the region call for the establishment of a standard for tradable low-carbon hydrogen and carbon footprint certification and joint work on policy provisions on maritime legislation, at the global level if possible, or regional level in the meantime.

In terms of energy policy, the Asia-Pacific region could be particularly innovative in applying an integrated approach to its energy systems, looking at varying decarbonising technologies, energy storage options, infrastructure requirements, and country context (e.g., current energy mix and resources) when considering hydrogen's positioning compared to alternatives. This approach can result in tackling all aspects of energy systems at once. More prioritisation in areas of hydrogen applications, productions methods and transport and storage techniques could be considered in the ramp up phase.

Finally, two specific areas for action priorities in the region relate to supporting hydrogen-related technology development; and facilitating the development of the supply chain for hydrogen use in the mobility sector, via direct investment, incentives, and subsidies, or (de)regulation. At this stage, little cross-countries cooperation has been identified on those two strategic priorities for the region, which could be areas to develop competitive advantages.

EUROPE

LOW-CARBON HYDROGEN DEMAND PERSPECTIVES

Europe is taking the lead in the hydrogen run today, with a huge investment plan and commitment to the Green Revolution using low-carbon hydrogen. Demand in the European Union is estimated at 60 million tonnes by 2050, of which 30 million tonnes may have to come from imports (Word Energy Council - Europe, 2021). To stay on track with the goals of the Paris Agreement, an increased penetration of low-carbon hydrogen in the European energy mix requires that infrastructure and project developments accelerate in order to unlock the significant growth potential for low-carbon hydrogen that is emerging today. For this to be successful, hydrogen would first have to be produced locally as large quantities cannot be imported yet due to a lack of infrastructure. In Europe, low-carbon hydrogen use is predicted to increase in areas where there are limited alternatives for carbon abatement. Industry, including the chemical industry, will be a first mover to decarbonise its processes with low-carbon hydrogen. In the mobility sector, the use of hydrogen is likely to play a significant role in the heavy-duty transport, as well as in the aviation and shipping sector in the longer term, especially after further processing into hydrogen-based fuels. In the long run, hydrogen might also be used as storage of renewable electricity in order to run hydrogen-fired gas plants as back-up for intermittent renewable electricity generation. International trade and import of low-carbon hydrogen will be critical for Europe, due to its lack of fossil fuel resources, its current need to diversify from a gas dependence, and as the capacity of renewable energy in the continent is likely to be insufficient to produce hydrogen at the scale required. Therefore, the EU is actively engaging with potential regional exporters, notably through financing grants and loans, technology transfer and or sharing, human capacity building, enabling markets for increased renewables focus. On another note, a balance should be found between importing low-carbon hydrogen to the European market and ensuring that exporting countries retain sufficient quantities to benefit their own decarbonisation efforts, which Europe globally advocates.

Opinions diverge regarding the role of hydrogen blending with natural gas in the early phase of low-carbon hydrogen uptake. While blending can be an intermediate solution to help decarbonise the natural gas end-use applications which are lacking current suitable alternatives, other experts argue that it can divert currently limited low-carbon hydrogen volumes from direct end-users. This highlights the issue of matching supply and demand, as European industries' decarbonisation ambitions can be hindered by the current lack of sufficient quantities of low-carbon energy solutions.

SUPPLY CHAINS

Production sources

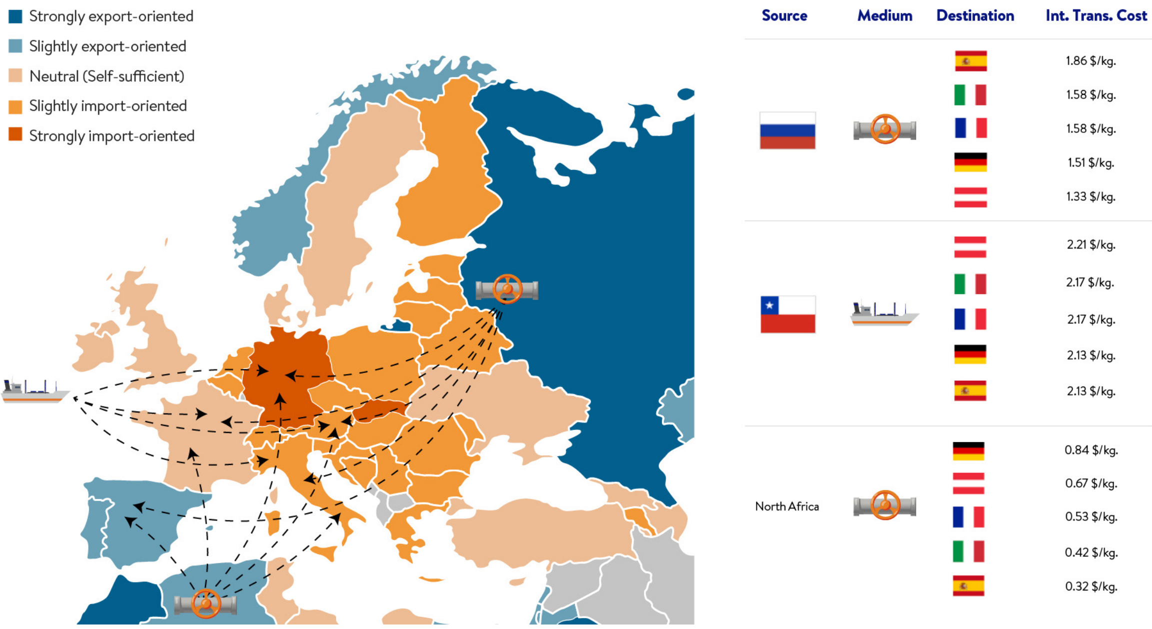
The European region overall strongly favours hydrogen from renewable energies. However, more production sources increasingly appear necessary in the future, especially in the scaling-up period (e.g., from nuclear, fossil-based with CCUS or by methane pyrolysis). Some European countries are looking at exporting low-carbon hydrogen to their neighbours, such as hydrogen from natural gas with CCUS or locally with methane pyrolysis from Norway or Russia, hydrogen from nuclear from France, or renewable hydrogen from Portugal and the Netherlands – with ports such as the Port of Rotterdam acting as a hub to connect outside exporters to European importers. However, import volumes will likely remain relatively limited until 2030, while infrastructure gets built and low-carbon hydrogen prices decrease. Looking towards 2035, 2040 or 2050, when more integrated infrastructure is expected to be in operation, European countries rich in renewable resources, such as Greece, Iceland, Italy, Norway, Russia, Spain and Turkey, could provide lower cost low-carbon hydrogen for the region. Depending on offshore wind technology developments, more countries could also produce a portion of their direct use.

For this mainly low-carbon hydrogen importing region, it is particularly crucial in the current economics debate to consider and better assess additional costs in the final price, which are added to the production cost, for instance transport cost, including its carbon footprint, as well as taking into account the expected profit margin, etc. More analysis of transport costs across options is particularly needed, looking notably at maritime options – looking at different technologies' cost, readiness, realistic ramp-up time considering the number of ships needed, port infrastructure, etc., and pipeline options – using existing gas infrastructure with blending or fully dedicated to hydrogen transport for instance.

Transport and Storage

Three different scales of projects seem to be emerging in Europe to meet the region's growing demand in the short and long term. First, on-site projects are rising in Europe to answer the increasing demand in hard-to-abate sectors. Hydrogen hubs link production projects to closely located users (e.g., industrial hubs) or already include a dedicated demand player directly in the production plan. Europe hosts most of the existing or planned hydrogen hubs today (e.g., Europe's Hydrogen Hub: H2 Proposition Zuid-Holland/Rotterdam aiming for 3180 tonnes/day low-carbon hydrogen production; HyNet Worth West in the United Kingdom, aiming to produce 1600 tonnes/day). Producing low-carbon hydrogen where the demand is, helps to limit transport and storage costs, thus allowing these projects to reach more competitive delivered hydrogen prices. However, this leads to an increasing demand for electricity infrastructure. Secondly, European demand can be supplied with off-site electrolysers in regions with high renewable energy capacities, which can produce low-carbon hydrogen and transport it within a country for instance via pipelines to industries (e.g., electrolysers on the North coast of Germany producing hydrogen that will be used in other parts of Germany). Finally, to supply Europe with hydrogen from abroad, it is essential to develop the import infrastructure to transport hydrogen from regions with more favourable production conditions. Since large-scale infrastructure implementation such as pipelines and terminals take several years to a decade to materialise, construction needs to start as soon as possible, in parallel to the expansion of renewable and electrolyser capacities. The European Hydrogen Backbone vision calls for building and repurposing 11,600 kms of new and existing pipelines by 2030, and 39,700 kms by 2040. Similar projects aim to ensure that production locations and demand centres are interconnected.

Figure 11. Cost of imports from different sources to the EU



Source: World Energy Council

METHODOLOGY

The map is based on data available in (Word Energy Council - Europe, 2021). The report calculates the cost breakdown of the different low-carbon hydrogen imports from Russia, Chile, and North Africa, towards 5 EU member states (Austria, France, Germany, Italy, Spain) by 2030. The map compares exclusively the cost of international transport (excluding the cost of transmission and distribution) from the 3 sources (Chile by ship; Russia by pipeline; North Africa by pipeline) to the different EU member states.

One of the biggest unknown or gap in Europe's low-carbon hydrogen supply chain's development is its storage. Europe holds in its territories various salt caverns that could for instance be used for hydrogen storage, as seen in France, Germany, or the Netherlands for example. Some countries (e.g., Sweden, Switzerland) are also exploring the option of lined rock caverns as possible long-term storage for hydrogen and methane. However, long-term and large-volume storage solutions and infrastructures for hydrogen are lacking. Moreover, in the efforts to reach net-zero emissions by 2050, the issue of storage for low-carbon hydrogen is combined with that of capturing and storing carbon emissions.

ENABLERS FOR LOW-CARBON HYDROGEN RAMP UP

The European region counts the most countries with national strategies already published or in preparation. The implementation phase is underway; however, project owners highlight regulatory obstacles. Policymakers must now create suitable framework conditions to enable the market ramp-up of hydrogen.

In the European Union, misalignment between the different Member States' policies, due notably to conflicting views towards the various low-carbon technologies, is creating complexity for project owners and blockage for investments. The high electricity prices are also seen as an obstacle, and politicians are expected to develop measures to reduce them by reducing charges, taxes, and levies especially during the initial market growth phase. A good balance must be found in additionality requirements, between regulated requirements for the purchase of electricity for hydrogen production, and the need to avoid strangling a nascent industry. Care must also be taken to ensure that the Renewable Energy Directive (RED II) requirements, including additionality and time matching principles, are still feasible and pragmatic. If these principles are interpreted too rigidly; this would make the ramp-up of the renewable hydrogen market in the EU significantly more difficult, more expensive and delay it by years in all sectors. To this end, it is of great importance that the delegated act for RED II, which is intended to set out the rules for the production of renewable hydrogen - as well as other renewable fuels of non-biological origin (RFNBOs) - from electricity via electrolysis, and which was announced for the end of 2021, is published promptly and in a pragmatic way so that planned projects are not slowed down further. Carbon contracts for difference are also seen as a particularly helpful tool in closing the price gap between renewable hydrogen and currently used fossil alternatives. For sectors that can pass on their CO_2 costs to their customers (e.g., refineries, automotive industry), quotas for the blending of low-carbon products are also a good instrument. In addition, in this centre of expected high demand for low-carbon hydrogen, more financial support mechanisms should target demand-side management, for instance with tax credits).

For a mainly net importing region, the development of international trade of hydrogen and derived products (e.g., liquid fuels) is essential. Therefore, a priority for Europe is the development of trading regulations or standards, certification schemes to support demand players, and working towards making low-carbon hydrogen a commodity, which requires new infrastructure investments, new off takers, etc. This requires increasing cooperation between European countries, as well as worldwide and across the supply chain (e.g., between renewable energy expertise and chemical expertise). In that context, moving towards more coordinated hydrogen diplomacy action, from a reality of bilateral agreements to one where the EU plans ahead in the name of the entire EU-28, could support the scaling-up process, notably in terms of volumes, and increase the development of projects across the EU.

LATIN AMERICA AND THE CARIBBEAN

LOW-CARBON HYDROGEN DEMAND PERSPECTIVES

Low-carbon hydrogen uptake in Latin America and the Caribbean will be seen first in the hard-to-abate industry and mobility sectors. Low-carbon hydrogen particularly shows potential to decarbonise heavy duty and long-haul transport, notably for food transport, and the public transport sector, notably buses. There is also high demand potential for low-carbon hydrogen in the steel sector, for existing buyers of fossil-based hydrogen in oil and gas refineries and petrochemical industry, and in the cement industry. In mining, low-carbon hydrogen could be deployed at scale in the short term for the transportation of heavy minerals and to decarbonise inputs required for the mining process such as ammonium nitrate. The agriculture sector is another end-use area of potential for low-carbon hydrogen in Latin America and the Caribbean, specifically for the local production of green fertiliser. Ammonia already presents a potentially important market in the region and is projected to remain one of the largest consumers of hydrogen in the long-term. Brazil, for instance, currently imports 80% of the ammonia used for making fertiliser.

Finally, many countries in Latin America and the Caribbean aim to explore their potential to export low-carbon hydrogen and its derivatives in the short (Chile, Brazil, Uruguay), mid- (Colombia), or long term (Peru). Various hydrogen derivatives and low-carbon products are being considered, notably goods in which low-carbon hydrogen is substituted in the existing production process (food produced with green fertilisers, green steel in cars, cements, etc.).

SUPPLY CHAINS

Production sources

In Argentina and Colombia, the existing fossil fuel derived hydrogen industry constitutes a strength point, and therefore production of low-carbon hydrogen using fossil resources and CCUS is considered as a transition, at least in the short and medium terms. Similarly, in Trinidad and Tobago, the focus is on this type of hydrogen production method since mature oil fields already exist and captured CO_2 could be used and injected for Enhanced Oil Recovery (EOR) operations. The country is exploring renewable hydrogen projects as well, with the announced project “NewGen hydrogen project” expected to produce 27 thousand metric tonnes per year. In terms of cost competitiveness, the cost of low-carbon hydrogen using fossil resources and CCUS will depend on the price of natural gas and sequestration of CO_2 in each country.

As for other LAC countries, renewable hydrogen is the priority production method. In Chile, the national strategy focuses only on hydrogen produced from renewable energy. Similarly, Costa Rica, Paraguay and Uruguay are considering only renewable hydrogen production and disregarding low-carbon alternatives due to the complicated infrastructure requirements of CCUS, lack of adequate oil and gas reserves, as well as the lack of appetite for hydrogen from non-renewable energy sources from prospective importing countries.

In terms of cost competitiveness, renewable hydrogen will be competitive in producing countries with existing incentives for renewable energy from the government. Although the cost estimates are uncertain, in Uruguay, a joint study withthe Port of Rotterdam has highlighted that the price of local hydrogen in Uruguay could come down to ~USD 1.51 /kg[4] by 2030, and the price delivered in Rotterdam near ~USD 2.9 /kg. In Colombia, the expected cost of renewable hydrogen varies between the different regions and the technology used. Table 2 showcases the expected cost of renewable hydrogen production towards 2050 in Colombia. For low-carbon hydrogen from fossil fuels with CCUS, various factors affect the cost, including anticipated CO_2 prices, as well as the rising natural gas and coal prices. On average, the estimated cost is ~USD 2.4/kg (assuming a 20 USD/tCO_2 price) in 2040.

Table 2. Evolution of renewable LCOH in Colombia (USD/kg H2)

	Northern Caribbean Region (Wind)	Northern Caribbean & Northern Andes Regions (Solar)	Southern Caribbean, Southern & Central Andes, Orinoco and Amazon Regions (Solar)	Pacific Region (Solar)
2020	2.8	4.8	5.5	6.6
2030	2.2	2.7	3.1	3.7
2040	1.8	2.2	2.5	3
2050	1.5	1.7	2	2.4

Source: Ministry of Mines and Energy - Colombia, 2021

Transport and Storage

Most LAC countries are still weighing their options in terms of transport mediums for the produced hydrogen. However, a major consensus and a clear favourite in the short term is ammonia as a carrier for continental exports. Another form of transport being explored is methanol, but nothing is final yet as countries still explore the most cost-effective options, as well as the requirements of the future prospective importers (mainly Europe). In terms of imports and exports between LAC countries, the existing natural gas infrastructure could play a major role in the transport of low-carbon hydrogen between countries. Although the network is irregular, with a concentration of pipelines in the North (starting from Venezuela and Trinidad and Tobago) and the South (starting from Bolivia), which illustrates the unequal economic situation and energy policies of the different countries, new gas pipelines are still under construction. The LAC regional policy is aimed currently at strengthening the capabilities of the existing pipelines, which arrive in Argentina and Brazil from Bolivia.

However, scaling up hydrogen transport will require in parallel a scale up of storage infrastructure and port terminals, which will require significant investments and time. Large-scale hydrogen value chains in the future will require a broad variety of storage options. Geological storage is the best options for large-scale and long-term storage, specifically for countries like Trinidad and Tobago, Argentina, and Brazil (i.e., storage within salt caverns, saline aquifiers, depleted natural gas or oil reservoirs[5]). For short-term and small-scale storage, storing hydrogen as a gas or liquid in tanks (i.e., compression/cryogenic systems) seems the most suitable option.

Figure 12. Natural gas pipelines infrastructure - Latin America and the Caribbean

Source: Snam S.p.A., 2018

[4] *Exchange rates applied: 1 EUR = 1.16 USD.*

[5] *Storing CO_2 in a depleted hydrocarbon fields has challenges. It necessitates a purification process of the hydrogen after extraction since they contain sour gases and hydrogen sulphide, in addition to other corrosive gases. Mobility and other industrial applications require hydrogen with a minimum of 98% purity.*

ENABLERS FOR LOW-CARBON HYDROGEN RAMP UP

Reinforcing regional cooperation could particularly benefit hydrogen development in Latin America and the Caribbean. Before competition on export can happen between countries (e.g., on low-carbon hydrogen or on products using low-carbon hydrogen in the production process, like green fertilisers), cooperation is needed to bring more visibility to the continent, attract international investments and establish its role as a low-carbon hydrogen market. With collaboration, countries in the region can have more aggregated value in the low-carbon hydrogen economic chain, which is hard to do alone, particularly for small countries. Cooperation can happen especially at the technical level, building on the individual countries' strengths (e.g., between great resources in Argentina, potential for investments in Chile, many possible off-takers in Argentina or Colombia, one of the cheapest electricity costs in Paraguay and Brazil, etc.) to fully utilise each country's advantages.

Some common regulation priorities for low-carbon hydrogen development at the country level have been identified in the region. Firstly, defining hydrogen in energy laws is a priority issue to resolve. Brazil is amending the law and incentives for biofuels (e.g., hydrogen produced from biomass recognised as a biofuel). Biofuels have taxes and are not subsidised, however there is a programme in place for companies using biofuel to have certain benefits. Chile is working on a law to treat hydrogen as a fuel, in order to send a strong signal to the market, while Colombia is looking to implement for hydrogen a legislation similar to the Law 1715 of 2015 which promotes the use and development of renewable energy in the national energy system through tax incentives. Secondly, various countries are assessing hydrogen blending in the gas grid: notably Argentina and Colombia would need to review existing legislation to assess feasibility and safety of using the existing natural gas pipeline network for hydrogen blending; and in Chile, a new energy efficiency law requiring hydrogen blending in gas grids (up to 10%) was passed in February 2021.

MIDDLE EAST AND GULF STATES

LOW-CARBON HYDROGEN DEMAND PERSPECTIVES

In the Middle East and the Gulf States (MEGS) region, several countries have already announced their pledges for net zero carbon emissions by 2050 (i.e., KSA, UAE), in which low-carbon hydrogen can play a major role. In a region characterised by vast oil and gas fields, as well as excellent clean natural resources (sun and wind) and vast acres of land, the MEGS region is at the epicentre of the low-carbon hydrogen momentum.

In terms of demand, the MEGS region is clearly focused on exporting hydrogen and ammonia to potential markets in Europe and Asia, playing a major role in helping fulfil other countries' climate objectives. However, major players that are showing interest in developing low-carbon hydrogen are only focusing on its exports and thus overlooking its potential opportunities in the local demand market. In order to develop the industry and scale it for exports, the region needs to start addressing low-carbon hydrogen demand from its local domestic market today. Initial opportunity for low-carbon hydrogen penetration lies in replacing fossil-based hydrogen used in industrial operations (fertilizer production, petrochemical production, refineries). The major challenge governments are facing in the region is making low-carbon hydrogen competitive. To overcome this challenge, countries are exploring and analysing different policy strategies to spur the demand in their energy systems.

As of today, the major low-carbon hydrogen projects are being undertaken by off-takers willing to make the first-mover risk. The low-carbon hydrogen market is being shaped by the financing for long term off-take agreements that provide security of contract for the buyers and sellers, by matching supply and demand directly (i.e., the Air Products-ACWA Power-Neom project). It is widely agreed within the region that long term off-take agreements are crucial during initial market development, before moving into more flexible contracts as the market develops and infrastructure is laid out.

Besides low-carbon hydrogen and its derivatives, other by-products are emerging in the MEGS region, and are currently being explored and assessed by the major players. An example is oxygen, which can be used by the pharmaceutical industry for different industrial applications. Another example is the extraction of minerals from the desalination plant brine, where an estimated 10% of global magnesium demand can be met with renewable hydrogen projects from within the region. Magnesium can be used in aluminium alloy production and hydrogen storage.

SUPPLY CHAINS

Production sources

The Middle East and Gulf States region is exploring both low-carbon hydrogen production pathways (from renewables and from fossils with CCUS). Having rich oil and gas reserves, along with vast expertise in the sector, hydrogen using fossil fuels constitutes a rational choice for the short term. Similarly, excellent sun and wind resources, coupled with vast lands with high solar insolation and long-term renewable energy targets, result in globally competitive renewable energy generation costs and therefore cost competitive renewable hydrogen production. Both production pathways are major supporters of the regions Circular Carbon Economy strategy (and its associated 4 Rs: Reduce, Reuse, Recycle, Remove), with renewable hydrogen enabling the Reduce aspect, and other low-carbon hydrogen with CCUS technology enabling the Remove and Reuse aspect.

On a country level, Saudi Arabia is developing a USD 6.5 billion renewable hydrogen plant, to be powered by 4 GWs of renewable energy, to produce 650 tonnes of hydrogen per day starting in 2026 (MEED,2022). In parallel, 2020 has witnessed the first pilot shipment of 40 tonnes of ammonia derived from low-carbon hydrogen with CCUS from Saudi Arabia to Japan, to be used in zero-carbon power generation. In the UAE, the government is targeting 25 % of the global low-carbon hydrogen market share by 2030. Low-carbon hydrogen projects and pilots are underway over the whole spectrum of production options: solar PV and renewable hydrogen production facilities, low-carbon ammonia production plants,and many other domestic projects in the aim of establishing the UAE as a hydrogen hub within the region (Emirates NewsAgency - WAM, 2021).

Transport and Storage

Most MEGS countries are envisioning exporting their low-carbon hydrogen to potential markets in Europe and Asia in order to foster economic growth. Bilateral agreements are being announced with other countries, which helps and accelerates the shaping of the market. Exporting hydrogen and its derivatives requires complex infrastructure. The region can use a lot of the existing infrastructure (particularly for low-carbon hydrogen produced using fossil fuels and CCUS) and can leverage its experience in ramping up large projects and expediting their execution, albeit with associated higher costs. The region will leverage its advantage and is likely to go downstream and produce low-carbon hydrogen derivatives and export them as well to maximise the benefits. More specifically, Saudi Arabia and the UAE have both successfully implemented pilot projects in CCUS with Enhanced Oil Recovery, which provide successful business models for CCUS technology (i.e., Al Reyadah CCUS project in UAE). Moreover, the region's history of production and consumption of hydrogen within their petrochemical industry, coupled with its strategic relations based on current energy geopolitics, provides it the leverage tobecome leading exporters in the hydrogen global trade.

Another challenge for exports is the associated transport cost, and the related sophisticated infrastructure required. For example, liquified hydrogen requires special tankers that are not available in the region yet. Accordingly, MEGS countries are exploring the export of natural gas and producing hydrogen on site, or even exporting renewable electricity and producing renewable hydrogen on site (regional interconnections across the Mediterranean region are already underway). Blending low-carbon hydrogen in LNG shipments (~ 10%) is also a viable solution to overcome the need for new infrastructure. However, this necessitates regulatory actions, like mutually recognised international Guarantees of Origins that acknowledges that the shipment contains a certain percentage of clean hydrogen blend and different gas specifications.

For storage, salt caverns in the region are relatively low-cost options for hydrogen storage, and are widely available in KSA, Oman, and the UAE. Moreover, depleted oil and gas reserves can also be used as storage options in the future.

ENABLERS FOR LOW-CARBON HYDROGEN RAMP UP

As the MEGS region is very focused on exporting low-carbon hydrogen and its derivatives, a globally or at least regionally recognised Guarantee of Origins certificate is crucial to the success of the region's export plans. Importing countries, mainly in Europe and Asia, will need to know the colour, carbon content, blend level (if any), and quality of the low-carbon hydrogen shipments they are off-taking, especially if they relate to the climate objectives these countries are trying to accomplish.

Governments in the region should give guidance for hydrogen consuming companies on the parameters of future anticipated internal carbon penalty. Companies need to prepare beforehand, and it is helpful to involve them early in the process to adjust internal operations on time and avoid moving in too early.

Regulatory support will be crucial to ensure a level playing field for low-carbon hydrogen opportunities. Several policies need to be considered, explored, and well-crafted to ensure a careful transition away from high to low-carbon alternatives. Carbon pricing as well as a system of Guarantees of Origins certifications are the most discussed policies at the moment. However, major uncertainties lie with the latter as they take a lot of time to develop, especially for standards that are on regional and international levels. Additionally, carbon accounting constitutes a major uncertainty for hydrogen produced from carbonised sources, with complexities rising from the scientific, as well as political aspects of accounting for carbon.

Overall, the region needs to learn from its failings. All the upcoming necessary action plans necessitate regional and global collaboration, however in the past, major regional projects failed to be delivered (i.e., Desertec & Mediterranean Solar Plan). The region needs to learn from these failures, which were caused by a lack of a regional regulatory scheme.

Case Study: Desertec

The Desertec Industrial Initiative was an industrial initiative launched in 2009 by 12 companies aiming to explore the potential to export solar energy from the desert areas of Northern Africa and the Middle East into the European electricity markets via high voltage cables. The initial project was estimated at EUR 400 billion and aimed at providing 15% of Europe's electricity needs by imported solar power. However, it failed notably due to transportation and cost inefficiency problems. Difficulties arose in 2012 when several industrial partners withdrew from the initiative due the fast-changing market conditions of the solar industry and the resulting steep drop in costs. Additionally, some partnering European countries questioned the business model of the initiative, particularly when southern European countries were struggling to absorb the excess renewable energy generated in their own markets. Similarly, North African countries realised that meeting their own domestic power demands made more economical sense than exporting their energy to Europe. Desertec 3.0, operating currently from Dubai, has been readjusted with a new concept and mission to accelerate the energy transition in the Arab World towards the supply of 'green electrons' and 'green molecules' across the regional and global energy value chains.

NORTH AMERICA

LOW-CARBON HYDROGEN DEMAND PERSPECTIVES

For North America, the low-carbon hydrogen demand sectors differ across different countries. In Canada, technology readiness around fuel cells is high, with major fuel cell technology providers already located across the country, and currently exporting their technology globally. In the short term, the priority target is the transport sector, mainly heavy-duty trucks and buses, as well as the industrial sector. Industrial processing applications in Canada (i.e., refineries, chemicals, fertilisers) are being stimulated by international demand for these products, as well as by the carbon pricing and the pending low-carbon fuel standard. This is driving investment by the private sector into large scale low-carbon hydrogen production for decarbonising the industry. Similarly, the transport sector is witnessing a growing network of hydrogen refuelling stations, particularly in Vancouver where the provincial government is providing support through Clean Fuel Credits that are available through the USD 1.5 billion Clean Fuel Fund.

In the United States, California is the leading jurisdiction in terms of implementation of a hydrogen ecosystem thanks to a clear and consistent policy approach that is targeting the transport sector. The US was leading the global deployment of Fuel Cell Electric Vehicles (FCEVs) up until 2020, before being overtaken by South Korea. Most FCEVs are deployed in California with the support of different programs and incentives targeting HRS infrastructure and low-carbon hydrogen mobility as a whole (e.g., incentives for public transit buses FCEVs, etc.). The Low-Carbon Fuel Standard mechanism in California is helping de-risk the projects over time and driving the build out of hydrogen infrastructure for mobility applications within the state. Elsewhere in the US, low-carbon hydrogen uptake opportunities are emerging mainly in the petrochemical sector. The US is one of the largest producer and consumer of hydrogen, particularly in the refining sector and in ammonia production, therefore decarbonising these two demand sectors is a priority.

In Mexico, low-carbon hydrogen has not picked up the same momentum. There are still many challenges for the development of projects - mostly associated to the legal uncertainties and lack of clear regulatory framework for the sector. However, the demand prospects are significant in the country, particularly in the industrial sector. Unless financial incentives and regulatory frameworks are put in place, market prospects for low-carbon hydrogen in Mexico are scarce. With the right policies and incentives in place, the country has a potential to install over 670 MW of electrolysis by 2030, powered mostly by solar energy. In terms of demand, renewable hydrogen can reach cost competitiveness first in the road transport sector, particularly in public transport buses and freight trucks. Moreover, the mining sector can also benefit from renewable hydrogen opportunity, with demand expected to reach 0.5 million tons per year by 2050 (HINICIO, 2021).

SUPPLY CHAINS

Production sources

Production sources for low-carbon hydrogen in the North American continent are diverse and are mainly linked to the different available energy resources in the different regions. States or provinces rich in existing oil and gas fields and assets are focusing on low-carbon hydrogen projects using these resources with CCUS (i.e., Alberta, British Columbia, and Saskatchewan in Canada), while other areas rich in natural resources like sun, wind, and hydropower, will be leaning towards renewable hydrogen (i.e., Quebec in Canada). In Canada, focus is on the "low-carbon intensity" hydrogen, which comprises production from renewable source (hydropower, solar, wind, etc.) and from natural gas coupled with CCUS. The production pathway will depend on each region's unique local resources and economic factors. In the US, a similar approach towards production exists. Regions with natural gas and coal fields are witnessing low-carbon hydrogen production with CCUS or via methane pyrolysis, whereas in other areas, renewable hydrogen projects are emerging.

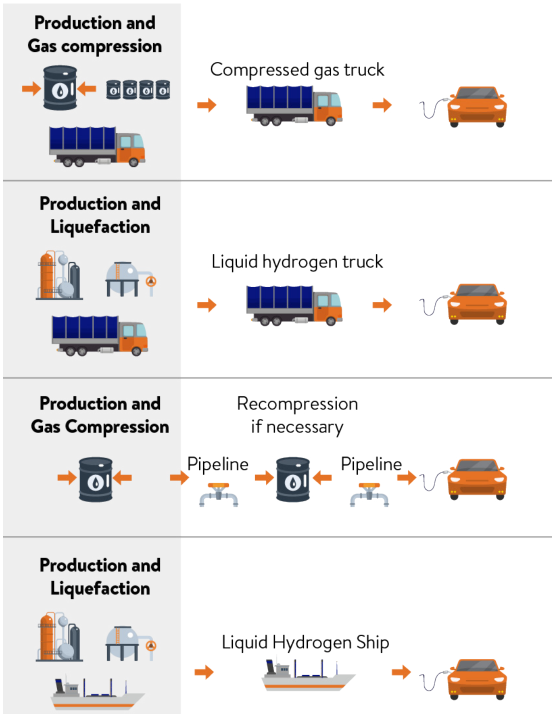
The US and Canada are leading the hydrogen production from fossil fuels with CCUS technology, with more than 80% of global production capacity (IEA, 2021). Several policies are supporting this type of hydrogen production, with "Tax Credit for Carbon Sequestration" in the US rewarding "qualified" carbon oxide – carbon oxide that would have been released into the atmosphere if not for the qualifying equipment. The tax credit range depends on whether the carbon oxide is sequestered or reused for enhanced oil recovery. In Canada, major low-carbon intensity projects with CCUS have been or are being developed, boosted by the Net Zero Accelerator initiative.

Transport and Storage

With its vast resources, Canada is envisioning to become a powerhouse in low-carbon hydrogen production, and potentially start exporting by 2030. Potential export markets are mainly in Asia and Europe, as well as the US. Key challenges for Canada lie in the domestic transport of hydrogen within its borders. As a vast country, low-carbon hydrogen produced in certain areas might not be close to the consumption clusters or port terminals. Therefore, investments in infrastructure, including new pipelines, is key to enabling the transport of hydrogen. With the dedicated hydrogen pipelines in the province of Alberta, coupled with the unique geological storage sites that include salt caverns and depleted natural gas wells, Canada can leverage its assets and experience to position itself as a major distributor of low-carbon hydrogen, locally and in international markets. However, major challenges related to regulations around blending with natural gas can hinder the progress.

Similarly in the US, hydrogen transportation, distribution, and storage aspects constitute the main challenges for integrating it into the energy system. For long distance, the US can use and expand existing dedicated hydrogen pipeline networks, similar to the ones located in the Gulf Coast between Texas and Louisiana. The region already hosts a vast network of hydrogen pipelines, hydrogen storage caverns, and plants. Another form of transport can be the existing domestic natural gas pipelines which have the potential to support the transportation of hydrogen, mainly through blending. Another option for long distances can be liquid tankers. Besides pipelines, hydrogen in the US can be transported for short distances via trucks with liquid tankers or tube trailers.

Figure 13. Primary means of hydrogen transportation



Source: U.S Department of Energy, 2020

Mexico has also great potential to export hydrogen to international markets by leveraging its excellent renewable energy resources and its geographic location which gives it access to the Pacific as well as the Atlantic Ocean. Besides marine shipping to international markets, low-carbon hydrogen could also be delivered by pipeline to the US, and particularly California.

ENABLERS FOR LOW-CARBON HYDROGEN RAMP UP

In North America, Canada and the US are already large producers and consumers of hydrogen, therefore significant opportunities to decarbonise their existing demand exist with low-carbon hydrogen. Both countries are exploring all ways of low-carbon hydrogen production - renewable hydrogen and hydrogen derived from fossil fuels with CCUS. On the policy front, the Canadian government has pushed through several programs to incentivise the implementation of use cases around low-carbon hydrogen. The Clean Fuels Fund, Net Zero Accelerator, Clean Fuels Standard, among many others, are all support programs promoting the development of clean solutions that include low-carbon hydrogen projects. In the US, a new tax credit was recently released to support renewable hydrogen, worth up to USD 3/Kg. Only hydrogen with lifecycle greenhouse gas emissions of less than 0.45 kg of CO_2eq per kg of hydrogen will be eligible for the full USD 3 credit, therefore the lower the carbon content is in the hydrogen produced, the higher the tax credit received by producers.

However certain obstacles are impeding this momentum. In Canada, the development of standards for hydrogen in natural gas pipelines is still slow. Moreover, the transport and distribution of hydrogen from the production sources to the far away demand centres or the export ports, requires major investments in infrastructure, particularly for a large country like Canada. Accordingly, the region is focusing on supporting and directing investments towards the creation of hubs, which will act as core centres for both demand and supply of low-carbon hydrogen, therefore de-risking the projects and supporting the adjacent local communities. In the US, the Department of Energy (DoE) has established the Bipartisan Infrastructure Law, which includes 8 billion USD for the creation of regional clean hydrogen hubs, aiming to create jobs and expand the use of low-carbon hydrogen in the economy.

ENABLERS FOR LOW-CARBON HYDROGEN MARKET RAMP-UP

To support the low-carbon hydrogen market ramp-up in the coming years, many policy enablers have been identified by the energy+ community, at the global, regional, and national levels (see summary in Table 4). 5 enablers appear particularly crucial across the board.

AT THE GLOBAL LEVEL

Enhanced international cooperation is needed, particularly on the development of harmonised standards, sharing of good practices and lessons learned notably from the leading countries in low-carbon hydrogen development, as well as to develop cross-border trade infrastructure and infrastructure for hydrogen transport between more distant exporters and importers. Strong and coordinated climate action with appropriate instruments is particularly fundamental in driving low-carbon hydrogen interest.

A GLOBAL GUARANTEE OF ORIGINS SCHEME WITH SUSTAINABILITY REQUIREMENTS

Experts unanimously call for the creation of a harmonised standard for low-carbon hydrogen at the global level, accompanied by a certification system to deliver guarantees of origins and facilitate the development of global trade for hydrogen. The main multi-stakeholders and intergovernmental bodies on the topic of hydrogen, and standardisation bodies should be involved in the process. This standard would need to provide clear GHG calculation rules and carbon intensity associated with the different hydrogen production methods, and provide sustainability indicators related to the full life cycle of hydrogen production (e.g., water utilisation, land use, impact on biodiversity, social and societal impact, etc.), as well as be accompanied by a certification system for the Guarantees of Origin. While experts call for the need of an international standard, which can take time and poses the risk of establishing a deliberately simplified or less ambitious framework (i.e., agreeing on the lowest common denominator) (Sailer, Reinholz, Lakeit, & Crone, 2022), national and regional initiatives are emerging to tackle the issue today, leading to the possibility of multiple competing standards. Until work progresses globally on the topic, transparency and cooperation is critical in existing initiatives to limit potential gaps or divergences between the standards.

A GLOBAL MONITORING AND REPORTING TOOL

Projects developers and stakeholders along the low-carbon hydrogen supply chain need more publicly open and up-to-date information on actual low-carbon hydrogen production and use in order to facilitate decision-making and risk assessment related to potential significant investments for future projects. Therefore, the creation of a global monitoring and reporting tool on projects developing would usefully track progress towards long-term goals. This live open platform could present existing and announced low-carbon projects and a timeline of their execution by showcasing the project description and its step-by-step implementation (e.g., project type – production, transport, demand –, funding origin, production source, price, CO_2 emissions in the period, etc.), updated regularly. The open platform would target both the experts' community and general public, with a user-friendly interactive map and performance dashboards to support awareness and literacy efforts, as well as raw data available for the informed public.

AT THE NATIONAL LEVEL

HUMANISING ENERGY

The Council's Humanising Energy agenda aims to put people at the centre of the energy dialogue and action. It enables a shift to a customer-centric perspective which is essential to better anticipate new and shifting patterns of demand, and it directs leadership attention to questions of 'pace' and societal resilience (such as full costs, affordability, justice agenda). It also enables a shift towards a broader stakeholder-centric approach, whereby the needs and expectations of the different key stakeholders involved need to be balanced and taken into consideration. Humanising Energy is critical for low-carbon hydrogen uptake; the social elements of a value-added hydrogen economy should be fundamental to national hydrogen strategies and should guide national action. Some priority areas where the Humanising Energy agenda can enable low-carbon hydrogen uptake locally include: understanding more concretely the skills needed in the low-carbon hydrogen industry, the job perspectives, and assessing workforce upskilling and job requirements; evaluating low-carbon hydrogen's place in the national energy transition and its potential impact on the affordability of the transition; delivering increasingly transparent information on low-carbon hydrogen projects to the general public ; improving public participation in low-carbon hydrogen projects and empowering the users, etc. Low-carbon hydrogen application is a relatively new technology, and therefore it provides a level playing field for all countries to develop local content programs, while allowing human capacity building opportunities.

ACROSS THE BOARD: GLOBALLY, REGIONALLY, NATIONALLY

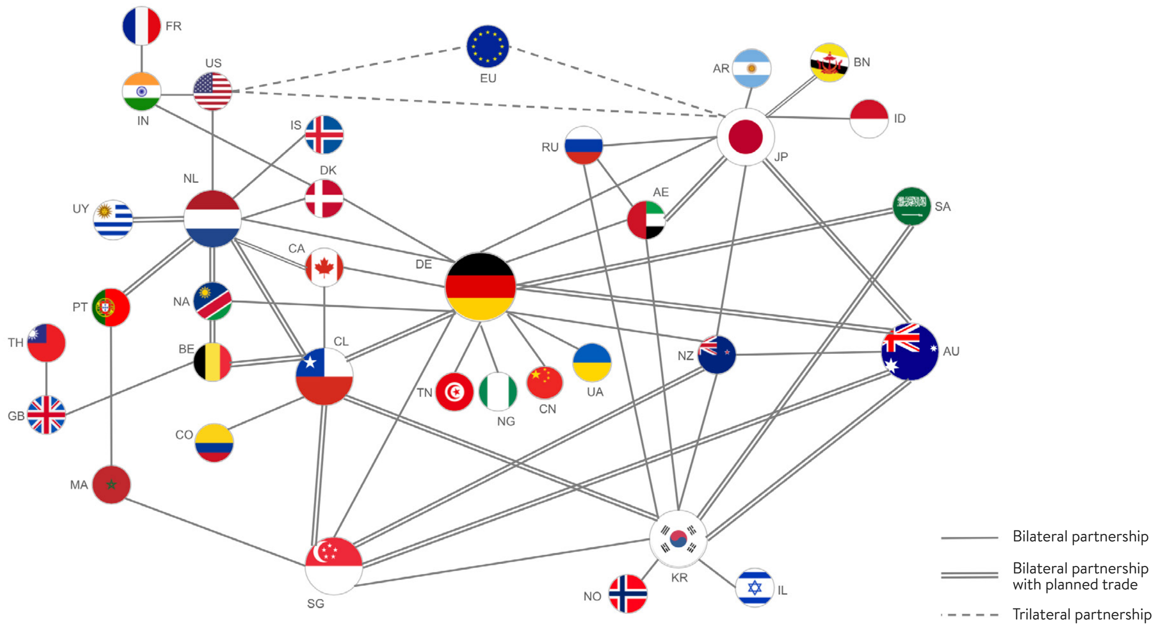
MOBILISING PUBLIC AND PRIVATE FINANCING

Mobilising public and most importantly private finance is crucial to de-risk investments, increase the number of low-carbon hydrogen projects, as well as support infrastructure development. Investments in low-carbon hydrogen projects have been increasing dramatically in recent years, but a change of scale is needed. Many actions can be taken to support hydrogen project financing, for example the development of dedicated lines of credit, the sharing of best practices in financing low-carbon hydrogen, as well as looking at previous experience in developing new industries (e.g., solar industry and LNG uptake). Financing institutions also require bankable low-carbon hydrogen projects. In addition to all the enablers identified previously and actions highlighted in each region, increasing dialogue between financers and engineers could help bring more projects to fruition. Finally, in the context of mobilising public and private financing, it is important to note that financial support in certain regions can lead to over-subsidies in certain parts of the world, which is detrimental to other producers/consumers as it blocks them from the market. Therefore, financial support offered to this industry needs to be coordinated to reduce the probability of such unintended consequences. Similarly, disincentives to other types of energy should also be coordinated to ensure healthy market development.

INCREASING MULTI-STAKEHOLDER COOPERATION

Cooperation is increasing across the board to help the low-carbon hydrogen market develop and better match supply and demand (i.e., the “chicken-and-egg problem”). Bilateral cooperation is particularly advanced, with public-private agreements being increasingly used in the low-carbon hydrogen industry, while more and more bilateral partnerships are signed between countries, mainly around the future biggest net-importers (see Figure 13). Cooperation is key and should involve the triple helix academia-private sector-government, while ensuring end users’ involvement, including citizens. Cooperation is particularly called upon within each region to facilitate sharing of best-practices and learnings between two or more countries, but also between different parts of the future global supply chain. More multi-stakeholder cooperation and sustained coordination is needed to tackle the global obstacles to low-carbon hydrogen uptake.

Figure 14. State of play of bilateral partnerships



Source: World Energy Council

METHODOLOGY

The bilateral partnerships are exclusively government-to-government agreements that can encompass trade relations around hydrogen (import/export of hydrogen fuel and/or technologies), as well as demonstrations projects, cooperation on R&D, and Memoranda of Understandings. Based on information available on 04/03/2022.

Table 3. Overview of main enablers for low-carbon hydrogen uptake in the short-term

GLOBAL LEVEL

Enablers:
- Creating harmonised standards, GOs and sustainability requirements
- Sharing good practices (in installations, policies, finance mechanisms, etc.)
- Monitoring and reporting on projects
- Developing cross-border infrastructure

Topics to tackle:
- Bridging the cost gap between low-carbon hydrogen and alternatives
- Safety across the supply chain
- Raising awareness
- Hydrogen carbon intensity according to production methods

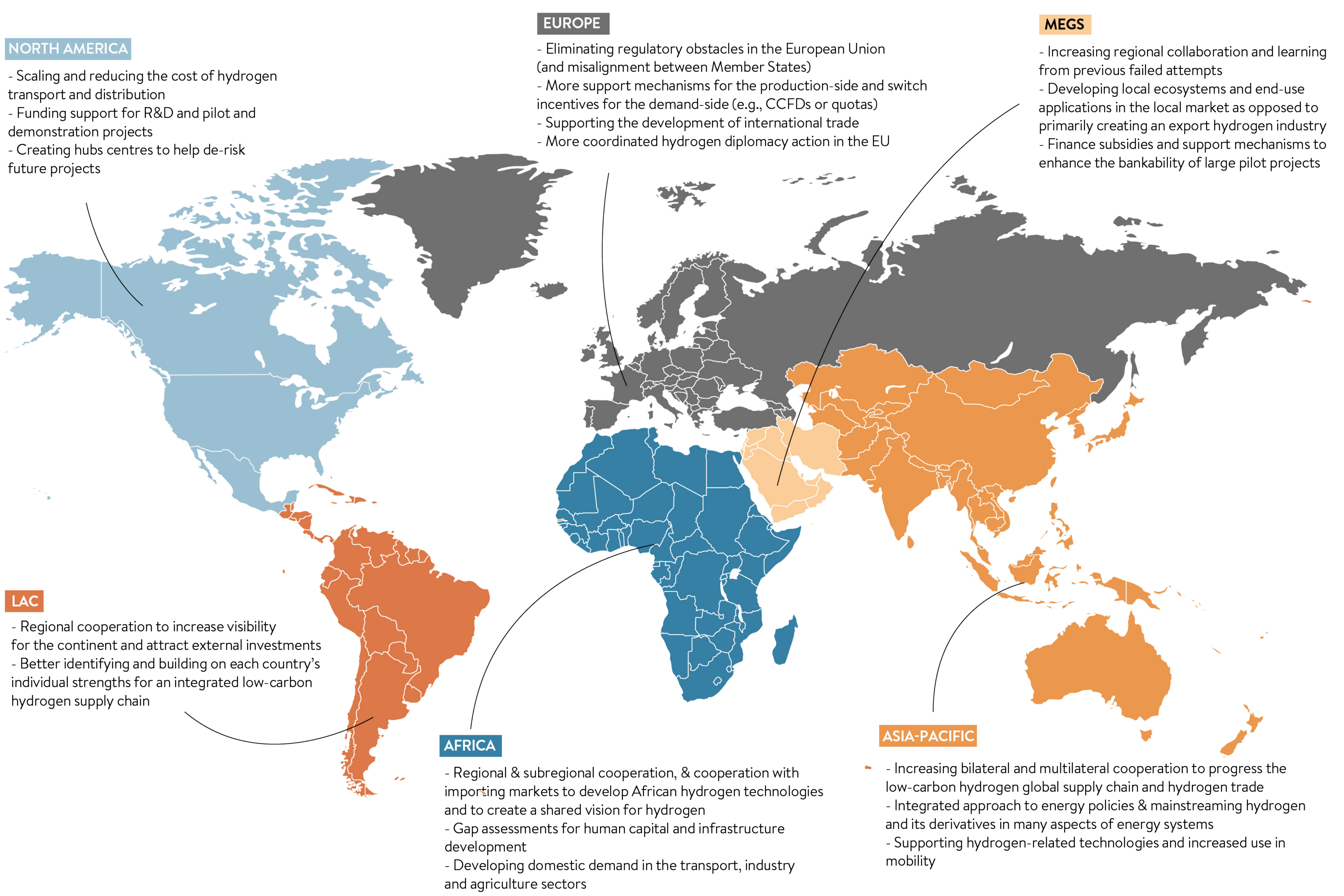
NATIONAL LEVEL

Enablers:
- Providing long term visibility
- Quickly updating regulation to address policy obstacles, notably adapting legislation to allow for clean molecules to be part of the energy mix
- Economic and financial mandates and incentives, inc. carbon pricing, blending quota, low-carbon fuel credits, etc.
- Support the development of hydrogen hubs to facilitate the creation of local demand
- Humanising energy to ensure successful energy transitions locally

Topics to tackle:
- Supporting the creation of projects along the supply chain
- Upskilling and transitioning the workforce
- Stakeholders' engagement and social acceptance

AT THE 3 LEVELS

- Increasing multi-stakeholder cooperation
- Stringent climate policies
- Safety standards and regulation
- Mobilising public and private finance: *de-risking of investments, development of dedicated lines of credit, sharing of best practices in financing hydrogen, etc.*



METHODOLOGY

Synthesis of the main enablers at the global, regional and national levels identified by hydrogen experts during dedicated regional workshops between July 2021 and February 2022.

Source: World Energy Council

ANNEX 1

REGIONAL DASHBOARDS

AFRICA

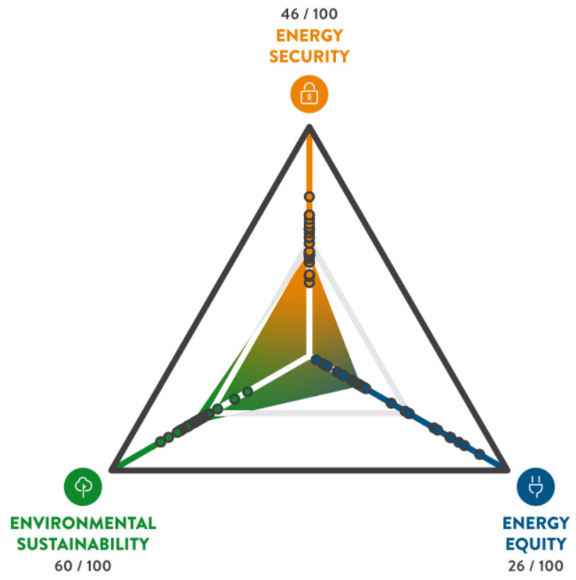
CONTEXT

AFRICA PERFORMANCE IN WE TRILEMMA INDEX 2021

46/100 Energy Security
60/100 Environmental sustainability
26/100 Energy equity
0 countries in the top 14 performers
3 countries in the top 10 improvers

AFRICAN VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

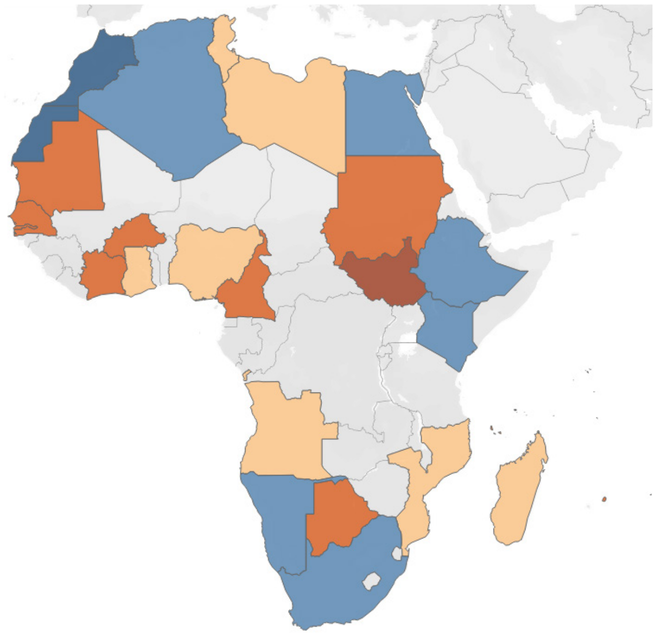
#10/25 uncertainties
#24/25 impact



SDGS

POSITIONING IN THE IMPORT-EXPORT SPECTRUM BY 2040

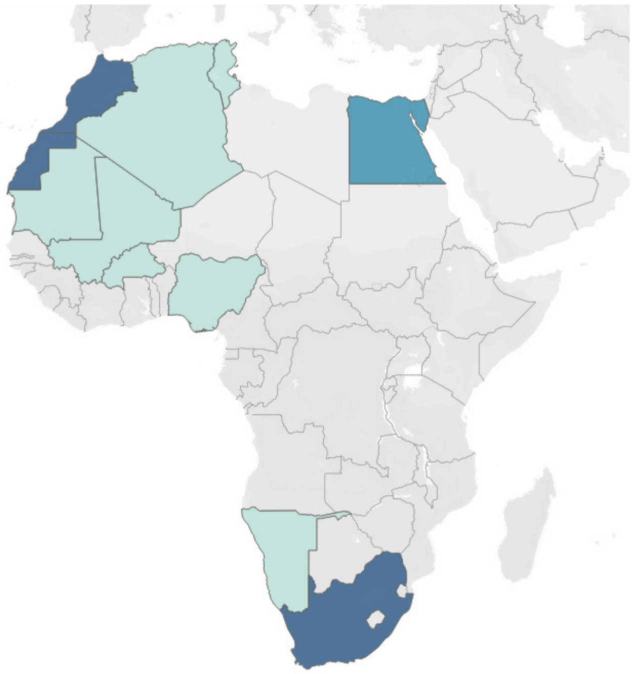
- 1 **strongly-export** oriented countries
- 6 **slightly-export** oriented countries
- 7 **self-sufficient** countries
- 11 **slightly-import** oriented countries
- 1 **strongly-import** oriented countries



NATIONAL STRATEGY DEVELOPMENT

As of March 2022:

- **2 strategies published:** 2021 – Morocco; 2022 – South Africa
- **1 strategy in preparation:** Egypt
- **8 countries with initial discussions & pilot projects:** Algeria, Burkina Faso, Cape Verde, Mali, Mauritania, Namibia, Nigeria, Tunisia



MARKET OPPORTUNITIES

End-uses priorities: 1- Energy access, 2- Agriculture, 3-Export, 4- Industry
Unique regional issue: hydrogenation of unsaturated vegetable oils
Production sources: 1- Renewable hydrogen, 2- Natural hydrogen, 3- Hydrogen from natural gas with CCUS

A HUGE POTENTIAL BUT LITTLE INFRASTRUCTURE: HOW DOES AFRICA ENABLE AN EXPORT MARKET AS WELL AS GROW A DOMESTIC ONE?

REGIONAL PATH

- Developing low-carbon hydrogen could help Africa in tackling issues of energy access, energy independence, food security and local employment

- Africa has sizeable renewable energy resources to develop low-carbon hydrogen production & important mineral resources to be part of the value chain of energy transition technologies

- However, there are many challenges to overcome: some countries' concrete ability to take advantage of the hydrogen economy is limited by the lack of infrastructure and general awareness, political and economic challenges, and lack of demand security, as well as water stress

- North Africa has more favourable conditions - Morocco, Algeria and Egypt in particular could be first movers and exporters of hydrogen and its derivatives

- In the early stage of hydrogen development, there are opportunities to unlock in the hydrogen innovation space that could position African countries as technology-setters, not takers

KEY POLICY ENABLERS

- Regional & subregional cooperation, & cooperation with importing markets to develop African hydrogen technologies and to create a shared vision for hydrogen

- Gap assessments for human capital and infrastructure development

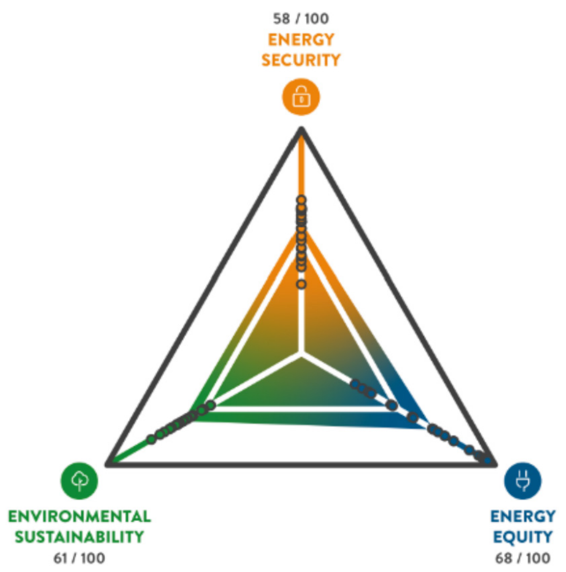
- Developing domestic demand in the transport, industry and agriculture sectors

ASIA-PACIFIC

CONTEXT

ASIA-PACIFIC PERFORMANCE IN WE TRILEMMA INDEX 2021

58/100 Energy Security
61/100 Environmental sustainability
68/100 Energy equity
1 country in the top 14 performers
5 countries in the top 10 improvers



SDGS

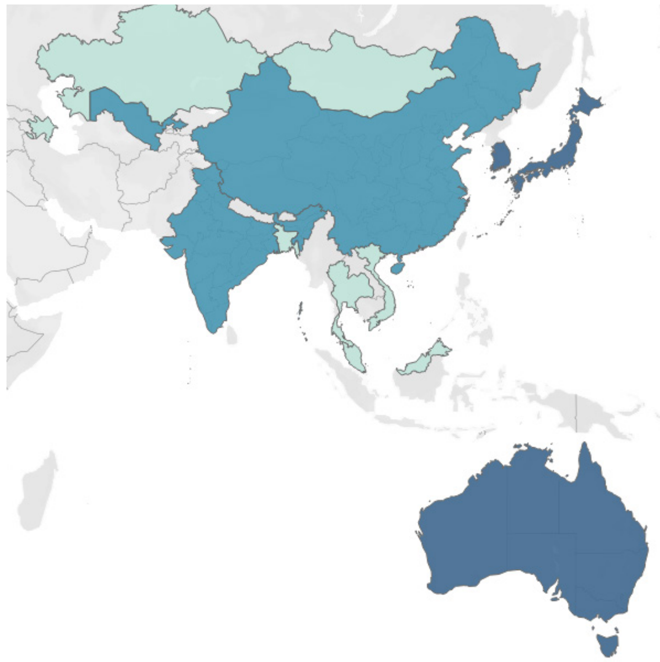
ASIA-PACIFIC VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#5/25 uncertainties
#13/25 impact

NATIONAL STRATEGY DEVELOPMENT

As of March 2022:

- **3 strategies published:** 2017 – Japan; 2019 – Australia, South Korea
- **5 strategies in preparation:** Hong Kong - China, India, New Zealand, Singapore, Uzbekistan
- **7 countries with initial discussions & pilot projects:** Bangladesh, China, Malaysia, Maldives, Mongolia, Thailand, Vietnam

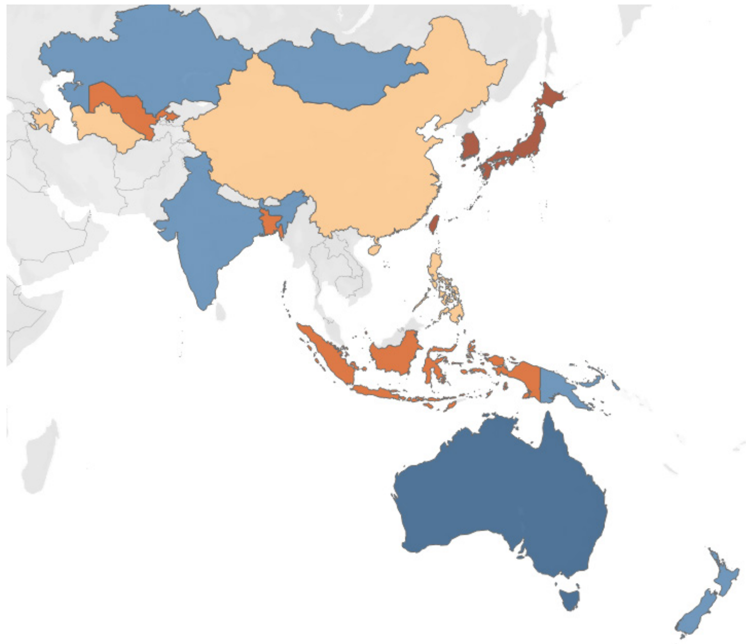


MARKET OPPORTUNITIES

End-uses priorities: 1- Industry, 2- Mobility, 3- Power generation
Unique regional issue: export of technologies (FCs, electrolysers); Iron ore
Production sources: 1- "Carbon-free" hydrogen (i.e., low-carbon; no prejudice of the type of hydrogen - renewable hydrogen, low-carbon hydrogen from natural gas and coal with CCUS)

POSITIONING IN THE IMPORT-EXPORT SPECTRUM BY 2040

- **1 strongly-export** oriented countries
- **4 slightly-export** oriented countries
- **4 self-sufficient** countries
- **5 slightly-import** oriented countries
- **4 strongly-import** oriented countries



MAINSTREAMING LOW-CARBON HYDROGEN AND ITS DERIVATIVES AND CAPTURING RELATED ECONOMIC OPPORTUNITIES

REGIONAL PATH

- Asia-Pacific region at the epicentre of the movement towards a "hydrogen economy" - Japan, South Korea and Australia released a strategy first

- Integrated approach to low-carbon hydrogen-based fuels that can support decarbonisation efforts across a multitude of applications and sustain economic growth via innovation and new technologies for export

- Interest increasing in other countries; although the overarching plans are yet to be released, inc. from key players China and India

- In the early stage of low-carbon hydrogen uptake: defining priorities between fuels could facilitate the scale up and more regional and global cooperation is needed to tackle the obstacles to global trade development (e.g., lack of harmonised definition of hydrogen sources, updating maritime regulations, etc.)

KEY POLICY ENABLERS

- Increasing bilateral and multilateral cooperation to progress the low-carbon hydrogen global supply chain and hydrogen trade

- Integrated approach to energy policies & mainstreaming hydrogen and its derivatives in many aspects of energy systems

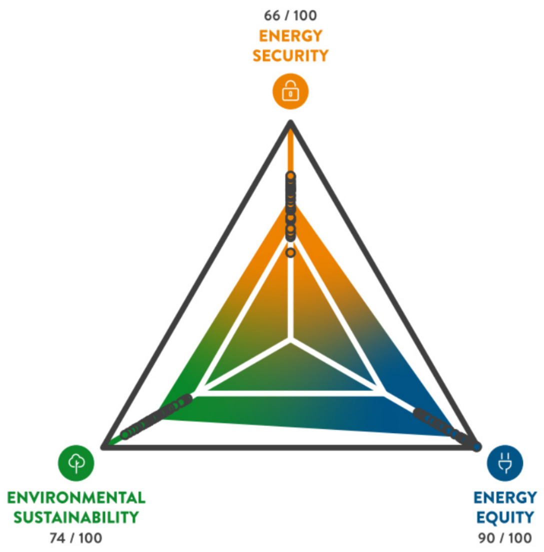
- Supporting hydrogen-related technologies and increased use in mobility

EUROPE

CONTEXT

EUROPE PERFORMANCE IN WE TRILEMMA INDEX 2021

66/100 Energy Security
74/100 Environmental sustainability
90/100 Energy equity
11 countries in the top 14 performers
0 countries in the top 10 improvers



SDGS

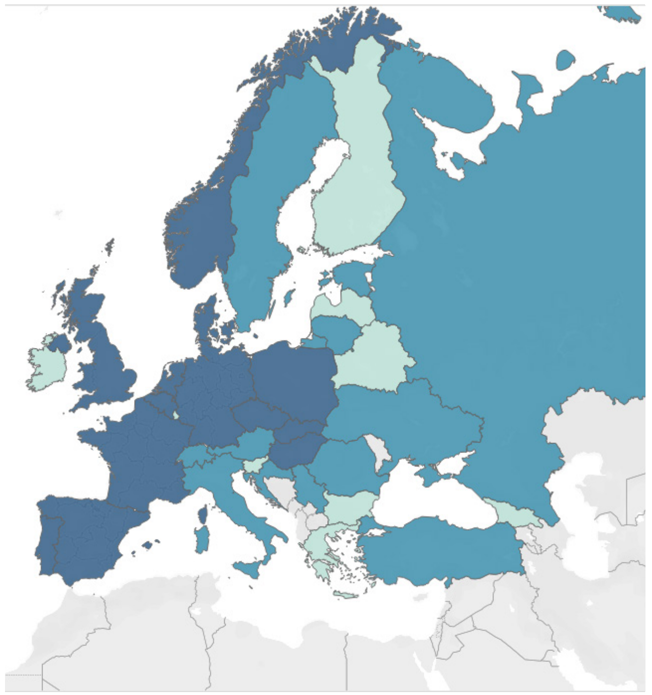
EUROPEAN VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#3/25 uncertainties
#19/25 impact

NATIONAL STRATEGY DEVELOPMENT

As of March 2022:

- **14 strategies published:** 2020 – European Union, France, Germany, Netherlands, Norway, Portugal, Spain; 2021 – Belgium, Czech Republic, Denmark, Hungary, Poland, Slovakia, United Kingdom
- **12 strategies in preparation:** Austria, Croatia, Estonia, Italy, Lithuania, Romania, Russian Federation, Serbia, Sweden, Switzerland, Turkey, Ukraine
- **13 countries with initial discussions & pilot projects:** Azerbaijan, Belarus, Bulgaria, Finland, Georgia, Greece, Iceland, Ireland, Kazakhstan, Latvia, Luxembourg, Malta, Slovenia

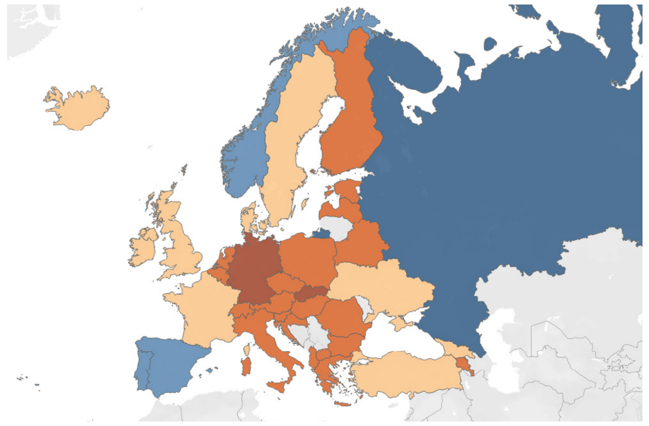


MARKET OPPORTUNITIES

End-uses priorities: 1- Industry, 2- Mobility
Unique regional issue: divergences on using H_2 in blending
Production sources: 1- Renewable hydrogen, 2- Hydrogen from natural gas with CCUS, 3- Hydrogen from other sources (nuclear, waste, biogenic methane, methane pyrolysis, etc.)

POSITIONING IN THE IMPORT-EXPORT SPECTRUM BY 2040

- **1 strongly-export** oriented countries
- **4 slightly-export** oriented countries
- **9 self-sufficient** countries
- **21 slightly-import** oriented countries
- **5 strongly-import** oriented countries



A HIGH AMBITION TO DECARBONISE AS FAST AS POSSIBLE, WHILE INCREASING SECURITY OF SUPPLY AND TACKLING THE FLEXIBILITY ISSUE

REGIONAL PATH

- Impulse given by Germany - now Europe is at the forefront of hydrogen development worldwide

- The EU plans to rely heavily on low-carbon hydrogen to support its decarbonisation ambitions, with high targets for imports (from North Africa, Latin America, Gulf States, etc.)

- Several challenges in the EU
  - More dissonant voices: e.g., on blending; on which low-carbon production sources, pure hydrogen vs. intermediate steps (e.g., power to methane, ammonia, liquid fuels), etc.
  - Developing harmonised standards and streamlining regulations is key for low-carbon hydrogen ramp up

- Timeline gap between the ambitious climate agenda and hydrogen infrastructure implementation: very large infrastructure projects (notably for import) operational after 2030. In the meantime, within Europe, on-site projects and hydrogen hubs are developing to answer existing demand players, and off-site electrolysers in regions with high renewable energy capacities could supply part of the European demand

KEY POLICY ENABLERS

- Eliminating regulatory obstacles in the European Union (and misalignment between Member States)

- More support mechanisms for the production-side and switch incentives for the demand-side (e.g., CCFDs or quotas)

-Supporting the development of international trade

- More coordinated hydrogen diplomacy action in the EU

LATIN AMERICA AND THE CARIBBEAN

CONTEXT

LAC PERFORMANCE IN WE TRILEMMA INDEX 2021

62/100 Energy Security

72/100 Environmental sustainability

68/100 Energy equity

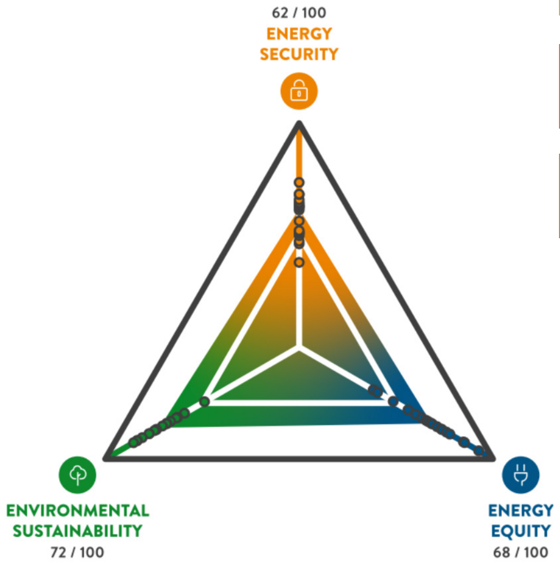
0 country in the top 14 performers

2 countries in the top 10 improvers

LAC VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#18/25 uncertainties

#14/25 impact



SDGS

NATIONAL STRATEGY DEVELOPMENT

As of March 2022:

- **3 strategies published:** 2020 – Chile; 2021 – Colombia
- **4 strategies in preparation:** Brazil, Costa Rica, Panama, Paraguay, Uruguay
- **4 countries with initial discussions & pilot projects:** Argentina, Bolivia, Peru, Trinidad and Tobago

MARKET OPPORTUNITIES

End-uses priorities: 1- Industry, 2- Mobility, 3- Agriculture, 4- Export (H2 & products using H_2)

Unique regional issue: biofuels; explosives; pulp & paper industry

Production sources: 1- renewable hydrogen, 2- hydrogen from all locally available fossil fuels with CCUS

POSITIONING IN THE IMPORT-EXPORT SPECTRUM BY 2040

- **2 strongly-export** oriented countries
- **8 slightly-export** oriented countries
- **0 self-sufficient** countries
- **0 slightly-import** oriented countries
- **0 strongly-import** oriented countries

INCREASING SELF-SUFFICIENCY AND DEVELOPING NEW REGIONAL COOPERATION

REGIONAL PATH

- Wide interest to develop hydrogen production and use, focusing mainly on hydrogen from renewable energy, but considering all resources available on the continent

- Developing local demand is the primary objective to help decarbonise the economy

- Chile is the early mover and gave the impulse on hydrogen in the continent, which is now very dynamic; momentum is picking up and regional cooperation is increasing

- The continent is attracting increased attention from potential importing markets (e.g., Netherlands, Australia, Japan)

- Cooperation could increase to attract more foreign investment and install the LAC region in the global hydrogen market

KEY POLICY ENABLERS

- Regional cooperation to increase visibility for the continent and attract external investments

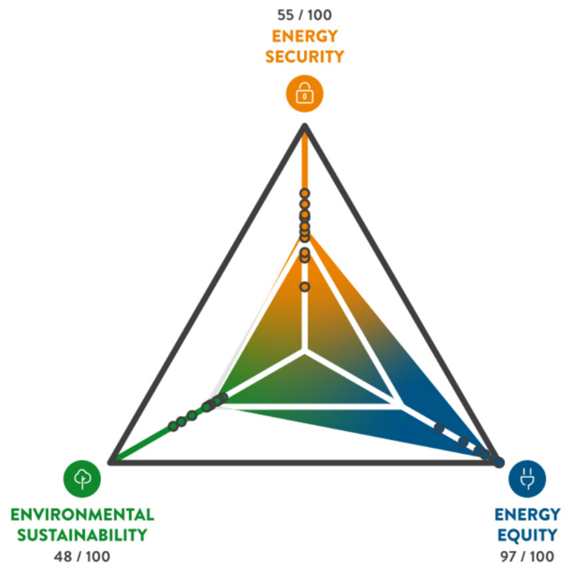
- Better identifying and building on each country's individual strengths for an integrated low-carbon hydrogen supply chain

MIDDLE EAST AND GULF STATES

CONTEXT

MEGS PERFORMANCE IN WE TRILEMMA INDEX 2021

55/100 Energy Security
48/100 Environmental sustainability
97/100 Energy equity
0 country in the top 14 performers
0 country in the top 10 improvers



SDGS

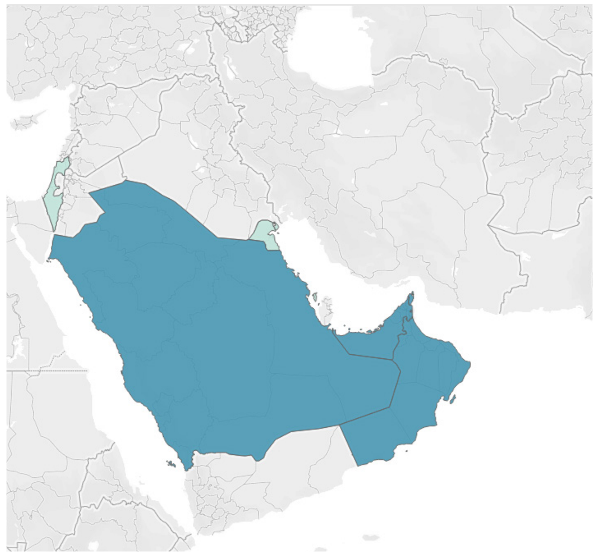
MEGS VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#4/25 uncertainties
#15/25 impact

NATIONAL STRATEGY DEVELOPMENT

As of March 2022:

- **0 strategy published**
- **3 strategies in preparation:** Saudi Arabia, United Arab Emirates
- **3 countries with initial discussions & pilot projects:** Bahrain, Israel, Kuwait



MARKET OPPORTUNITIES

End-uses priorities: 1- Export, 2- Industry
Unique regional issue: by-products being explored: oxygen, magnesium
Production sources: 1- hydrogen from all locally available fossil fuels with CCUS, 2- renewable hydrogen

POSITIONING IN THE IMPORT-EXPORT SPECTRUM BY 2040

- **4 strongly-export** oriented countries
- **3 slightly-export** oriented countries
- **1 self-sufficient** countries
- **0 slightly-import** oriented countries
- **1 strongly-import** oriented countries

LOW-CARBON HYDROGEN DRIVEN BY CIRCULAR CARBON ECONOMY AND SUSTAINING ENERGY EXPORT

REGIONAL PATH

- Momentum in MEGS is driven by the energy incumbents, in addition to the region's Circular Carbon Economy agenda

- Investments are being implemented with the end goal of sustaining energy exports to existing markets in Europe and Asia

- Existing vast oil and gas assets, coupled with excellent natural resources for renewable energy production, are making the production of low-carbon hydrogen in the region among the most competitive in the world

- Saudi Arabia, the UAE, and Oman are driving the momentum for low carbon hydrogen

- Aspirations to become an export hub of low-carbon hydrogen and its derivatives

- Foreign laws and regulations can create policy obstacles that might hinder these goals, particularly regulations related to potential exports

KEY POLICY ENABLERS

- Increasing regional collaboration and learning from previous failed attempts

- Developing local ecosystems and end-use applications in the local market as opposed to primarily creating an export hydrogen industry

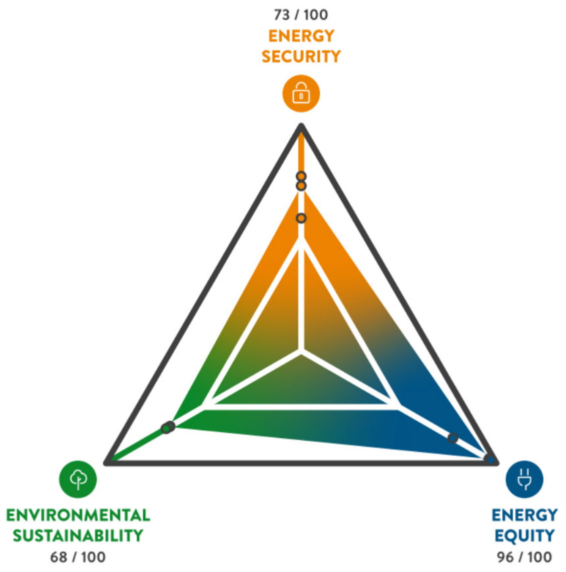
- Finance subsidies and support mechanisms to enhance the bankability of large pilot projects

NORTH AMERICA

CONTEXT

NORTH AMERICA PERFORMANCE IN WE TRILEMMA INDEX 2021

73/100 Energy Security
68/100 Environmental sustainability
96/100 Energy equity
2 countries in the top 14 performers
0 country in the top 10 improvers



SDGS

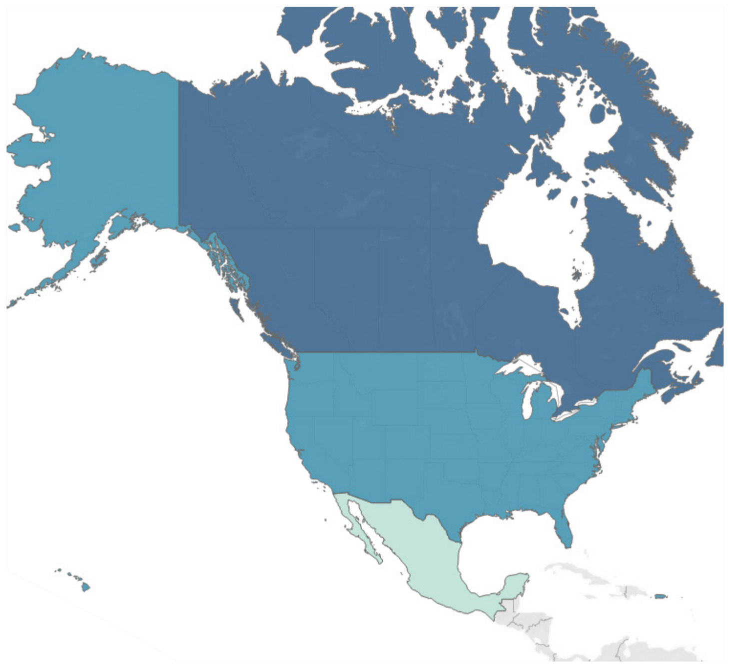
NORTH AMERICA VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#1/25 uncertainties
#22/25 impact

NATIONAL STRATEGY DEVELOPMENT

As of March 2022:

- **1 strategy published:** 2020 – Canada
- **1 strategy in preparation:** United States of America
- **1 country with initial discussions & pilot projects:** Mexico

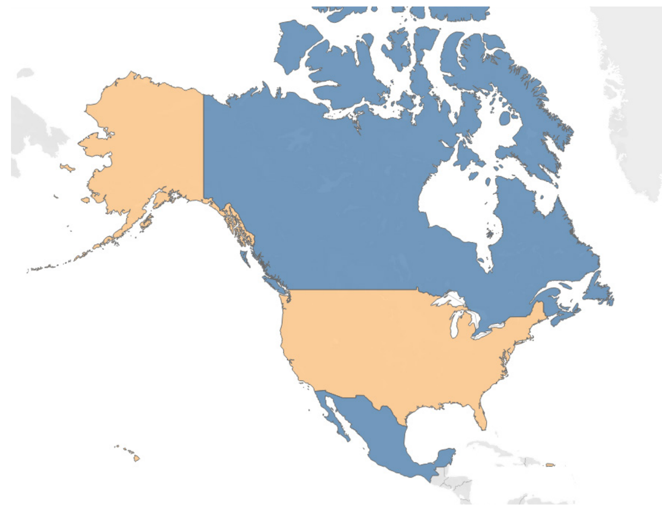


MARKET OPPORTUNITIES

End-uses priorities: 1- Industry, 2- Mobility
Unique regional issue: export of technologies (FCs)
Production sources: Low-carbon hydrogen (renewable hydrogen, fossil fuel based with CCUS, etc.)

POSITIONING IN THE IMPORT-EXPORT SPECTRUM BY 2040

- **0 strongly-export** oriented countries
- **2 slightly-export** oriented countries
- **1 self-sufficient** countries
- **0 slightly-import** oriented countries
- **0 strongly-import** oriented countries



HIGH TECHNOLOGY READINESS FACILITATING MARKET CREATION IN SPECIFIC SECTORS OF THE ECONOMY, WITH EXPORTS AMBITIONS

REGIONAL PATH

- Momentum is emerging in Canada and in specific states within the US.
- Goal is to increase and enhance overall resiliency of the energy systems over the coming decades
- High technology readiness is pushing the domestic market to pick up end-use applications particularly in the transport sector
- Developed regulations and incentives targeting clean mobility are pushing further the use of low-carbon hydrogen in the transport sector
- Export ambitions of low-carbon hydrogen and its derivatives are also emerging, especially as the region is an existing energy net exporter
- Priority is on the creation of hubs where supply and demand are located in the same place

KEY POLICY ENABLERS

- Scaling and reducing the cost of hydrogen transport and distribution
- Funding support for R&D and pilot and demonstration projects
- Creating hubs centres to help de-risk future projects

ANNEX 2

LIST OF LOW-CARBON HYDROGEN VALLEYS

The below table shows the list of selected hydrogen hubs projects included in Figure 1. The projects were selected from “The Hydrogen Valley Platform” database, the “Hydrogen Forward” database, and other online sources, based on their ability to combine and link both production and consumption of low-carbon hydrogen and on the anticipated significant volumes involved.

Name	Lead developer	Main Location
Advanced Clean Energy Storage Project	Mitsubishi Power and Magnum Development	United States
Basque Hydrogen Corridor BH2C	Petronor (Repsol Group)	Spain
BIG HIT (Building Innovative Green Hydrogen Systems in Isolated Territories)	Foundation for the development of new hydrogen technologies in Aragon (project coordination)	Spain
Black Horse	Bioway	Slovakia
CEOG (Centrale Electrique de l'Ouest Guyanais)	HDF (Hydrogène de France)	French Guiana
Crystal Brook Hydrogen Superhub	Neoen Australia	Australia
eFarm	GP JOULE Think GmbH & Co. KG	Germany
Europe's Hydrogen Hub: H2 Proposition Zuid-Holland/Rotterdam	Port of Rotterdam	Netherlands
Eyre Peninsula Gateway	H2U	Australia
FH2R (A model of hydrogen-based society in Fukushima using Fukushima Hydrogen Energy Research Field)	NEDO - New Energy and Industrial Technology Development Organization	Japan
Foshan Nanhai Xianhu Lake Hydrogen Valley Town	Foshan City Government	Japan
Green Crane (Western route)	Enagás Renovable	Spain
Green Hydrogen & Chemicals Oman	ACME Group (Green Hydrogen & Chemicals (UK) Pvt. Ltd & ACME Cleantech Solutions Pvt. Ltd)	Oman
Green Hydrogen @ Blue Danube	Verbund AG	Romania
Green Hysland	Enagás	Spain
Green Octopus	WaterstofNet vzw	Belgium
H2Rivers	Metropolregion Rhein-Neckar GmbH	Germany
HEAVENN	New Energy Coalition	Netherlands
Hy-Fi (Hydrogen Facility Initiative)	CORFO (Corporación de Fomento de la Producción)	Chile
HyBalance	Air Liquide	Denmark
HyBayern	District Office (Landratsamt) Landshut	Germany
Hydrogen Delta	Smart Delta Resources	Netherlands
Hydrogen Valley Port of Amsterdam Region	Port of Amsterdam together with market parties	Netherlands
Hydrogen Valley South Tyrol	IIT - Institut für Innovative Technologien Bozen	Italy
HyNet North West	Progressive Energy	United Kingdom
HyWays for Future	EWE AG	Germany
NDRL (Norddeutsches Reallabor - Living Lab Northern Germany)	Joint development	Germany
Normandy Hydrogen	Normandy Region	France
Phi Suea House Project	Enapter	Thailand
Port of Los Angeles Shore to Store Demonstration Project	Port of Los Angeles	United States
Regional Hydrogen Roadmap	Dijon Métropole Smart Energy	France
Rugao Hydrogen Energy Town	Rugao City government	China
Sines Industrial hub		Portugal
WIVA P&G (Wasserstoffinitiative Vorzeigeregion Austria Power & Gas)	Our energy model region has 10 corporate and 4 research partners	Austria
ZEV - Zero Emission Valley	Auvergne-Rhône-Alpes Regional Council	France
Zhangjiakou demonstration project	Zhangjiakou Municipal People's Government	China
Waste-to-hydrogen hubs	Hyzon Motors - Raven SR	United States
Mississippi Hydrogen Hub	Hy Stor Energy LP and Connor Clark & Lun	United States
BayoTech Hydrogen Hub (first of 50 planned)	BayoTech	United States
North Dakota Hydrogen Hub	Bakken Energy and Mitsubishi Power	United States
Green hydrogen hub at the Port of Corpus Christi	Apex Clean Energy, Ares, EPIC Midstream, and PCCA	United States
Tallgrass Energy - Eastern Wyoming Sequestration Hub	Wyoming Energy Authority and Energy Resources Council	United States
Edmonton Region Hydrogen HUB	Western Economic Diversification Canada (WD), Province of Alberta	Canada

REFERENCES

Africa–Europe High–Level Platform for Sustainable Energy Investments in Africa. (2019). Scaling-up energy investments in Africa for inclusive and sustainable growth. European Commission.

Baronas, J. G. (2019). Joint Agency Staff Report on Assembly Bill 8: 2019 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California. California Energy Commission and California Air Resources.

D'haeseleer, W. (2021). A possible role of hydrogen-based technologies for system service assistance in fully RES-Dominated energy systems. KU Leuven.

Emirates News Agency - WAM. (2021, 11 04). UAE announces Hydrogen Leadership Roadmap, reinforcing Nation's commitment to driving economic opportunity through decisive climate action. Abu Dhabi, United Arab Emirates.

Fasihi, M., & Breyer, C. (2020). Baseload electricity and hydrogen supply based on hybrid PV-wind power plants. Journal of Cleaner Production.

HINICIO. (2021). Green Hydrogen in Mexico: towards a decarbonization of the economy. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH .

IEA. (2021). Global Hydrogen Review 2021. Paris: International Energy Agency.

IEA. (2021). Hydrogen in Latin America: From near-term opportunities to large-scale deployment. Paris: International Energy Agency.

IRENA. (2022). Geopolitics of the Energy Transformation: The Hydrogen Factor. Abu Dhabi: International Renewable Energy Agency.

Jens, J., Wang, A., Van der Leun, K., Peters, D., & Buseman, M. (2021). Extending the European Hydrogen Backbone. Utrecht: Guidehouse.

Mayyas, A. T., Ruth, M. F., Pivovar, B., Bender, G., & Wipke, K. (2018). Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. United States: National Renewable Energy Laboratory (NREL).

MEED. (2022, February 24). Neom hydrogen scheme to advance. Retrieved from Power Technology: https://www.power-technology.com/comment/neom-hydrogen-scheme

Ministry of Mines and Energy - Colombia. (2021). Colombia's hydrogen roadmap. Bogotá: Government of Colombia.

Sailer, K., Reinholz, T., Lakeit, K. M., & Crone, K. (2022). Global Harmonisation of Hydrogen Certification. Berlin: German Energy Agency; World Energy Council – Germany.

Sambo, A. (2021). Potentials of hydrogen in the energy sector. Sokoto: Faculty of Engineering and Environmental Design - Usmanu Danfodiyo University.

Snam S.p.A. (2018). South America Gas Pipeline. Retrieved from http://www.snamatlas.it/world_of_gas?focus=14

U.S. Department of Energy. (2020). Hydrogen Strategy: Enabling a low-carbon economy. Washington DC: Office of Fossil Energy - United States Department of Energy.

Word Energy Council - Europe. (2021). Decarbonised hydrogen imports into the European Union: challenges and opportunities. La Revue de l'Énergie.

Hydrogen Forward. (2022). United States of Hydrogen. Retrieved from Hydrogen Forward: https://www.hydrogenfwd.org/united-states-of-hydrogen

Fuel Cells and Hydrogen Joint Undertaking; Mission Innovation. (n.d.). Hydrogen Valleys. Retrieved from The Hydrogen Valley Platform: https://www.h2v.eu/hydrogen-valleys

ACKNOWLEDGEMENTS

PROJECT MANAGEMENT

Dr Angela Wilkinson (Secretary General & CEO), Neil Hughes (International Executive Director, EPRI), Jeroen van Hoof (Global Power & Utilities Leader, Partner, PwC Netherlands), Paul Appleby (Chief Insights Officer), Olulana Nwosu (Director, Policy & Markets), Cliodhna O'Flaherty-Mouscadet (Senior Manager, Partners), Gina Domanig (Innovation Executive Co-chair), Richard Lancaster (InnovationExecutive Co-chair), Sam Muraki (Vice Chair of Asia Pacific and South Asia), Adj. Prof. Dr Juergen Peterseim (Global H2Industry Lead, PwC), Dr Olesya Hatop (Global Clients & Markets Industry Executive, PwC)

PROJECT TEAM

LEAD AUTHORS: Lucie Togni (Senior Manager, Insights), Rami Fakhoury (Manager, Insights)

Joseph Stekli (Program Manager, Low Carbon Resources Initiative, EPRI), Florian Schäfer (Senior Associate, Sustainability Services, PwC), Dajana Czaja (Global Marketing Organisation, Strategic Marketing Manager, PwC)

WORLD ENERGY COUNCIL STUDIES COMMITTEE

ADVISOR AND REVIEWERS: Andrea Maria Quaggia (Italy) - Burkhard Von Kienitz (Germany) - Claudio Huepe Minoletti (Chile) - François Dassa (France) - Hans-Wilhelm Schiffer (Germany) - Juan Benavides (Colombia) - Mamadou Diarra (Niger) - Nawal Yousif Alhanaee (United Arab Emirates) - Rebecca Yuen (Hong Kong) - Tina Schirr (New Zealand) - Tom Kober (Switzerland) - William D'haeseleer (Belgium) - Yuji Matsuo (Japan)

Leonhard Birnbaum (Chair, Germany) - Alejandro Perroni (Uruguay) - Andrea Heins (Argentina) - Andrey Logatkin (Russian Federation) - Atul Sobti (India) - Barış Sanlı (Turkey) - Berardo Guzzi (Italy) - Edouard Sauvage (France) - Herwig Klima (Austria) - Jean-Baptiste Galland (France) - Jeanne Chi Yun Ng (Hong Kong) - Joseph Al Assad (Lebanon) - Kambiz Rezapour (Iran, Islamic Republic of) - Katerin Osorio Vera (Colombia) - Klaus Hammes (Sweden) - Lawrence Ezemonye (Nigeria) - Mehdi Sadeghi (Iran, Islamic Republic of) - Miguel Perez de Arce (Chile) - Nalin Shinghal (India) - Stefan Gheorghe (Romania) - Yanbing Kang (China) - Yongping Zhai (China)

WORLD ENERGY COUNCIL WORKING GROUP MEMBERS

We would also like to thank particularly the working group members for their insights and help: Alan Sakar (Mexico) - Ana Angel (Colombia) - Ana Sousa (Portugal) - Andrew Clennett (New Zealand) - Angel Landa Ugarte (Spain) - Angela Ogier (New Zealand) - Ardit Cami (Belgium) - Baldur Pétursson (Iceland) - Bartlomiej Kolodziejczyk (Australia) - Bassem Mneymne (Qatar) - Brock King (Canada) - Burkhard Von Kienitz (Germany) – Maira Kusch (Germany) - Carlos Navas Pérez (Spain) - DMR Panda (India) - Elena Pashina (Russian Federation) - Ekaterina Derbilova (Russian Federation) - Gabriel Guggisberg (Chile) - Gassem Fallatah (Saudi Arabia) - Hans-Wilhelm Schiffer (Germany) - James Tyrrell (Australia) - Jean-Eudes Moncomble (France) - Jitendra Roychoudhury (Saudi Arabia) - Jón B. Skúlason (Iceland) - Jose Caceres Blundi (Switzerland) - Lucia Fuselli (Luxembourg) - Massimiliano Cervo (Argentina) - Meriem Bellizim (United Arab Emirates) - Nabil Bouraoui (Tunisia) - Nabil Jedaira (Morocco) - Pedro Ernesto Ferreira (Portugal) - Rainer Block (Germany) - Renata Viggiano (Italy) - Russell Pendlebury (Australia) - Shane Gowan (New Zealand) - Sebastian Veit (Germany) - Tina Schirr (New Zealand) - Tinashe Chinembiri (Zimbabwe) - Ulrike Hinz (Germany) - Victor Andres Martinez (Panama) - Victorio Oxilia (Paraguay) - William D'haeseleer (Belgium)

We would also like to thank particularly the Chairs and moderators of each regional workshop for their support in the organisation and successful running of the sessions. We finally thank all the participants in each regional workshop for sharing valuable insights into hydrogen regional specificities for the development of these World Energy Insigths.

TRUSTEES

WORLD ENERGY COUNCIL PARTNERS

California ISO

EDF

ENGIE

Oliver Wyman

PwC

Swedish Energy Agency

Tokyo Electric Power Co

WORLD ENERGY COUNCIL MEMBER COMMITTEES

Algeria
Argentina
Armenia
Austria
Bahrain
Belgium
Bolivia
Bosnia & Herzegovina
Botswana
Bulgaria
Cameroon
Chile
China
Colombia
Congo (Dem. Rep.)
Côte d'Ivoire
Croatia
Cyprus
Dominican Republic
Ecuador
Egypt (Arab Rep.)
Estonia
eSwatini (Swaziland)
Ethiopia
Finland
France
Germany
Greece
Hong Kong, China SAR
Hungary
Iceland
India
Indonesia
Iran (Islamic Rep.)
Ireland
Italy
Japan
Jordan
Kazakhstan
Kenya
Korea (Rep.)
Kuwait*
Latvia
Lebanon
Lithuania
Malta
Mexico
Monaco
Mongolia
Morocco
Namibia
Nepal
Netherlands
New Zealand
Niger
Nigeria
Norway
Pakistan
Panama
Paraguay
Poland
Portugal
Romania
Russian Federation
Saudi Arabia
Senegal
Serbia
Singapore
Slovenia
Spain
Sri Lanka
Sweden
Switzerland
Syria (Arab Rep.)
Thailand
Trinidad & Tobago
Tunisia
Turkey
United Arab Emirates
United States of America
Uruguay
Vietnam

*awaiting membership approval

62–64 Cornhill
London EC3V 3NH
United Kingdom
T (+44) 20 7734 5996
F (+44) 20 7734 5926
E info@worldenergy.org

www.worldenergy.org | **@WECouncil**