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HOUSE OF REPRESENTATIVES
COMMONWEALTH *of* PENNSYLVANIA

House Democratic Policy Committee Hearing

Developing a Hydrogen Hub
Wednesday, Aug. 10, 2022 | 10 a.m. to noon
Representative Nick Pisciottano

10 a.m. Opening remarks: Chairman Rep. Ryan Bizzarro, Rep. Nick Pisciottano. Overview of Hydrogen Hub.

PANEL ONE

10:10 a.m. Matt Smith, President
Greater Pittsburgh Chamber of Commerce
Michael Ducker, Senior VP/Head of Hydrogen Infrastructure
Mitsubishi Power
Christopher J. Masciantonio, Director, Government Affairs and Public Policy
United States Steel Corporation

Q & A with Legislators

PANEL TWO

10:50 a.m. Darrin Kelly, President
Allegheny/Fayette Central Labor Council

Q & A with Legislators

PANEL THREE

11:10 a.m. Rob Altenberg, Senior Director Energy/Climate
Penn Future
Katie Blume, Political Director
Conservation Voters of PA
Joanne Kilgour, Executive Director
Ohio River Valley Institute

Q & A with Legislators

11:50 a.m. Closing remarks: Rep. Nick Pisciottano

Testimony of Matt Smith
President, Greater Pittsburgh Chamber of Commerce
August 10, 2022

Good morning, Representative Pisciottano and the House Democratic Policy Committee,

On behalf of the Greater Pittsburgh Chamber of Commerce, the advocacy and public policy affiliate of the Allegheny Conference on Community Development, I would like to thank you for the opportunity to speak today about the Regional Clean Energy Hydrogen Hub development and its importance in Pennsylvania's, and more specifically the Pittsburgh region, critical effort to be a national and global leader in energy-related economic development. Let me simply say at the outset that with the combination of our robust supply of natural gas, a catalyst fuel, our energy innovation, and our geology, the Pittsburgh region holds a set of cards that any market in the world would love to possess.

I also want to note that we look forward to expressing our commitment to reducing emissions at the Global Clean Energy Action Forum this September, learning from international leaders about their clean energy transitions and demonstrating to the world how innovations ready for deployment from Pittsburgh can lead to climate improvement, equity, and U.S. competitiveness.

The regional energy transition strategy recently released by the Allegheny Conference on Community Development's Energy Task Force charts a path for the region to be a leader in climate resiliency while at the same time remaining economically competitive, both of which are critical and not exclusive objectives, the task force brought leaders from industry and various stakeholder groups together to begin the necessary conversation and work related to advancing key initiatives like the development of hydrogen as a fuel source. This is an area where business leaders and labor leaders can and will come together for our region's future.

Hydrogen can be produced using energy sources such as solar, wind, and nuclear power, and it can also be produced sustainably by using natural gas along with carbon capture and storage. Hydrogen can be used as a fuel to produce electricity, serve as an input to produce steel, cement, and fertilizer, and it can power railroad locomotives and ocean-going vessels, all while reducing emissions.

To make the most efficient and productive use of hydrogen to transform the economy, it makes sense for suppliers, distributors, and users of hydrogen as well as the necessary elements of the supply chain, including energy sources, transmission infrastructure, carbon capture, research, and skilled work force capacity, to all be located within a given geographic area. That's where the Pittsburgh region's opportunity and our existing assets connects to enacted legislation. The Infrastructure Investment and Jobs Act created a program that will invest $8 billion to develop this technology to meet national climate goals. Through the Regional Clean Hydrogen Hubs program (H2Hubs), the U.S. Department of Energy (DOE) aims to establish regional networks of hydrogen producers, consumers, and necessary infrastructure to expedite the adoption of hydrogen as a clean energy carrier. DOE currently plans to award funds to six to ten Hydrogen Hub projects in different regions across the country. DOE expects the program to provide a minimum award range of $400 to $500 million and a maximum range of $1 to $1.25 billion with a 50 percent minimum non-federal cost share. Hydrogen Hub projects are expected to be carried out over the course of eight to twelve years.

On May 16, 2022, Governor Tom Wolf announced at the Allegheny Conference's event: Charting an Energy Transition Path Towards Economic Growth, that the Commonwealth of Pennsylvania would actively pursue a path forward for industrial sector decarbonization with an emphasis on the deployment of hydrogen and carbon capture, utilization, and storage technologies. The Governor indicated that the Commonwealth would apply for the funding from the US Department of Energy for a Regional Clean Hydrogen Hub.

In selecting projects, DOE will look for regions that have the essential elements of a hydrogen hub, such as feedstock diversity, specifically including fossil fuels and natural gas, renewable energy, and nuclear energy; end-use diversity, including electric power generation, industrial, residential and commercial heating and transportation sectors; and geographic diversity. Our region is poised to be successful in the hydrogen energy production sector because of its geological ability to permanently store carbon, existing natural gas capacity, strong existing workforce and labor support, expansive industries, and commitment from local leaders to lower emissions. DOE anticipates publishing the Hydrogen Hubs funding announcement in September or October of 2022.

Developing hydrogen is an essential element of the necessary pathway, and the Conference Energy Task Force report found that taking that pathway with all its necessary elements, including hydrogen, will generate $40 billion of additional spending on necessary infrastructure, and will create more jobs and more better paying jobs, than the current pathway.

For the hydrogen component alone, assuming that a hydrogen buildout would render similar economic impacts as the industrial gas manufacturing sector currently does in southwestern Pennsylvania, the Pennsylvania Economy League of Greater Pittsburgh projects that every $1.00 spent from the DOE grant could be expected to generate $2.53 in total value added to the region over the length of the hub buildout as the spending ripples through the region's economy. Additionally, for every job directly created in the hydrogen space, nearly four additional jobs would be created indirectly and from added spending of income. The analysis also showed an exceptionally strong multiplier effect on taxes, returning $6.55 in taxes for every $1.00 in direct tax revenues from the hydrogen hub.

We can expect that DOE funding will prime the pump for equal or even larger private investment in the development of hydrogen hubs. Regions that develop the first hubs will dominate the market and become magnets for population growth and economic activity.

There is a critical role for state public policy to make this happen. Over the coming months, along with many other key stakeholders, we plan to advocate for regulatory, permitting, and legislative reforms that are critical path to make our region a global leader in this space.

Establishing a hydrogen hub in our region would offer tremendous economic and job opportunities for Pennsylvania while continuing the southwestern Pennsylvania region's leadership role in the energy sector and bolstering our position as a leader in addressing climate change. The region's huge shale gas production, diversified base of industrial production, world-class research institutions with unparalleled research and development efforts, and skilled workforce are key strengths. A hydrogen hub will preserve and create good-paying jobs and can help revitalize distressed communities. Southwestern Pennsylvania has an unprecedented opportunity to become one of the regions of the nation that successfully establishes a viable, market-driven hydrogen hub that will be a transformational driver of the U.S. economy.

MITSUBISHI POWER

Testimony of Michael Ducker

Senior Vice President, Hydrogen Infrastructure

Mitsubishi Power Americas, Inc.

before the

Pennsylvania House Democratic Policy Committee

Hearing on Developing a Hydrogen Hub in Western Pennsylvania

August 10, 2022

Good morning. Thank you, Chairman Bizzarro, Representative Pisciottano, and members of the Committee for allowing me to testify before you today regarding Western Pennsylvania's pursuit of a hydrogen hub in conjunction with the US Department of Energy's Hydrogen Hub Program. I am glad to discuss Mitsubishi Power's extensive and unique experience in hydrogen infrastructure development, our collaboration with US DOE in this space, and share my perspective on the considerable statewide benefits of a hydrogen hub in the region.

Background and Introduction

My name is Mike Ducker, I serve as Senior Vice President, Head of Hydrogen Infrastructure at Mitsubishi Power, a power generation and energy storage solutions provider in the energy industry. Mitsubishi Power's mission is to provide power generation and storage solutions to our customers, empowering them to affordably and reliably combat climate change and advance human prosperity. In addition to my role leading the Hydrogen Infrastructure business, I serve as the Chief Operating Officer of ACES Delta LLC, a joint venture between Mitsubishi Power and Magnum Development that develops, owns, and operates commercial-scale green hydrogen production and storage projects and is currently developing the world's largest renewable hydrogen hub.

My team is responsible for developing and deploying clean hydrogen production, storage, and delivery infrastructure to enable large scale availability of renewable energy and decarbonization options in the power, transportation, industrial, and commercial sectors. Additionally, I oversee all commercial activities, project development, engineering, and operations for the ACES Delta JV.

Before joining Mitsubishi Power, I worked for the US Department of Energy where I developed market models to evaluate advanced energy technologies being pursued by the DOE. I earned my BS in Mechanical Engineering from the Pennsylvania State University and my MS in Mechanical Engineering from the George Washington University.

About Mitsubishi Power

Mitsubishi Power Americas, Inc. (Mitsubishi Power) headquartered in Lake Mary, Florida, employs more than 2,300 power generation, energy storage, and digital solutions experts and professionals. Our employees are focused on empowering customers to affordably and reliably combat climate change while also advancing human prosperity throughout North, Central, and South America. Mitsubishi Power's power generation solutions include gas, steam, and aero-derivative turbines; power trains and power islands; geothermal systems; PV solar project development; environmental controls; and services. Energy storage solutions include green hydrogen, battery energy storage systems, and services. As you may be aware, Oriden, a Mitsubishi Power subsidiary, is headquartered here in Pittsburgh as a full-service renewable energy developer since 2019. And although I oversee our hydrogen efforts across the entire Western Hemisphere and major projects being implemented across the nation, I am proud to also be based here in Pittsburgh and having been born and raised in the South Hills. I can speak unequivocally as to why this region has the characteristics and capabilities to deliver a world-class infrastructure hub.

Industry Leadership

Mitsubishi Power has taken a leadership role in the hydrogen energy space, developing novel commercial projects such as the Advanced Clean Energy Storage (ACES) Project in Delta, UT. Recently, ACES Delta worked with the DOE Loan Program Office to successfully deploy its first project and recently closed on a $504.4 million DOE loan, the first loan for a renewable energy project by the Department in over a decade. Mitsubishi seeks to repeat this success across the U.S. and has been furthering such a strategy since 2019 through the collaboration with partners across the nation and world through Joint Development Agreements in the hydrogen space, ranging from regional demand to utilities to joint ventures in manufacturing and technology. The work of these Joint Development Agreements is building towards submission to DOE's Regional Clean Hydrogen Hubs program, and Mitsubishi Power plans to submit these shovel-ready concepts to DOE in the coming months.

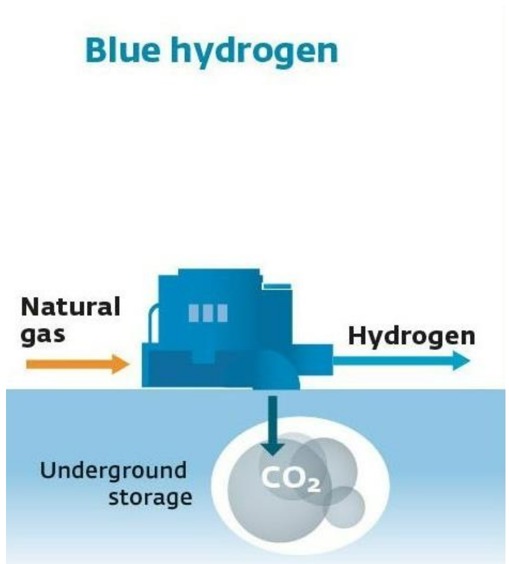

Figure 1 (Source: Gasunie)

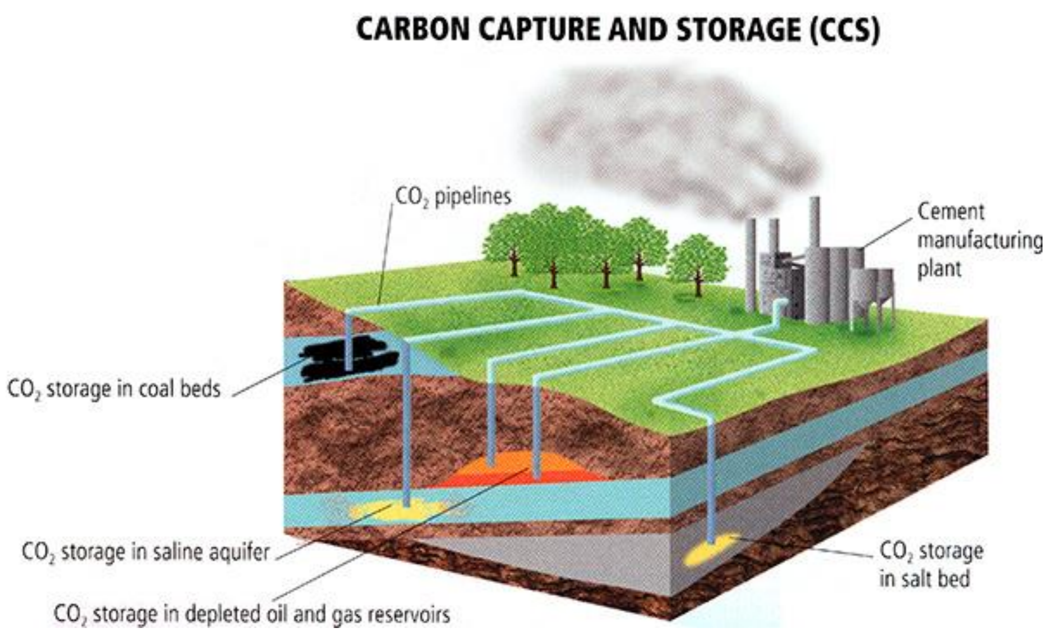

Figure 2 (Source: Penn State University)

101: Hydrogen and Carbon Capture, Utilization, and Storage

To better understand why this region is an optimal location for a hydrogen hub, allow me to first explain the fundamentals of hydrogen energy production and carbon sequestration:

The most common way hydrogen is produced is when natural gas is split into hydrogen and carbon dioxide through steam reforming, which brings together natural gas and heated water in the form of steam. The hydrogen is then supplied for end-use applications, while carbon capture, utilization and storage (CCUS) technologies trap and safely store the carbon. See Figure 1 above.

According to the U.S. Department of Energy, 95% of hydrogen is produced from natural gas, making it the cheapest and most advanced method of hydrogen production available. Hydrogen can also serve as a replacement for natural gas and, at certain percentages, be blended into existing pipeline networks as a low-carbon fuel.

Carbon Capture Utilization and Storage (CCUS) is a collection of technologies to capture carbon dioxide (CO2) from major point sources, including power generation and industrial facilities that use natural gas, and store it safely underground, where it reacts with porous igneous rocks to form limestone. This approach mimics the geological processes that bury CO2 on geological timescales, and provides a potential means for long-term geological sequestration of CO2. See Figure 2 above.

In basic terms, a hydrogen hub is a cluster of assets that incorporates a number of hydrogen-based energy services. These services, in conjunction with high-volume storage, match the supply and demand of a variety of surrounding industries. Because of the geological, workforce and market-access advantages of the tri-state region, it is an optimal place in the United States for the location of a hydrogen hub. Not only do we sit on the largest natural gas field in the country — a major feedstock for blue hydrogen — but we also have salt, limestone and sandstone formations that provide favorable conditions for large-scale carbon dioxide storage. This region also possesses a highly developed natural gas pipeline infrastructure that can transport hydrogen to markets.

Hydrogen energy production and carbon capture, utilization and storage (CCUS) offer our region the ability to create thousands of jobs, lower emissions, fight climate change, and elevate our communities. Mitsubishi

Power is working to make a hydrogen/CCUS hub a reality in the tri-state region. Key to this effort will be partnerships with municipalities, communities, business leaders and labor stakeholders. We will succeed only if all of us work together to advance our goals.

Benefits of a Hydrogen Economy in PA

The tri-state region is home to incredible assets, from our world-class universities and national laboratories to deep-rooted industrial capabilities in manufacturing, materials and energy. Our region is home to an abundance of natural resources that can be used to produce hydrogen with net-zero emissions and advance job opportunities and environmental justice initiatives across our communities.

Establishing a hydrogen ecosystem across the tri-state area will provide jobs and contribute to our region's prosperity through technical innovation and adoption. Our region is home to a highly skilled, experienced workforce and a strong, growing startup ecosystem.

To create a just and equitable energy transition, incorporating strong labor components into hydrogen hub development should play a central role in ensuring a just transition to long-term high-quality jobs at all phases of development. Workforce development efforts can be augmented by the inclusion of organized labor; community colleges, universities, and vocational schools; Minority Serving Institutions; and community-based organizations. Including these organizations in project teams will ensure that adequate training opportunities are accessible in key areas of the hydrogen hub so that workers are available to fill jobs.

Mitsubishi Power's High-Level Hydrogen Policy Recommendations

To ensure proper stewardship of taxpayer dollars and ensure programs meet their objectives, hydrogen programs need to be well-structured and well-managed. Strong stakeholder engagement, state and regional collaboration, and independent and transparent processes will ensure we meet the region's social, economic, and environmental challenges while encouraging the energy innovation process.

Typical of any large infrastructure project, all hub projects will be required to obtain the necessary permits before commencing construction. Pipeline transportation will be critical to move hydrogen from production and storage to end-use markets to truly get to national adoption. This will require accelerated adoption of standards for hydrogen transportation to minimize risk for developers and transporters. Permitting processes should be streamlined to expedite hydrogen pipeline projects.

From both a permitting and community engagement perspective, leveraging existing rights of way (ROW) for infrastructure yields significant benefits. Underground pipelines or conduit ROW with space for additional laterals or conduits have benefits (such as "dig-once"), but the real value of existing ROW is the existing relationship between a pipeline ROW owner and the ROW land owners, which allows for the quick negotiation and development of new pipeline plans. Similarly, CO2 capture projects will benefit greatly if located in regions with existing natural gas production and the opportunity for sequestration in existing infrastructure.

Conclusion

I am optimistic that this Committee's continued leadership on energy policies will support the development of comprehensive hydrogen energy solutions that foster a more sustainable and robust regional economy. Mitsubishi Power appreciates your commitment to seeking solutions that would provide industry with added certainty as we build a hydrogen ecosystem in Western PA across the United States.

Again, I would like to thank Chairman Bizzarro and the members of the Committee for giving attention to the issues revolving around the development of a hydrogen hub in Western PA. Mitsubishi Power stands ready to continue working in partnership with you to develop and expand Western Pennsylvania's hydrogen ecosystem.

--- END ---

House Democratic Policy Committee
"Developing the Hydrogen Hub"
Wednesday August 10, 2022
Pittsburgh, PA

By:

Christopher J. Masciantonio
Director, Government Affairs & Public Policy
cjmasciantonio@uss.com

United States Steel Corporation

- I am pleased to provide brief testimony today on behalf of U. S. Steel regarding opportunities to help grow a sustainable economy while also addressing the impacts of climate change. Some of the material I will present today can also be found in greater detail in U. S. Steel's Climate Strategy Report.

- Climate change is not easily addressed. For our company, we must think differently about how we make and use steel from the raw materials to the processes used. Our team of engineers and research scientists are continually exploring innovative ways to develop steel solutions and create better products for consumers.

- As part of this vision, U. S. Steel is intensifying efforts to become an industry leader in lower-carbon production methods. We have been progressing on our 2030 goal to reduce our global greenhouse gas (GHG) emissions intensity by 20%, and in April 2021, we announced an ambitious goal to achieve net-zero carbon emissions by 2050.

- While we are committed to doing all that we can, we know that one company's actions are not enough, which is why we have partnered with like-minded companies and stakeholders to seek solutions.

- The challenges of climate change must be addressed by the global community and supported by our governments to create an environment where innovation and investment are encouraged.

- Moving from our 2030 goal to our 2050 net-zero goal will involve the development and commercialization of various technologies, some of which have yet to be invented or available on a broad scale. As a result, we are actively engaged in various industry initiatives, task forces and discussions with policymakers, universities, NGOs, and corporate partners to advance technology required to meet our carbon reduction goals.

- One of the technology approaches crucial to decarbonizing the steel industry and will help us achieve our net-zero by 2050 target involves hydrogen.

- Advancements in hydrogen technologies are essential in the transition to green steel. Government funding for hydrogen R&D and pilot projects can help drive down costs and other barriers to implementation, allowing us and other steelmakers to adopt hydrogen as a reasonable alternative to natural gas.

- At U. S. Steel, we are committed to doing our part to enabling a shift towards a cleaner, healthier future. However, we cannot walk the path to net-zero alone. The road to mitigate climate change starts with the collective actions of governments and companies, like U. S. Steel, working together.

Appalachian Energy Future: *www.appalachianenergyfuture.org*

- One organization that U. S. Steel is very active with is the Appalachian Energy Future, or AEF. AEF is an industry-led alliance of companies from the energy, industrial, and manufacturing, sectors, working with community leaders and others to develop a Tri-State regional hub for hydrogen and CCUS. (Ex: U. S. Steel, Shell, EQT, GE Power, Equinor, Williams and Marathon Petroleum, among others.)

- The alliance for the Appalachian Energy Future views the Hydrogen Hub opportunity as perfect for our region. The ecosystem they are planning to develop could serve as a model for the rest of the country on how to advance clean energy evolution and sustainably.

- Our region is home to a highly skilled, experienced workforce and a strong, growing startup ecosystem that are primed to be the catalysts for this once-in-a-generation opportunity.

- There is a national and global movement to reduce carbon emissions in an urgent manner, and the Appalachian Energy Future approach answers this call.

Pennsylvania Energy Horizons Cross-Sector Collaborative

- Another organization that U. S. Steel is an active participate with is the Pennsylvania Energy Horizons Cross-Sector Collaborative – a statewide organization lead by the Team Pennsylvania Foundation, which is co-chaired by Governor Tom Wolf.

- The Team Pa Foundation, on behalf of the Pennsylvania Energy Horizons Cross-Sector Collaborative, has enlisted the help of the Great Plains Institute to develop a study which will provide a "ROADMAP ON CARBON MANAGEMENT AND HYDROGEN DEVELOPMENT IN PENNSYLVAINA."

- The study will be released very soon (maybe this week), and you will see recommendations on how PA can grow opportunities for its citizens and maintain its leadership role in the nation's industrial and energy sectors, while meeting anticipated climate and decarbonization goals.

- However, the Commonwealth of PA must consider how best to support and deploy the full suite of carbon management (capture, transport, storage, and utilization) and hydrogen infrastructure, and hydrogen production and storage opportunities.

What can the members of the state legislature do to help support this effort?
Answer: Create the right statutory framework.

- Pennsylvania currently lacks a sufficient statutory framework to allow for large scale deployment of carbon management projects. Without laws and policies that provide a supportive environment for project developers, and investors, the Commonwealth may miss out on this opportunity.

- To remedy this deficiency, the PA General Assembly should aggressively pursue legislation and work with the appropriate state agencies to enact rulemaking to support regional decarbonization, development of a hydrogen hub and deployment of carbon capture and sequestration opportunities.

- Importantly, there is significant funding under the "Federal Bipartisan Infrastructure Law" set aside specifically to address many of the issues and tasks necessary for the full-scale commercial deployment of carbon management projects and hydrogen production to decarbonize.

- The Commonwealth should consider as many funding mechanisms as possible to advance Pennsylvania-centric deployments, such as those outlined in the Federal Bipartisan Infrastructure Law technical assistance guide.

Reinventing Northern Appalachia for the 21st century

Our proposed regional hydrogen hub and carbon capture ecosystem honors Northern Appalachia's past while powering our future. It's what our communities have been waiting for.

The Appalachian Energy Future Vision

There has never been an opportunity so perfect for our region. This ecosystem will serve as a model for the rest of the country on how to advance the clean energy evolution sustainably. Our vision for the Appalachian Energy Future is:

Forward thinking. We live in an age of rapid change. With this ecosystem, we can futureproof the region for continued resilience and growth, ensuring Northern Appalachia remains a global energy and manufacturing powerhouse.

Innovative. Our region has always been innovative: The commercial oil industry began here, and our steel helped win World War II. Fast-forward to today, and we're producing the natural gas that fuels the world. This ecosystem, like what came before it, will define our region for generations to come.

Elevating communities. This ecosystem will create jobs across the region, ushering in a new era of economic prosperity for our communities. We will also prioritize equity and environmental and energy justice, and help empower others to take part in this endeavor.

Collaborative. This can't happen without the region working together. We are three states but one region. Together, we're unstoppable, because we have the people, the resources and the expertise, not to mention world-class universities, laboratories and industrial/manufacturing capabilities.

Decarbonized. The hydrogen we will manufacture will help decarbonize our industrial base, with emissions stored away safely thanks to CCUS technologies, in the fight against climate change.

DEFINING OUR REGION'S NEXT ERA

Our proposed ecosystem consists of a hydrogen hub and carbon capture, utilization and storage (CCUS) technologies:

- A hydrogen hub would produce clean hydrogen from our abundant natural gas and convert it into low-carbon fuels. Hydrogen applications include fuel for airplanes, cargo ships, tractor-trailers and more, and it is also used as a fuel source and/or production feedstock by sectors such as food and beverage; primary and fabricated metal; plastics and rubbers; and fertilizer.
- CCUS technologies capture carbon emissions and store them safely away to prevent them from entering the atmosphere.

APPALACHIAN ENERGY FUTURE

Advancing Our Region's Clean Energy & Industrial Evolution

OHIO · PENNSYLVANIA · WEST VIRGINIA

Join us to advance our region by seizing this moment.

www.appalachianenergyfuture.org

A powerful partnership for the region's progress

We are an industry-led alliance of interested stakeholders connecting companies from the energy, industrial, manufacturing and other sectors with community leaders and others to develop a regional hub for hydrogen and CCUS. We are taking a long-term, large-scale, regional approach to support collaboration among public and private stakeholders across borders and sectors.

EQT · equinor · GE · MARATHON · MITSUBISHI POWER · MPLX · Shell · USS

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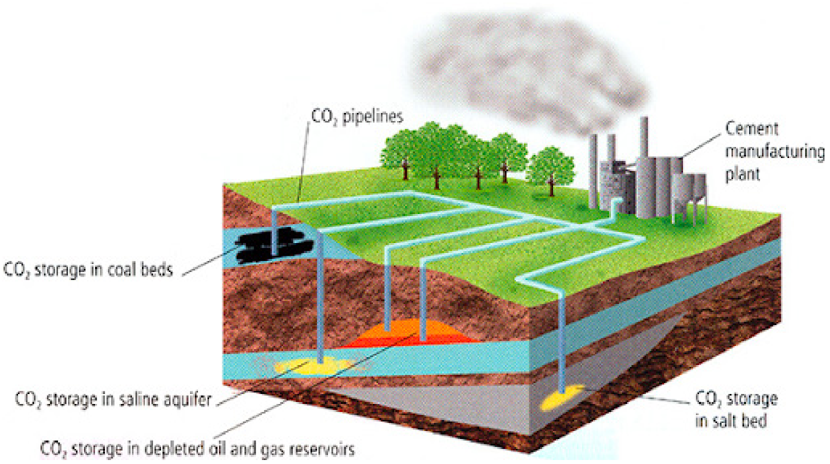
Carbon Capture, Utilization & Storage (CCUS) Overview

What is CCUS?

CCUS is a collection of technologies to capture carbon dioxide (CO_2) from major point sources, including power generation and industrial facilities that use natural gas.

How it works



Images Source

Meeting global energy and climate goals with CCUS

Once it is captured, there are a variety of ways that the CO2 can be used, shipped or stored. It can be used for on-site industrial needs, transported in compressed form by pipeline, ship, rail or truck for several applications, or injected into deep geological formations for permanent storage — otherwise known as long-term geologic sequestration. [4]

[4] A new era for CCUS – CCUS in Clean Energy Transitions – Analysis - IEA

NORTHERN APPALACHIA CCUS APPLICATIONS

We would use CCUS in the production of blue hydrogen as part of our proposed ecosystem, or hub. In basic terms, a hydrogen hub is a cluster of assets that incorporates a number of hydrogen-based energy services. These services, in conjunction with high-volume storage, match the supply and demand of a variety of surrounding industries.

Because of the geological, workforce and market-access advantages that Ohio, Pennsylvania and West Virginia share, there is no better place in the United States to place a hydrogen hub. Not only do we sit on the largest natural gas field in the country — a major feedstock for blue hydrogen — but we also have salt, limestone and sandstone formations that provide favorable conditions for large-scale carbon dioxide storage. This region possesses a highly developed natural gas pipeline infrastructure that can transport hydrogen to markets.

APPALACHIAN ENERGY FUTURE
Advancing Our Region's Clean Energy & Industrial Evolution
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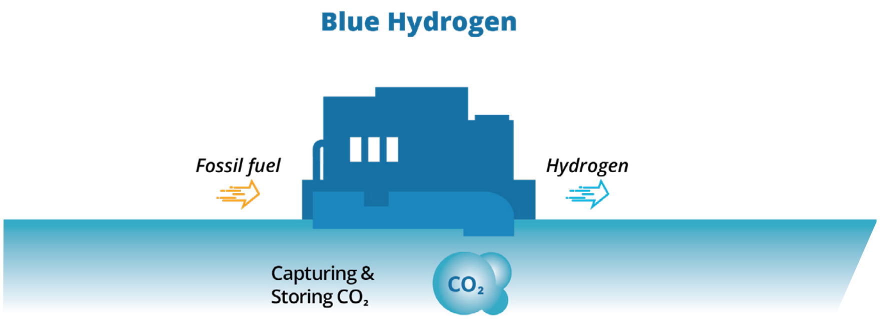
Blue Hydrogen Overview

What is blue hydrogen?

Blue hydrogen is produced when natural gas is split into hydrogen and carbon dioxide through steam reforming, which brings together natural gas and heated water in the form of steam. The hydrogen is then supplied for end-use applications, while carbon capture, utilization and storage (CCUS) technologies trap and store the carbon. [1]

How it works



Achieving net-zero emissions with blue hydrogen

Blue hydrogen can serve as an ideal transitional step in the decarbonization of the economy.[2] According to the U.S. Department of Energy, 95% of hydrogen is produced from natural gas, making it the cheapest and most advanced method of hydrogen production available. Hydrogen can also serve as a replacement for natural gas and, to an extent, be blended into existing pipeline networks as a low-carbon fuel.[3]

Why Northern Appalachia for blue hydrogen?

Our region is home to major energy and industry producers and end users, and one of the world's largest natural gas basins. Northern Appalachia is a middle point between the East Coast and Great Lakes population centers, creating economics of scales to protect jobs and contribute to job growth and economic prosperity across the tri-state region. We are poised to meet America's energy needs while leading the low-carbon and industrial evolution.

[1] The hydrogen colour spectrum | National Grid Group
[2] HYDROGEN STRATEGY Enabling A Low-Carbon Economy
[3] Hydrogen Hubs: The State of Play - Great Plains Institute

HYDROGEN FACTS

- Hydrogen is the most abundant chemical element, estimated to contribute 75% of the universe's mass
- It is the lightest of all elements, yet it has an extremely high energy density
- Hydrogen contains approximately three times as much energy as oil

HOW IS BLUE HYDROGEN USED?

Sectors within the tri-state region that use hydrogen include:

- Chemicals
- Food and beverage
- Petroleum and coal products
- Transportation
- Plastics and rubber products
- Primary and fabricated metal products
- Paper manufacturing

APPALACHIAN ENERGY FUTURE

Advancing Our Region's Clean Energy & Industrial Evolution

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Charting Pennsylvania's Path for Industrial Sector Decarbonization: Deploying Carbon Capture, Utilization, and Storage (CCUS) & Clean Hydrogen Technologies

Pennsylvania has always maintained an unrivaled position in energy production and industrial output which has allowed the commonwealth to contribute meaningfully to the nation's economic growth and play a leading role in every major energy transition since our inception. The commonwealth is now well positioned to lead again as we work collaboratively to expand and modernize our industrial and manufacturing base with less carbon intensive forms of energy.

Key to this transition will be the development of a range of innovative and flexible clean energy pathways, including CCUS, clean hydrogen production, and the creation of a diverse market for clean hydrogen end-use. The signatories to this letter commit their engagement to make these pathways a reality and signal their support to develop the necessary conditions for the commonwealth to be a leader in deploying these technologies.

Pennsylvania has all the building blocks it needs to be successful in this new energy ecosystem: a competitive advantage in energy production, promising geology for permanently storing carbon dioxide, a diverse economy with a strong industrial base and highly skilled workforce, and a commitment to reducing greenhouse gas emissions. In addition, as demonstrated by the diverse signatories to this letter, we have the broad base of cross-sector support that will be critical to successfully pursuing these opportunities and making them a reality.

Over the past year, the commonwealth has partnered with the Team Pennsylvania Foundation to convene energy and industrial stakeholders across a variety of sectors to build consensus and develop the public private partnerships needed to address the challenge of industrial sector decarbonization with a focus on the following:

- Identifying priority opportunities and requirements for deploying CCUS and hydrogen with an emphasis on preparing Pennsylvania to compete for energy-related funding in the Bipartisan Infrastructure Bill.
- Taking action to ensure that we capitalize on our potential to unleash innovative, technological, and market-driven solutions to reducing emissions while creating jobs in the industrial sector.
- Working collaboratively with business and industry to ensure that we deliver practical recommendations and solutions.
- Building this initiative with a broad set of stakeholders to ensure that the work is nonpartisan and sustainable.

There is a tremendous amount of work to be done which will require close collaboration among all sectors of Pennsylvania's economy. The undersigned are aligned in their commitment to take the steps necessary to create a regional ecosystem to achieve decarbonization, to transition to clean hydrogen, and to ensure the commonwealth is competitive in attracting investment and creating jobs in all parts of its economy.

In the coming months, this group will build on this remarkable momentum to deliver on the promise of jobs, the economy, and improving the environment. We recognize that a regional ecosystem for the deployment of these technologies may require new cooperative arrangements with stakeholders beyond the commonwealth's borders to maximize our goals around carbon management and decarbonization. We are committed to working together to determine the resources required for leveraging Pennsylvania's competitive position in energy production and industrial sector productivity to emerge as a national leader in navigating the energy transition.

Signed,

AirProducts and Chemicals, Inc.

Allegheny Conference on Community Development

Allegheny County Executive

Allegheny-Fayette Central Labor Council

Battelle

Boilermakers Local

Clean Air Task Force

Commonwealth of Pennsylvania

CS Energy

Epcot Crenshaw Corporation

EQT Corporation

Great Plains Institute

IBEW Local

IN-2-Market, Inc.

KeyState to Zero, KeyState Energy

Mitsubishi Power Americas

PA Chamber of Business and Industry

PECO Energy Company

Pennsylvania Environmental Council

Piasecki Aircraft Corporation

Pittsburgh Works Together

Shell

Team Pennsylvania Foundation

The University of Pittsburgh

TRC Companies, Inc.

United States Steel Corporation

Legislative Testimony
Hearing before the Pennsylvania House Democratic Policy Committee
Developing a Hydrogen Hub

August 10, 2022

Robert C. Altenburg,
Senior Director for Energy and Climate,
Citizens for Pennsylvania's Future (PennFuture)

In June of 1988—more than thirty-four years ago—NASA scientist Dr. James made it clear in his U.S. Senate testimony that climate change had already begun.[1] We still have a narrow window of opportunity to avoid its worst effects by keeping our emissions under a very strict budget, but that window is closing rapidly. As of 2019 more than 80 percent of our budget has already been emitted.[2]

At this point, merely lowering the carbon intensity of our energy infrastructure or other half measures are not good enough. <u>We need to implement policies that put us on a pathway to net zero carbon emissions by 2050</u>.[3]

The Intergovernmental Panel on Climate Change (IPCC) lays out such a pathway saying:

> "Reducing GHG emissions across the full energy sector requires major transitions, including a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation. *The continued installation of unabated fossil fuel infrastructure will 'lock-in' GHG emissions.* [4]

[1] Testimony of Dr. James Hansen, Director of the NASA Goddard Institute for Space studies, before the U.S. Senate Committee on Natural Resources (June 23, 1988)
[2] IPCC, 2022*: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, B.1.3* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
[3] IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24, doi:10.1017/9781009157940.001.
[4] IPCC 2022, C.4 (emphasis added)

The most important thing our House of Representatives can do relative to developing a hydrogen hub is to ensure that only proposals that are consistent with this pathway to net zero emissions by 2050 are supported.

Will hydrogen be a "bridge fuel" or a bridge to nowhere?

At the beginning of the fracking boom, we were told methane gas could be a "bridge fuel" to aid in the transition to the clean renewable energy we knew we would need, but that is not what happenend. In the years since, Pennsylvania failed to prioritize the policies and investments needed to make that transition to clean energy a reality and instead put all its eggs in the fracking basket. As a result, more than half our electricity generation now comes from methane gas and the fracking industry has gained significant political power and influence. Consequently, we are languishing far behind neighboring states in deployment of renewable generation, and half the time we had to make the transition to clean energy has been wasted.

We are now being told that we need to use polluting fossil fuels to make hydrogen today, but that it can also "bridge" to using clean energy in the future. If we continue to neglect investment in clean energy, that isn't any more likely to be true this time around.

While electricity from clean sources like solar or wind can be used to produce hydrogen, basic physics tells us that using the clean energy directly in our homes, cars, and industry, is far more efficient—and will always be cheaper—than adding an extra step to convert it to hydrogen.

Using hydrogen produced from clean renewable energy may be a reasonable choice to decarbonize industries that are difficult or impossible to electrify with existing technologies, but if we are going to use clean energy to make hydrogen, *we need excess clean energy beyond those other more efficient uses*.

Diverting some clean energy from the grid to hydrogen production doesn't solve the problem. We need enough for both and we simply don't have time to kick the can down the road and hope that clean generation will be built in time. If we aren't investing in that clean energy today it will not be there when we need it.

Where will the market be for this hydrogen?

When the fracking companies came to Pennsylvania seeking significant tax expenditures, streamlined permitting, and other subsidies, we were told that in return the industry would bring hundreds of thousands of jobs and economic prosperity to the region. In the wake of a glut of gas rapidly outstripping demand, we saw anemic job growth and little economic benefit across the region.[5] The solution, we were told, was even more massive taxpayer-funded subsidies—this time to encourage companies to buy the excess gas.

[5] Ohio River Valley Inst., *The Natural Gas Fracking Boom and Appalachia's Lost Economic Decade*, (Feb. 2021).

To avoid making that same mistake again, we need to be certain that there will be a demand for this new hydrogen and, more importantly, that any applications are compatible with achieving our carbon targets.

Unfortunately, these applications are limited. Currently, the highest demand for hydrogen is petrochemical refining—clearly a use we need to transition away from as it represents one of the most polluting industries in the world. Also, the inherent inefficiency of hydrogen production along with the difficulty transporting and storing the gas, likely rules out any meaningful role decarbonizing other significantly polluting sectors of our economy including large scale electric generation, highway vehicles, and home and commercial heating.

There are niche sectors such as steelmaking, long-distance transportation, and other industrial processes that may have potential, assuming the technology can be developed and made ready for commercialization in time. It is by no means clear that such narrowly targeted use cases will require the significant, multi-state build-out of hydrogen capacity that is being discussed, but these are questions that must be answered before we build.

Planning to fail isn't an option

The fracking industry provides one more cautionary example of what to avoid: don't let failure masquerade as progress until it's too late.

The industry frequently claims that because gas has largely driven dirtier coal-fired generation out of business, they are responsible for the bulk of our carbon reductions we have made so far. This claim fails in two main respects.

First, looking at carbon emissions sector by sector is misleading at best. Yes, we need to reduce emissions from electric generation, but if that results in increased emissions of methane gas in the extractive industries and supply chain, there may be no real progress.

Second, and more importantly, even if the industry could demonstrate an economy-wide reduction in carbon pollution, that isn't good enough because it simply isn't a path to net-zero emissions. As of now, all but one of our large coal-fired power plants has already announced their plans to retire. For all the "reductions" switching from coal to gas may have achieved, that is over. Now we are largely dependent on polluting methane gas and are running out of time to make the transition to clean energy we knew we needed all along.

We can't afford to make this same mistake again. If the policy that comes out of this hydrogen hub development isn't designed from the start to achieve net zero by 2050, it is a plan for failure.

Legislative Testimony
Hearing before the Pennsylvania House Democratic Policy Committee
Developing a Hydrogen Hub
August 10, 2022

Joanne Kilgour, Executive Director
Ohio River Valley Institute (ORVI)

Good morning, Chairman Bizzarro, Rep. Pisciottano, and members of the committee. Thank you for having me here today to speak to you about the proposed development of a hydrogen hub in Pennsylvania.

My name is Joanne Kilgour, and I serve as the Executive Director of the Ohio River Valley Institute, an independent, nonprofit research and communications center producing sound research for a more sustainable, equitable, and prosperous Appalachia.

Over the last two years, our research team has been analyzing the environmental, economic, and financial landscape of the proposed buildout of hydrogen and carbon capture and sequestration (CCS) infrastructure in Pennsylvania and throughout the Ohio Valley. Based on this analysis, my testimony today focuses on five key issues for consideration by this committee:

1. The underlying economics of the proposed hub are costly and uncompetitive;
2. The proposed hub currently lacks both a plan and a viable business model;
3. The entire cost, including a profit margin for industry, will be inflicted on taxpayers and ratepayers and will come at a premium;
4. The proposed hub is unlikely to deliver growth in jobs and prosperity; and,
5. Resources and attention devoted to the false promise of the hydrogen hub could delay true clean energy transition in our region and prevent consideration and development of better, more viable economic and job development strategies.

At the time of this testimony, the Inflation Reduction Act (IRA) is pending passage by the United States Congress. For the purposes of this hearing, I have included a discussion of how the passage of the IRA would interact with the proposed hydrogen hub. Regardless of the status of the IRA, the fundamental concerns that run through my testimony would remain, though some of the specific figures would change.

First, I will address the underlying economics of the proposed hub and why our research shows that it would be costly and uncompetitive.

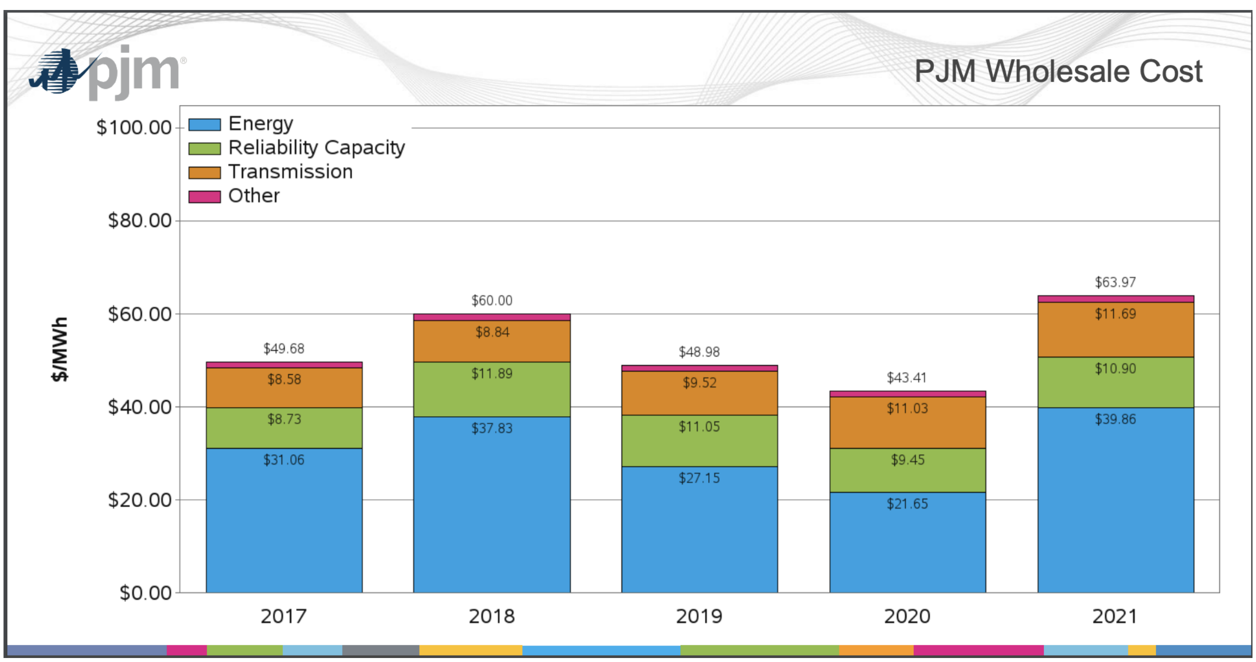
It is important to reinforce that while the framing for this proposed new infrastructure buildout has focused on hydrogen, a hydrogen hub in Pennsylvania would necessarily be accompanied by a significant build out of complementary carbon capture, use, and sequestration infrastructure. For that reason, throughout my testimony I will be discussing both hydrogen and CCS.

In October 2021, the Roosevelt Project released a study titled "A Low Carbon Energy Transition in Southwest Pennsylvania." This study examined the cost of a carbon capture hub for a 13-county region in southwestern Pennsylvania and found that it would cost $2.9 billion per year - or just over $2,300 per household - for the 1.25 million household study region. (See page 96 of the above-linked report).

Using the same cost data as the Roosevelt study, our researchers at the Ohio River Valley Institute conducted an analysis of the cost impact of CCS in gas and coal-fired power generation, and found that:

- The cost to generate electricity at gas plants would rise by $38.70/MWh;
- The cost to generate electricity at coal plants would rise by $61.90/MWh; and
- If CCS were implemented in PA's existing coal and gas-fired plants, residential electric bills would rise by $266/year or 26%.

By comparison, in 2021 the average wholesale cost of energy in the PJM market was $39.86/MWh, which means that the incremental cost of CCS alone would be as great or greater than the market value of the electricity being produced.



Meanwhile, renewable resources, energy efficiency, and storage can provide electricity at costs at or below the current wholesale price and without any carbon dioxide emissions.

With respect to how this relates back to the hydrogen production component of a proposed hub, the economic outlook for blue hydrogen - hydrogen produced from natural gas - suggests that even the blue hydrogen manufactured using CCS will be matched or undercut in cost by 2030 by green hydrogen - hydrogen generated from renewable energy - which is completely free of carbon emissions.

With the pending Inflation Reduction Act, it is worth noting that the poor economic outlook for blue hydrogen and CCS discussed above would not be fully mitigated by the provisions of the IRA that pertain to CCS. Recent analyses show that, even with near 100% subsidies for carbon capture and sequestration contained in the IRA bill, at best only 20-30% of gas fired power would be retrofitted for CCS and only 10-15% of coal-fired power would be retrofitted. In the most optimistic of analyses, CCS is expected to capture only 20% of current emissions from coal and gas-fired power by 2035 and less than 10% of industrial emissions by 2035. Further, the Inflation Reduction Act would not fund construction in the region of the nearly 1,000 miles of CO2 pipelines that would likely accompany a hydrogen hub in southwestern Pennsylvania, infrastructure that would cost tens of billions of dollars and require additional legislation and appropriations. Even where federal investments may be available, it is important to note that access to federal funds does not make a project free - residents end up paying through our tax bills, our utility bills, or a combination of both.

Next, I will discuss why it matters that the proposed hub currently lacks both a plan and a viable business model.

Another key issue for consideration by this committee is that there is, as yet, no specific plan for the hydrogen and carbon capture hub infrastructure in southwestern Pennsylvania or the broader Ohio Valley. We do not currently have insight into which facilities would be included or excluded. We do not currently have insight into the extent of pipeline build-out that would be necessary to accompany such hub development, or the extent of the overall footprint of that pipeline network within our communities. Similarly, we lack information on the share of industrial emissions that a regional hydrogen and carbon capture hub would capture or fail to capture.

Similarly, no viable business model has been proposed or may even be possible given that:

- Many of the presumed customers for the carbon capture component of the proposed hub, including coal and gas-fired power plants, are already struggling to remain competitive with low-cost renewable resources and, therefore, would require near-100% subsidies to absorb a technology that would in many cases increase operating costs by two times or more;
- Because the proposed subsidies for carbon capture provided in the Inflation Reduction Act would last only 12 years, few plants and factories will be able to fully recover the immense up-front capital investment required by CCS; and
- Prospective CCS hub customers won’t assume the incremental cost themselves unless they know their competitors will either be compelled or taxed into assuming added costs as well.

The publicly available document closest to being able to suggest a business model for the proposed hydrogen and carbon capture hub is the "Building to Net-Zero" report from the Labor Energy Partnership. But the conditions for the quasi-federal business model (see page 40 of the linked report) suggested by former Energy Secretary Ernest Moniz and his colleagues in this report, which is based on the Bonneville Power Administration (BPA), do not exist. The BPA is a self-financing entity whose costs are paid entirely by its customers. Neither BPA nor its customers receive federal appropriations. Moniz's suggestion that a federal entity would own and operate the carbon pipeline network and sequestration operations and charge the cost back to its customers would likely require that those customers receive a federal subsidy greater than the value of the service. In other words, the federal government would have to give the customers the money to hand back to the federal government.

Next, it is likely that the entire cost of a hydrogen and carbon capture hub, including a profit margin for industry, would be inflicted on taxpayers and ratepayers and will come at a premium.

The proposed solution to the financing and economic problems described above is 100%+ taxpayer subsidization of carbon capture, use, and sequestration.

One key mechanism for taxpayer subsidization of activities like carbon capture have come in the form of tax credits. The Inflation Reduction Act of 2022 would raise the value of the section 45Q tax credit to $85/MTCO2 and make it a direct payment for up to seven years, which means that it would no longer be necessary for the taxpayer to have sufficient tax liability in order to take advantage of the credit. In most cases, the $85/MTCO2 figure is equal to or greater than the actual cost of carbon capture and that doesn't include many other tax and regulatory provisions the administration is recommending that states take to reduce industry costs and shift liability.

If enacted, these IRA provisions would result in a 100%+ taxpayer subsidy for technologies that are not market competitive. The need for a 100%+ subsidy isn't just our contention, it's a fact verified by this briefing document that emerged from a meeting between Sen. Joe Manchin, the chair of the West Virginia Public Service Commission, and the CEO of American Electric Power, one of the nation's largest investor-owned electric utilities. The parties were discussing the possibility of outfitting a 1,300 MW coal-fired power plant with CCS. Quoting from the briefing document:

- "If the entire plant could be converted, the capital cost may be between $3 to $5 billion and operating costs may increase by 25% to 35%."
- "Adding a utility level rate of return to a $4 billion capital investment for the carbon capture would add close to $400 million per year, or close to $50 per ton, or $50 per MWH."
- "That level of cost for utility customers in West Virginia is unsustainable. Therefore, federal funding of close to 100% of the capital costs is needed."

Shortly after this meeting, Senator Manchin said this to reporters. "I'd love to have carbon capture, but we don't have the technology because we really haven't gotten to that point. And it's so darn expensive that it makes it almost impossible."

Even the subsidies included in the Inflation Reduction Act, if enacted, may still not be sufficient to spur widespread adoption of CCS because:

- The subsidy is only available for 12 years, which in many cases will not provide sufficient time for prospective adopters to recover their capital costs;
- The subsidy will be adequate only for facilities that have comparatively high capacity factors, thus excluding many coal and gas-fired power plants; and
- CCS technology is still not ready for widespread commercial adoption and, by the time it is, sometime around the end of this decade, many prospective adopters, especially coal-fired power plants, may have retired.

In addition to the challenges noted above, the proposed hydrogen and carbon capture hub is unlikely to deliver growth in jobs and prosperity.

The principal effects of a regional hydrogen and carbon capture hub would be the preservation and possible expansion of the natural gas industry. In fact, the Allegheny Conference in its recently released decarbonization pathway, anticipates significant growth in the shale gas industry between now and 2030.

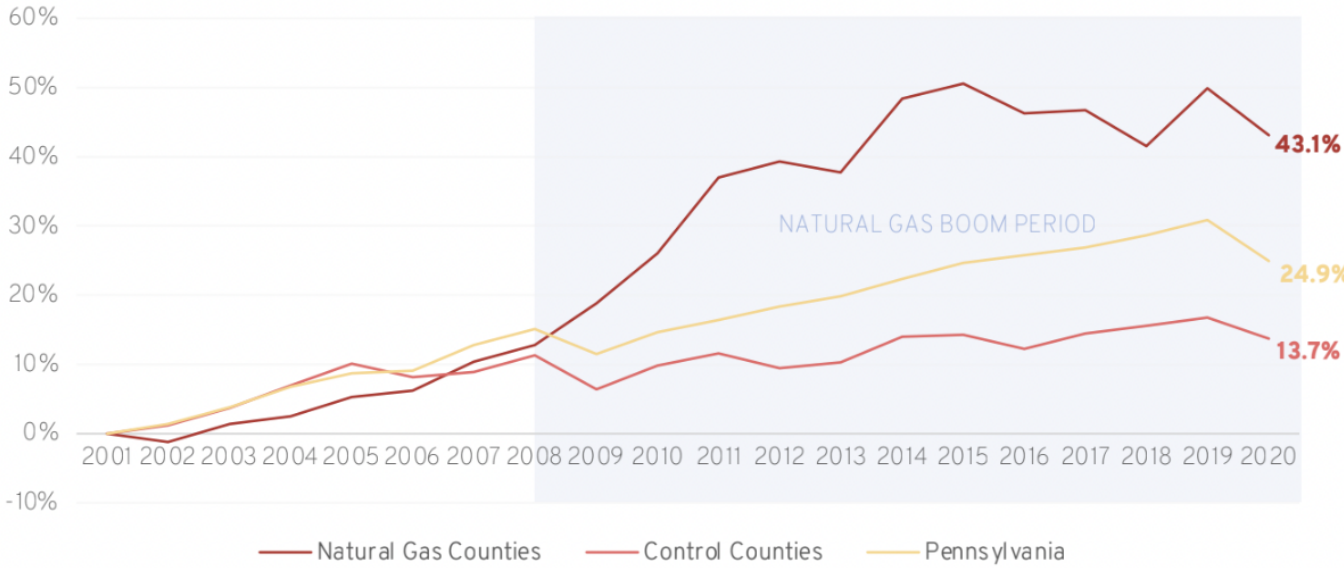
However, the natural gas industry's past failures and structural inability to induce job growth and prosperity, especially in PA's rural counties, have now been well-documented.

A February 2021 Ohio River Valley Institute report found that, despite immense growth in GDP, fracking counties experienced meager growth in jobs and income and absolute losses in population.

A follow-up report determined that the reasons for these failures are structural and, therefore: increased natural gas production is unlikely to deliver job growth; and any job growth that does arise diminishes over time.

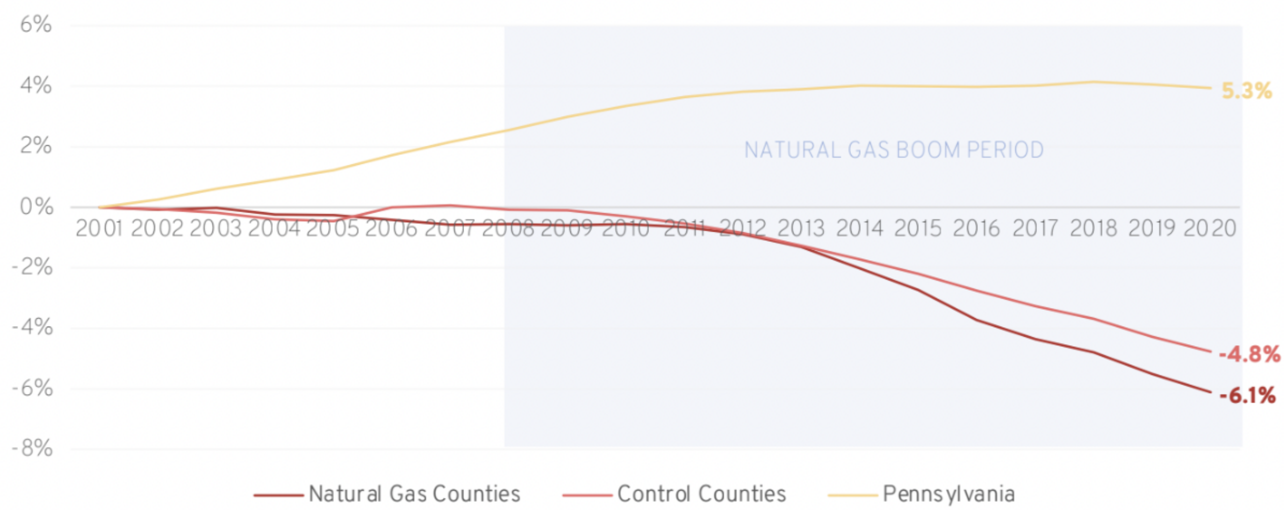
And a third report, released just this week, validated the two preceding reports and demonstrates that PA rural counties that participated heavily in the natural gas boom did little better than those that did no for job growth and experienced even greater population loss. Findings from this new report are shared below:

Figure 3: Change in Real GDP, 2001-2020



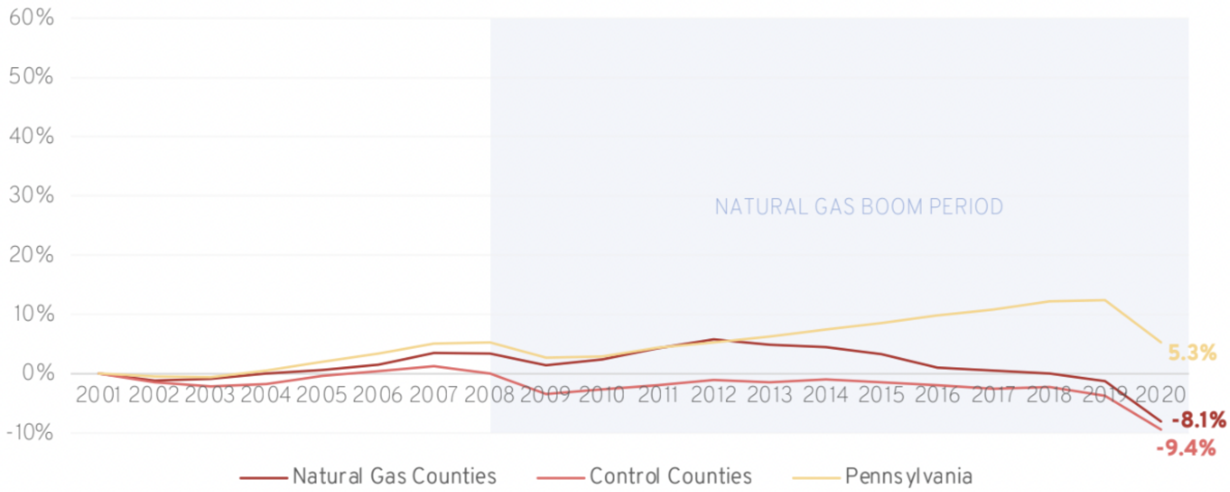
Source: Author's calculations using Bureau of Economic Analysis data

Figure 5: Change in Population, 2001-2020



Source: Author's calculations using Bureau of Economic Analysis data

Figure 4: Change in Total Employment, 2001-2020



Source: Author's calculations using Bureau of Economic Analysis data

Finally, it is important for this committee to consider that resources and attention devoted to the likely false promise of the hydrogen hub could delay true clean energy transition in our region and prevent consideration and development of better, more viable economic and job development strategies.

The Allegheny conference decarbonization pathway report is one example of local leaders premising regional economic development strategies on industries, like the oil and gas industry, strategies that have failed to deliver lasting, shared prosperity to our local communities.

Pursuit of these strategies would further shackle the region to these industries and divert resources that could be used to help the region join the rest of the country in benefitting from the cost savings and job growth associated with true clean energy transition.

While jobs in fossil fuels are declining, the clean energy sector is adding jobs at a rate 50% faster than the nation as a whole.

We even see this in communities that have been historically dependent on fossil fuel industries, but which have chosen to transition. One is rural Lewis County, Washington where a coal mine and power plant were the anchors of the local economy and where, for decades, jobs and population change mirrored that of many Appalachian counties. But, when Lewis County embraced an economic transition strategy focused on investments in energy efficiency, education, and renewable generation, it caused job and income growth to spike, with incomes growing 50% faster than the national average and jobs growing at twice the rate of the nation.

We have been down this path of grandiose visions and promises before, first with the natural gas boom and then with the "petrochemical manufacturing renaissance" for which we contributed billions of taxpayer dollars and assumed immense liability, but for which industry still owes us 200,000 jobs in the case of the fracking boom (See chart on page 34) and another 100,000 jobs in the case of the petrochemical cluster that they never delivered. I urge you to consider these past visions that failed to materialize at the scale that was promised as a cautionary tale for what we can expect with this new promise of a regional hydrogen hub.

Thank you for the opportunity to speak with you all today.

August 3, 2022

Pennsylvania House of Representatives
Democratic Policy Committee

Dear Committee Member,

The Sierra Club Pennsylvania Chapter respectfully submits these comments and the following document outlining our positions and concerns related to potential hydrogen development in Pennsylvania. It is imperative that we eliminate half of all climate disrupting carbon pollution from all sectors of the economy by 2030, and all such emissions by 2050. Hydrogen may have a small but important role to play in this effort, but as the attached document explains, its role must be limited to applications in which it is actually the most efficient and least polluting option.

Protect Communities

The development of hydrogen and associated infrastructure has the potential to significantly impact nearby communities and must be subject to strong community protection standards. Nevertheless, it is likely that some level of community impact is inevitable, especially if hydrogen is being produced from methane gas, because these communities will bear prolonged impacts from continued fossil gas development. Minimizing unavoidable impacts from hydrogen development is necessary, but not sufficient, to move forward with hydrogen development. It is just as important to ensure that hydrogen related development does not worsen historical inequities and environmental impacts in communities of color and low-income communities. Any development **must actually benefit** the communities where facilities are located.

Target Hydrogen Production to Limited End Uses

We must target hydrogen production to certain hard-to-decarbonize end uses and utilize hydrogen **only when it is the most efficient and affordable pathway** to decarbonization. Hydrogen is an energy-intensive resource and is often a relatively costly option, and in some cases, there are already more efficient solutions like direct electrification. Applications where hydrogen may prove useful include certain manufacturing processes, long-term storage of renewable energy, aviation, maritime transportation, and long-haul trucking. However, it is possible that more cost-effective technologies could emerge for these applications as well.

Regulate Emissions

Different hydrogen production methods can have very different impacts on human health, the environment, and the climate. Hydrogen can be produced using zero-emission energy like wind and solar, or emission-intensive fossil fuels like methane gas, which can be paired with carbon capture, utilization and storage (CCUS) to mitigate some of those emissions. Pennsylvania must focus solely on hydrogen produced with zero- and near-zero-carbon emissions. We can achieve this by adopting strong emissions standards that take into account **the full life-cycle emissions** involved in production.

Any investment and development of hydrogen derived from methane will only make it harder to transition to hydrogen derived from emission-free sources. CCUS does not fully mitigate emissions and continued methane use will only reduce our carbon budget. All of these factors should be accounted for in setting policies and priorities.

Respectfully,

Tom Schuster
Interim Director
Sierra Club, Pennsylvania

Jen Quinn
Legislative and Political Director
Sierra Club, Pennsylvania

Attachment:
Hydrogen: Future of Clean Energy or a False Solution?

TESTIMONY OF THE NATURAL RESOURCES DEFENSE COUNCIL

Mark C. Szybist, Senior Attorney

Before the House Democratic Policy Committee

Concerning Carbon Capture

Philadelphia, Pennsylvania
July 22, 2021

Chairman Bizzarro, Representative Hohenstein, honorable members of the Committee: good morning and thank you for the invitation to speak to you on the topic of carbon capture.

My name is Mark Szybist and I am a senior attorney with the Natural Resources Defense Council, a nationwide non-profit environmental organization with approximately 17,000 members in Pennsylvania. My job is to advocate for equitable clean energy policies in the Commonwealth.

My testimony[1] has three parts:

- First, I will summarize the actions that Pennsylvania and the world need to take – including the deployment of carbon capture technology – to eliminate greenhouse gas (GHG) emissions on a net basis by 2050, which is necessary to avoid the worst effects of climate change;[2]
- Second, I will discuss in general terms the role that NRDC envisions for carbon capture in decarbonizing the United States' economy; and
- Third, I will discuss the need to eliminate carbon dioxide (CO_2) emissions from the manufacture of concrete and recommend policy steps that Pennsylvania legislators can take to drive the production of "low embodied carbon concrete" and, in turn, the use of carbon capture.

In addition to the present testimony, NRDC is also submitting testimony by my colleague Rachel Fakhry that discusses the potential role of hydrogen in decarbonizing Pennsylvania's economy and describes the three most commonly discussed pathways for the production of low or zero-carbon hydrogen: "green hydrogen" (the production of hydrogen from water using electrolysis powered by renewable energy), "pink hydrogen" (the production of hydrogen from water using nuclear-powered electrolysis) and "blue hydrogen" (the production of hydrogen using conventional steam methane reforming technology with carbon capture).

Decarbonizing the Economy

In 2018, the United Nations Intergovernmental Panel on Climate Change (IPCC) issued a special report titled *Global Warming of 1.5º C.*[3] It concluded that to avoid the worst impacts of climate change, we must keep the increase in average global temperatures below 1.5 degrees Celsius, and that to do that the world must reduce net GHG emissions 45 percent by 2030, and attain net zero emissions by 2050.

Since the IPCC report, a number of studies have analyzed different technological pathways for attaining these goals, which are often described as pathways to "deep decarbonization." The consensus emerging from those studies[4] is that to achieve deep decarbonization, we must:

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[1] This testimony was written by Chris Neidl (cneidl@gmail.com) and Sasha Stashwick (sstashwick@nrdc.org) from NRDC's Industrial Decarbonization team.

[2] For a comprehensive overview of the current and projected impacts of climate change in Pennsylvania, see the Department of Environmental Protection's most recent Climate Impacts Assessment, released in May, 2021, at https://www.dep.pa.gov/Citizens/climate/Pages/impacts.aspx

[3] Available at https://www.ipcc.ch/sr15/.

[4] *See* NRDC, "The Biden Administration Must Swiftly Commit to Cutting Carbon Pollution at Least 50 Percent by 2030," FN 6. Available at https://www.nrdc.org/sites/default/files/2030-biden-climate-pollution-ib.pdf.

- Generate our electricity from zero-carbon sources, especially renewables;
- Electrify our buildings and our vehicles;
- Improve the energy efficiency of our buildings and industrial processes;
- Reduce emissions of GHGs other than CO_2, including methane, nitrous oxides, and fluorinated gases; and
- Increase our capacity to remove CO_2 from the atmosphere through forest protection and reforestation, improved agricultural practices, carbon capture, and other practices.

Reducing our net emissions by 45 percent in the next eight years and achieving net zero emissions by 2050 is a massive undertaking. But the analyses also show that it is both possible and affordable, to a large extent with existing technologies[5] and established legal and policy pathways.[6]

Crucially, decarbonizing our economy is also a massive opportunity to invest in American workers and families and create a fairer, more sustainable, and less precarious economy than the one we have now. That is why many U.S states are developing ambitious plans to drive renewable energy, limit carbon pollution, and pursue other decarbonization pathways. Since 2008, for example, state and local commitments have led to a near-doubling of renewable energy generation in the U.S. and six states have made legal commitments to 100 percent carbon-free electricity by 2050 or earlier. Another 10 states have longer-term 100 percent goals.[7] Pennsylvania, though, has fallen behind.

The Role of Carbon Capture in Deep Decarbonization

The selective use of carbon capture, utilization, and storage (CCUS) should not be viewed as a leading decarbonization strategy on par with avoiding emissions in the first place via energy efficiency and renewable energy, but as a complement to those strategies. NRDC opposes reliance on CCUS in the power sector because there, more than anywhere, efficiency and renewables are readily available superior alternatives and the use of CCUS could lead to continued dependence on fossil fuels. Not only are the alternatives available, they are also far cheaper. In addition, NRDC opposes subsidies for CCUS applications that compete with clean, renewable energy or energy efficiency.

By contrast, NRDC sees an important role for CCUS as one of a suite of advanced technologies to decarbonize emissions-intensive industrial subsectors in which a significant share of emissions cannot be abated using energy efficiency, fuel switching and/or electrification and where

[5] *See id.* at 3.
[6] *See* Michael B. Gerrard and John C. Dernbach, editors, *Legal Pathways to Deep Decarbonization* (March, 2019). Available at https://www.eli.org/eli-press-books/legal-pathways-deep-decarbonization-united-states.
[7] *See* NRDC (Sophia Ptacek with support from Amanda Levin), "Race to 100% Clean," at https://www.arcgis.com/apps/Cascade/index.html?appid=714cd31f37a64314b8d1e7e502c13c58

industrial materials have no readily available replacements. NRDC supports funding for carbon capture projects at industrial facilities like cement and steel plants that send captured CO_2 to secure saline geologic storage rather than for enhanced oil recovery. However, policy safeguards are needed to ensure that CCUS is effective in isolating captured CO_2 and leads to measurable, securely stored, and long-term emissions reductions.

Major investment in cleaning up heavy industry here in the United States is much-needed. The industrial sector is responsible for roughly one-third of U.S. emissions when accounting for direct and indirect (i.e., electricity-use) emissions. Under business as usual, the industrial sector is on track to become the largest source of U.S. GHG emissions within the decade. According to the Pennsylvania Department of Environmental Protection's most recent emissions inventory, the industrial sector is already the largest source of emissions in Pennsylvania. Thus, as in the power, transportation, and buildings sectors, decarbonizing U.S. industry is critical to achieving near-term climate targets. Modeling analysis by NRDC shows that to reduce economy-wide GHG emissions 50 percent by 2030, industrial emissions must fall by one-third below 2005 levels.[8]

Because heavy industry is heterogeneous, heavily dependent on fossil fuels, and has complex supply chains, decarbonizing it will not be simple. Yet, we cannot avoid decarbonizing the sector; industrial building materials like cement and steel are foundational to our way of life. Our communities will continue to depend on industrial products for our infrastructure for years to come, so we need to take steps to make our domestic industrial manufacturing base compatible with our climate targets.

To an extent, we can reduce emissions from manufacturing cement (and other emissions-intensive industrial products) by relying on energy efficiency, electrification and/or fuel switching. But, as is discussed in detail below with respect to cement, making industrial products like cement and steel often involves unavoidable processes that release CO_2. Thus, beyond 2030, as we begin to need much deeper decarbonization in these sectors to stay on track to meet net-zero midcentury emissions targets, carbon capture and storage offers an available and viable lever to abate the substantial remaining emissions that cannot be tackled via these other strategies. However, for these advanced technologies to be available at scale when we need them, investments must start now to bring down their costs and risks.

[8] Rachel Fakhry and Starla Yeh, NRDC Issue Brief, "The Biden Administration Must Swiftly Commit to Cutting Climate Pollution at Least 50 Percent by 2030, March 30 2021, https://www.nrdc.org/resources/biden-administration-must-swiftly-commit-cutting-climate-pollution-least-50-percent-2030

Decarbonizing Concrete

Concrete is the second most commonly used material on earth, after water; and by a large margin the world's most common building material.[9] Approximately 18 billion tons of it are produced annually around the globe.[10] According to the Pennsylvania Aggregates and Concrete Association, our yearly output here in the state is roughly 13.4 million tons[11], or 9.6 million cubic yards -- a volume that could fill 450 Heinz Fields to a depth of 10 feet (or up to the field goal crossbar).

These figures provide a measure not only of the staggering scale of concrete's use, locally and globally, but of its indispensability to contemporary construction, and architectural and engineering knowledge and practice. Its unique physical, performance, supply and cost characteristics make it, quite literally, a foundation of the modern built environment; and, critically, one with no viable substitute that can realistically replace it at scale in the foreseeable future.

Further, it is safe to assume that not only is concrete here to stay, but that its footprint will expand in the 21st Century. This growth will be driven by increased urbanization in emerging economies, as well as building stock and infrastructure renewal in wealthier nations like the United States.[12]

Concrete is not only a key ingredient in the buildings, roads, bridges and countless other forms of infrastructure that our way of life depends on; it is also the direct and indirect source of tens of thousands of jobs here in Pennsylvania, and millions around the globe. The material's physical properties require it to be produced close to where it is used. As a result, its supply overwhelmingly comes from local businesses, many of them small, privately-owned, and deeply anchored in the communities in which they are located. And the same holds for the many construction and contracting firms that pour, pave and install concrete throughout the state. According to the National Ready Mix Concrete Association, concrete-related economic activity contributes as much as $1.5 billion annually to Pennsylvania tax revenue.[13]

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[9] Shuchi Talati, Na'im Merchant, Neidl, Chris. 2020. "Paving the Way for Low Carbon Concrete: Recommendations for a Federal Procurement Strategy". Carbon180. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5fd95907de113c3cc0f144af/1608079634052/Paving+the+Way+for+Low-Carbon+Concrete

[10] Cao, Z., Masanet, E., Tiwari, A., and Akolawala, S. 2021. "Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China". Industrial Sustainability Analysis Laboratory, Northwestern University, Evanston, IL.

[11] The Pennsylvania Aggregates and Concrete Association. 2021. "Our Industry: About the Aggregates, Ready Mixed Concrete and Cement Industries in Pennsylvania". https://www.pacaweb.org/community/our-industry

[12] Cao, Z. et al. 2021

[13] The Portland Cement Association. 2016. "Pennsylvania Cement Industry: Building the Foundation of Pennsylvania's Economy," https://www.cement.org/docs/default-source/ga-pdfs/cement-industry-by-state-2015/pennsylvania.pdf?sfvrsn=2&sfvrsn=2

Concrete's importance, value and staying power are clear and uncontroversial. However, the material's present and future relationship to our changing climate presents a far more complex picture, and one that must be assessed by policymakers in terms of its own distinct features, constraints and opportunities. First and foremost, what must guide policymaker thinking about concrete and climate is that the material is here to stay – or, at minimum, it is sure to remain with us during the critical timeframe for action to address the climate emergency. This is also likely to hold, though perhaps to a lesser extent, for concrete's core binding ingredient, Portland cement. The latter, as I will discuss at greater length below, is overwhelmingly responsible for the emissions associated with concrete's production and use.

Concrete, Cement and the Climate

State and federal policy making related to concrete decarbonization is a relatively new domain, but one that is today making up for lost time. As more climate responsive legislatures and executives seek effective avenues to help realize economy-wide emissions reductions, attention to concrete and cement has inevitably been elevated in recent years.

These efforts have brought to the fore many of the unique complexities that are inherent to these industries and must be grappled with in efforts to reduce their emissions. Some important questions concerning concrete's net impact on the climate necessitates a nuanced perspective. Exploring this basic matter with the objective of reaching informed policy decisions requires us to make three important distinctions.

Concrete has both positive and negative climate attributes

First, we must distinguish between concrete's *operational carbon* and *embodied carbon*; or between the emissions that can be linked to concrete post-construction, over its full lifecycle, and those that are produced, up front, as a result of its production. On balance, once installed, concrete offers many advantages in terms of climate and environmental performance that should not be discounted. It's high thermal mass boosts building energy efficiency by limiting heating and cooling loads. It is durable and long-lasting; and at the end of its life, it can be recycled and locally reused as an input in new concrete, substituting sand and gravel as *aggregate*. Concrete's relatively high *albedo* means that it reflects more light than alternative materials used for road and sidewalk construction, such as asphalt, and therefore contributes less to the urban heat island effect.

Less widely appreciated but more pertinent to our discussion today, concrete also has the remarkable property of absorbing and storing CO_2 directly from the air over time through a gradual process known as *carbonation*. A recent peer-reviewed study published in the journal

Nature found that nearly half of CO_2 generated in the production of concrete may be reabsorbed back into the material over its lifetime.[14] Concrete's unique natural function as a *carbon sink* can now be enhanced and augmented with new technologies and methods, a development which will be explored later in this testimony.

<u>Concrete and cement are related but separate materials. Effective policy responses must internalize this fact.</u>

The greatest challenges linking concrete to the climate relate to the material's *embodied carbon*, or the emissions generated during the manufacturing process, prior to construction. This points to an important second distinction that must be made in our analysis, one that differentiates between *concrete* and *cement*, and more specifically, *Portland cement*, the most widely used form of the latter. Portland cement is the ingredient within concrete which, when activated by water, binds and gives it its unique properties of strength and versatility. In common usage, even in policy circles, much confusion is caused when the word "cement" is all too often mistakenly used interchangeably with "concrete."

Cement is an ingredient in concrete, not a synonym for it. But when we assess the challenges and opportunities of concrete within the context of climate action, we are almost entirely concerned with the status of cement. This is because Portland cement, while typically making up no more than 10 percent of concrete by mass in most applications, accounts for approximately 80 percent of emissions linked to concrete production.[15]

Under conventional conditions, the production of 1 ton of cement generates over 800 kG of CO_2, making it one of the most carbon-intensive materials on the planet.[16] At a global annual output of nearly 5 billion tons, CO_2 emissions generated by cement production account for up to 8 percent of total emissions, a volume rivaled only by iron and steel among industrial sector sources.[17] If cement were a country, it would be the world's fourth largest emitter of CO_2.

Cement is produced through the *pyroprocessing* of limestone in kilns at temperatures of 2700 degrees Fahrenheit. Attaining this heat level is achieved using carbon-rich, energy dense fossil

[14] Xi, F., Davis, S., Ciais, P. *et al.* 2016. Substantial global carbon uptake by cement carbonation. *Nature Geosci* **9,** 880–883. https://doi.org/10.1038/ngeo2840
[15] Cao, Z. et al. 2021
[16] Cao, Z. et al. 2021
[17] Thomas Czigler, Reiter, S., Schulze, P. and Somers, K. (2020). "Laying the Foundation for Zero-Carbon Cement." McKinsey & Company. https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement

fuels, and most commonly coal.[18] However, over half of the CO_2 released in cement production is from so-called *process emissions* that result not from fuel incineration but from the chemical breakdown of limestone (CaCO3) at these ultra-high temperatures. Consequently, even if cement kilns are retrofitted in the future to accommodate low-carbon fuels, such as green hydrogen or electrification, the majority of CO_2 emissions produced in the process will remain unaffected.

Unlike in the power and transportation sectors, this reality all but ensures an essential role for point source carbon capture at cement plants if the sector is to be significantly decarbonized in the coming decades. Indeed, the International Energy Agency (IEA) and Sustainable Cement Initiative's 2019 Technology Road Map projects that nearly 50 percent of CO_2 emissions reductions in the cement sector by 2050 will need to be realized through carbon capture technologies.[19] And capturing carbon at scale also entails the development of infrastructure to transport it to sites where it can be permanently and safely sequestered.

The IEA report estimates that the investment required globally to scale up capture and storage capacity across the global cement industry would be on the order of $370 billion dollars.[20] For a trade exposed commodity industry in which competition is fierce and price sensitivity extreme, this requires carefully designed policies that combine incentives with common-sense emission reduction requirements.

Today there are only a handful of carbon capture and sequestration demonstration projects operating at cement facilities around the world. However, growing commitments by the sector's leading producers -- pressed by investors and public regulation and laws -- to attain net-zero emissions by mid-century are beginning to materialize in specific plans for commercial projects, and comprehensive strategies for investment. HeidelbergCement, the world's fourth largest cement manufacturer, announced last month its plan to commission the first carbon neutral cement plant in Sweden by 2030. The plant will capture 1.8 million tons of CO_2 per year which will be transported and sequestered offshore.[21] This project will follow from the company's present CCS project under development in Brevik, Norway, which will capture 50 percent of plant emissions starting in 2024. Within this same timeframe here in the United States, Lafarge Holcim, the largest cement manufacturer in the world, plans to commission CCS technology at its plant in Florence, Colorado. Carried out in partnership with the Canadian CCS technology

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[18]Andrew Logan. 2020. Explained: Cement vs. concrete — their differences, and opportunities for sustainability". MIT News. https://news.mit.edu/2020/explained-cement-vs-concrete-understanding-differences-and-sustainability-opportunities-0403

[19] The International Energy Agency and the Sustainable Cement Initiative. 2018. "Technology Roadmap: Low Carbon Transition in the Cement Industry." https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf

[20] International Energy Agency, et al. 2018

[21] Christoph Beumelburg. 2021. "HeidelbergCement to build the world's first carbon-neutral cement plant". HeidelbergCement Group. https://www.heidelbergcement.com/en/pr-02-06-2021

provider Svante and with grant support from the U.S. Department of Energy, the project will capture upwards of 700 thousand tons of CO_2 annually.[22]

While the emergence of these and other projects provide some indication of movement, change is not happening fast or widely enough. Here in the United States at the federal and state level a more concerted effort to drive investment and transition to carbon capture at cement plants with secure saline storage for the captured CO_2 must materialize. Pennsylvania can play a leadership role in this effort, and we have an obligation to do so. According to the U.S. Geological Survey our state is the 7th largest cement manufacturing state in the country,[23] producing upwards of 4 million metric tons of cement per year at 9 different plants.[24] Our position creates an opportunity for us to act, in partnership with local industry, large cement consumers and counterparts in other states and at the federal level.

The emissions profile of concrete today could change dramatically in the future given different technological, policy and market conditions.

The imperative to advance CCS in the cement industry, globally and locally, points to a third and final important distinction that we must make in our planning and analysis. And that is between what concrete is and means for the climate today, versus what it could be and mean in the future, under different innovation, policy and market scenarios.

Concrete is an ancient material that has resisted transformation due to both internal and external influence and inertia. But today this is changing. A growing spectrum of alternative methods, materials and technologies can be employed at various stages of the supply chain to improve the climate performance of concrete. Some of these are highly innovative, cutting edge and just now emerging; while others are decidedly simple and low-tech, and already well established or underway.

Efficiency, waste reduction and reuse measures can be realized economically throughout the process, from cement manufacturing to final concrete installation. Improvements in cement plant efficiency have largely already been implemented across much of the United States in recent years, but additional incremental gains can still be realized. At the other end of the process,

[22] Cementnet.com. 2020. "LafargeHolcim awarded US$1.5m grant for Florence carbon capture project“. https://www.cemnet.com/News/story/169743/lafargeholcim-awarded-us-1-5m-grant-for-florence-carbon-capture-project.html
[23] The United States Geological Survey. 2021. ”Cement Data Sheet - Mineral Commodity Summaries 2020“. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cement.pdf
[24] The Portland Cement Association. 2015. “Pennsylvania Cement Industry: Building the Foundation of Pennsylvania's Economy“. https://www.cement.org/docs/default-source/ga-pdfs/cement-industry-by-state-2015/pennsylvania.pdf?sfvrsn=2&sfvrsn=2
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methods of avoiding or repurposing unused, wasted and demolished concrete at the construction stage are becoming more common and sophisticated. The use of recycled concrete aggregate (RCA) in place of conventional aggregate is another emerging application that substitutes locally available demolished concrete that would otherwise be landfilled, for sand and gravel. This reduces emissions tied to material processing and transportation. More sophisticated waste reduction methods at an earlier stage of market deployment show promise. These include both forms of modular construction methods, and 3D-printing production methods that cut down on material waste through improved precision, accounting and process optimization.

Another decarbonization lever is fuel substitution in the process of making Portland cement. Hydrogen and even electrification may represent longer-term options.[25]

Many other decarbonization levers involve altering the proportion of conventional, high emissions ordinary Portland cement used in concrete mixes. Many established and emerging inputs, called *supplementary cementitious* materials, or SCMs, include silica fume, calcined clay, natural pozzolans, and ground glass pozzolan, which is made from post-consumer glass.

More recent developments with longer-term promise involve substituting ordinary Portland cement with alternative novel cements produced with materials that have lower carbon chemistries. Examples such as reactive belite cement clinker, calcium sulfoaluminate, celitement, and Magnesium oxides derived from magnesium silicates (MOMS) are in various stages of commercial development and have the potential to dramatically reduce both process and thermal emissions.[26]

Perhaps one of the most high-impact and viable measures that can be taken to reduce cement content and decarbonize concrete in the near-term involves standards embedded in construction practice and building codes, rather than specific technologies and methods, per se. Here I refer to the need for a general transition away from *prescriptive specification standards* and towards more *performance-based specification standards.*

Prescriptive specifications dictate the specific material inputs and proportions that are acceptable for different construction applications. By contrast, performance-based specifications are agnostic to materials and proportions, and instead dictate desired performance conditions, including strength and durability. The advantage of the latter approach is that it creates more openings for innovation and improvement, but without compromising quality and safety. The persistence of prescriptive standards in building codes represents a substantial and fundamental

[25] Julio Friedmann. 2020. ”Concrete Change: Pathways to Decarbonize Cement and Concrete Production and Use”. Presentation to the Natural Resources Defense Council. New York City. https://www.youtube.com/watch?v=jgHI6xUKjsc
[26] Cao, Z. et al. 2021.

barrier to many of the transitional and breakthrough approaches that I am describing in this testimony.

Over time, moving to a performance-based standard will catalyze market-based innovation and improvements throughout the concrete supply chain and material palette.[27] One recently published case study from California shows the promise that this shift holds within the context of a single project. By moving to a performance-based standard for concrete, the project empowered project managers and their vendors to identify workable, cost-effective local solutions that resulted in a 24 percent embodied carbon reduction at no additional cost.[28] It's not difficult to imagine how a general transition to performance-based specification standards on the municipal, state and federal level would catalyze change.

I have already introduced the special circumstances that make CCS an important tool within the context of cement decarbonization. This relates to the high degree of process emissions that cannot be mitigated through alternative energy pathways. The most efficient technology categories of carbon capture today are oxy-fuel firing and post-combustion capture.[29] The former promises high efficiency capture rates of up to 80-99 percent, but can entail substantial redesign of existing plant systems; whereas the most common form of post-combustion capture, chemical absorption using amines, require comparatively less investment in capital upgrades, and has been in use in some industries for many years. Calcium looping is a newer alternative post-combustion capture method that could deliver high thermal efficiency gains relative to more established practices. Recently, amine-based absorption and calcium-looping technologies have been piloted in the cement sector in both China[30] and Norway.[31]

Carbon capture represents a key long-term component of emissions management in the cement process, but to produce a climate benefit the captured CO_2 must be safely and permanently sequestered. Geological sequestration on a large scale -- along the lines of what is being pioneered in Northern Europe -- will be necessary. And opportunities exist for substantial carbon storage here in our state. Indeed, the Pennsylvania Department of Conservation and Natural

[27] Michael Thomas. 2020. "The Case for Performance Based Concrete Specifications," https://www.carboncure.com/concrete-corner/concrete-expert-dr-michael-thomas-makes-the-case-for-performance-based-specs/

[28] Donald Davies, Price, K., Berahman, F., 2021, "A New Benchmark for Reducing High-Rise Construction Costs and Carbon Footprints," Structure. https://www.structuremag.org/?p=17858

[29] Cao, Z. et al. 2021.

[30] Global CCS Institute. 2018. "World's largest capture pilot plant for cement commissioned in China". https://www.globalccsinstitute.com/news-media/insights/worlds-largest-capture-pilot- plant-for-cement-commissioned-in-china/

[31] Bjerge, L.-M.; Brevik, P. 2014. "CO2 Capture in the Cement Industry, Norcem CO2 Capture Project (Norway)," *Energy Procedia, 63*, 6455–6463. https://doi.org/10.1016/j.egypro.2014.11.680.

Resources has been studying carbon storage potential in our state for nearly 20 years[32] and is an active participant in multi-state collaborative efforts to study storage opportunities in the broader region.[33] Determining viable, economic and safe pathways for storage here will depend on further coordination between state regulators and their federal counterparts, and partnership with private sector actors and asset owners in cement and other hard-to-abate industrial sectors of prominence in Pennsylvania (most significantly steel manufacturing).

However, geological sequestration does not represent the only pathway for permanently storing CO_2. Concrete is by far projected to be the largest potential market within the emerging carbontech or carbon utilization building sector. An analysis by the leading think tank and advocacy organization Carbon180 estimates an $800 billion dollar market opportunity.[34] Today it is also the most mature, with multiple carbon utilization and mineralization technologies and methods already commercialized or approaching market entry. The most common category of carbon utilization involves different curing methods that deploy CO_2 from industrial sources as an input in concrete production. The CO_2 used in the process can displace Portland cement, as well as water and other resource, and represents a permanent form of chemical storage as, or more, reliable than geological sequestration. According to a 2020 McKinsey and Company market report, current low-carbon cement technologies can store up to 5 percent of CO_2, with an upward potential of 30 percent.[35]

Another promising form of carbon utilization in concrete involves making or enhancing other common high-volume inputs, such as aggregate and SCMs, with CO_2. Aggregate, which makes up roughly 80 percent of most concrete mixes by mass, could one day amount to a substantial carbon sink if cost effective methods can be scaled. Two companies, U.S-based Blue Planet and England-based Carbon8, have already developed commercial products that produce carbon mineralized aggregate.

Companies such as CarbonCure, Solidia, CarbonBuilt and Blue Planet represent early market leaders in the concrete carbon utilization space. But they are joined by a growing number of other investor-backed firms, helping establish a new and still emerging, but diverse industrial category.

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[32] The Pennsylvania Department of Conservation and Natural Resources. (accessed) 2021. "Carbon Capture Utilization and Storage."
https://www.dcnr.pa.gov/Conservation/ClimateChange/CarbonCaptureStorage/Pages/default.aspx

[33] The Midwest Regional Carbon Initiative. https://www.midwestccus.org/

[34] Rory Jacobson and Lucas, M. 2018. "A Review of Global and U.S. Total Available Markets for Carbontech." Carbon180.
https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5c0028d270a6ad15d0efb520/1543514323313/ccr04.executivesummary.FNL.pdf

[35] Thomas Czigler, Reiter, S., Schulze, P. and Somers, K. (2020). "Laying the Foundation for Zero-Carbon Cement." McKinsey & Company. https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement

How far, practically, can the combined impacts of decarbonization approaches, carbon capture and carbon utilization take us towards a fully climate benign concrete in the future? Leading subject expert and founding director of MIT's Concrete Sustainability Hub, Professor Jeremy Gregory is not alone in asserting that a carbon negative -- not just neutral -- concrete that stores more CO_2 than is released in its production is not just pie in the sky, but an actual future scenario worth aspiring towards.[36] "We are not there yet," according to Gregory, "but in the right circumstances the production of concrete could actually store more CO_2 than it releases into the atmosphere."

Potential Policy Interventions to accelerate decarbonization of concrete in Pennsylvania.

Given the scale and ubiquity of concrete use, the prospect of evolving the material into a net carbon sink for the planet would have enormous climate benefits. Targeted public policies implemented at the federal and state level can play a significant role in removing barriers and accelerating concrete's transformation into a low or even carbon negative material. The following measures represent areas of strategic focus that can be explored and acted upon in the near-term in Pennsylvania.

Leverage public procurement dollars to create demand for lower carbon concrete.

As much as 39 percent of all concrete in North America is purchased by public agencies.[37] This means that the purchasing power and decisions of federal and state governments have the unique potential to catalyze demand for various forms of low carbon concrete. Neighboring New Jersey and New York have either introduced or passed legislation in the last year that, as law, would require state agencies to factor embodied carbon into selection criteria.[38]

The California Legislature is considering legislation to amend its existing environmental procurement program, Buy Clean, to include concrete and cement as regulated materials. The City of Portland Oregon was the first in the nation to implement a low carbon concrete procurement program which will require vendors bidding on city contracts to ultimately meet certain carbon-intensity thresholds to participate in RFP solicitations. Pennsylvania can learn from and adapt these and other approaches to develop a low carbon concrete program that aligns with its state goals and targets.

[36] Jeremy Gregory. 2020. "Concrete". MIT Climate Portal. https://climate.mit.edu/explainers/concrete
[37] Hasanbeigi, A., and Khutal, H. 2021. "Scale of government procurement of carbon intensive materials in the U.S. Tampa Bay, FL." Global Efficiency Intelligence, LLC. Accessed March 25 2021. https://www.globalefficiencyintel.com/scale-of-government-procurement-of-carbonintensive-materials-in-us

[38] Sasha Stashwick. 2021. "In NY, a Chance to Create a Model Policy to Green Concrete," The Natural Resources Defense Council, https://www.nrdc.org/experts/sasha-stashwick/ny-chance-create-model-policy-green-concrete

<u>Shift to a Performance-Based Specification Standard for Concrete.</u>

As detailed earlier, innovation and market acceptance of new low carbon materials and approaches is halted by overly prescriptive specifications in local and state building codes. To fully unleash the creative power of markets and private sector initiative, Pennsylvania should convene a stakeholder process to develop and implement performance-based specification standards for concrete. The state can learn from best practices employed in a host of private sector projects from around the country, as well as initiatives taken by the public sector. For example, Marin County, California Low Carbon Concrete Building Code, implemented in 2020, incorporates a performance-based specification standard pathway that can offer valuable design guidance for efforts in other jurisdictions, including PA.[39]

Thank you again for the opportunity to testify today. I look forward to answering any questions you may have and discussing these important issues.

[39] County of Marin Low Carbon Concrete Project. https://www.marincounty.org/depts/cd/divisions/sustainability/low-carbon-concrete-project

WORLD ENERGY COUNCIL

WORLD ENERGY INSIGHTS: WORKING PAPER

REGIONAL INSIGHTS INTO LOW-CARBON HYDROGEN SCALE UP

In collaboration with PwC and EPRI

ABOUT

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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.

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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.

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- 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.*

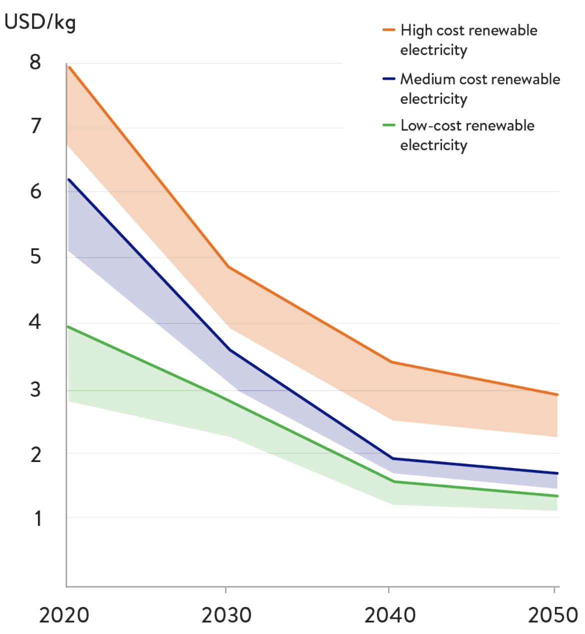
POTENTIAL FOR A SIGNIFICANT ROLE BY 2040

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)

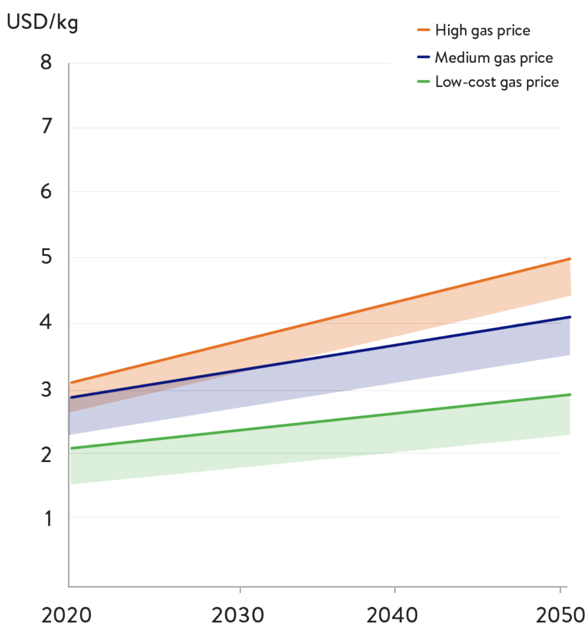
The high cost of transporting hydrogen means that most hydrogen will be consumed in the country or region where it is produced. The two largest energy markets, China and the USA, are likely to be more or less self-sufficient in hydrogen. Nevertheless, there is potential for significant global trade flows 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

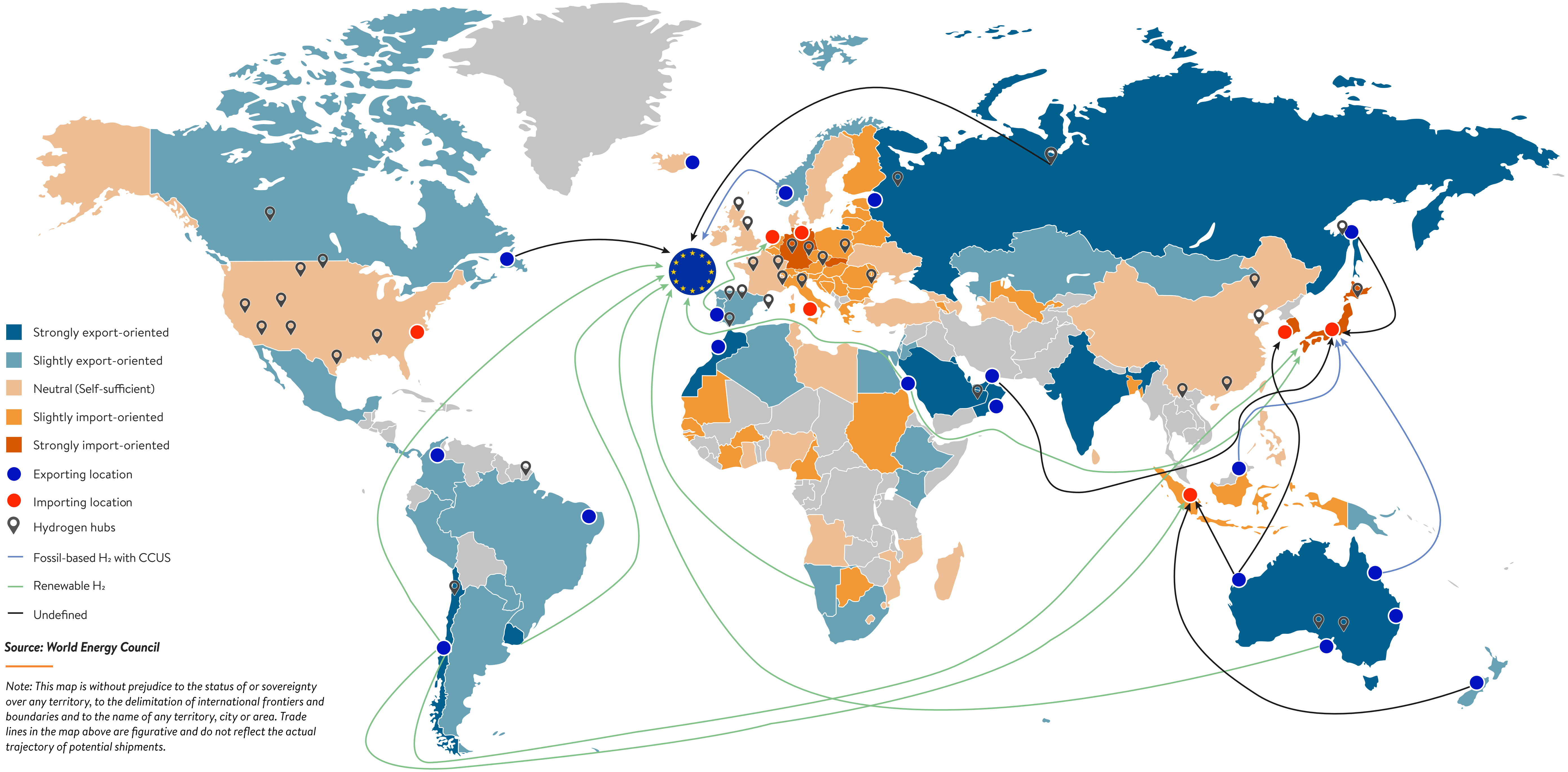
Figure II. Projected cost by 2050 of low-carbon hydrogen from natural gas with CCUS



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.

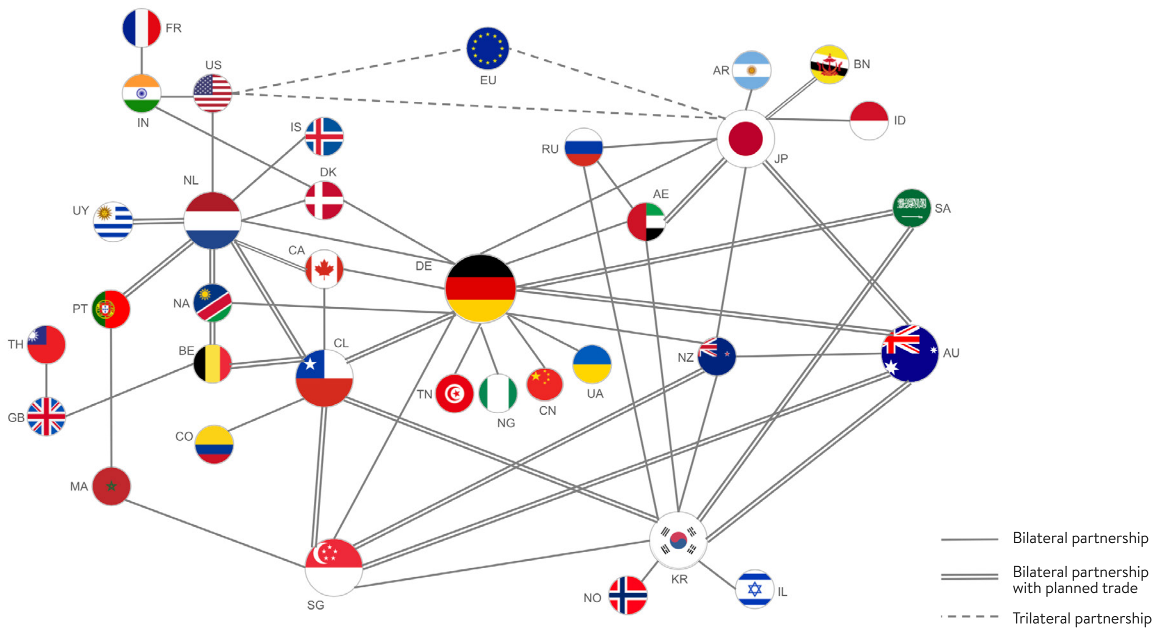
- *Can bankable projects emerge and the gap between engineers and financers be bridged?* **There is a gap between what technology providers could deploy and what bankers will finance.** What steps can be taken to ensure that new business models work, and that low-carbon hydrogen becomes competitive with 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 ZERO HUNGER — *2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture*
- 7 AFFORDABLE AND CLEAN ENERGY — *7: Ensure access to affordable, reliable, sustainable and modern energy for all*
- 8 DECENT WORK AND ECONOMIC GROWTH — *8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all*
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE — *9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*
- 11 SUSTAINABLE CITIES AND COMMUNITIES — *11: Make cities and human settlements inclusive, safe, resilient and sustainable*
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION — *12: Ensure sustainable consumption and production patterns*
- 13 CLIMATE ACTION — *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:

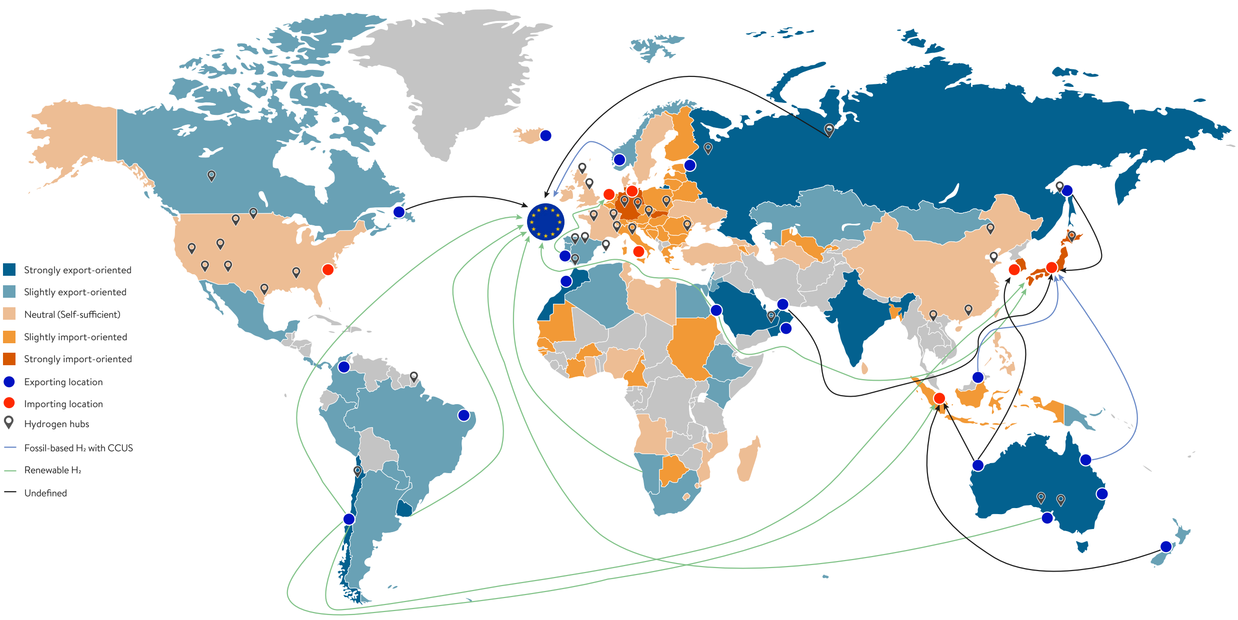
A GLOBAL COMMODITY IN THE FUTURE?

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

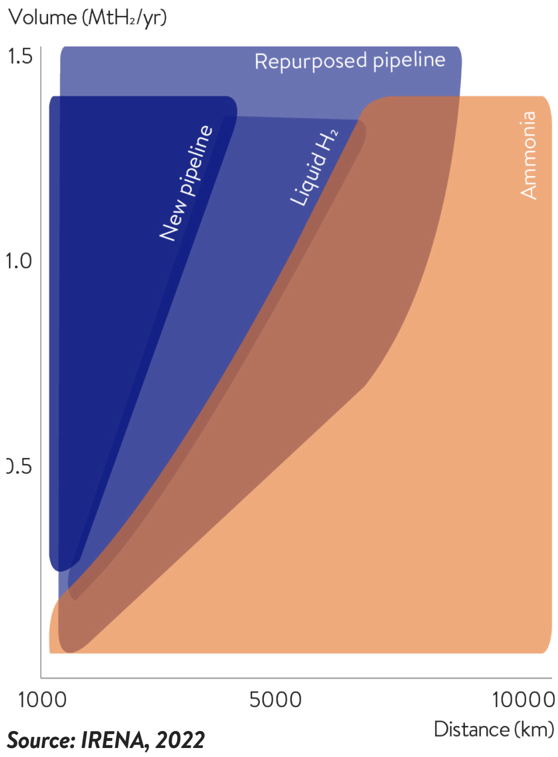


Source: World Energy Council

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

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.

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



Source: IRENA, 2022

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.

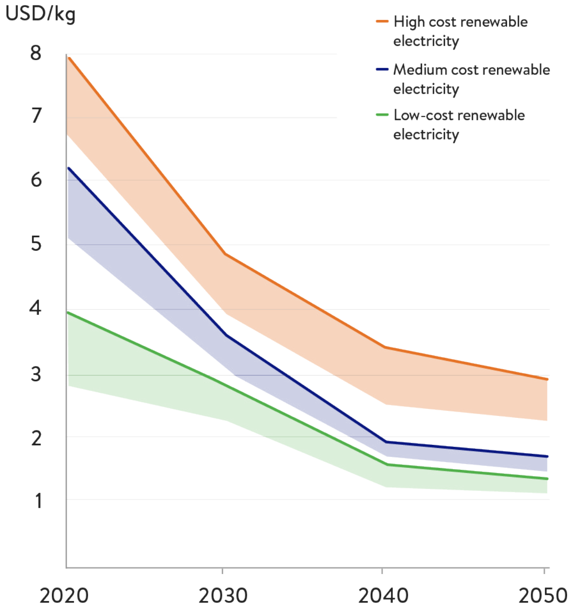
To face these challenges, cooperation is crucial between all actors involved in the supply chain. Increased cooperation is called upon and driven by many actors, and collective enablers are emerging to reduce barriers to global trade (see in the section on Enablers for low-carbon hydrogen market ramp-up).

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.

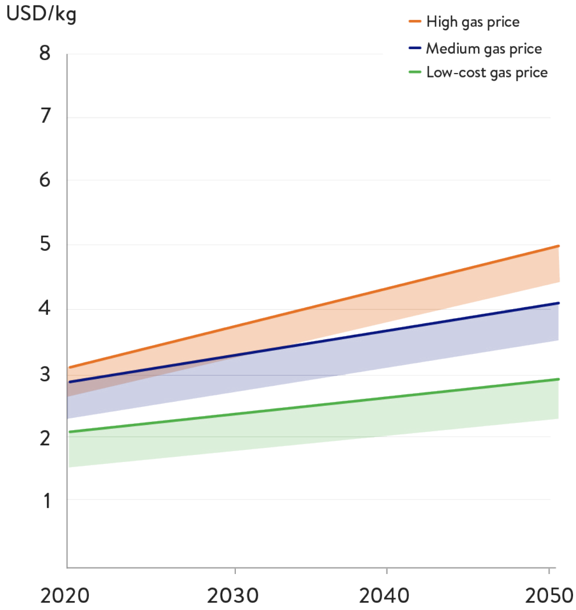
The continuous decrease in renewable hydrogen cost (Figure 3) will lead to a situation where in 2050 it will be cheaper to produce low-carbon hydrogen using SMR with CCUS only in few regions with continued low gas prices, low availability of renewable electricity and good access to CO_2 storage sites.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

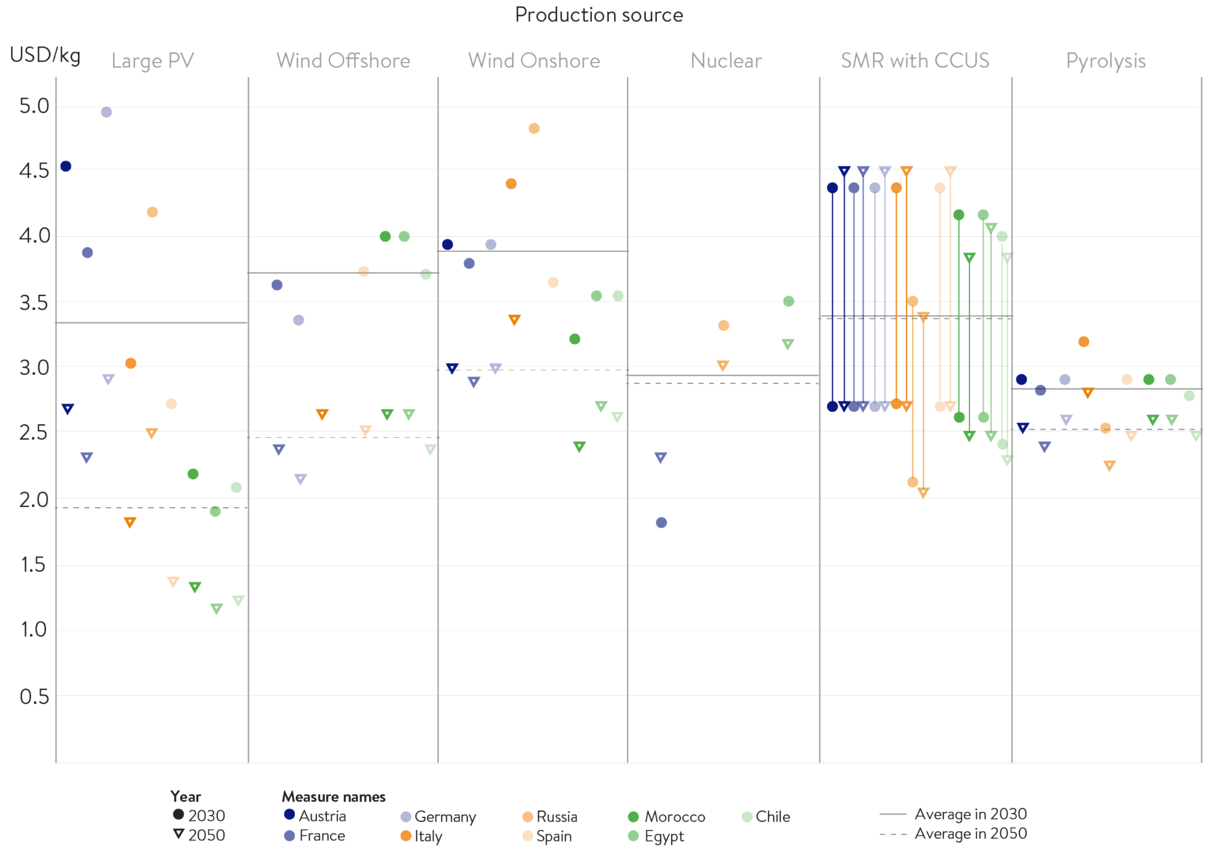
METHODOLOGY

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)



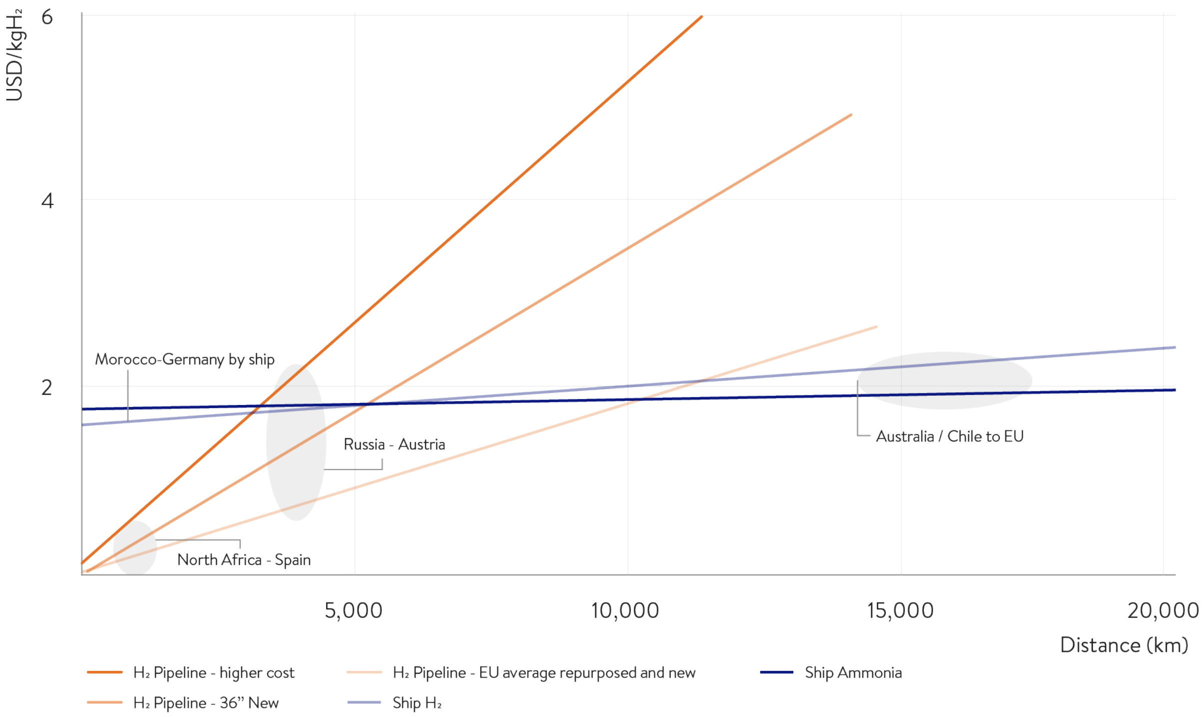
Source: World Energy Council

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

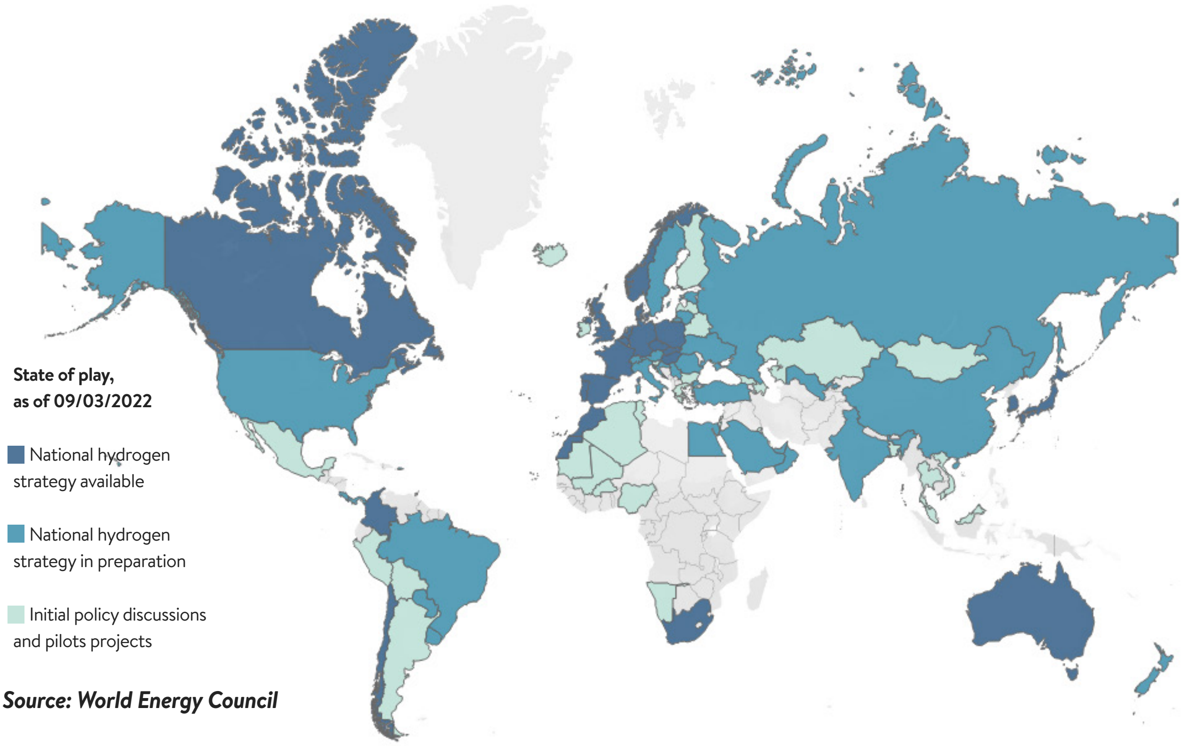
Besides the cost projection, the stability of supply and volume availability of low-carbon hydrogen can affect the retail price significantly. For instance, intermittency in the production of renewable energy because of weather fluctuations can directly impact the supply of low-carbon hydrogen to end-users, 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.

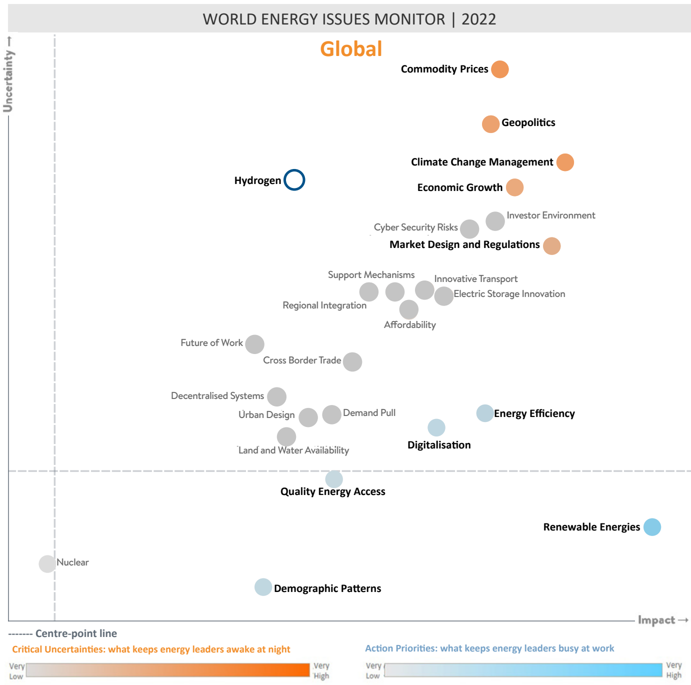
Figure 7. Overview map of the countries activities towards developing a hydrogen strategy



Source: World Energy Council

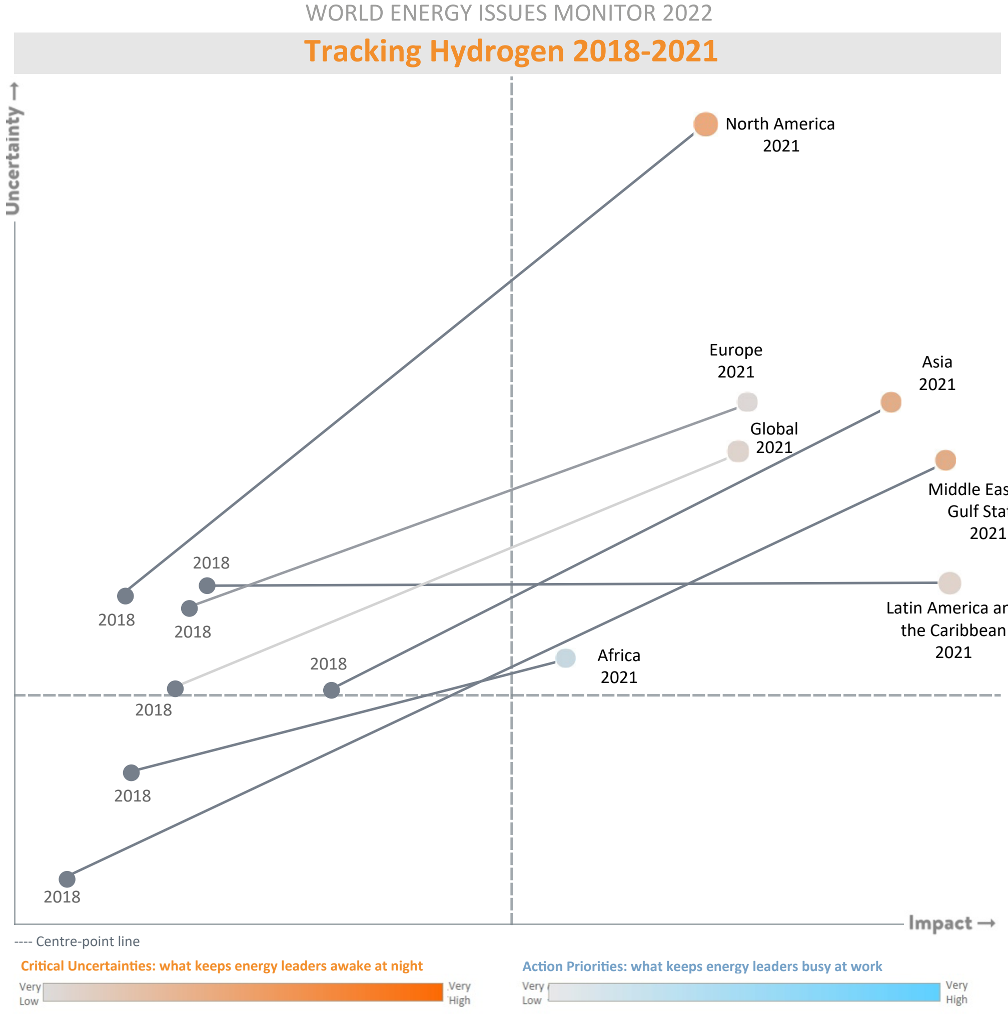
Figure 8. World Energy Issues Monitor 2022 - Global map with Hydrogen

Source: World Energy Council



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

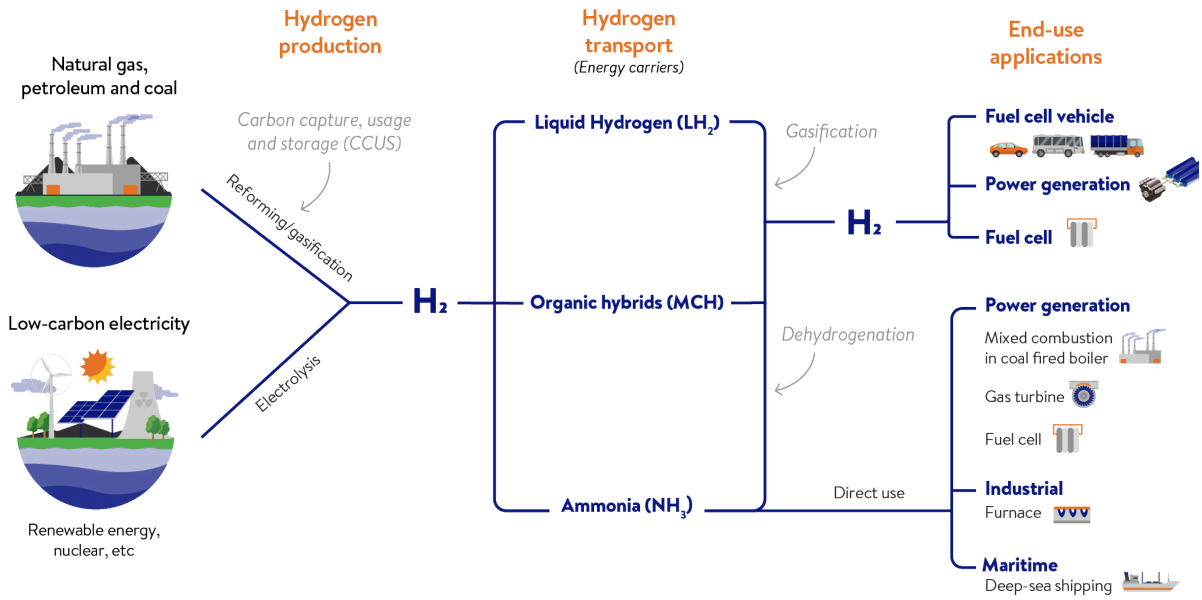
The shaping of the low-carbon hydrogen supply chain is already underway in the Asia-Pacific region, with Japan, South Korea and Australia having been the first countries worldwide to release a dedicated national hydrogen strategy. Japan and South Korea are already identified as future significant net-importers 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

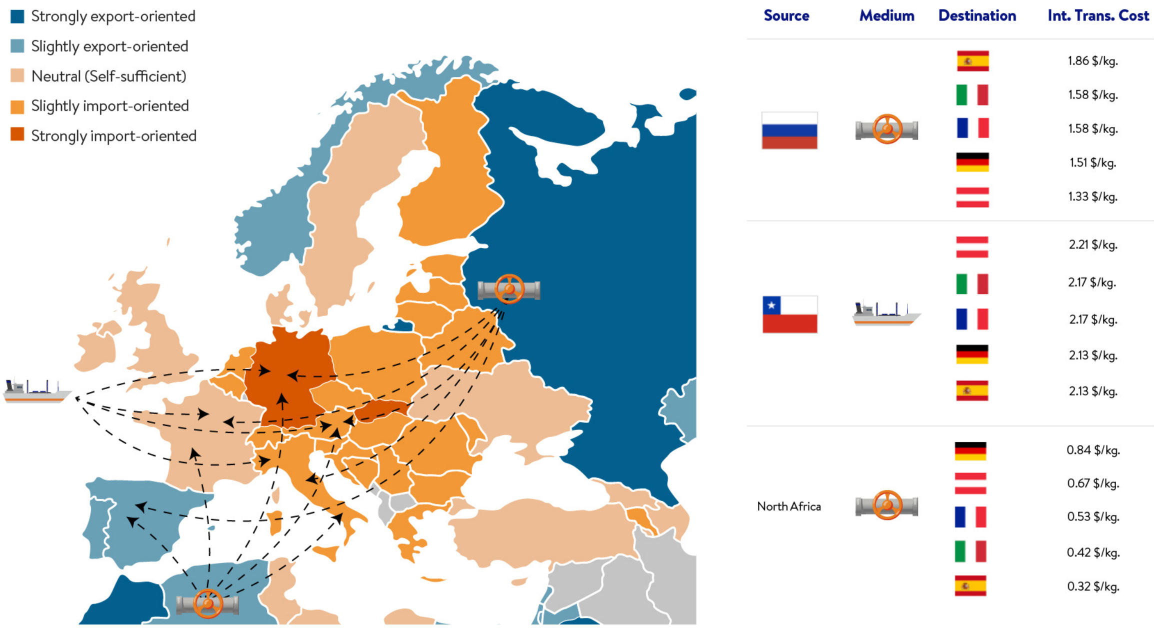
The European region overall strongly favours hydrogen from renewable energies. However, more production sources increasingly appear necessary in the future, especially in the scaling-up period (e.g., from nuclear, fossil-based with CCUS or by methane pyrolysis). Some European countries are looking at 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.

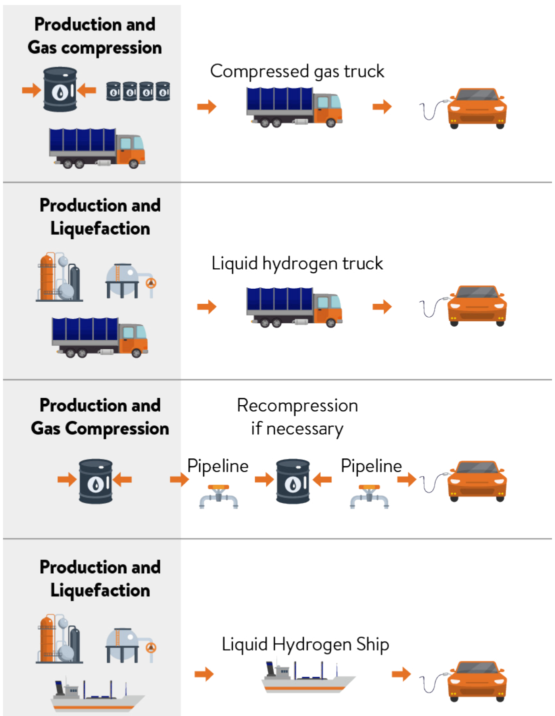
The US and Canada are leading the hydrogen production from fossil fuels with CCUS technology, with more than 80% of global production capacity (IEA, 2021). Several policies are supporting this type of hydrogen production, with "Tax Credit for Carbon Sequestration" in the US rewarding "qualified" carbon 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 CO2eq 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

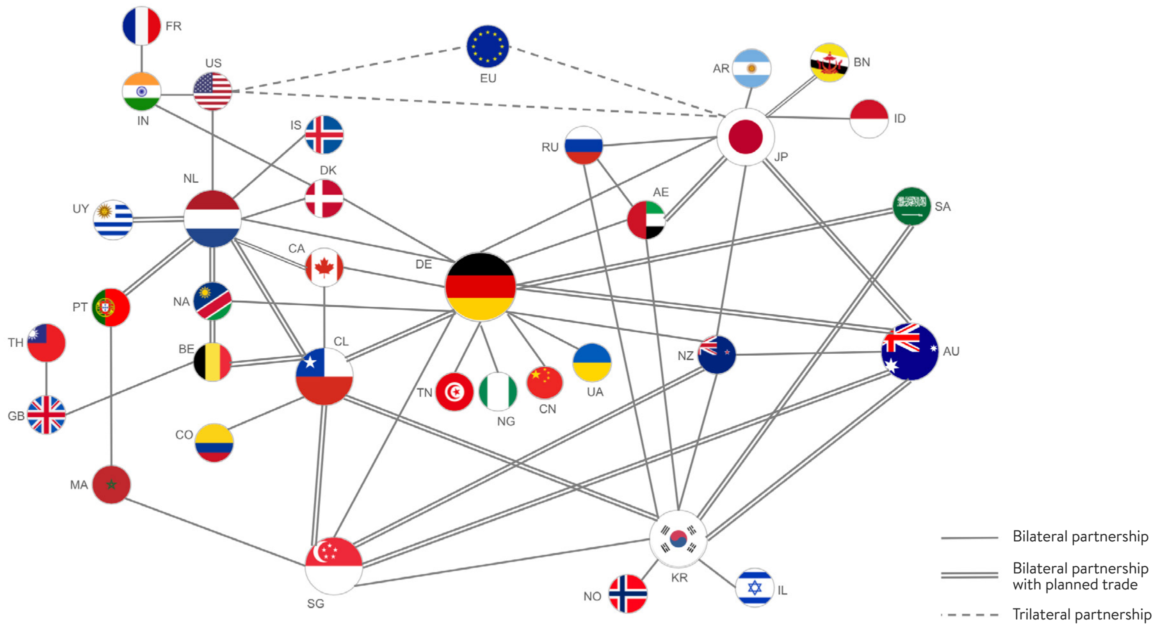
MOBILISING PUBLIC AND PRIVATE FINANCING

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

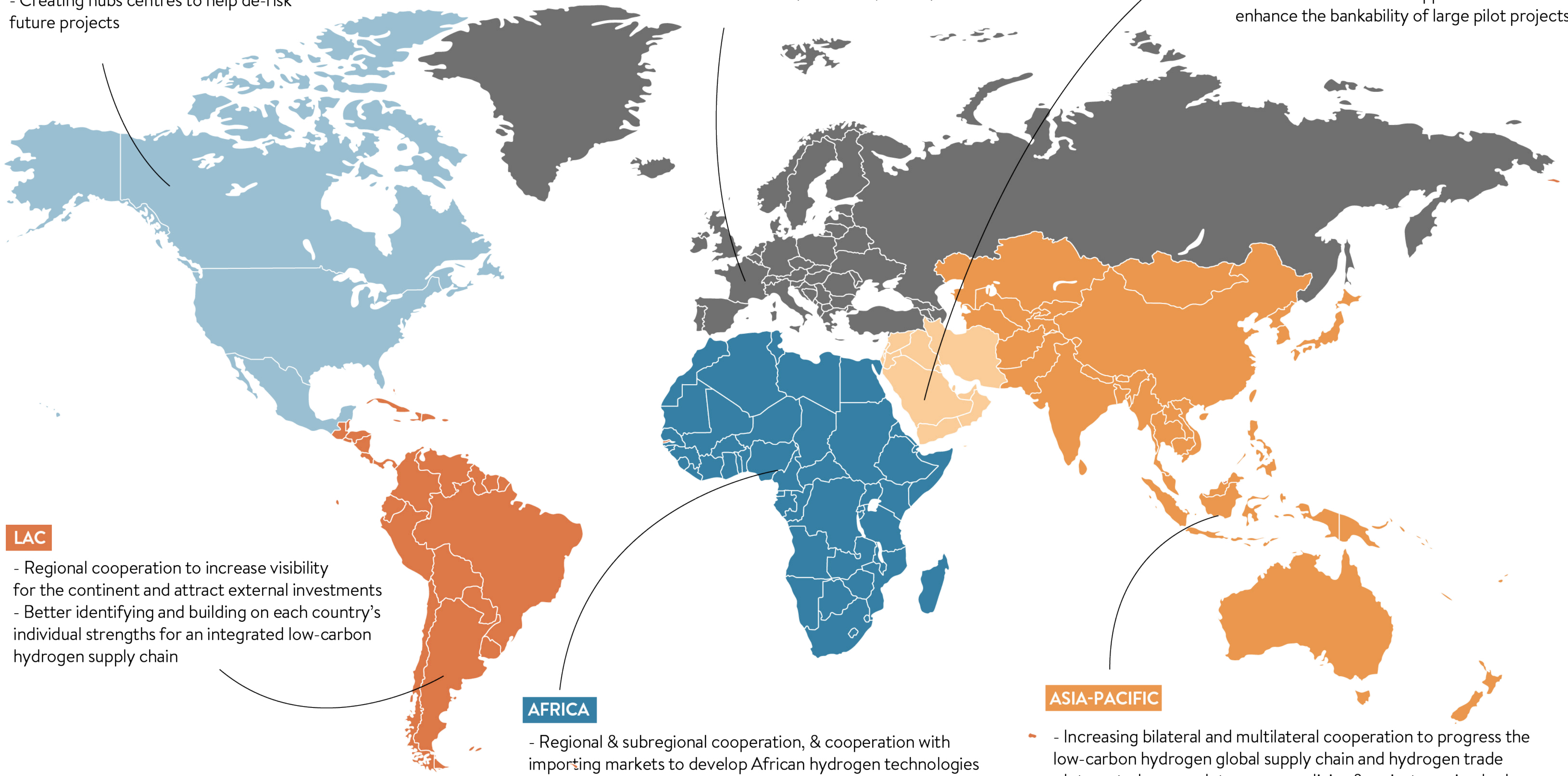
NATIONAL LEVEL

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.*



NORTH AMERICA

- 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

EUROPE

- 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

MEGS

- 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

LAC

- 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

AFRICA

- 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

- 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

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

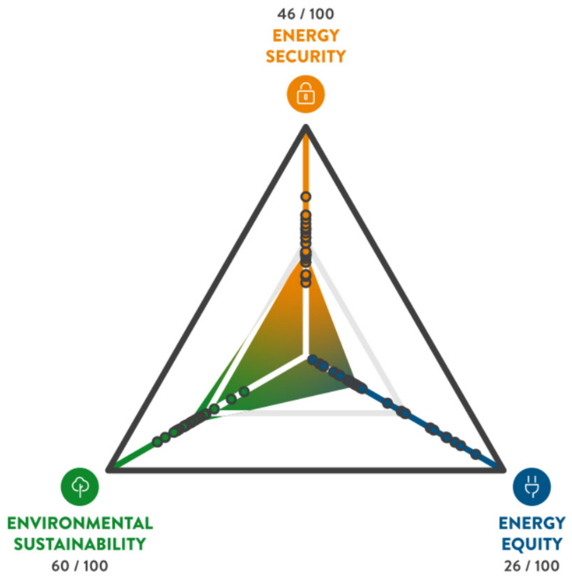
REGIONAL DASHBOARDS

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



SDGS

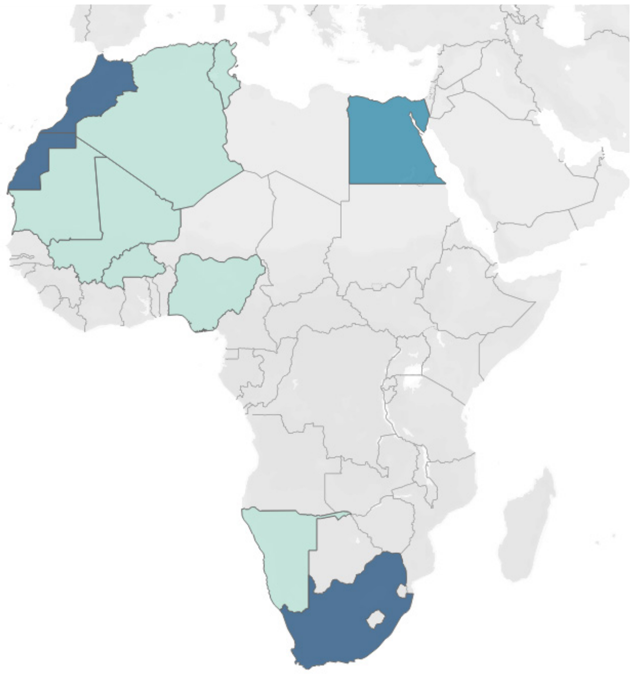
AFRICAN VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#10/25 uncertainties
#24/25 impact

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

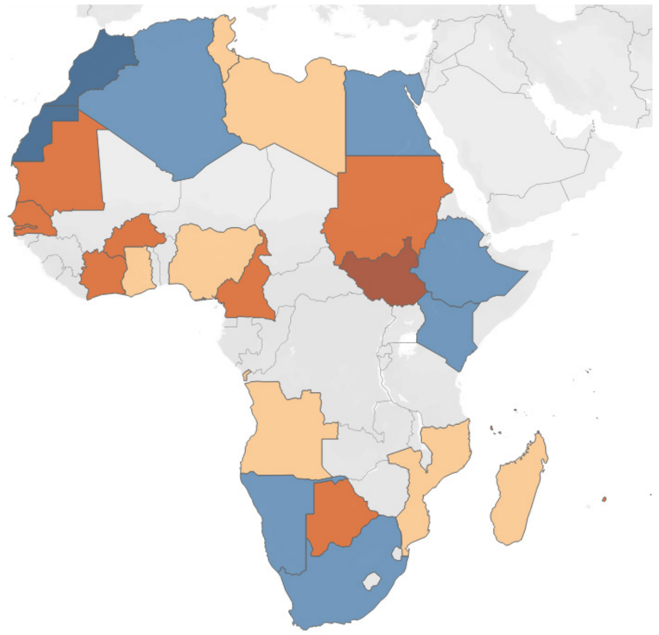


MARKET OPPORTUNITIES

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

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



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

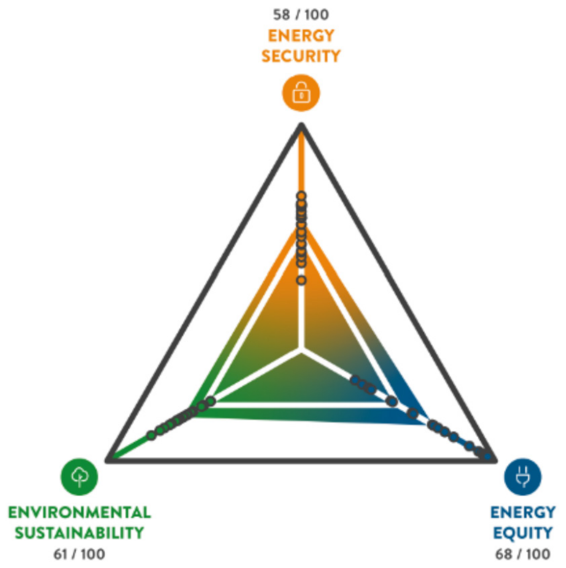
- Developing domestic demand in the transport, industry and agriculture sectors

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

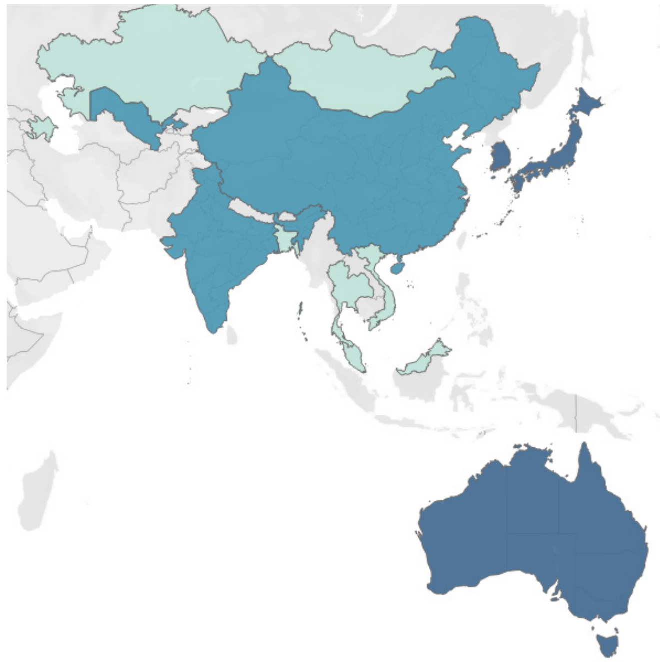
ASIA-PACIFIC VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#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

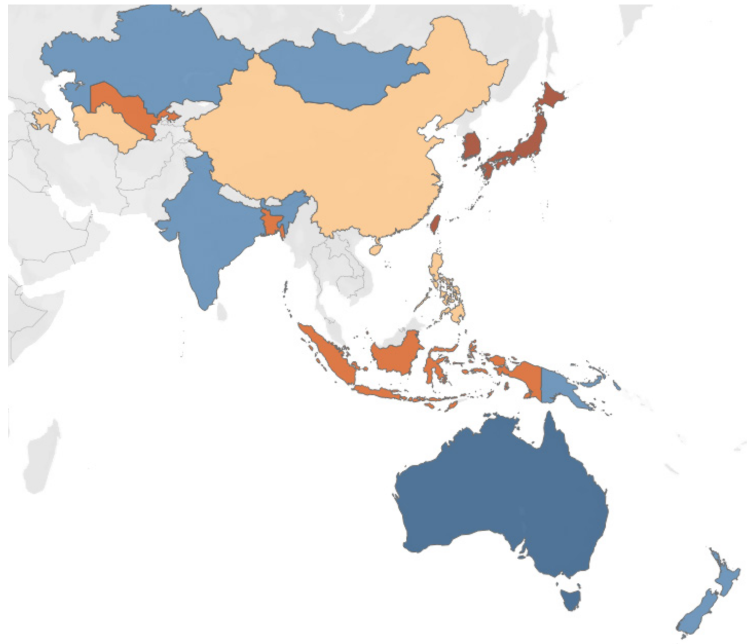


MARKET OPPORTUNITIES

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

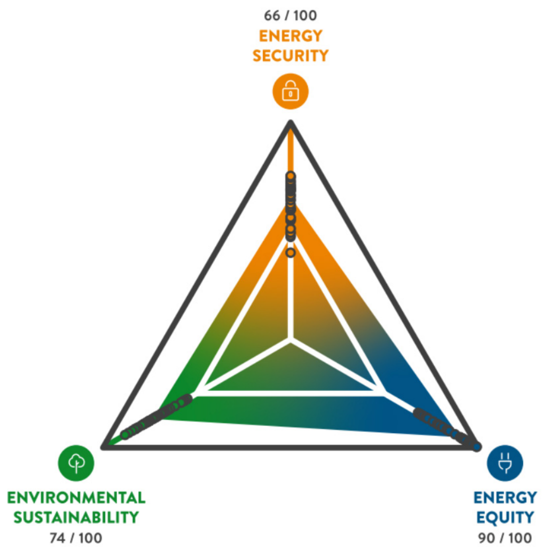
CONTEXT

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

EUROPEAN VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#3/25 uncertainties
#19/25 impact

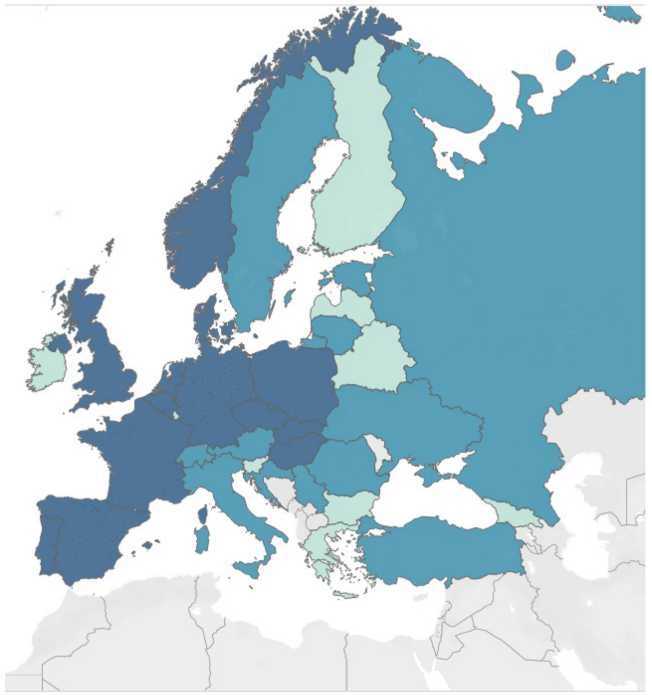


SDGS

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

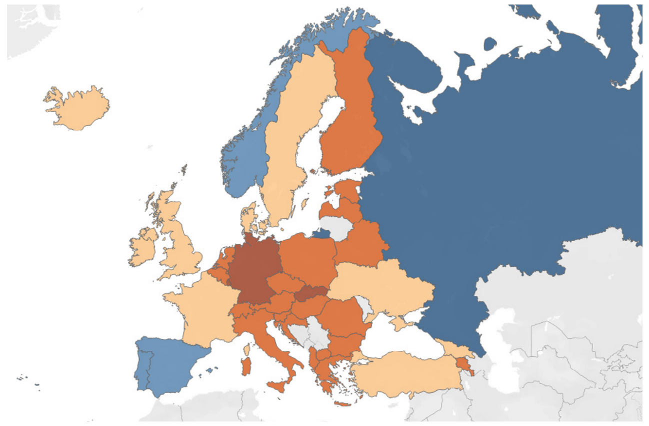


MARKET OPPORTUNITIES

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

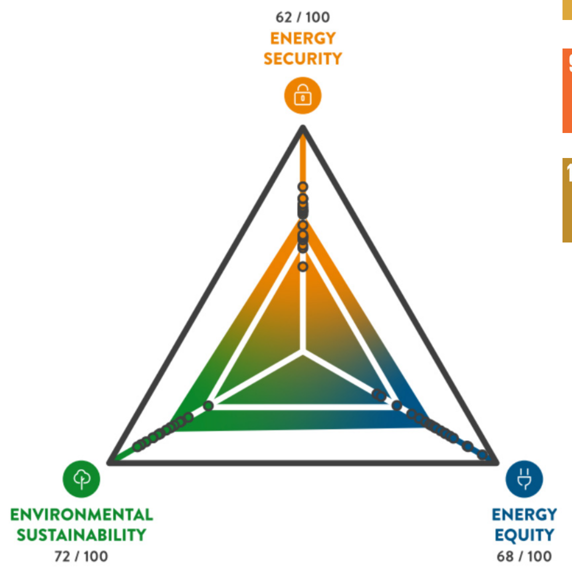
- More coordinated hydrogen diplomacy action in the EU

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



SDGS

LAC VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#18/25 uncertainties
#14/25 impact

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

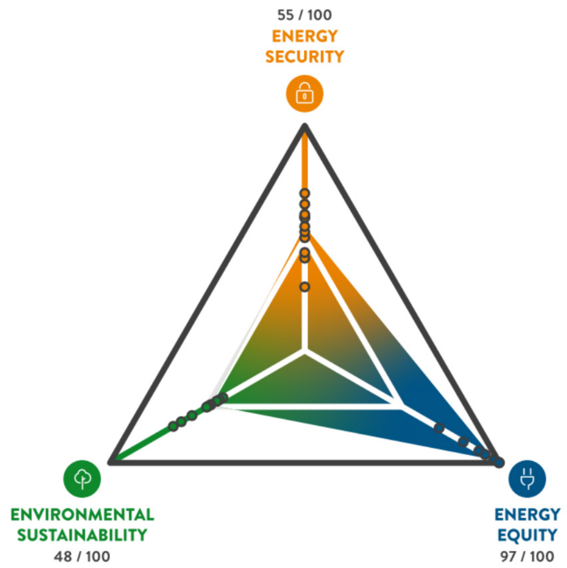
CONTEXT

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

MEGS VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#4/25 uncertainties
#15/25 impact



SDGS

7 AFFORDABLE AND CLEAN ENERGY

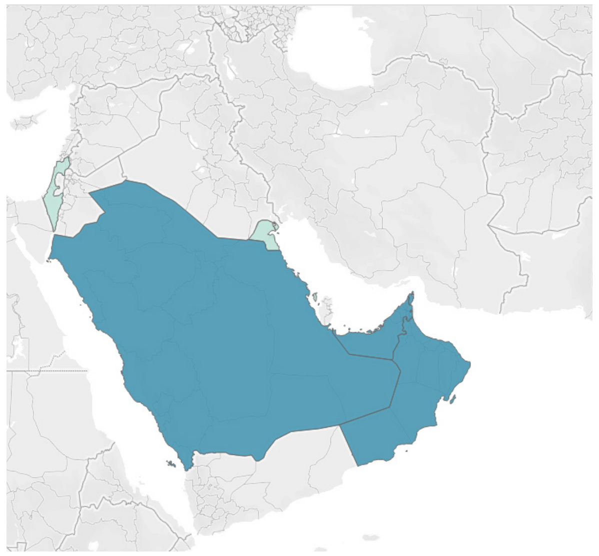
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

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

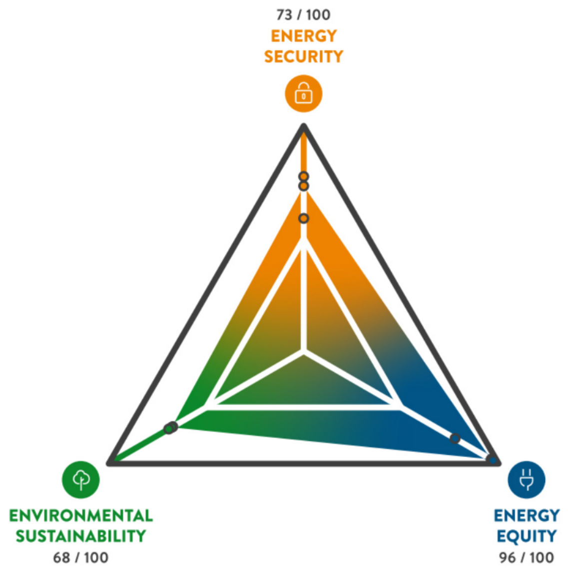
- Finance subsidies and support mechanisms to enhance the bankability of large pilot projects

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

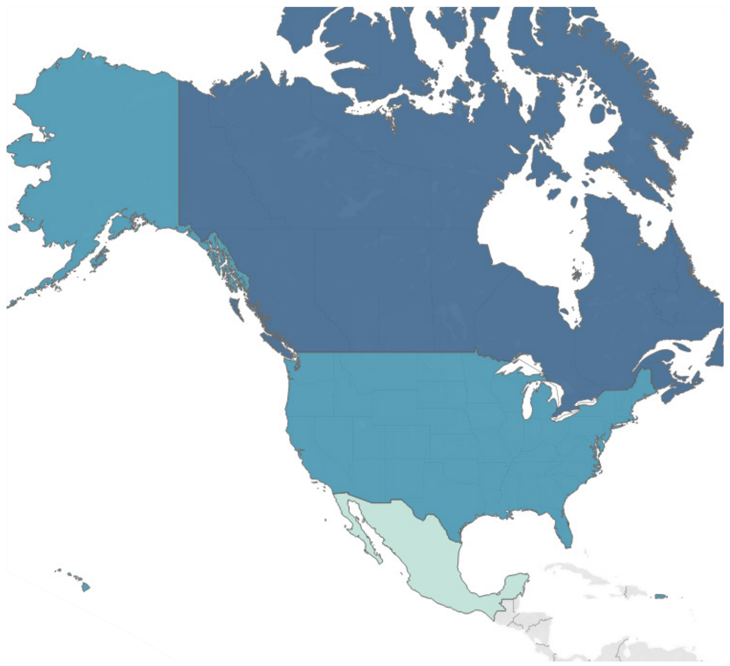
NORTH AMERICA VIEWS ON HYDROGEN IN ISSUES MONITOR 2022

#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

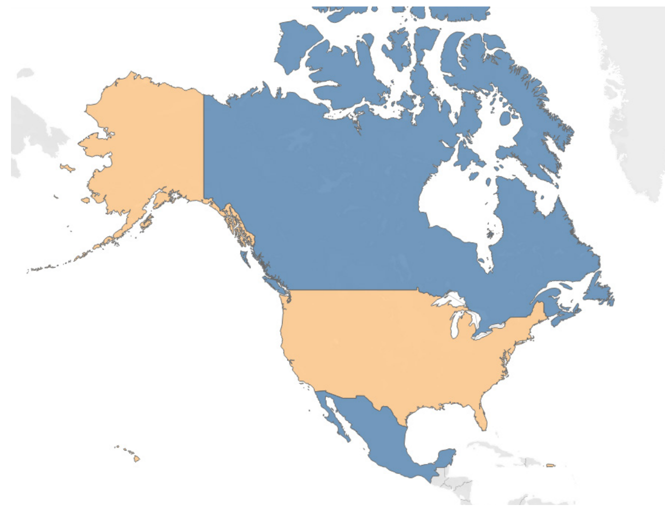


MARKET OPPORTUNITIES

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

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