low-carbon hydrogen

A PATH TO A GREENER FUTURE

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INTRODUCTION

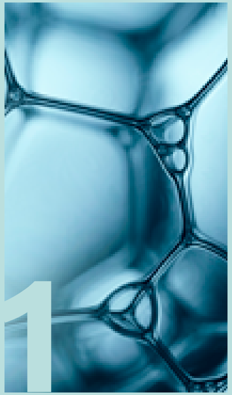
The energy transition and the global imperative towards sustainability have driven organizations to explore new energy models and solutions. Low-carbon hydrogen is gaining recognition as one of the possible routes to accelerating decarbonization of high-emission sectors such as industry and heavy mobility. Many countries including US, China, Japan as well as many European Union countries amongst others have announced major investments to accelerate its development.

However, today prominent production pathways for hydrogen continue to rely on the use of fossil fuels. The move to "low-carbon hydrogen" could avoid the annual emission of 830 million tons of CO_2 currently emitted by conventionally produced hydrogen,[1] a vital contribution to securing a clean-energy future. Francesco La Camera, Director-General of the International Renewable Energy Agency (IRENA), comments: *"Cost-competitive low-carbon hydrogen can help us build a resilient energy system that thrives on modern technologies and embraces innovative solutions fit for the 21st century."*[2] This fuel source is creating new commercial opportunities throughout the value chain – including alternative revenue streams, as well as new business models – but it must present an economically competitive alternative to carbon-based hydrogen if businesses are to consider it as viable in the long term.

To understand how organizations could capitalize on low-carbon hydrogen's potential, we conducted a global survey across 13 countries, with responses from 500 executives from energy and utilities (E&U) firms and 360 executives from end-user sectors, including heavy transportation, aviation, maritime transport, steel, chemicals, and refining[3]. To complement the quantitative insights, we also conducted more than 20 in-depth interviews with supply- and demand-side organizations, startups, venture capital (VC) organizations, academics, researchers, and regulators.

INTRODUCTION

In this report, we will be exploring five major themes



The decarbonization potential of low-carbon hydrogen

Evolving business models, as well as existing and emerging use cases

Investments in low-carbon hydrogen, from regulatory/policy and organizational perspectives

Key challenges and major roadblocks across the value chain

Key business, organizational, and technological factors in accelerating low-carbon hydrogen projects

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Underpinned by a global shift towards decarbonization, hydrogen is gaining significance as an energy vector, especially for high-emission sectors that do not use electricity directly. Most organizations in our research believe that low-carbon hydrogen will be a long-term contributor to achieving emissions and sustainability goals:

- 63 percent of energy and utilities (E&U) organizations see it is as a key tool to decarbonize economies
- 62 percent of end-user organizations are looking to introduce low-carbon hydrogen to carbon-intensive parts of their business
- E&U organizations expect low-carbon hydrogen to meet up to 18 percent of energy demand by 2050

With government support, declining renewable-energy costs, rapid technological advances, and a growing focus on decarbonization and sustainable energy solutions, the demand for low-carbon hydrogen is expected to increase multifold. Sectors with traditional hydrogen applications, particularly in petroleum refining, chemicals and fertilizers, and steel, have high potential for adoption of low-carbon hydrogen. Demand for hydrogen in new applications such as long-range ground mobility (for heavy-duty trucks, coaches), long-haul aviation specifically sustainable aviation fuel (SAF), or maritime is expected to pick up.

Our research suggests that a majority (64 percent) of E&U organizations are planning to invest in low-carbon hydrogen initiatives by 2030; and 9 in 10 plan to do so by 2050. On average, 0.4 percent of total annual

EXECUTIVE SUMMARY

revenue is earmarked for low-carbon hydrogen by E&U organizations. Investments are flowing in across the hydrogen value chain – especially into development of cost-effective production technology (52% of organizations investing), electrolyzers and, fuel cells (45%), and hydrogen infrastructure (53%) to help create alternative revenue streams and aid in decarbonization efforts. From the regulatory side, 80+ countries across the world support clean-hydrogen production, either through hydrogen policies or roadmaps, or by providing support for low-carbon hydrogen projects and R&D via subsidies or emission-trading schemes, or by levying taxes on carbon-intensive hydrogen.

However, substantial challenges remain. Today, low-carbon hydrogen is 2–3 times more costly to produce than carbon-based hydrogen. Moreover, storage, transportation and energy losses across the value chain increase the total cost of operations (TCO). Finally, technology, engineering, infrastructural, and skill-related challenges are also impediments to more rapid hydrogen adoption.

While the emerging market for low-carbon hydrogen is both highly complex and fragmented, it holds real decarbonization potential. To seize this opportunity, mitigate costs, and scale at pace, organizations will need to address three aspects:

- Strategic: To scale up hydrogen production, investments must be shared between public and private players and customer demand must be strong. Organizations should evaluate new business models from sustainability as well as total cost of ownership perspectives. To enable these models, defining a governance structure dedicated to low-carbon-hydrogen production along with a focus on education

EXECUTIVE SUMMARY

and upskilling programs is required.

- Technological: Organizations must harness the potential of technology and digital engineering to mitigate challenges related to asset-level measurement of carbon intensity, cost-optimization, efficiency, safety, performance, profitability, and real-time decision-making. Technologies such as digital twins, artificial intelligence (AI), analytics, and blockchain can help address these implementation challenges by modelling various scenarios to maximize ROI and allowing data-driven decision-making throughout the lifecycle and across ecosystems.

- Ecosystem: Finally, to emerge as a preferred partner for end-user organizations, and to bring low-carbon hydrogen as a viable alternative, organizations should build partnerships with electrolyzer providers, renewable-energy producers, storage providers, and supply-chain entities to facilitate production at scale.

"While it's still in the early stages, I believe that hydrogen has the potential to be one of the most mature renewable technologies, capable of accelerating our transition towards sustainable energy."

Ann Rosenberg

Co-Founder of SDG Ambition at United Nations Global Compact

WHAT IS LOW-CARBON HYDROGEN?

What is low-carbon hydrogen?

Hydrogen is the simplest, lightest, and most abundant element in the universe. It does not exist freely in nature but rather is produced from sources such as fossil fuels, renewables, and nuclear, using a range of extraction and production techniques. Hydrogen's valuable attributes – such as high energy content per unit mass (three times more than gasoline)[4] lack of CO_2 emissions at point of use; and potential as a storage medium for electricity – make it an attractive energy vector and fuel. Moreover, its ability to be stored and transported in various forms (gaseous, liquid, or even converted to other molecules) makes it a powerful enabler for decarbonization – both in relation to energy systems and end-use applications.

However, not all hydrogen is created equal. Most hydrogen is currently produced via steam methane reforming of natural gas, emitting high levels of CO_2 during production. Figure 1 highlights the various hydrogen production methods and their associated carbon intensity. While the colors of hydrogen are a helpful way to categorize the production pathways, what is more important is the resulting carbon intensity, which can vary significantly even within a given color.

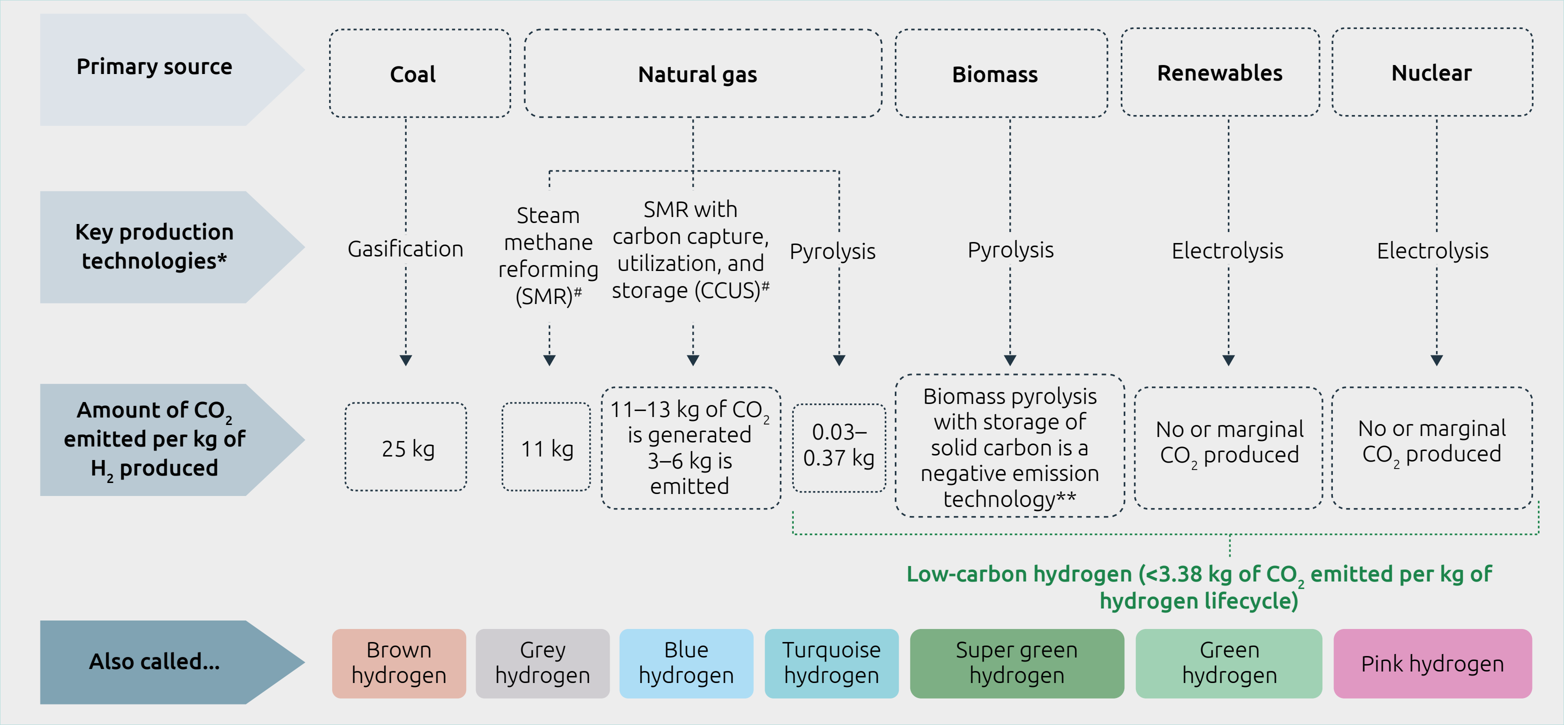
Low-carbon hydrogen

For hydrogen production to be considered low-carbon, it must come under the EU's proposed emissions threshold of 3.38 kg CO_2-equivalent per kg of hydrogen[5], which is 70% lower than that of the predefined fossil fuel comparator, including transport and other non-production emissions.[6] In the US, the corresponding carbon intensity value to qualify for hydrogen production tax credits under the IRA is 4.0 kg CO_2e/kgH_2.[7] Although low-carbon hydrogen can include biomass pyrolysis as well, in this research, our main focus includes renewable or nuclear-energy-powered electrolysis-produced hydrogen emitting no or marginal carbon.

WHAT IS LOW-CARBON HYDROGEN?

Fig.1

Different pathways of hydrogen production vary in carbon intensity



Note: This chart covers the main methods of hydrogen production currently in use.

*For further details of different hydrogen-production technologies, please refer to the appendix.

** The pyrolysis of biomethane, biomass, waste, or wastewater, with subsequent storage of solid carbon, is a negative-emission technology, since the CO2 previously removed from the atmosphere and neutralized in the biomethane is not released during the pyrolysis reaction or use of the hydrogen produced and, consequently, no climate-damaging greenhouse-gas effects are produced.

CO_2-eq emissions could be higher than indicated above when considering the efficiency of the CCUS process, methane leakage in the system, and the time horizon between 20 and 100 years for the Global Warming Potential (GWP).

Source: Capgemini Research Institute Analysis; World Economic Forum; IEA; Energy Cities; Enel; Institut Polytechnique de Paris; Hydrogen Europe; Capgemini, “The path to low-carbon hydrogen,” October 2022.

01

LOW-CARBON HYDROGEN IS A KEY TOOL FOR DECARBONIZING HIGH-EMISSION SECTORS

Organizations see low-carbon hydrogen as an important vector for energy transition

The global energy crisis initiated by the COVID-19 pandemic and exacerbated by ongoing geopolitical tensions has bolstered the case for low-carbon hydrogen. Governments and organizations across regions are looking to reduce dependency on fossil fuels, as well as advance progress towards decarbonization and enhancing energy security:

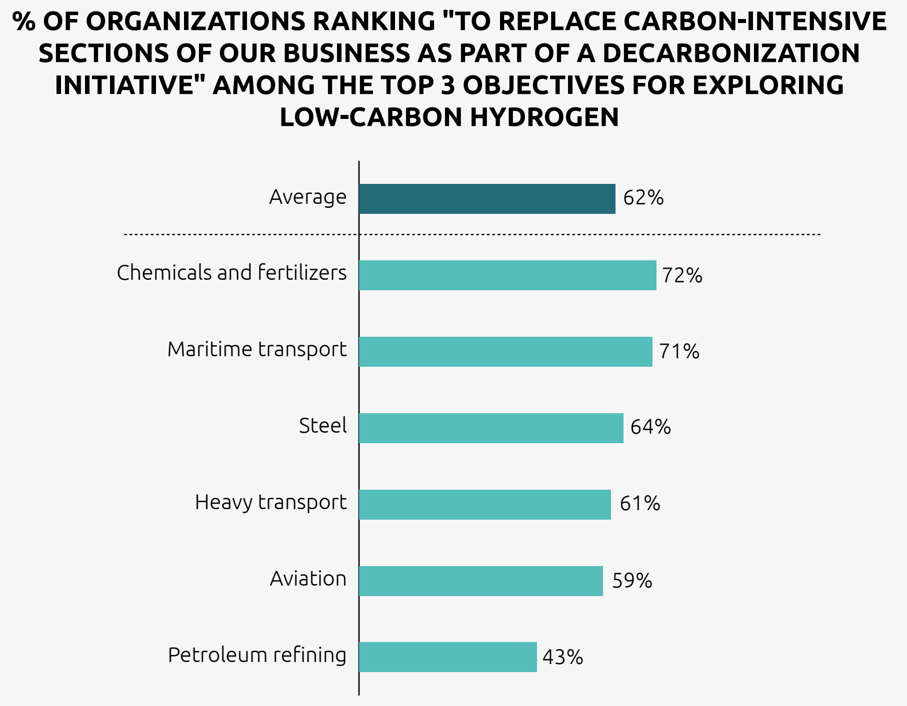
- In our research, 61 percent of energy and utilities (E&U) organizations believe that the current crisis has led nations to reconsider their energy mixes
- Almost two-thirds (62 percent) of E&U organizations believe that low-carbon hydrogen can help nations reduce dependence on fossil fuels and promote energy independence

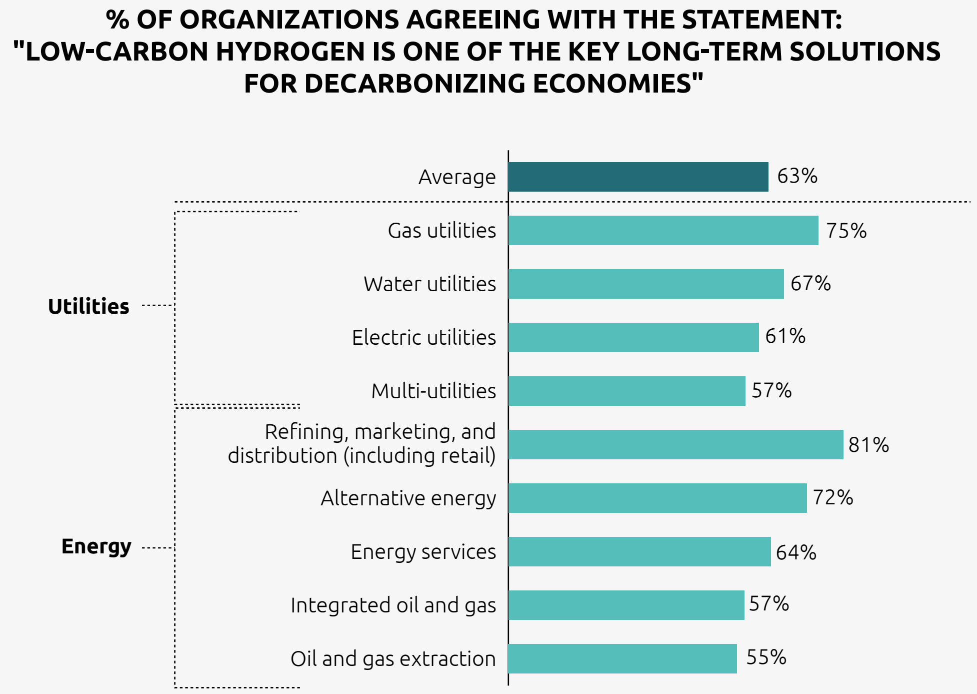
62%

of E&U organizations believe that low-carbon hydrogen can help nations reduce dependence on fossil fuels and promote energy independence

Fig.2

Organizations strongly believe in the potential of low-carbon hydrogen for decarbonization





Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations; N=447 respondents from unique energy and utilities organizations.

Hydrogen use would make it possible to decarbonize around 15 percent of the economy that is not suitable for the direct use of electricity. Research suggests that 86 million metric tons (MMt) of CO_2 emissions could be avoided annually in the EU, European Free Trade Association (EFTA), and UK by using low-carbon hydrogen in industries such as steel, chemicals, fertilizers, oil refining, etc.[8] Most organizations also believe that low-carbon hydrogen will be a long-term contributor to achieving emissions and sustainability goals. Ann Rosenberg, Co-Founder of SDG Ambition at United Nations Global Compact, says, *"The current situation has heightened the urgency to develop new energy technologies, and I'm optimistic about the growing focus on hydrogen as a potential solution. While it's still in the early stages, I believe that hydrogen has the potential to be one of the most mature renewable technologies, capable of accelerating our transition towards sustainable energy"*

As Figure 2 shows:

- 62 percent of end-user organizations are looking at low-carbon hydrogen to replace carbon-intensive systems
- almost 3 in 4 organizations in chemicals and fertilizers and the maritime transport sector are doing the same
- 63 percent of E&U organizations agree that low-carbon hydrogen is one of the key long-term solutions for decarbonizing economies

Wulf-Peter Schmidt, Director Sustainability, Advanced Regulation & Product Conformity at Ford, says, *"We are considering the use of low-carbon hydrogen (green hydrogen) in our logistics and supply chain. For example, a fundamental condition for near-zero emission steel is green hydrogen. But also in general, green hydrogen is key to ensure carbon neutrality across industries going forward and that's where we are working together with different partners and the industry. And we committed ourselves by being part of the First Mover Coalition."*

For the energy transition to succeed, another pressing challenge needs to be overcome: the issue around the intermittency of renewable-energy sources. Our survey shows that nearly three-quarters (71 percent) of E&U organizations believe that low-carbon hydrogen is a viable method of **energy storage from intermittent renewable sources**, acting as a battery and making renewable energy such as solar and wind available to even more applications. France-based HDF Energy, a hydrogen-to-power company, is evaluating new models in this space. Mathieu Geze, Director Asia, says, *"With our Renewstable® power plants, we combine renewable energy, hydrogen, and batteries to deliver something non-intermittent to the grid. These power plants are composed of an intermittent renewable source and a long-term on-site hydrogen energy storage. The beauty of those projects is that we don't sell hydrogen in those projects. We sell kilowatt hours. The hydrogen is just used to store electricity."*

Southern California Gas Company (SoCalGas) is collaborating with various partners to create an innovative green-hydrogen storage facility for its Colorado campus. The electrolyzer on site will use renewable sources and produce green hydrogen to be stored in fuel cells to produce renewable electricity on demand.[9] At the same time, organizations are trying to find solutions to challenges related to the cost and efficiency of power to gas to power (P2G2P) technologies.

71%

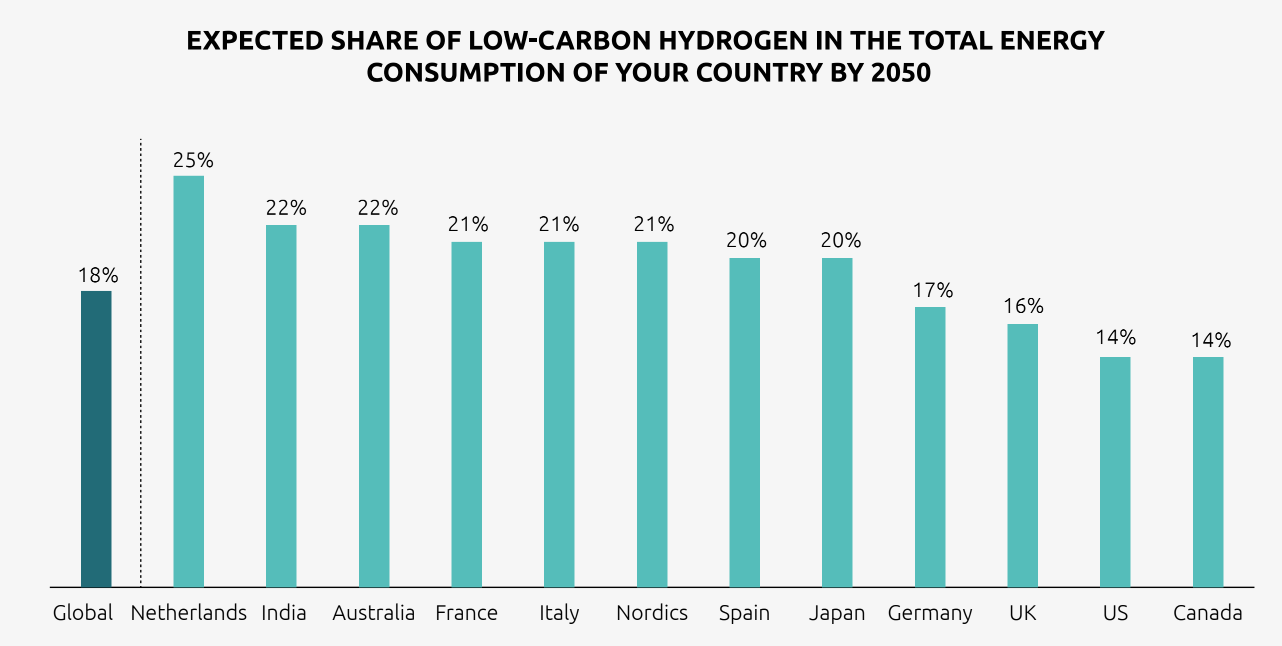
of E&U organizations believe that low-carbon hydrogen is a viable method of energy storage from intermittent renewable sources

Organizations are optimistic and ambitious about low-carbon hydrogen

Global hydrogen production stands at around 75 million tons (Mt) H_2/yr as pure hydrogen and an additional 45 Mt H_2/yr as part of a mix of gases. This is equivalent to 3 percent of global final energy demand.[10] Low-carbon hydrogen's share of total final energy consumption (TFEC) was less than 0.1 percent in 2020. The International Renewable Energy Agency (IRENA) estimates suggest that it could contribute up to 12 percent of TFEC by 2050.[11] We also asked E&U executives in our survey to estimate low-carbon hydrogen's share of TFEC in their country by 2050. As Figure 3 shows below, organizations are even more positive than the published estimates. On average, they expect low-carbon hydrogen to meet 18 percent of TFEC by 2050. They consider declining costs of electrolyzers and renewable energy – especially solar and wind energy – as a key enabler of this shift.

Fig.3

E&U organizations expect low-carbon hydrogen to meet one-fifth of energy demand by 2050



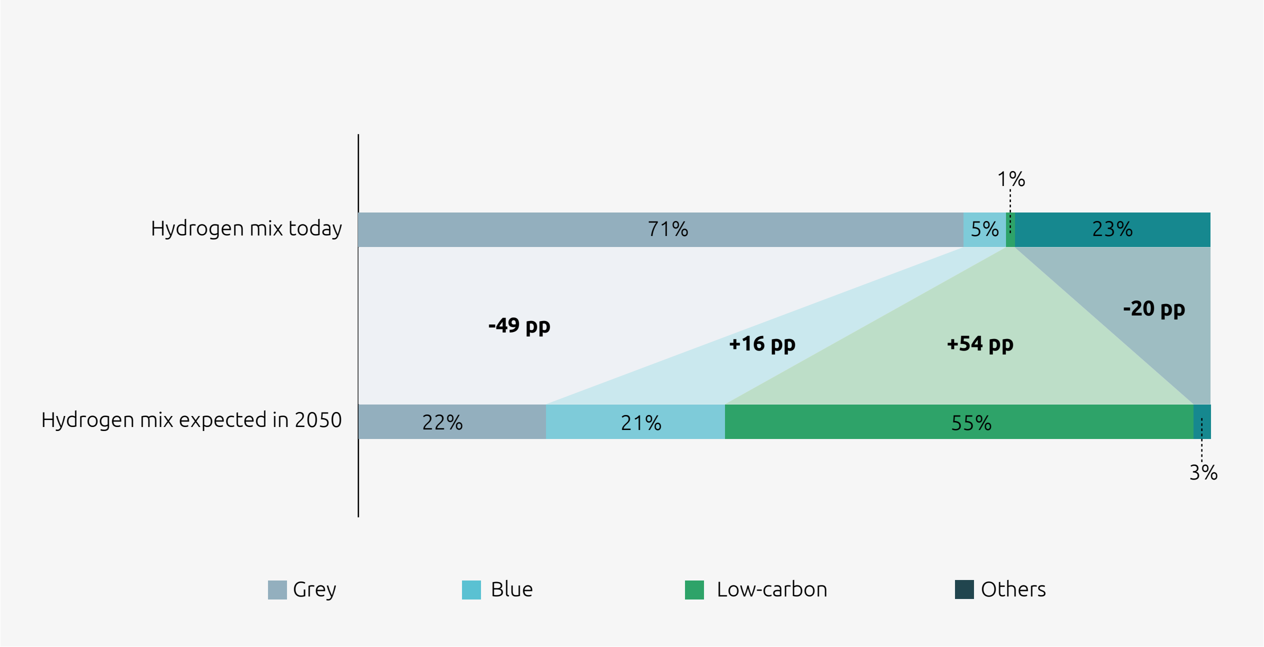
Note: This represents subjective organizational expectations of low-carbon hydrogen and is not based on present capabilities and investment levels.

Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=447 respondents from unique energy and utilities organizations.

Of total hydrogen currently produced, 76 percent comes from natural gas and 23 percent from coal. The share of low-carbon hydrogen is less than 1 percent of the total hydrogen mix today,[12] but this is expected to increase with the tailwinds of government support and lowering production costs: E&U organizations expect it to contribute up to 55 percent of the total hydrogen mix by 2050 (see Figure 4).

Fig.4

E&U organizations expect low-carbon hydrogen's share of the total hydrogen mix to increase significantly by 2050



Note: This represent subjective organizational expectations for low-carbon hydrogen and is not based on present capabilities and investment levels.

Source: IEA, *Hydrogen Tracking Report*, September 2022; Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=500 respondents from unique energy and utilities organizations.

Mathieu Geze

Director Asia,
HDF Energy

“With our Renewstable® power plants, we combine renewable energy, hydrogen, and batteries to deliver something non-intermittent to the grid. These power plants are composed of an intermittent renewable source and a long-term on-site hydrogen energy storage.”

Hydrogen with CCUS: Hope or just hype?

"Blue" hydrogen is often classified as "clean" because it is produced using carbon capture, utilization, and storage (CCUS) technology. It currently has a cost advantage over hydrogen produced with electrolysis ($2.27/kg for hydrogen produced with SMR CCUS vs. $5.96/kg for hydrogen produced with renewable electrolysis), and also requires less capital outlay as existing natural-gas infrastructure can be used. Hydrogen with CCUS is rapidly progressing in certain countries, such as the US. Around nine US states in the Midwest, Southwest, and Gulf Coast are competing for federal funding to develop their CCUS hydrogen economies.[13] Recently, US-based oil and gas company ExxonMobil unveiled plans for its new hydrogen production plant, which will use CCUS technology at its refining and petrochemical facility in Baytown, Texas. The proposed facility would produce up to 1 billion cubic feet per day (cu ft/day) of hydrogen. The CCUS infrastructure would have the capacity to transport and store up to 10 million metric tons (MMt) of CO_2 per year.[14] Another example includes Air Liquide, Chevron Corporation, LyondellBasell and Uniper SE forming a consortium to produce hydrogen using natural gas with CCS and renewable hydrogen via electrolysis in the US Gulf Coast to supply end-use markets.[15]

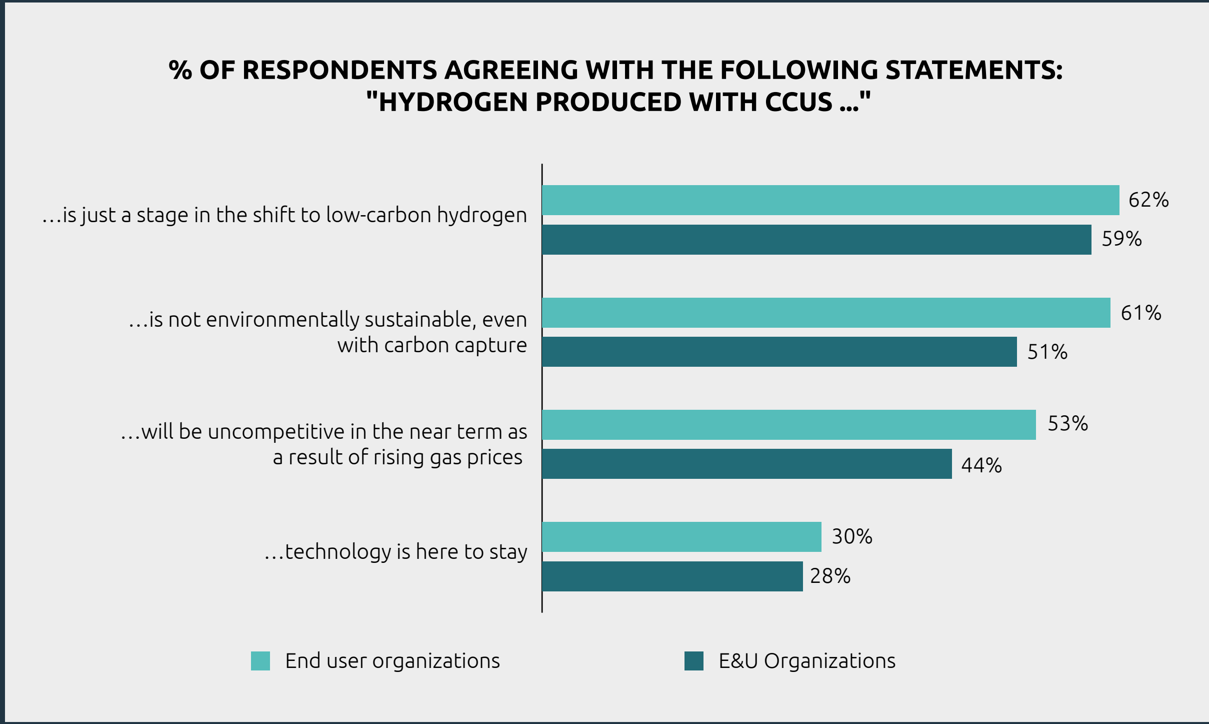
However, there is some debate around the efficiency of the technology:

- Research currently suggests that 10–20 percent of carbon generated during the production of hydrogen cannot be captured;[16] however, there are efforts underway to develop technologies that would capture more than 95% of carbon.
- There is also an additional risk of methane (the most potent greenhouse gas or GHG) leakage during the production of hydrogen; in our survey, 61 percent of end-users and 51 percent of E&U organizations believe that even hydrogen produced with CCUS is not environmentally sustainable.
- Lastly, as the price of CCUS-produced hydrogen is strongly influenced by the price of natural gas – which the current geopolitical crisis has pushed up – its cost-competitiveness may drastically diminish in the near future, especially in Europe; over half of end-user organizations (53 percent) and 44 percent of E&U organizations believe this to be the case.

Figure 5 shows that a majority of organizations (62 percent of end-user organizations and 59 percent of E&U organizations) believe that hydrogen produced with CCUS technology is only a stage in the long-term shift to low-carbon hydrogen. Less than one-third (28 percent of E&U and 30 percent of end-user) organizations believe that CCUS technology is here to stay.

Fig.5

Organizations are questioning the decarbonization potential of hydrogen produced with CCUS



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations; N=500 respondents from unique energy and utilities organizations.

02

DEMAND FOR LOW-CARBON HYDROGEN IS GROWING ACROSS KEY SECTORS

More than **80%**

of respondents from the refining and fertilizers and chemical industries believe that low-carbon hydrogen will have a high impact on their industry by 2030.

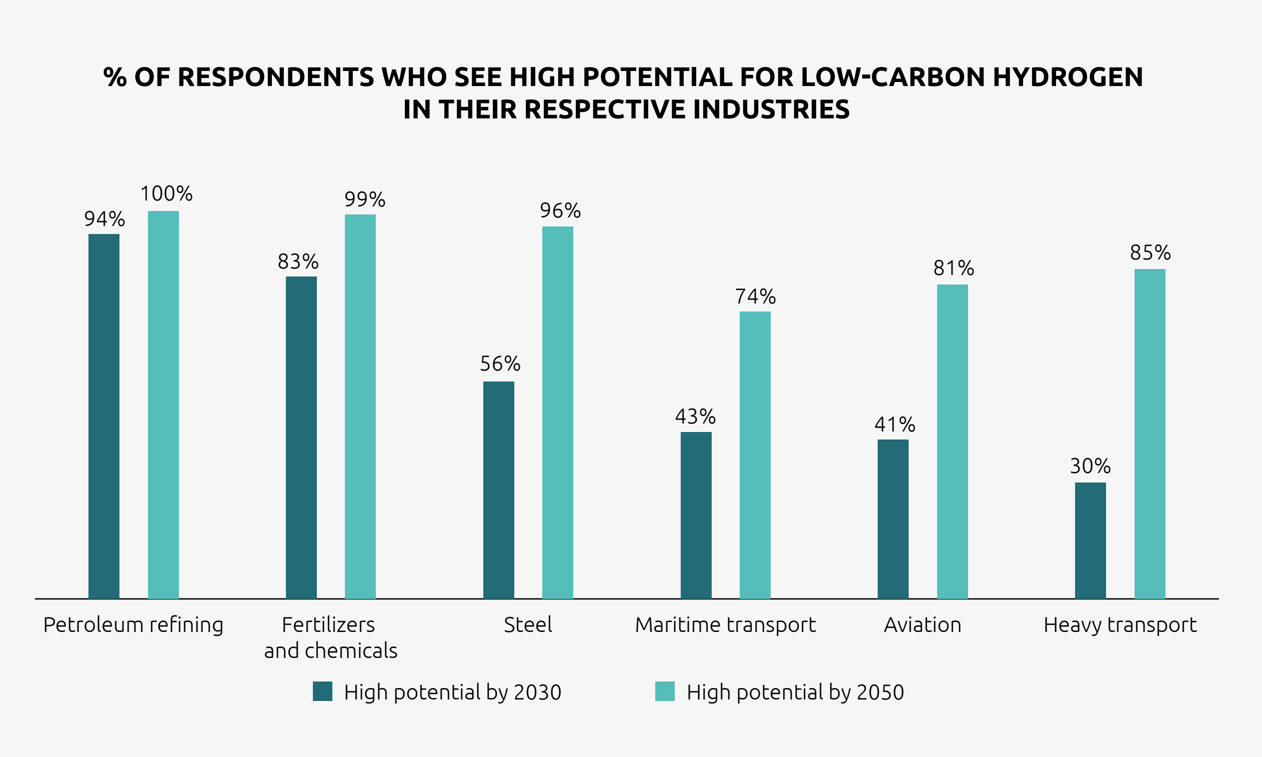
There is strong emerging potential for low-carbon hydrogen

Global hydrogen demand was more than 94 Mt in 2021, a 5-percent increase over 2020.[17] Our survey highlights that overall demand for hydrogen across industries and geographies has increased by more than 10 percent in the past three years, with a strong demand emerging in the chemicals and petroleum refining sectors. As per our survey data, demand for hydrogen from more than half of organizations has grown by more than 10 percent in France, India, the UK, Japan, the US, Germany, and Sweden.

Although the demand for low-carbon hydrogen is expected to increase across sectors, the strongest demand is coming from sectors where the opportunity for electrification is minimal and use cases could be realized in the short term, given localized volumes. Demand and potential of low-carbon hydrogen remains high for traditional hydrogen applications, particularly

Fig.6

Industries such as refining, fertilizers, and chemicals will widely harness low-carbon hydrogen



Note: Respondents from each sector answered about potential for their own industry only.

Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations

in petroleum refining, chemicals, fertilizers, etc. Demand for hydrogen in new applications, such as in heavy-duty transportation, aviation, and maritime, is expected to pick up slowly in comparison with other industrial sectors (see Figure 6). Our survey reveals that more than 80 percent of respondents from the refining, and fertilizers and chemical industries believe that low-carbon hydrogen will have a high impact on their industry by 2030.

A variety of low-carbon hydrogen use cases are emerging across various industries

Apart from the traditional hydrogen-user sectors, sectors with limited opportunities to electrify, such as heavy-duty transportation, aviation or maritime, etc., are also exploring low-carbon hydrogen use cases, mainly to achieve their sustainability targets and cut emissions.

Organizations expect different applications to mature at different rates and cost reduction and innovative business models will be required to scale up. An, Executive Vice-President at India-based steel company, says: *"The biggest use of low-carbon hydrogen in the steel industry will be making hydrogen-based DRI [direct reduced iron] plants, followed by use in blast furnaces."* Figure 7 highlights rising use cases of low-carbon hydrogen.

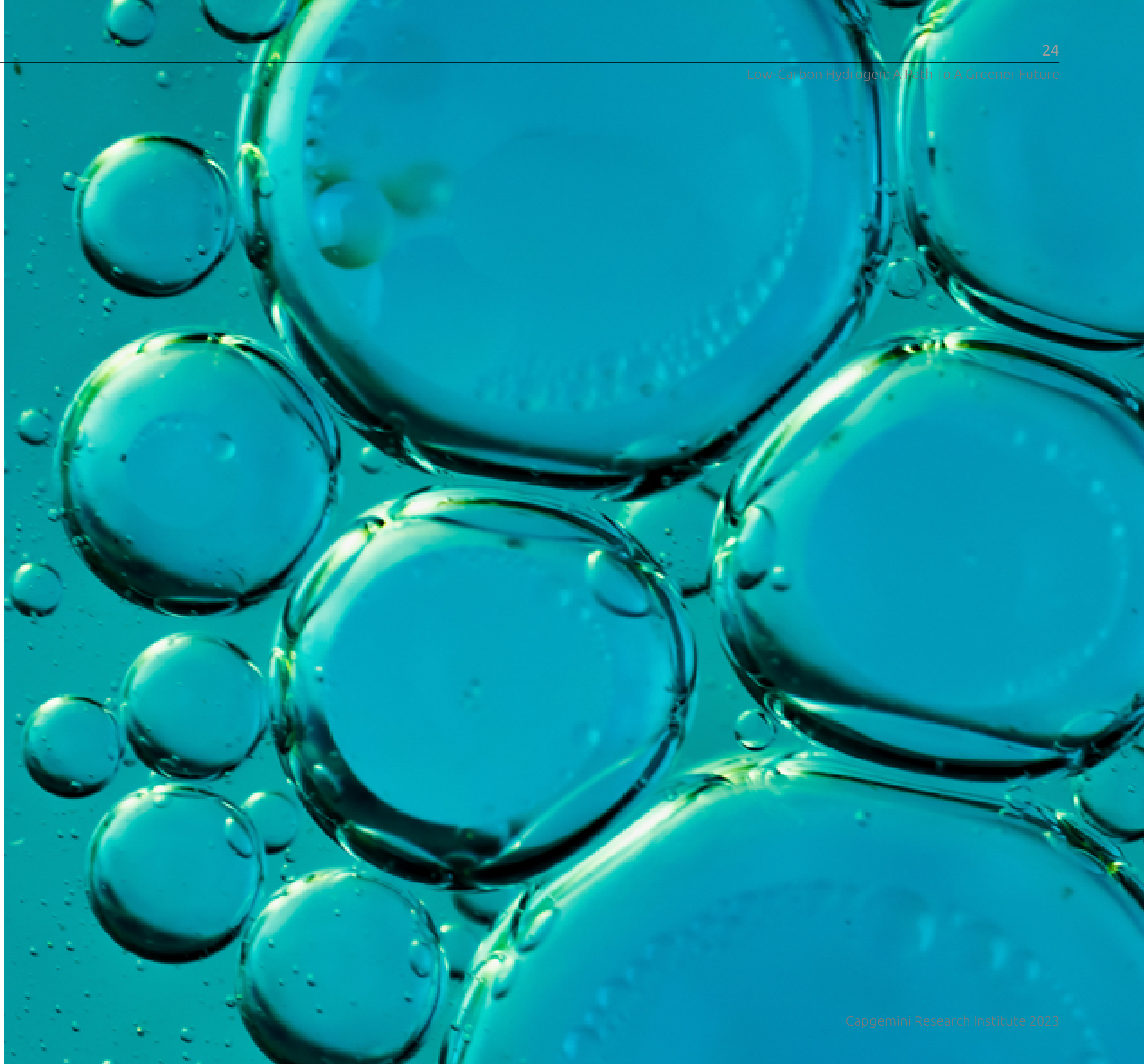


Fig.7

Newly commercialized applications of hydrogen are opening up opportunities in transportation and other energy-related sectors [18, 19, 20, 21, 22, 23, 24, 25, 26]

Industry	Low-carbon hydrogen use cases existing/emerging in the short term	Low-carbon hydrogen use cases emerging by 2025	Low-carbon hydrogen use cases emerging by 2030	Industry examples
Petroleum (refining)	• Create petroleum products, including gasoline and diesel (hydrocracking) • Desulfurization	• Clean feedstock for oil refining (hydrotreating)		• ExxonMobil is operating an advanced hydrocracker unit in Rotterdam, Netherlands to create products such as EHC Group II base stocks and ultra-low sulfur diesel[18]
Chemical & fertilizer	• Ammonia for industrial use (refrigerator, purificator & chemical stabilizer) • Ammonia for household use (ammonium hydroxide for cleaning products) • Ammonia as fertilizer • Methanol (fuels & additives, and as a chemical precursor)	• Industrial heat (used in industrial burners and boilers to provide low-carbon heat)		• Yara Clean Ammonia, a global unit of Yara International, is currently exploring the possibility of producing green ammonia as fertilizer using green hydrogen[19]
Steel	• Reducing agent in H_2-DRI (direct reduced iron)	• Hydrogen injection	• Hydrogen burners • Hydrogen plasma-smelting reduction	• ArcelorMittal has successfully tested the ability to partially replace natural gas (6.8%) with green hydrogen in the production of DRI at its steel plant in Contrecoeur, Quebec[20]
Heavy-duty transport (including buses /trucks, etc.)	• Combination of electric batteries and hydrogen fuel-cell electric vehicles (HFCEVs)	• e-fuels (carriers of hydrogen in liquid form - eMethanol, ammonia, ethanol, biofuels, biogas, synthetic e-fuels) for buses/trucks • Hydrogen internal combustion engines • HFCEVs - trucks/coaches etc.	• Hydrogen-blended compressed natural gas (H-CNG) clean-fuel coaches/trucks • Powering hydrogen refueling stations	• DAF Trucks is working on developing an internal combustion engine running on hydrogen[21] • Volvo is developing FCEV trucks powered by hydrogen[22] • Engineers at the University of New South Wales are working on developing new hydrogen-diesel hybrid engines for heavy vehicles such as mining trucks, etc.[23]
Maritime		• Synthetic e-fuels derived from hydrogen, such as ammonia • Hydrogen fuel cells for large vessels • Hydrogen fuel cells for port vehicles and equipment	• Hybrid solutions – hydrogen fuel cells and traditional propulsion for large vessels • Hydrogen combustion engines • Electrification of port terminals and battery-operated equipment	• MAN Energy Solutions has launched a 20% hydrogen-fired, stationary engine for the marine sector in 2021 and is currently working on developing a 100% hydrogen combustion engines for launch by 2030[24]
Aviation		• Liquid-hydrogen fuel cells	• Synthetic e-fuels • Liquid hydrogen combustion engines • Gaseous hydrogen fuel cell • Gaseous hydrogen combustion engines	• Airbus is developing a liquid-hydrogen-powered fuel cell engine and plans to test it on the largest commercial airplanes by 2026, to be fully operational by 2035[25] • Rolls-Royce and EasyJet have successfully converted a regular airplane engine to run on liquid hydrogen fuel, initially for short-haul flights and the trial will then expand to long-haul flights[26]

03

INVESTMENT IN LOW-CARBON HYDROGEN IS ON THE RISE

Organizations are investing across the hydrogen value chain

Leading E&U organizations are turning towards low-carbon hydrogen to transform into integrated energy providers. Hydrogen production capacity is estimated to reach 4.5 million tons per annum (mtpa) worldwide by the end of 2023. As of January 2023, 93 percent of both active and pipeline hydrogen projects were green-hydrogen projects.[27]

For instance:

- French multinational utility company, ENGIE, is investing in one of the world's first industrial-scale renewable-hydrogen projects. The A$87 million ($60 million) project in Western Australia includes a 10-MW electrolyzer to produce renewable hydrogen; an 18-MW solar PV system to power the electrolyzer; and an 8-MW/5-MWh lithium-ion battery[28]
- EDF Energy, also French-owned, has floated the idea of producing hydrogen at Sizewell C in the UK, a planned 3.2-GW nuclear-power station.[29]

93%

As of January 2023, 93% of both active and pipeline hydrogen projects were green hydrogen projects.

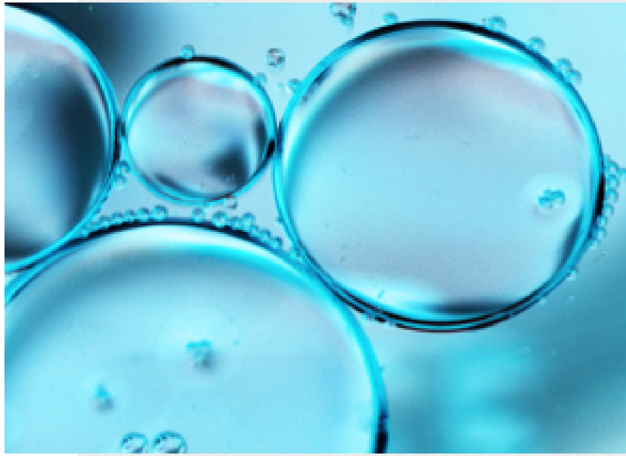


Fig.8

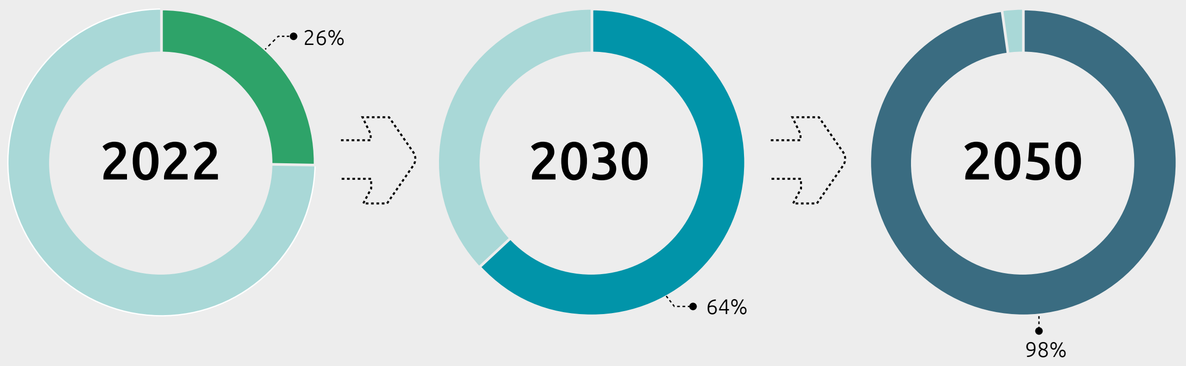
A majority of E&U organizations are planning to invest in low-carbon hydrogen initiatives

Our research shows that a majority (64 percent) of E&U organizations are planning to invest in low-carbon hydrogen initiatives by 2030; and 9 in 10 plan to do so by 2050 (see Figure 8).

64%

of E&U organizations are planning to invest in low-carbon hydrogen initiatives by 2030

% OF ORGANIZATIONS THAT ARE INVESTING/PLANNING TO INVEST IN LOW-CARBON HYDROGEN



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=447 respondents from unique energy and utilities organizations.

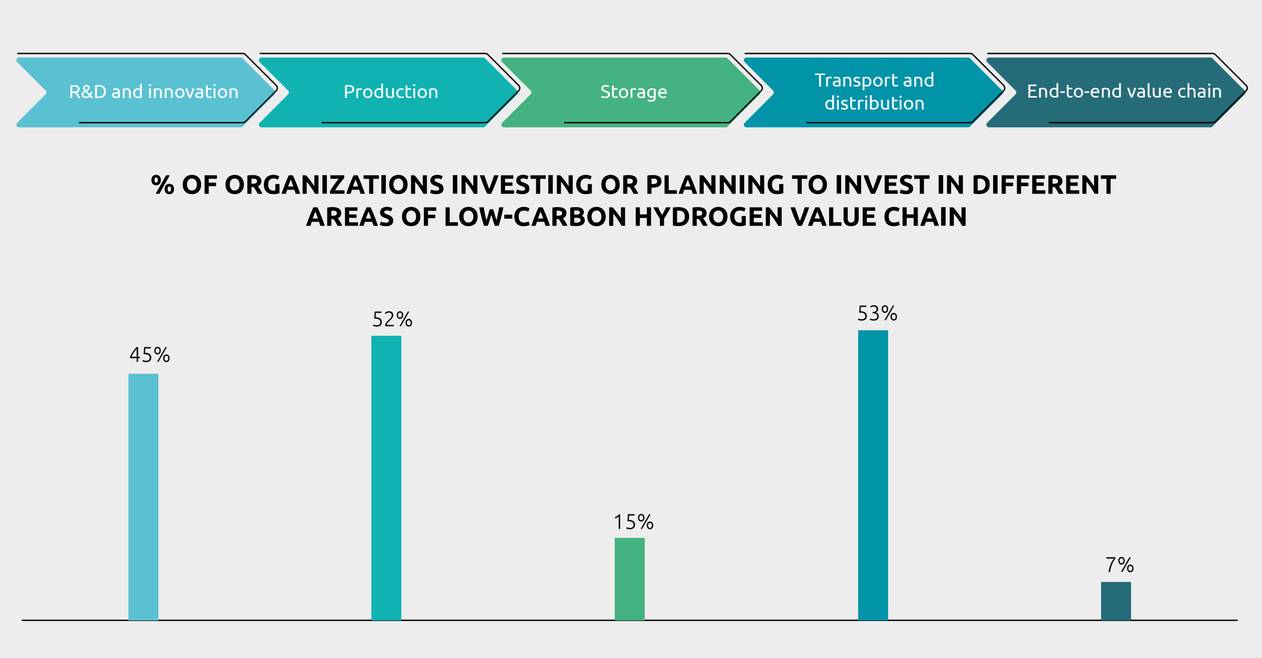
Of the E&U organizations that are planning to invest in low-carbon hydrogen by 2030:

- Nearly three in four (74 percent) plan to invest less than 0.5 percent of their expected revenue
- One in four (24 percent) plan to invest 0.5–1 percent of their expected revenue
- On average, 0.4 percent of total annual revenue is earmarked for low-carbon hydrogen by E&U organizations

Organizations are also increasingly realizing the need to accelerate commercialization and deliver significant reductions in CO_2 emissions; hence, massive investment is being made in the low-carbon hydrogen supply chain, including the development of cost-effective production technology. Investments have been made/planned in areas such as electrolyzers, fuel-cell technologies, refueling networks, and hydrogen infrastructure to help create alternative revenue streams in the energy sector, as well as support decarbonization efforts (see Figure 9).

Fig.9

E&U organizations are making investments across the low-carbon hydrogen value chain



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=500 respondents from unique energy and utilities organizations.

Research & development: Our research found that 45 percent of E&U organizations are investing in hydrogen-related R&D. Of those:

- More than 70 percent ranked electrolyzer technology enhancement (including alkaline, proton-exchange membrane [PEM], anion exchange membrane [AEM], and high-temperature electrolyzers such as solid-oxide electrolysis cell [SOEC]) among the top five technology-enhancement investment areas. In 2020, Spanish electric utility company, Iberdrola, established a separate company – Iberlyzer, dedicated to electrolyzer technology.[30] Organizations are focusing on:
  - **Improving efficiency and scaling production**. Paola Brunetto, Head of Hydrogen Business Unit at Enel Green Power, says: *"To reduce the cost of low-carbon hydrogen, a focus on innovation is very important. Electrolyzers are not yet produced at scale, so the cost should decrease, but we also think that innovation is crucial. Today, the efficiency of electrolyzers is just 60–65 percent. We need to have higher efficiency in order to reduce the electricity used to produce low-carbon hydrogen in a cost-effective way."* In May 2022, Hysata – an electrolyzer technology company based in Australia – developed a cutting-edge technology in which the electrolyzer operates at 95-percent system efficiency.[31]
  - **R&D for replacement of rare-earth metals (such as platinum, iridium, ruthenium, etc.) used in electrolyzers.** Extracting these rare-earth metals also poses several challenges, such as the environmental cost of mining along with geopolitical challenges associated with the location

of these metals. An executive at India based steel organization *"In India, another big issue for electrolyzers is the rare-earth metals used in them. We have to import these rare-earth metals – which is another cost, as well as a technical challenge."*

- Organizations are exploring other technologies, such as thermolysis or usage of biomass, for hydrogen production – this is ranked among the top five R&D priorities by 69 percent of E&U organizations. US oil giant Chevron recently committed $25 million to a California green waste-to-hydrogen project.[32] Houston-based Arbor Renewable Gas produces renewable gasoline and low-carbon hydrogen from gasification of wood waste and forest residue.[33] US-based H2 Energy Group uses woody biomass in a pyrolysis process that produces hydrogen-rich syngas (a mix of hydrogen, carbon monoxide, carbon dioxide, and methane). COO at H2 Energy Group Don Turner adds: *"The syngas can either go through a generator or a turbine to produce electricity or a post process to produce Hydrogen. The post process essentially involves a pressure swing adsorption to purify the hydrogen to 99.999%. We also absorb 13.2 tons of CO_2 in our energy grass per acre per year. Fifteen percent of all inputted biomass comes out as biochar from the reactor. Biochar coming out of reactors is essentially highly porous pure carbon that can be used for livestock farming as feed supplement, as well as in agriculture to promote soil health. It also represents a feedstock for the making of graphene – one of the most promising "super materials."*

- Fifty-nine percent also ranked fuel cells among the top five investment areas. Our recent research on Resources Awareness and Circular Economy Strategy (RACES) showcasing merit orders in automotive also highlights the criticality of hydrogen fuel cell electric vehicles (FCEVs). The research shows that hydrogen vehicles are less resource-critical per km than battery vehicles, but the hydrogen consumed in FCEVs is more critical than electricity.

Production: A significant proportion of E&U organizations globally are developing infrastructure to support production of low-carbon hydrogen. BP is leading the $36 billion Renewable Energy Hub project in Western Australia's Pilbara region to install 26 GW of solar and wind farms. At full capacity, it will produce around 1.6 MMt of hydrogen or 9 MMt of green ammonia per year.[34] Air Products, along with global energy company AES Corporation, plans to build a $4 billion low-carbon hydrogen plant in Texas, the biggest such plant in the US, with capacity to produce 200 Mt of hydrogen a day, as well as 1.4 GW of wind- and solar-power generation.[35]

Storage: Hydrogen must be stored either at high pressure or at low temperature, which is costly and technically challenging. Our research reveals that, of the E&U organizations investing in storage technologies:

- Four in 10 (41 percent) prefer compressed gaseous hydrogen as the storage mode; Salah Mahdy, Global Director – Renewable Hydrogen at Howden, a global leader of hydrogen compression solutions, says: *"There are three major technology areas that are critical to cost reduction of hydrogen: power generation, electrolyzers, and compression. We specialize in developed highly innovative compression solutions for our customers focused on optimizing the availability and reliability, which results in reducing the TCO (total cost of ownership) of our customers' operations."*

"To reduce the cost of low-carbon hydrogen, a focus on innovation is very important. Today, the efficiency of electrolyzers is just 60–65 percent. We need to have higher efficiency in order to reduce the electricity used to produce low-carbon hydrogen in a cost-effective way."

Paola Brunetto

Head of Hydrogen Business Unit at Enel Green Power

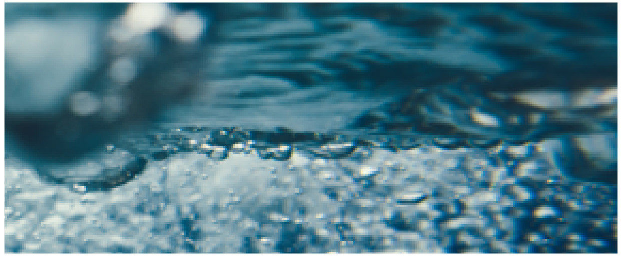
- Nearly a quarter (24 percent) are exploring liquefied-hydrogen-storage techniques
- 19 percent are investing in liquid organic hydrogen carriers (LOHC) technologies
- The remaining 16 percent are exploring derivatives, such as ammonia or metal hydrides

Organizations are also exploring the potential of underground hydrogen-storage facilities. Mitsubishi Power Americas along with Magnum Development are set to begin construction of a 300-GWh underground hydrogen-storage facility in the US.[36]

Transportation and distribution: While hydrogen can be transported via road, rail, water, or pipelines, costs can vary significantly. According to analysis from BloombergNEF, transporting hydrogen by pipeline over 100 km would cost a maximum of $0.23/kg; the same operation by road could cost as much as $1.73/kg.[37]

Spanish oil and gas group Cepsa has recently signed a deal with the Dutch port of Rotterdam to ship low-carbon hydrogen in the form of hydrogen derivatives such as ammonia or methanol from southern Spain to northern Europe through the first "green hydrogen corridor."[38]

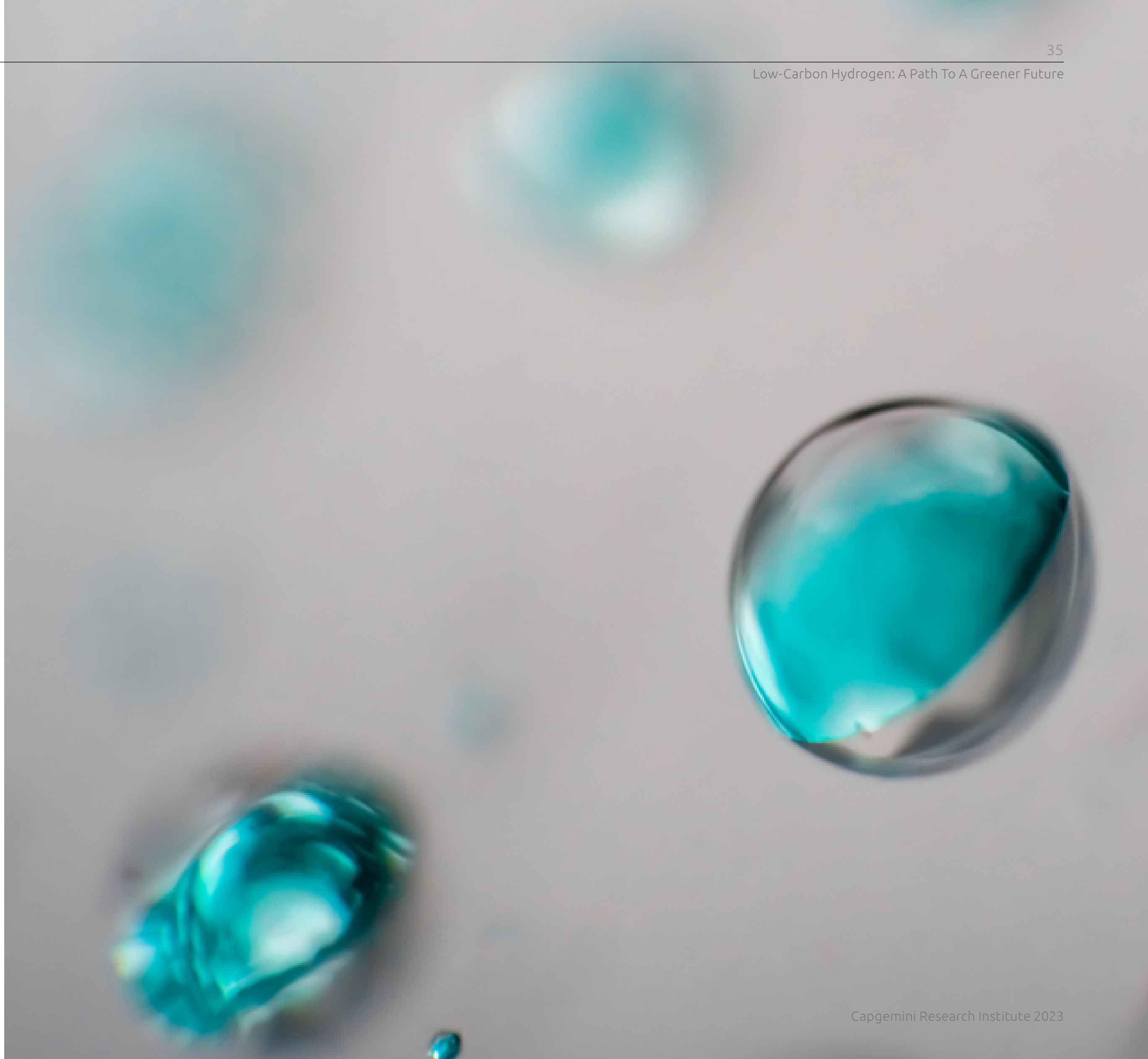
Of E&U organizations investing or planning to invest in transportation and distribution of low-carbon hydrogen, one-third (33 percent) are planning to explore existing natural-gas pipelines for hydrogen distribution. The European Hydrogen Backbone (EHB) initiative consisting a group of thirty-two energy infrastructure operators expect to re-purpose 69% of natural gas pipelines to transport hydrogen across the Europe by 2040.[39]



Cédric Van Hoonacker, Key Account Manager for Nextgrid H_2 & CO_2 at Fluxys, a Belgium-based natural-gas transmission system operator, comments: *"Pipeline transport offers a cost-efficient solution to connect areas of hydrogen excess supply with regions with hydrogen demand. We are already looking at repurposing of natural-gas pipelines. As mentioned in hydrogen strategy and studies at the European level, by 2050, 75 percent of the hydrogen grid will consist of repurposed natural-gas pipelines."*

It appears from our survey that the top three investment priorities for E&U organizations in the transportation and distribution area are:

- Improving distribution networks for H_2 transport
- Safe handling of hydrogen
- Managing leakages, as hydrogen leakages will also have an impact on atmospheric composition, as well as an indirect warming effect on the climate[40]



"The syngas can either go through a generator or a turbine to produce electricity or a post process to produce Hydrogen. The post process essentially involves a pressure swing adsorption to purify the hydrogen to 99.999%. We also absorb 13.2 tons of CO2 in our energy grass per acre per year...."

Don Turner

COO at H2 Energy Group

More than **80**

countries are supporting clean-hydrogen production.

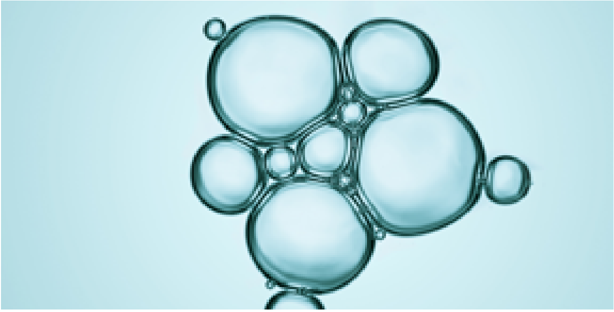
Countries across the globe have set ambitious targets for low-carbon hydrogen

Developing a homegrown national hydrogen industry presents a tripartite challenge:[41]

- Environmental: to reduce GHG emissions and fulfill net zero and decarbonization commitments
- Economic: to create added value and jobs
- Sovereignty: to develop energy independence, or even a new exportable resource

Countries are investing in both supply- and demand-side facilities and "hydrogen hubs" to create supply chains, lower costs, promote asset sharing and collaboration, and maximize economies of scale. Moreover, policies and regulations are making it more profitable for private-sector companies to invest in low-carbon hydrogen. For instance, the EU approved a €5.2 billion public grant to support hydrogen projects. This is projected to unlock an additional €7 billion in investment from the private sector.[42]

In total, 80 countries are supporting clean-hydrogen production. Below, we highlight a few key initiatives in various geographies. (NB: the list below is not exhaustive for any country/region.)



The EU's hydrogen roadmap to 2050:

In 2020, the European Commission launched its ambitious hydrogen strategy for a climate-neutral Europe, which sets out a plan to establish an integrated hydrogen-energy network in Europe by 2050.[43]

This transformation is accelerating following the publication of the REPowerEU plan in May 2022, which proposes a reduction of EU dependence on Russian fossil fuels by accelerating several climate-related targets. REPowerEU sets a target of 10 Mt of domestic renewable-hydrogen production and 10 Mt of renewable hydrogen imports by 2030.[44] Moreover, EU's Renewable Energy Directive defines hydrogen produced by renewables-based electricity and liquid fuels, such as ammonia, methanol or e-fuels produced from renewable hydrogen as RFNBOs (renewable liquid and gaseous fuels of non-biological origin), which will aid in growth of low-carbon hydrogen and its derivatives.[45]

THE EU'S HYDROGEN ROADMAP TO 2050:

2020–24

- In this phase, the EU will focus on installation of at least 6 GW of renewable hydrogen electrolyzers and production of up to 1 Mt of renewable hydrogen.

2025–30

- In this period, the EU will focus on making hydrogen intrinsic to the bloc's integrated energy system, which aims to install at least 40 GW of renewable-hydrogen electrolyzers and to ramp up hydrogen production to 10 million tonnes by 2030.

2030–50

- From 2030 onwards, the EU aims to deploy green hydrogen in all large-scale hard-to-decarbonize sectors.

Selected country-specific initiatives – Europe:

Over the coming eight years, France intends to spend €9 billion to encourage the transition of heavy industry to hydrogen, including scaling national green-hydrogen production to 6.5 GW by 2030.[46]

In 2021, the German government set up the H2Global initiative for green-hydrogen imports produced outside the EU. It features a contracts for difference (CfD) that offers compensation for a limited time for the difference between the purchase price (production plus transport costs) and the sale price (the current market price for fossil hydrogen) of renewable hydrogen and derived products.[47]

The UK plans to invest £4 billion ($4.8 billion) in creating a low-carbon hydrogen industry by 2030. It is targeting 5 GW of annual production capacity, sufficient to power around 3 million homes, as well as heavy industry.[48]

Spain intends to invest €1.5 billion to develop green hydrogen production over the next three years.[49]

The Belgian government has invested €95 million (around $100 million) in the construction of a hydrogen and CO_2 pipeline network. It has also earmarked an annual budget of €25 million for R&D and €16 million for the creation of a hydrogen expertise center in 2022. Belgium's hydrogen strategy focuses on four pillars: positioning the country as an import and transit hub for renewables in Europe; developing Belgian leadership in hydrogen technologies; establishing a robust hydrogen market; and focusing on collaboration and cooperation.[50]

Selected initiatives in North America

US

- The US Department of Energy (DOE) has initiated an $8 billion program (expected to be awarded in summer 2023 based on the applications) to develop a hub network (H_2 Hubs) for producing clean hydrogen.[51] The network will connect hydrogen producers, consumers, and local infrastructure. By November 2022, applications for nearly $60 billion total of federal funding were received from organizations that are willing to invest $150 billion of their own capital.[52]
- Under the Inflation Reduction Act (IRA) of 2022, a production tax credit for clean hydrogen was issued, with the credit amount varying according to the carbon-intensity of hydrogen produced, with a maximum credit rate of $3/kg for the lowest-carbon hydrogen.[53]
- An industry consortium, Open Hydrogen Initiative (with E&U organizations such as EQT, Exxonmobil, National Grid, and Shell as foundational sponsors) has been formed to measure and certify the carbon intensity of hydrogen at the production plant level.[54]

CANADA

- The Government of Canada's Clean Fuels Fund will invest CA$1.5 billion ($1.1 billion) to build new or expand existing production facilities for clean fuel, including hydrogen.[55]
- Canadian federal and provincial governments have also announced approximately CA$475 million in project funding for Air Products' net zero hydrogen energy complex in Alberta.
- The Hydrogen Strategy for Canada, 2020 outlines a strategy to create a CA$50bn domestic hydrogen market. Specific targets include making hydrogen 30% of the energy mix by 2050 at a cost of $1.20–2.80/kg.[56]

Selected initiatives in APAC:

INDIA

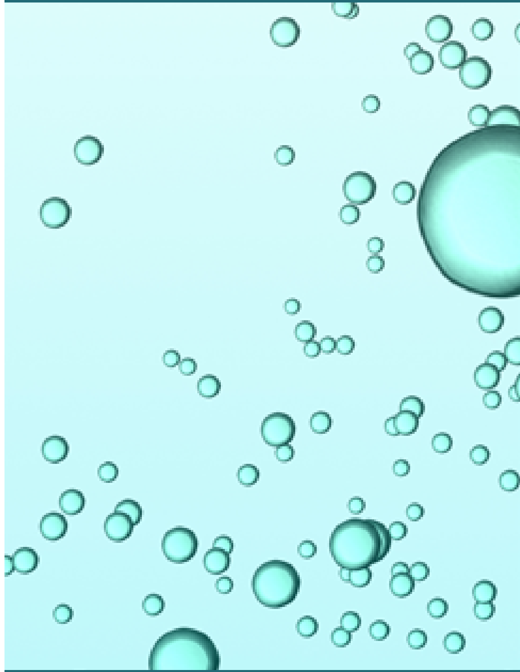
- India has approved a $2.4 billion National Green Hydrogen mission to boost production, utilization, and exportation of green hydrogen and its derivatives. The mission expects to realize 125 GW of renewable energy.[57]
- The Indian government expects industry to invest ₹8 trillion ($96 billion) in green hydrogen and its derivative, green ammonia, by 2030.[58]

AUSTRALIA

- The Australian Renewable Energy Agency (ARENA) has announced a further A$50m in funding across four hydrogen projects listed under the German-Australian Hydrogen Innovation and Technology Incubator (HyGATE) initiative. Germany invested an additional €40m in the joint initiative, focused on establishing a green-hydrogen supply chain.[59]

JAPAN

- Japan's Ministry of Economy, Trade and Industry (METI) proposed to allocate ¥300 billion ($2.3 billion) to the development of the hydrogen importation and supply chain.
- In addition, ¥70 billion is to be used to develop large-scale electrolyzer projects for hydrogen production.[60]



04

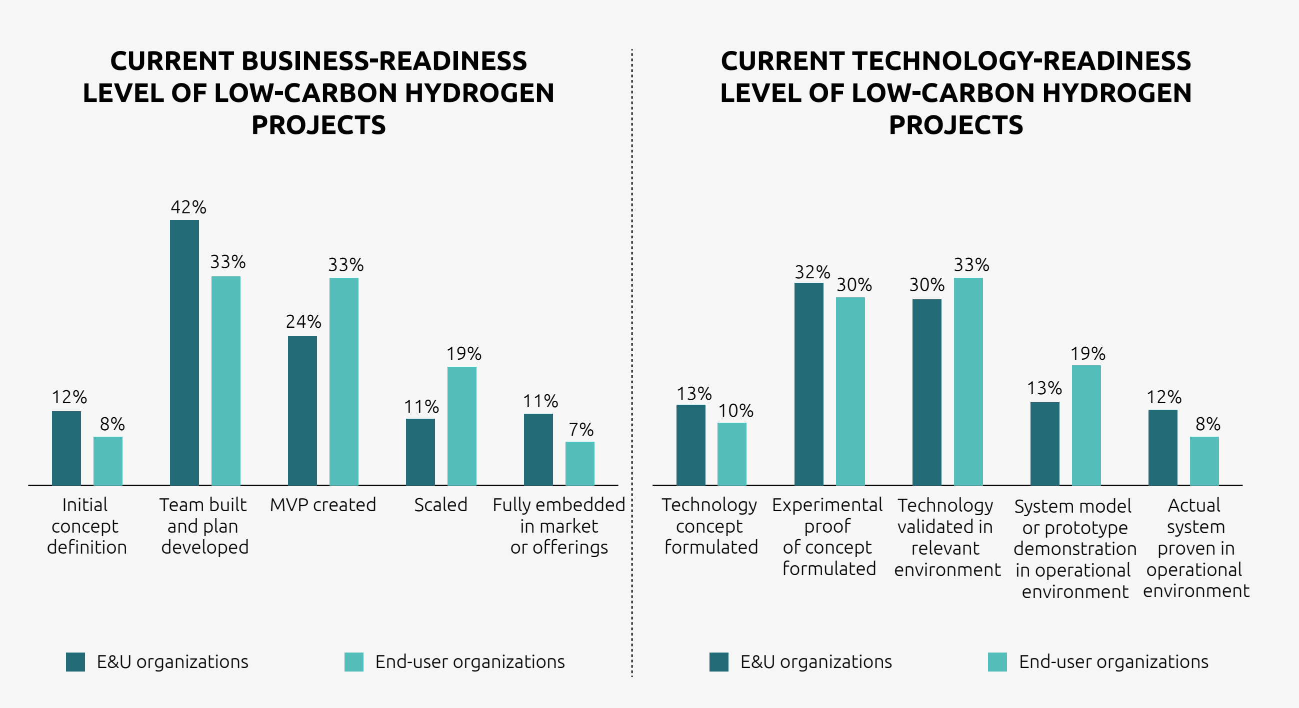
COST, ENGINEERING, AND SKILLS CHALLENGES ARE YET TO BE ADDRESSED

Our research suggests that 64 percent of E&U organizations will be investing significantly in low-carbon hydrogen by 2030. However, a majority of organizations are currently at proof-of-concept (PoC) or pilot stages. Figure 10 highlights the current maturity of E&U and end-user organizations on their low-carbon hydrogen journeys.

High production costs, low energy efficiency, and a lack of infrastructure and skilled resources are the current barriers to low-carbon hydrogen scalability. We discuss these challenges in detail below.

Fig.10

A majority of E&U and end-user organizations are still at the initial stages of their low-carbon hydrogen initiatives



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations; N=500 respondents from unique energy and utilities organizations.

The cost of low-carbon hydrogen is currently high

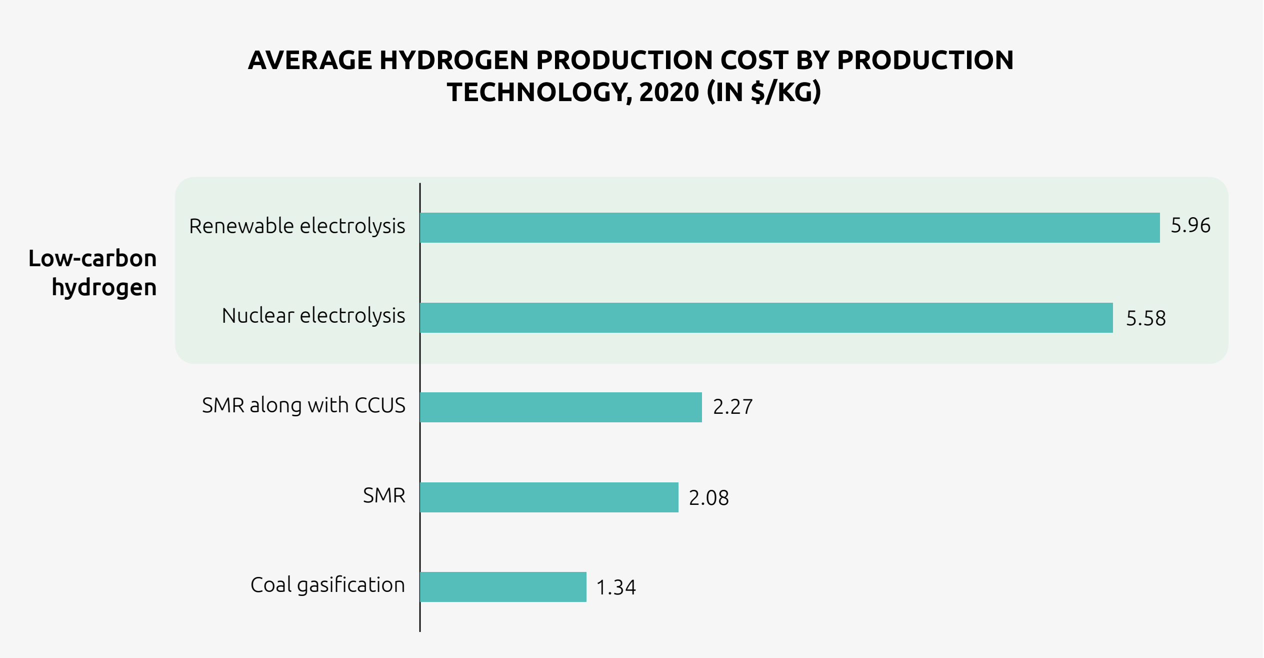
The cost of producing low-carbon hydrogen is mainly based on three factors: the cost of the electricity that powers the electrolyzers; the cost of installing the electrolyzers; and finally, the load factor resulting from the intermittency of renewable resources. Falling renewable-energy prices, coupled with improvements in electrolyzer technology, have increased the commercial viability of low-carbon hydrogen. However, it still costs $5–6 per kg to produce. Comparing low-carbon hydrogen to other fuels, as per estimates:[61]

- It is 2–3 times more expensive to produce than fossil fuels (considering long-term average fossil-fuel prices of $75/barrel for oil and $4–6/gigajoule for natural gas)
- Fuel cells and storage tanks for road transport are significantly more expensive than internal combustion engines
- Synthetic fuels for aviation are currently 3–6 times more expensive than jet fuel from fossil oil
- The cost premium for low-carbon hydrogen compared to fossil-based options can be 50–75 percent for ammonia, 150 percent for methanol and 30–40 percent for steel
- Producing low-carbon hydrogen is much more resource-critical per kWh than producing any other types of energies due to challenges associated with procurement, technology, and environmental impact. For more details on merit orders in energy, please refer to our published report: RACES: Resources Awareness and Circular Economy Strategy.

Fig.11

Low-carbon hydrogen is not yet cost-competitive

Figure 11 highlights the global average levelized cost of hydrogen (LCOH), by energy source, in 2020. Low-carbon hydrogen is around three times more expensive than carbonized hydrogen.



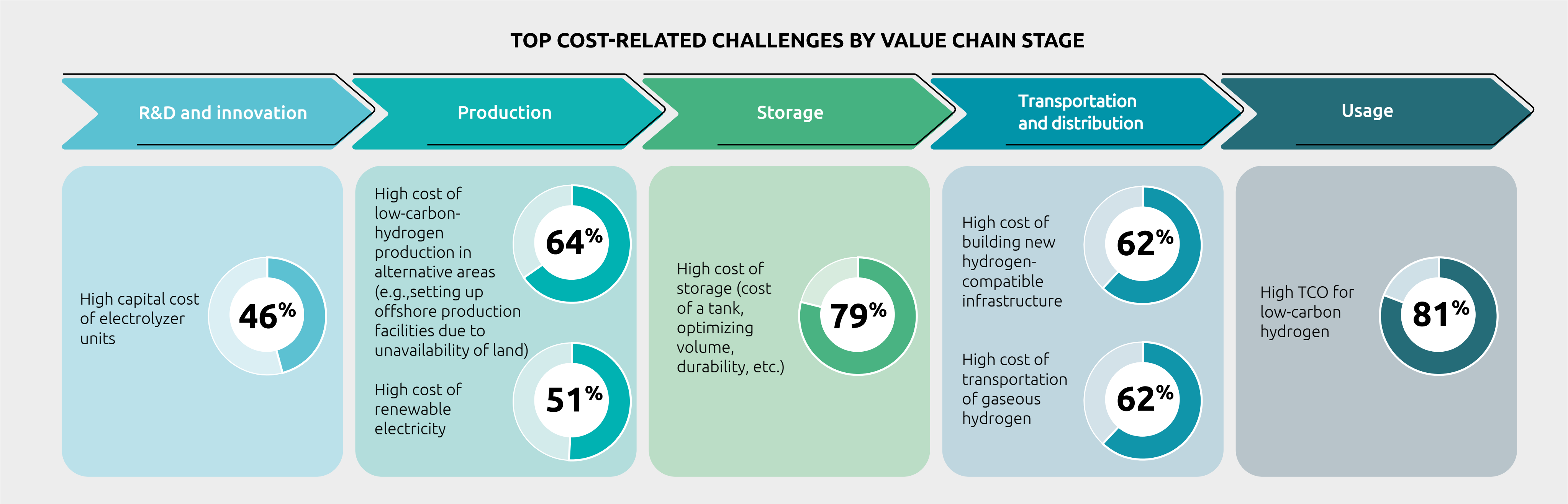
2–3

Low-carbon hydrogen is 2–3 times more expensive than carbonized hydrogen.

Source: IEA, GlobalData Power Webinar - Hydrogen Market, “Riding the sustainability wave,” February 3, 2022.

Fig.12

Organizations are facing cost-related challenges throughout the hydrogen value chain



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations; N=500 respondents from unique energy and utilities organizations.

Amid soaring natural-gas prices, the competitiveness of low-carbon hydrogen has improved slightly; however, rising inflation and cost of materials have contributed to higher CAPEX for projects. As per our survey, organizations face cost pressures throughout the hydrogen value chain (see Figure 12).

- **R&D and innovation:** Producing and operating electrolyzers is currently expensive owing to low technology efficiency; the large amount of rare metals required for electrolyzer membranes; and the lack of scaled production. According to IEA estimates, CAPEX requirements are currently in the range of $500–1,400/kWe for alkaline electrolyzers and $1,100–1,800/kWe for PEM electrolyzers, while the range for solid-oxide electrolyzer cells (SOEC) is $2,800–5,600/kWe.[62] In our research, 46 percent of E&U organizations rank higher capital cost of electrolyzers among their top three R&D challenges. Analysts expect the capital cost of electrolyzers to drop by 30 percent by 2025, as production scales.[63] For instance, in China, the production of alkaline electrolyzers costs one-fifth to half of that in Europe or North America.[64] The cost of electrolyzer stack replacement is also a major component for OPEX (typically required after around 60,000 hours).

- **Production:** In our research, more than half (51 percent) of E&U organizations ranked the price of renewable energy among the top three obstacles to the commercially viable scaling of low-carbon hydrogen.

  Availability of green electricity also needs to be ensured. For the EU to reach its hydrogen objectives, it must add 40 GW of renewables capacity by 2026, – a challenging target. Including nuclear electricity sources for low-carbon hydrogen production can

62%

of E&U organizations rank the high cost of building hydrogen-compatible infrastructure among the top five transportation challenges.

help to overcome these difficulties. Moreover, considering back up energy for low-carbon hydrogen manufacturing can help in flattening out peaks and troughs in renewable energy production. Recently, energy conversion equipment specialist Ingeteam has supplied a battery energy storage system (BESS) for Iberdrola's Puertollano facility in Spain – one of the world's largest operational green hydrogen plants.[65]

- **Storage:** Hydrogen's low molecular weight and low energy content by volume make storage expensive –a large majority (79 percent) of E&U organizations rank this among their top five storage-related challenges.
- **Transportation:** In our research, around 60 percent of E&U organizations rank the high cost of building hydrogen-compatible infrastructure and high cost of transportation of hydrogen in its gaseous state among the top five transportation challenges.
- **End usage:** Among end users, total cost of ownership is the main challenge. An executive at a global automotive organization says: *"You need to make a lot of investment to change the hardware. Processes such as heating, where we currently use natural gas, cannot simply switch because of the different calorific value of hydrogen, different leakage problems, different pressures, and so on."*

"We specialize in developed highly innovative compression solutions for our customers focused on optimizing the availability and reliability, which results in reducing the TCO of our customers' operations."

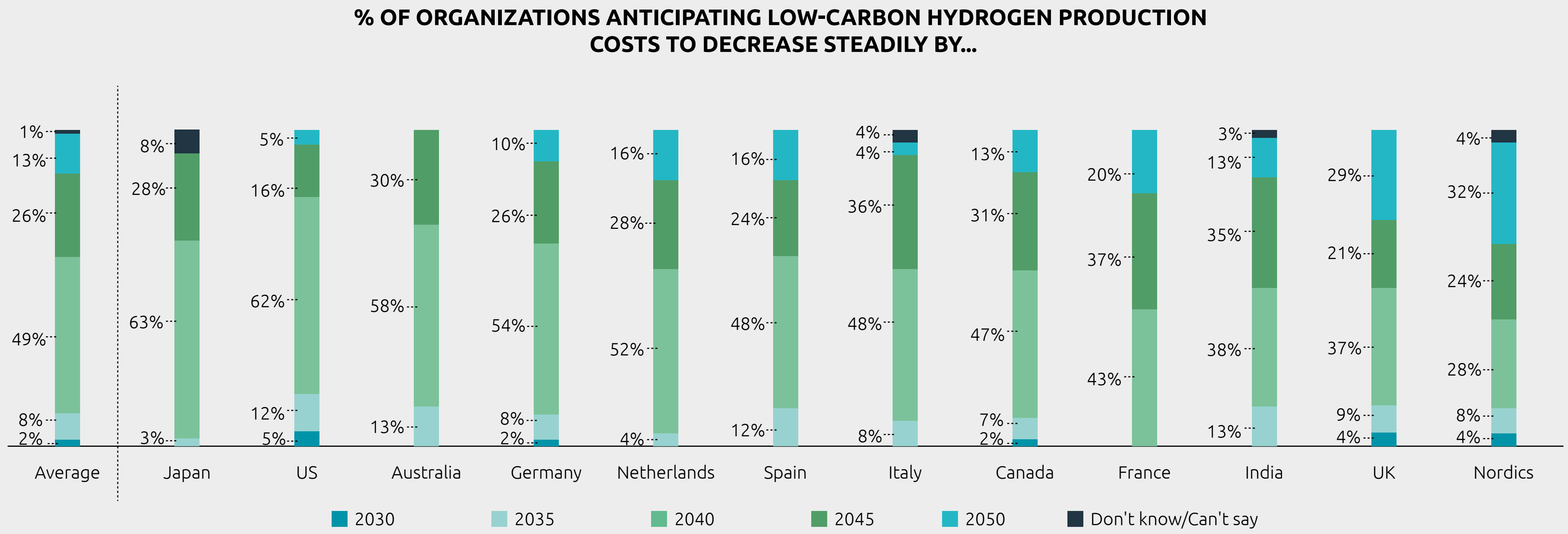
Salah Mahdy

Global Director – Renewable Hydrogen at Howden

Many expect improved economic viability of low-carbon hydrogen

Fig.13

A majority of organizations in our research expect the cost of low-carbon hydrogen to decrease steadily to 2040



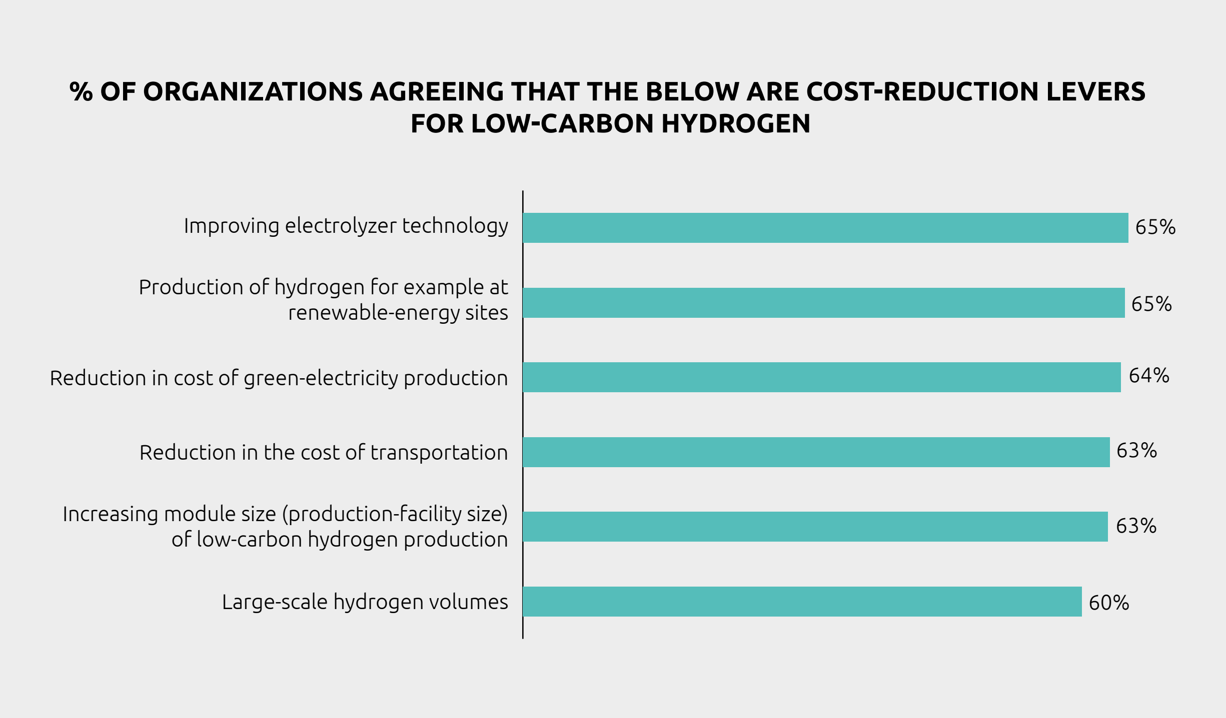
Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=500 respondents from unique energy and utilities organizations.

Organizations and researchers are also depending on favorable regulatory measures such as carbon taxes or renewable-energy incentives to facilitate this shift. For instance:

- The European Commission offers Carbon Contracts for Difference (CCfD) subsidies for green hydrogen through its Innovation Fund. The program supports a complete switch from natural gas to renewables in producing H_2. Under the CCfD scheme, EU governments will pay end users, not the producers, a certain amount for not emitting carbon.[66]
- The EU's Carbon Border Adjustment Mechanism (CBAM), which will be applicable from October 1, 2023, is set to apply a carbon border tax on imports of carbon-intensive hydrogen and H_2-derived products such as ammonia and methanol. Under the CBAM scheme, importers of these products will be required to pay the difference between carbon taxes paid in the country of origin and the price of emissions allowances under Europe's carbon-trading scheme, the Emissions Trading System (ETS).[67]

Fig.14

Organizations see improvements in electrolyzers, a falling cost of renewables, and scaled volumes as key cost-reduction levers



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=500 respondents from unique energy and utilities organizations.

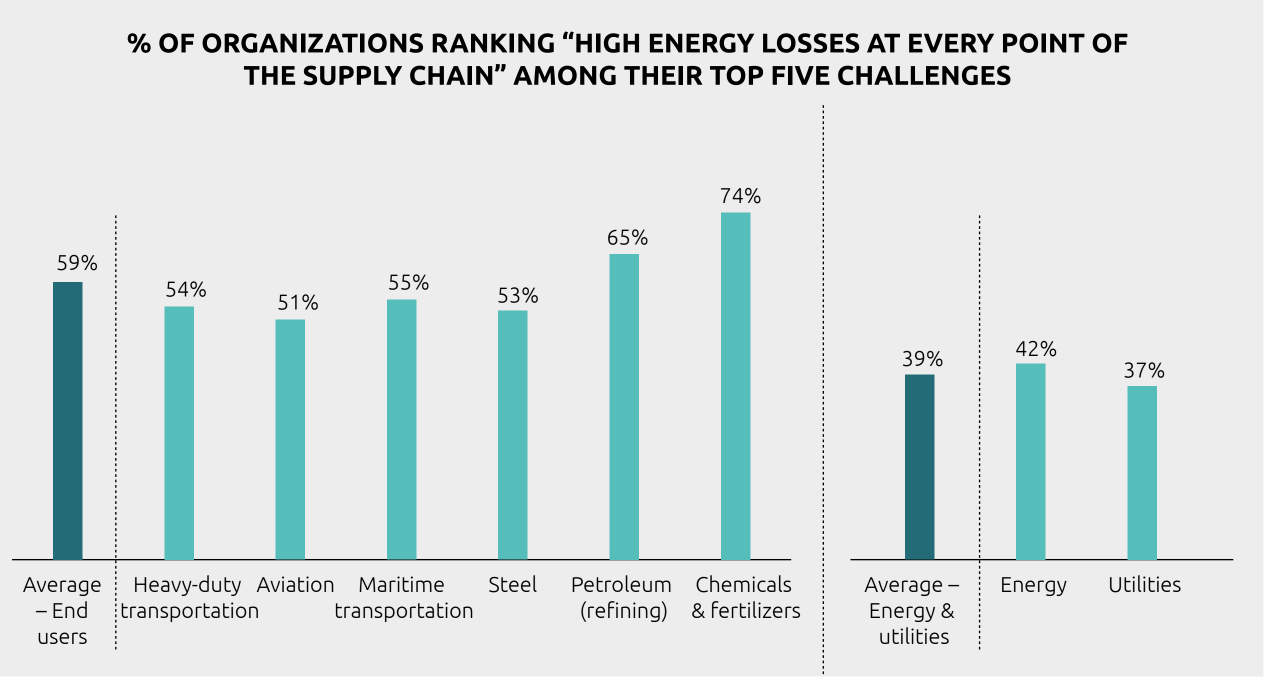
Engineering challenges are yet to be solved across the value chain

Cost challenges aside, for large-scale commercialization and deployment of low-carbon hydrogen, various engineering challenges must be solved.

- **Energy losses across the value chain:** Reducing energy losses is a key challenge from an innovation perspective:[68]
  - 30–35 percent of the energy used to produce hydrogen is lost during electrolysis
  - 13–25 percent of energy losses occur while liquefying hydrogen or converting into other carriers such as ammonia
  - Transporting hydrogen requires additional energy inputs, typically equal to 10–12 percent of the hydrogen's own energy content
  - Using hydrogen in fuel cells results in an additional 40–50 percent energy loss

Fig.15

Energy losses across the value chain are a challenge for end users and E&U organizations



Note: Figures highlighted in the above graph are as per survey respondents' views exclusively about their own sector.

Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations; N=500 respondents from unique energy and utilities organizations.

As figure 15 shows, 59 percent of end-user organizations and 39 percent of E&U organizations see this as a considerable challenge. Organizations are exploring digital technologies to mitigate this challenge and grow the hydrogen economy. We talk about them in detail in the next section.

72%

of E&U organizations believe digital technologies such as AI, ML, IoT, digital twins will be a key enabler to optimize RoI for low-carbon hydrogen projects.

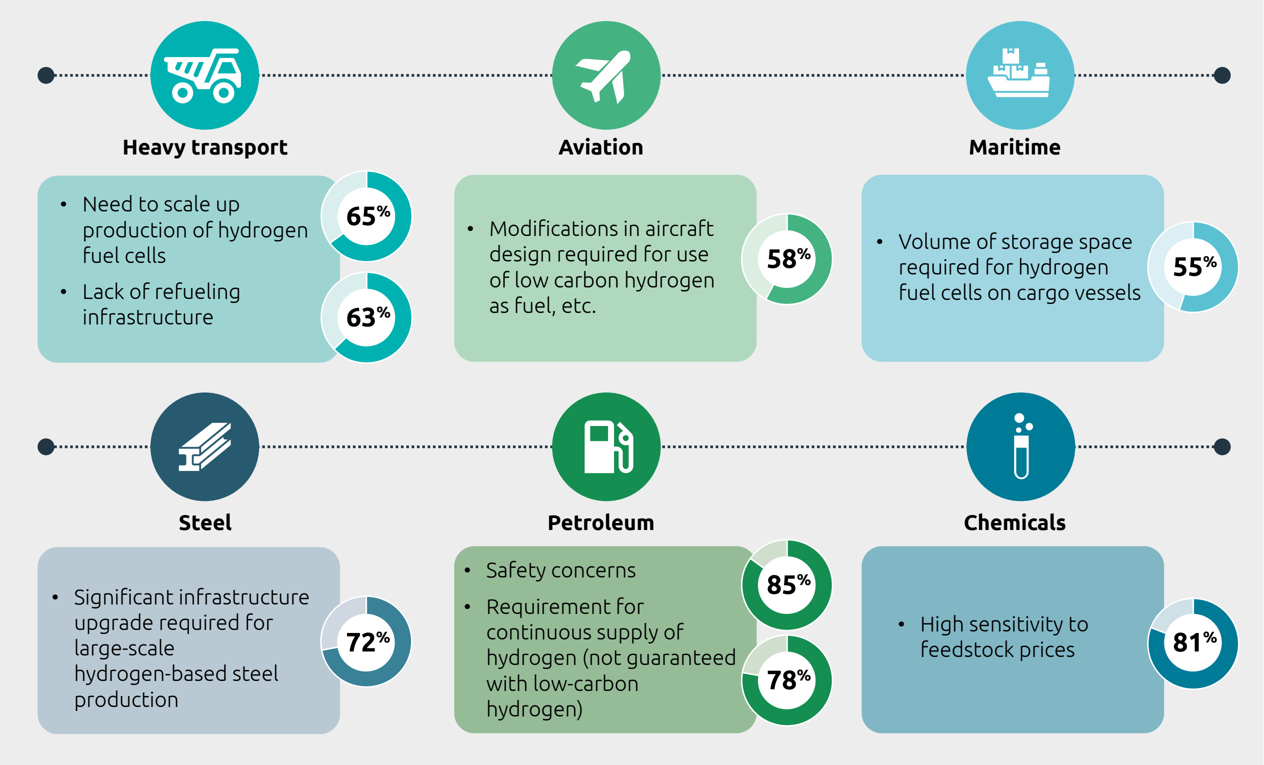
- **Engineering- and infrastructure-related challenges arise:** Efficiency, deterioration, durability, resilience, density, electrical-power capacity, electrolysis-grade water availability, as well as common engineering low-carbon hydrogen standards availability must all be addressed across the value chain for low-carbon hydrogen to be viable:
  - High energy consumption during production is ranked among the top five production challenges by half of E&U organizations
  - With hydrogen being a highly volatile, combustible gas with a very low energy content by volume, storage presents significant challenges:
    - High flammability raising safety concerns (ranked among the top five challenges by 81 percent of organizations)
    - Low durability of storage materials – such as fiber, metals, polymers, etc. (72 percent)
    - Required specificity of storage conditions (such as high pressure, cryogenic temperature, etc.) (69 percent)
  - Infrastructure requirements for transporting and distributing hydrogen are crucial:
    - Nearly 7 in 10 (68 percent) E&U organizations investing in low-carbon hydrogen transport rank “insufficient existing hydrogen pipeline infrastructure” among the top five challenges
    - Research is also ongoing into using existing gas pipelines for hydrogen transport by blending and deblending; if successful, this could help absorb price pressures during the initial phase of the hydrogen economy
    - Policy support is also required here, as 65 percent of E&U organizations investing in transportation rank “government-authorized storage sites being far from consumption sites” among the top five challenges

– Certifications: A lack of international standards on proof of origin is a challenge. The UK government, for instance, is seeking industry views on the design of a "globally recognized" certification scheme for low-carbon hydrogen in the UK, to build transparency and confidence in the carbon credentials of hydrogen.[69] Industry players such as ExxonMobil, National Grid, Duke Energy, Equinor, and others have formed a working group called the Open Hydrogen Initiative (OHI) to develop the models that will be used for hydrogen certification.[70]

For more details on engineering challenges, please refer to our recently published research: [Unlocking the hydrogen age](). These infrastructure and engineering challenges also impact end users. We list the top-ranked challenges by end-user sector (see Figure 16).

Fig.16

A majority of end-user organizations rank infrastructure and engineering issues among the top five challenges for their sector



Note: The figure highlights the percentage of end user organizations ranking the said challenge among top 5 hydrogen challenges for their respective sector.

Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations.

“Digital technologies are crucial to the hydrogen value chain – for surveillance of systems; early detection of faults and leaks; continuous cost-optimization, etc. In the development phase, digital twins and accurate modeling are going to gain importance.”

Thomas Holm

Hydrogen researcher from the Institute for Energy Technology, Norway

Organizations face critical-skill shortages

Our previous research on new-energy business models found that the transition to alternative decarbonized business models is being hindered: nearly 70 percent of organizations cite a lack of capabilities to develop new-energy business models, while around 62 percent report a deficit in in-house skillsets.[71]

Analysis by the UK Department for Business, Energy, and Industrial Strategy (BEIS) suggests the UK hydrogen industry could support 12,000 jobs by 2030, and 100,000 jobs by 2050 across production, transport, and storage technologies for domestic and export markets. However, industry experts estimate there to be 1,000–2,000 individuals in the UK who have very specific

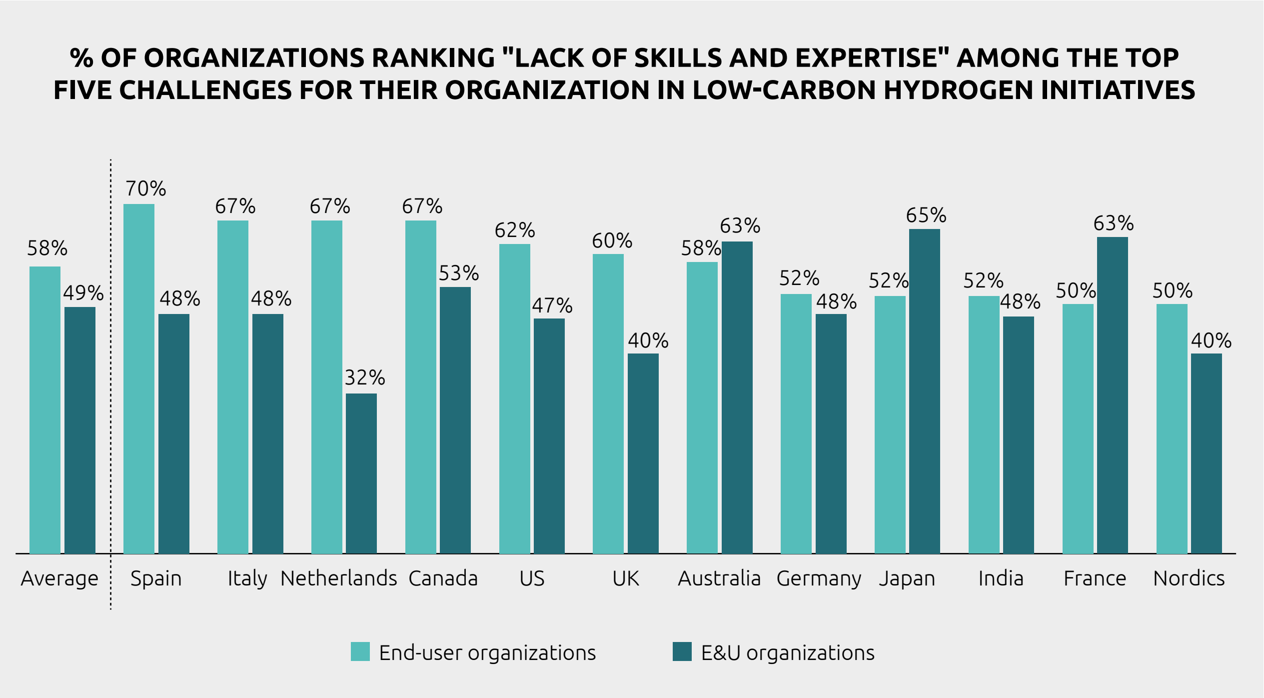
hydrogen-related skills.[72] Moreover, with applications and use cases of hydrogen extending to various industries, hydrogen talent and skills demand is only going to grow further.

In our research, a majority of organizations rank lack of skills and expertise among the top five challenges to scale hydrogen.

Other challenges, such as the lack of a transparent, open, and organized market to enable the exchange of hydrogen, also hinder scale. Despite these challenges, low-carbon hydrogen can play a critical role in energy transition and decarbonization.

Fig.17

Six in 10 end users and nearly half of E&U organizations recognize lack of required skills, expertise, and training as a challenge



Note: End user data for Netherlands, Spain and Italy is analyzed at a low base

Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=360 respondents from unique end-user organizations, N=500 respondents from unique energy and utilities organizations.

05

HOW CAN ENERGY AND UTILITIES ORGANIZATIONS CAPITALIZE ON THE LOW-CARBON HYDROGEN OPPORTUNITY?

To seize the opportunities in low-carbon hydrogen, mitigate costs, and scale at pace, organizations will need to answer a number of questions:

- Strategic: How to establish the business case for hydrogen? Which markets, segments, or use cases should we target? How to transition to a new business model? What should be the governance and operating model? Which skills will be required to succeed and how to recruit and train workers in them?
- Technological and IT: Which solutions to select? Are they sufficiently mature? How to implement them? How to develop and scale them up to an industrial level? Which steering and simulation tools should we select?
- Partner ecosystem: How do we select a partner? What will be the respective roles? How do we design and implement projects in unprecedented ecosystem configurations (large groups, small and medium-sized enterprises (SMEs), startups, local authorities, etc.)? How do we secure a reliable partnership network?

With these key questions front of mind, and drawing on our survey analysis and interviews, as well as our own experience in this area, we recommend the following steps to capitalize on the growing low-carbon hydrogen opportunity:

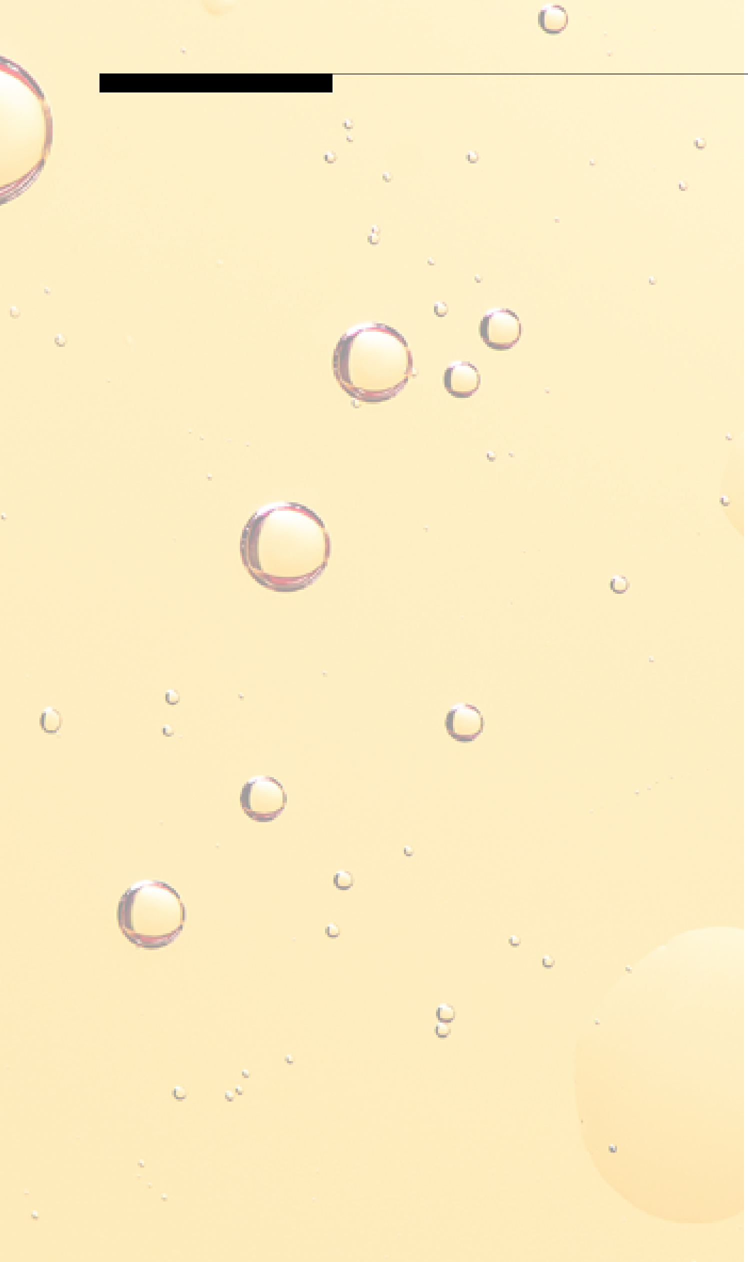
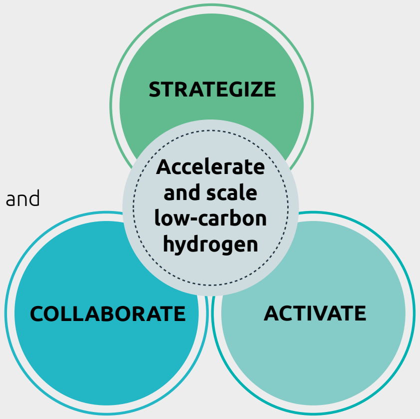


Fig.18

Actions for scaling low-carbon hydrogen initiatives

- Tailor the business-case assessment to your organization
- Establish governance models to support new business models
- Establish hydrogen-competence centers for skills development



- Clearly articulate partnership strategy and design appropriate trade-offs while partnering with:
  - Primary energy producers
  - Equipment suppliers
  - Storage-system developers
  - Infrastructure providers
  - End users
  - End-to-end value chain

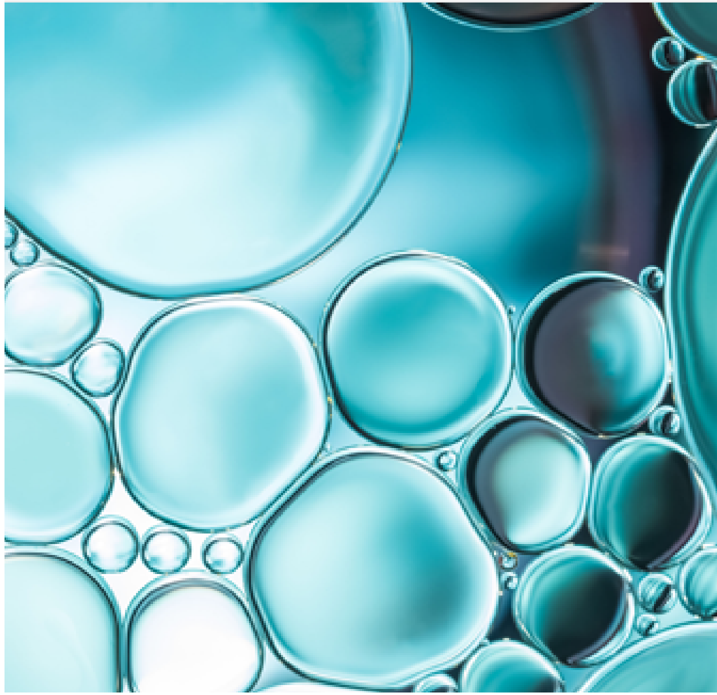
- Harness the potential of digital-twin technologies to reduce cost and operational risks
- Develop robust data and technology foundations to maximize agility and resilience in the supply chain

Source: Capgemini Research Institute Analysis.

58%

of organizations believe that the clean hydrogen economy will create wealth and substantial job opportunities

1. Strategize: Align organizational strategy and capabilities to develop new business models



Tailor the business-case assessment to your organization:

Low-carbon hydrogen technology requires improvement and scaling up to contribute positively to overall cost reductions. In parallel, there is a requirement to evaluate new business models from sustainability and TCO standpoints. Detailed analysis of both CAPEX and OPEX is required.

Assess and monitor regulatory developments:

As mentioned previously, governments across the world are focusing heavily on decarbonized hydrogen through investments, low-carbon hydrogen subsidies, emission trading schemes, carbon taxes, etc. The regulatory landscape is fast evolving, so it is crucial for organizations to assess, evaluate, and monitor these options. Our research shows that 64 percent of E&U organizations see inadequate government funding today as a key impediment to progress in this space.

Secure customer demand and share investments and risks between public and private players:

The low-carbon hydrogen market is currently facing a Catch-22 situation. To build up large-scale production facilities, producers need guaranteed customer demand. At the same time, to commit to upfront investments, end-users are asking for a reliable supply of low-carbon hydrogen. In our research, 68 percent of E&U organizations consider the uncertainty of outputs of large-scale deployments to be a key challenge for hydrogen R&D.

Our research shows that the leading E&U players are focusing on identifying the market and analyzing end usage potential. An executive from a German energy company adds: “In order to make large projects bankable, you have to align potential supply with demand. That is still a challenge because you end up with a large upfront investment, but uncertain demand and pricing. But we're identifying first customers and starting to commit to certain volumes.”

The design of a low-carbon project will also need to consider the strength of the offtaker. By combining multiple offtakers, organizations can share investments and risks. Smaller local offtakers can also be approached for lower-cost hydrogen supply, accelerating operational breakeven. It is also important that the price is attractive to buyers. To scale up the industry, different players in the value chain must share investments as well as leverage public aid.

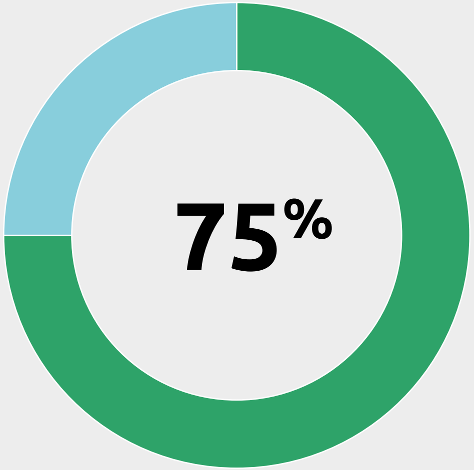
There are other uncertainties that organizations must assess, such as natural-gas prices, spot power prices, sufficient renewable-power supply, and available areas for the production site, which can be expanded further based on demand, requirements, etc.

Establish governance models to support new business models:

In 2020, Germany's RWE set up a new hydrogen business unit within RWE Generation SE, one of the group's main divisions, which holds its fleet of gas, hard-coal, hydro, and biomass power plants. Spain's Iberdrola SA has also announced a green-hydrogen business unit.[73]

Fig.19

A majority of organizations are evaluating a concurrent business model integrating both traditional and new low-carbon hydrogen capabilities into one



...of E&U organizations have launched or plan to launch an initiative to integrate existing and low-carbon-hydrogen business models for concurrent operation

Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=500 respondents from unique energy and utilities organizations.

Establish hydrogen-competence centers for skills-development:

Our previous research highlights that only 38 percent of E&U organizations say they have the necessary digital and IT skills to develop alternative fuels (including hydrogen).[74]

Organizations should establish hydrogen-competence centers and implement education and upskilling programs, as well as manage stakeholder expectations through careful strategic communication. As part of its NextHy project, Enel Green Power is developing a green-hydrogen center of excellence in Sicily, Italy. As well as engaging with startups, VCs, and universities, the facility will host webinars, expert-led dissemination events, and training courses.[75]

Organizations must focus on external hiring, as well as upskilling of talent. One of the German energy companies is promoting the training and upskilling of specialists in hydrogen-related occupational fields. An executive from a German energy company adds *"We are strongly ramping up the workforce in the hydrogen division and a large share of this workforce is engaged in project development. We are focusing on developing engineering competence to operate and maintain future projects of hydrogen production, understanding electrolyzers, production of hydrogen derivatives, etc."* In our research, nearly 6 in 10 (58 percent) of E&U organizations agree that a clean-hydrogen economy will create wealth and generate job opportunities.

87%

of the E&U organizations have already begun utilizing data and analytics in their hydrogen value chains

2. Activate: Accelerate the low-carbon hydrogen economy through technology and digital engineering

Thomas Holm, a hydrogen researcher from the Institute for Energy Technology, Norway, says: *"Digital technologies are crucial to the hydrogen value chain – for surveillance of systems; early detection of faults and leaks; continuous cost-optimization, etc. In the development phase, digital twins and accurate modeling are going to gain importance."* As the hydrogen economy grows, it is vital for organizations to look at digital technologies that extend across the value chain. Our research indicates that approximately three out of four (72 percent) E&U organizations believe digital technologies such as artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), and digital twins will be key enablers to optimize return on investment (ROI) for low-carbon hydrogen projects, helping organizations to reduce their capital and operating cost and risk by improving uptime, safety, and reliability while maximizing agility and resilience in the supply chain.

Harness the potential of digital-twin technologies to reduce cost and operational risks:

UK-based electrolyzer manufacturer ITM Power plans to build a commercial green-hydrogen electrolysis facility with 1-GW capacity in Humberside, UK. To realize this, the company is using digital twins.[76]

Digital twins can help organizations in the hydrogen value chain to:

- model multiple designs and scenarios to maximize ROI (estimates indicate that digital-twin analysis can trim CAPEX by 10–15 percent, while reducing risk in the hydrogen value chain by 30–50 percent);[77]
- monitor operations in real time to enhance performance and profitability;
- optimize preventive maintenance to minimize costly unscheduled downtime;

- test controls and safety measures;
- enable predictive preparation for demand and resources disruption;
- improve employee safety and facilitate training;
- allow data-driven decision-making throughout the lifecycle and across ecosystems;
- enhance sustainability by limiting the use of resources along the value chain.

Digital twins can strategically develop economic hydrogen production models while offering decision-making support on investment risks, financial benefits, and the optimal configuration of low-carbon hydrogen production systems.

Digital solutions and modeling can also help organizations design storage spaces for hydrogen by considering a range of factors, such as stationary or mobile application, duration of storage, etc. These models can help organizations to predict pressure changes and fluid movements during transportation that damage tanks and cause leakages. The UK's National Grid has collaborated with the Centre for Modelling & Simulation (CFMS), DNV, Premtech, and Durham University (UK) to develop digital twins to test hydrogen transportation.[78]

On the end-user side, Ford has developed a fully functional prototype demonstrator transit fuel-cell electric vehicle (FCEV), and a digital twin that is fully validated to capture the key functional features of the physical prototype.[79]

Develop robust data and technology foundations to maximize agility and resilience in the supply chain:

With advanced analytics and AI, organizations can maximize yields, prevent energy losses, forecast failures, model demand, optimize storage and transport, reduce costs, and de-risk innovation and adoption. Our survey shows that nearly 87 percent of E&U organizations have already begun utilizing data and analytics in their hydrogen value chains; nearly 60 percent claim that they use AI extensively for their low-carbon hydrogen initiatives.

Organizations should:

- Unify data from siloed sources and create an integrated data-management system
- Focus on data-landscape modernization
- Invest in data-sharing ecosystems
- Incentivize innovation and foster a data-powered culture

Various platform providers are emerging to guarantee the renewable origin of green hydrogen, while also allowing consumers to quantify, record, and monitor the decarbonization process of their own energy supply and to verify the transportation and delivery process. Zane McDonald, Executive Director of the Open Hydrogen Initiative, led by GTI Energy says: *"A standardized approach to data and digitalization plays a critical role in understanding the carbon intensity of hydrogen. It ensures that hydrogen investors and policymakers can base decisions on credible information, and that we can achieve deep economy-wide decarbonization at an economically viable price. We aspire to increase the utilization of measured data that characterizes the operational parameters of a hydrogen production facility in real-world conditions. Defining hydrogen's facility-level* *carbon intensity creates an attribute that can be used by decision makers to ascribe value to hydrogen based on its environmental bona fides."* Nobian, a Germany-based chemicals company, is piloting blockchain solutions for the certification of green hydrogen to ensure traceability across the value chain.[80]

Envision Digital, which specializes in the deployment of IoT solutions dedicated to renewable energy, partnered with Capgemini Engineering to develop digital twins applied to the green hydrogen value chain. These tools will allow the control and study of the availability and profitability of the different systems and processes of its value chain. Moreover, they will certify the origin of the produced hydrogen, as well as enable analytical solutions to characterize the performance, reliability, and cost of the various systems.[81]

"...We aspire to increase the utilization of measured data that characterizes the operational parameters of a hydrogen production facility in real-world conditions. Defining hydrogen's facility-level carbon intensity creates an attribute that can be used by decision makers to ascribe value to hydrogen based on its environmental bona fides."

Zane McDonald

Executive Director of the Open Hydrogen Initiative, led by GTI Energy

3. Collaborate: Partner to scale low-carbon hydrogen technology

Given the uncertain economic environment and huge capital requirement to build the low-carbon hydrogen value chain, partnerships could enable E&U organizations to share risks and costs, as well as the capabilities that are critical to scaling. Partnerships will also allow companies to set up exploratory projects across different geographies, technologies, and use cases, raising the probability of finding a market-winning solution.

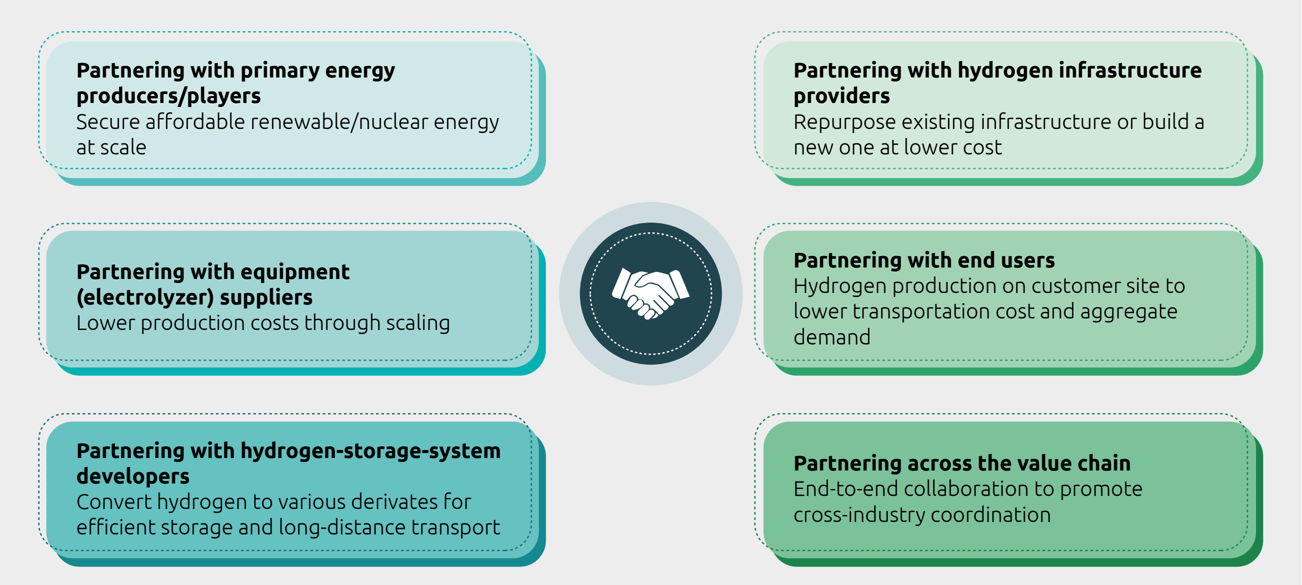
Partnerships can also encourage co-ordination between investors, policymakers, and other stakeholders to shape the market and its regulatory framework. The organizations that can identify, negotiate, and structure partnerships most effectively will have a competitive advantage in the low-carbon-hydrogen economy.

Clearly articulate partnership strategy and make thoughtful trade-offs:

Firstly, organizations must find answers to key questions, such as with whom to partner in the value chain, and why and how to collaborate with clients, peers, and other players to generate scale benefits, manage conversion, enhance the storage and distribution of hydrogen, build/repurpose existing infrastructure, and aggregate demand. These could be joined by technology providers, offering the required niche engineering, technical, and digital expertise. We found that 44 percent of the E&U organizations we surveyed highlighted integrated supply structure and 45 percent highlighted establishing collaboration across the value chain as key success factors for large-scale hydrogen projects. Organizations must clearly identify the "white spaces" in their low-carbon-hydrogen strategies (see Figure 20).

Fig.20

The right partner ecosystem could help E&U organizations scale low-carbon hydrogen technology



Source: Capgemini Research Institute analysis

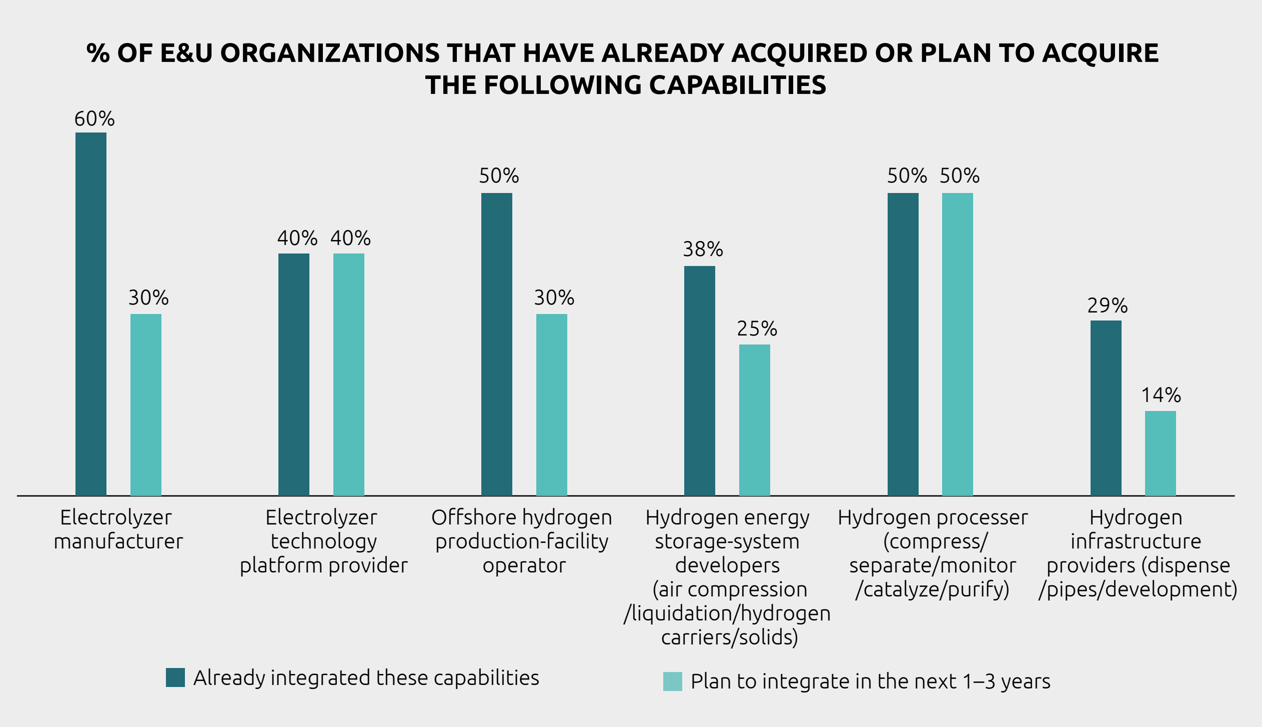
According to our survey, a majority of E&U organizations are partnering to share various capabilities across the value chain (see Figure 21).

61%

organizations believe new alliances will form to develop hydrogen projects through cross-sector collaborations

Fig.21

E&U organizations are combining their capabilities



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=33 respondents from unique E&U organizations investing across all areas of the value chain.

Partnering with primary energy producers/players:

We found that 63 percent of E&U organizations we surveyed have energy partnerships with solar-/wind-energy producers to secure electric supply to produce low-carbon hydrogen. For example, BP and Spanish clean-energy company Iberdrola formed a joint venture (JV) for large-scale green-hydrogen production in Spain, Portugal, and the UK.[82]

As an intermediate step before committing to a specific project, E&U organizations could also explore:

- commercial arrangements with renewable/nuclear-energy providers for locking in volumes and pricing under a preferred partnership agreement (PPA) or purchase agreement with a third-party offtaker;
- forming JVs to develop, operate, and maintain integrated primary energy and production facilities;
- joint-development agreements with green-energy companies to co-develop production facilities and provide green energy at advantageous prices.

Partnering with equipment (electrolyzer) suppliers and process developers:

Electrolyzer costs are the greatest contributor to the overall TCO of low-carbon hydrogen. E&U organizations could secure access to the equipment through one of the following approaches:

- form preferred-supplier alliances with electrolyzer providers and influence technical-design specifications
- partner with engineering, procurement, and construction (EPC) partners to standardize a scalable approach to plant design
- take equity stakes in the equipment supply chain or offer a stake to an electrolyzer manufacturer in production volumes to share capital risk

Several organizations are exploring this route to reducing the overall production cost:

- Shell India and Ohmium International, a green-hydrogen company that designs, manufactures, and deploys PEM electrolyzers, are collaborating to assess opportunities from technical, commercial, and safety perspectives[83]
- China Petrochemical Corporation (Sinopec Group) and Cummins Inc. have formed a 50:50 joint venture to produce green-hydrogen technologies; Cummins will initially invest RMB 300 million ($47 million) in PEM electrolyzers[84]

Partnering with hydrogen storage system developers:

Unused low-carbon hydrogen must be stored, at additional cost. E&U organizations have established/are planning to establish partnerships with hydrogen storage-system developers for their specific technical expertise. Alternatively, low-carbon hydrogen producers can explore pathways such as:

- securing a partnership to convert hydrogen to other forms, such as methylcyclohexane (MCH), making it easier to store and transport over long distances;
- expansion of operations to become a green-ammonia producer, tapping into the existing

ammonia supply chain; an example is Air Products, ACWA Power, and NEOM, who are partnering on a $5 billion green-hydrogen-based ammonia-production facility powered by renewable energy to supply 650 tons of green hydrogen per day for global transportation.[85]

Belgium-based natural-gas transmission system operator Fluxys is developing renewable hydrogen import facilities and has partnered with Advario, a liquid storage logistics player, to invest, build, and operate these facilities. Cédric Van Hoonacker from Fluxys comments, *"There is a necessity of the import facilities, with the role to import renewable hydrogen from continents with more sun and wind. We need the import facilities within Belgium as well. There, we partnered up with Advario in the harbor of Antwerp to build and operate, and to invest in import facilities together. So, we have partnerships for some projects, for instance, an ammonia import facility, ammonia storage, ammonia handling, and ammonia cracking towards hydrogen, with connection to our grid."*

Partnering with hydrogen infrastructure providers:

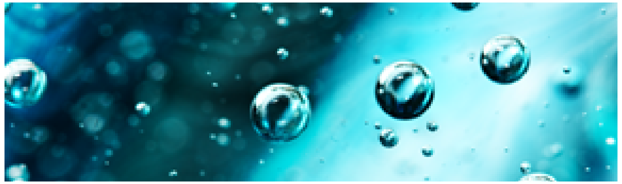
E&U organizations are partnering to stimulate development of transportation infrastructure for low-carbon hydrogen. E&U organizations are also sharing the risk and cost associated with developing new pipelines/infrastructure by making them partners in their production plants.

Partnering with end users:

Low-carbon hydrogen producers are also partnering broadly with potential end users to stimulate market demand and de-risk projects. This ranges from joint research and development to broader sector collaborations.

End-user industries such as steel, cement, mining, and fertilizers are looking for guaranteed access to low-carbon hydrogen and are willing to take equity stakes in co-located projects that exclusively benefit their businesses. A Swedish steelmaker, SSAB, has entered a JV with power utility Vattenfall and mining group LKAB to develop green hydrogen to power the Hybrit steel plant in Lulea, Sweden.[86] And Volvo Cars will be the first carmaker to secure SSAB steel made from hydrogen-reduced iron from the HYBRIT pilot plant in Luleå, Sweden. [87]

In our research, 69 percent of end-user organizations list hydrogen-supply security (broad availability of green hydrogen on an industrial scale) as a key success factor in large-scale hydrogen projects. Half of the end-user organizations we surveyed expect to sign long-term low-carbon hydrogen supply contracts with E&U organizations prior to commercial deployment.



"…. We partnered up with Advario in the harbor of Antwerp to build and operate, and to invest in import facilities together. So, we have partnerships for some projects, for instance, an ammonia import facility, ammonia storage, ammonia handling, and ammonia cracking towards hydrogen, with connection to our grid."

Cédric Van Hoonacker

Key Account Manager for Nextgrid H_2 & CO_2 at Fluxys

Partnering across the value chain:

E&U organizations are also forming end-to-end collaborations. Multiple regional green-hydrogen hubs are emerging to minimize infrastructure costs by consolidating renewable-energy generation, green-hydrogen production, and offtake at commercial scale. Many of these hubs also collaborate with local, regional, and national governments to promote cross-industry coordination, cutting through red tape and tapping into government subsidies. Companies like Plug Power and Cummins are building a global ecosystem of partnerships with peers to improve R&D, create scalable solutions, and consolidate activities, and with their customers to lock in demand, including through selective equity stakes in hydrogen production projects.

Cross-industry partnerships would also enable E&U organizations to lock in guaranteed offtake for green-hydrogen production, reducing the risk involved in capital investment. We also found that 61 percent of E&U organizations we surveyed believe hydrogen projects will arise through new cross-sector collaborations; 55 percent of end-user organizations believe the same.

Developing your own ecosystem

Large industrial players and governments could also explore other pathways such as developing their own ecosystem spanning across the value chain to include own funding, building and managing plant operations, storage, marketing and distribution of molecules as well as developing infrastructure that serves owners directly plus third parties on a tolling basis. This would enable large players to achieve scale benefits with competitive advantage.

With growing demand for cleaner energy sources, E&U organizations must scale their low-carbon hydrogen initiatives with some urgency to make a meaningful impact on the total energy mix. This can also lead to further production-cost reduction, a cleaner overall energy profile, and preferred-partner status with large end-user organizations looking to reduce their carbon profiles – specifically scope-1 emissions.

On scaling, Pierre-Etienne Franc, CEO of Hy24, a joint venture between asset managers Ardian SAS and FiveT Hydrogen, says: *"You can't move from 10-MW size to gigawatt size just like that. First, it is necessary to build facilities 10 times the size of pilot projects currently operating in Europe. Those will provide the operational knowledge and the electrolyzer-manufacturing capacity necessary to scale up to the next level."*[88] E&U organizations look at scaling as a critical lever for low-carbon hydrogen cost reduction. Our survey found that almost two-thirds (60 percent) of organizations surveyed believe that large-scale production is vital to cost reduction.

Conclusion

Low-carbon hydrogen is emerging as one of the promising tools for emissions reduction and is recognized globally by governments and business organizations as a crucial facilitator in achieving a greener future. Although the potential varies across sectors and regions, the share of renewable and nuclear-produced hydrogen in total hydrogen produced is expected to grow exponentially.

Organizations are working towards strengthening the low-carbon hydrogen supply chain by investing across the value chain. Countries globally are promoting low-carbon hydrogen adoption and are setting up ambitious targets. End-users in hard-to-abate sectors are also keen to explore the decarbonization potential of low-carbon hydrogen.

Despite the broad support and strong project pipeline, sizeable barriers exist in turning ambitious visions into reality. Regulatory requirements, commercial challenges, engineering barriers, as well as safety and skill hurdles are yet to be tackled.

Governments have been working to fill policy gaps and provide confidence to investors and stakeholders. Organizations need to identify the synergies across the value chain to overcome the barriers. The complexity associated with developing industrial-scale low-carbon hydrogen projects can be managed by:

- evaluating new business models from sustainability and total cost of ownership standpoints and securing demand
- leveraging technologies such as digital twins, AI, and analytics to solve engineering and cost challenges
- identifying synergies and collaboration opportunities across the value chain.

Appendix

Hydrogen-production technologies currently available	Description	Type of hydrogen produced
Gasification	The process converts organic or fossil-based carbonaceous materials into CO, H_2, and CO_2.	Black/brown hydrogen
Steam methane reforming (SMR)	In this process, methane reacts with steam under 3–25 bar pressure in the presence of a catalyst to produce hydrogen, CO, and a relatively small amount of CO_2.	Gray hydrogen
SMR with carbon capture, utilization, and storage (CCUS)	In this process, CO_2 is captured (85–90 percent) at the production facility and stored separately (i.e., not released into the environment).	Blue hydrogen
Pyrolysis	The thermal decomposition of methane is known as methane pyrolysis and produces solid carbon as a by-product.	Turquoise hydrogen
Renewable-energy electrolysis	Hydrogen generated through electrolysis of water powered by renewable energy such as solar/wind power.	Green hydrogen
Nuclear-energy electrolysis	Hydrogen produced from electrolysis of water, using nuclear energy.	Pink hydrogen

Type of electrolyzers	Description
Alkaline electrolyzers	Alkaline electrolysis makes use of two electrodes submerged in an alkaline electrolyte solution (such as potassium or sodium hydroxide); a non-conductive porous membrane called a diaphragm is used to separate the O_2 and H_2 from water.
PEM (proton-exchange membrane) electrolyzers	PEM electrolyzers use a solid polymer membrane that absorbs positively charged hydrogen atoms (separated from oxygen using electricity) and allows them to flow into a separate tank, where they re-bond into H_2 molecules.
AEM (anion-exchange membrane) electrolyzers	Hydrogen production using water electrolyzers equipped with an AEM.
SOEC (solid-oxide electrolyzer cell) electrolyzers	An SOEC is a solid-oxide fuel cell that runs in regenerative mode to achieve the electrolysis of water by using a solid-oxide, or ceramic, electrolyte to produce H_2 and O_2.

Terms used in the report:

- Power to gas to power technology: Process of producing hydrogen (through electrolysis using electricity) and then storing it to be used to generate electricity.
- DRI: Direct reduced iron is the product of the direct reduction of iron ore in the solid state by carbon monoxide and hydrogen.
- Hydrogen plasma smelting reduction: The process of using hydrogen thermal plasma to reduce iron oxides.
- Hydrocracking: Process by which the hydrocarbon molecules of petroleum are broken into simpler molecules (gasoline or kerosene) by the addition of hydrogen under high pressure and in the presence of a catalyst.
- Hydrotreating: Process of removing contaminants such as sulfur, nitrogen, and metals from crude-oil fractions.
- Levelized cost of electricity (LCOE): According to the US Energy Information Administration (EIA), LCOE *"represents the average revenue per unit of electricity generated that would be required to cover the costs of building and operating a generating plant during an assumed financial life and duty cycle."*

Research methodology

To understand the growing prominence of low-carbon hydrogen from both organizational and regulatory/policy perspectives, along with evolving business models and the current maturity of organizations, we carried out extensive qualitative and quantitative research.

In-depth interviews

We conducted 21 in-depth interviews with industry executives from various organizations, including senior executives from energy and utilities (E&U) firms and end-user organizations (petroleum, steel, chemicals, heavy-duty transportation, maritime, aviation, etc.), policymakers, tech startups, academics, economists, etc.

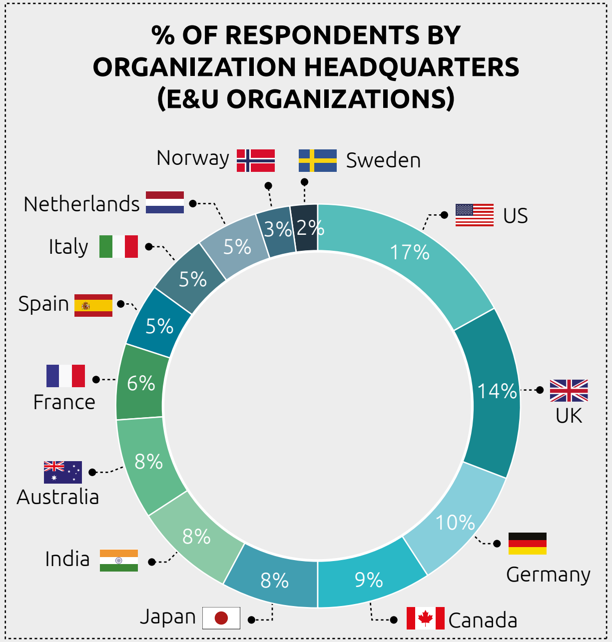
Interviewees are involved in the planning and development of low-carbon-hydrogen initiatives and work across functional areas such as strategy, product/service development, innovation and engineering, operations (supply chain – procurement, transportation, etc. / production), business units specifically dealing with hydrogen, renewables, new energies, decarbonization, the environment, sustainability, energy transition, end usage (hydrogen used for fuel cells / engines), etc.

Executive survey

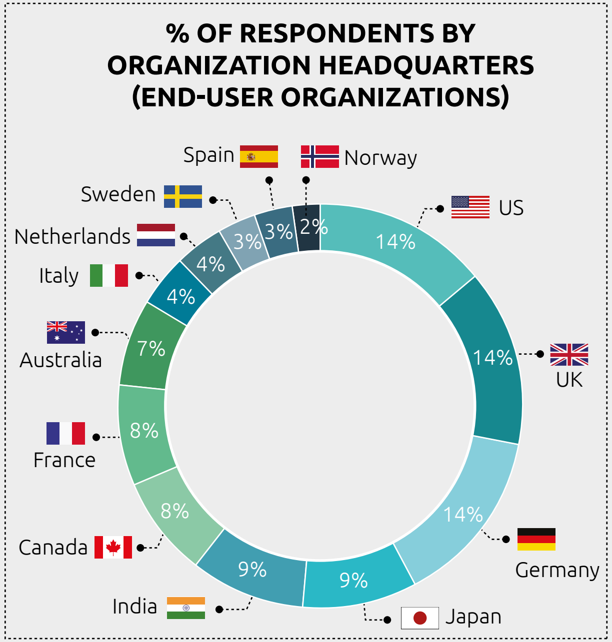
We surveyed a total of 860 respondents from unique organizations across 13 countries, of which:

- 500 were from unique E&U firms working on low-carbon-hydrogen initiatives with more than $500 million in annual revenue
- 360 were from end-user sectors, including petroleum, steel, chemicals and fertilizers, heavy-duty transportation (including coaches/heavy trucks), aviation, and maritime transportation, with more than $1 billion in annual revenue

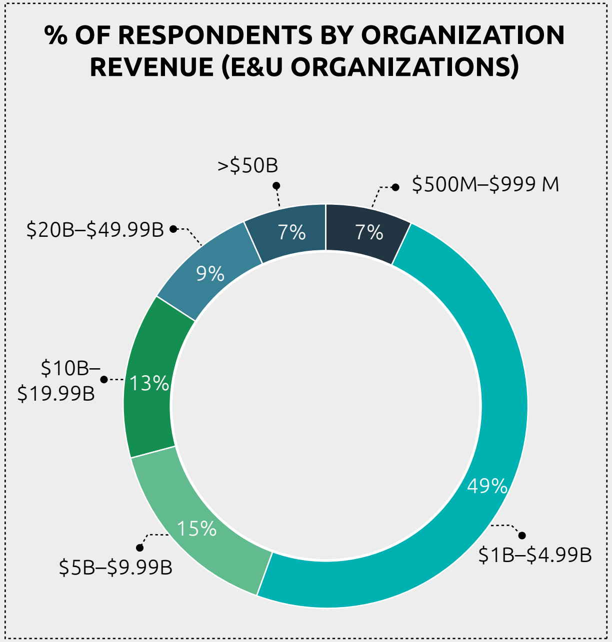
The respondents were at director level or above and were responsible for either planning or implementing low-carbon-hydrogen projects/initiatives in their organizations or being closely associated with them. The distribution of respondents and their organizations is provided in the following figures. The study findings reflect the views of respondents to our online questionnaire for this research and are aimed at providing directional guidance. Please contact one of the Capgemini experts listed at the end of the report to understand specific implications.

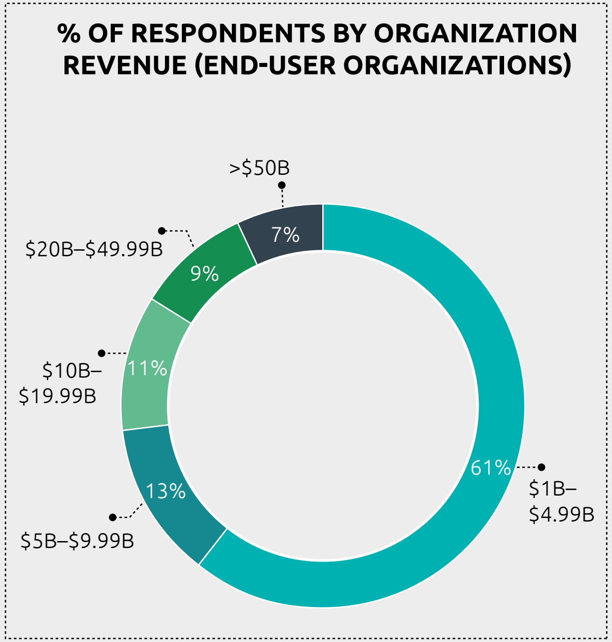


Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022; N=500 respondents from unique energy and utilities organizations.



Source: Capgemini Research Institute, low-carbon hydrogen survey, November–December 2022, N=360 respondents from unique end-user organizations.





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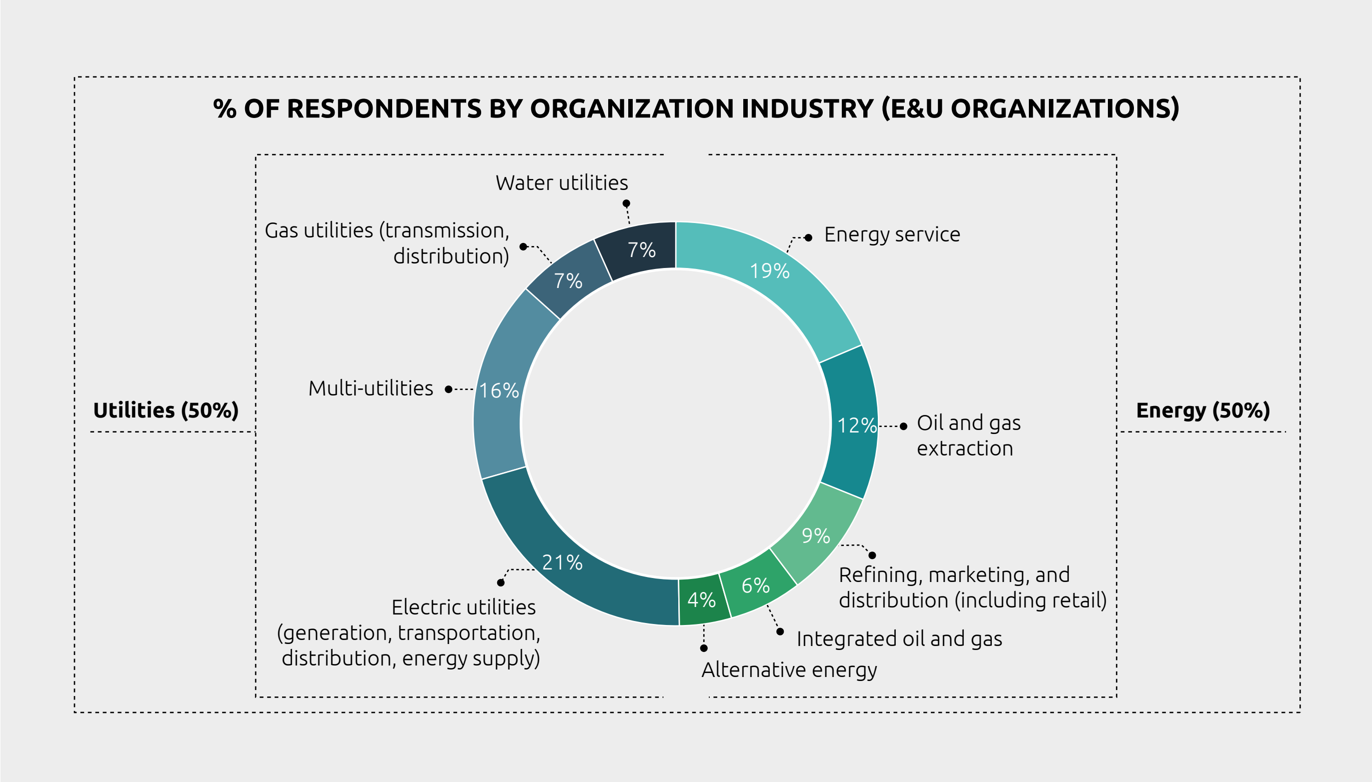

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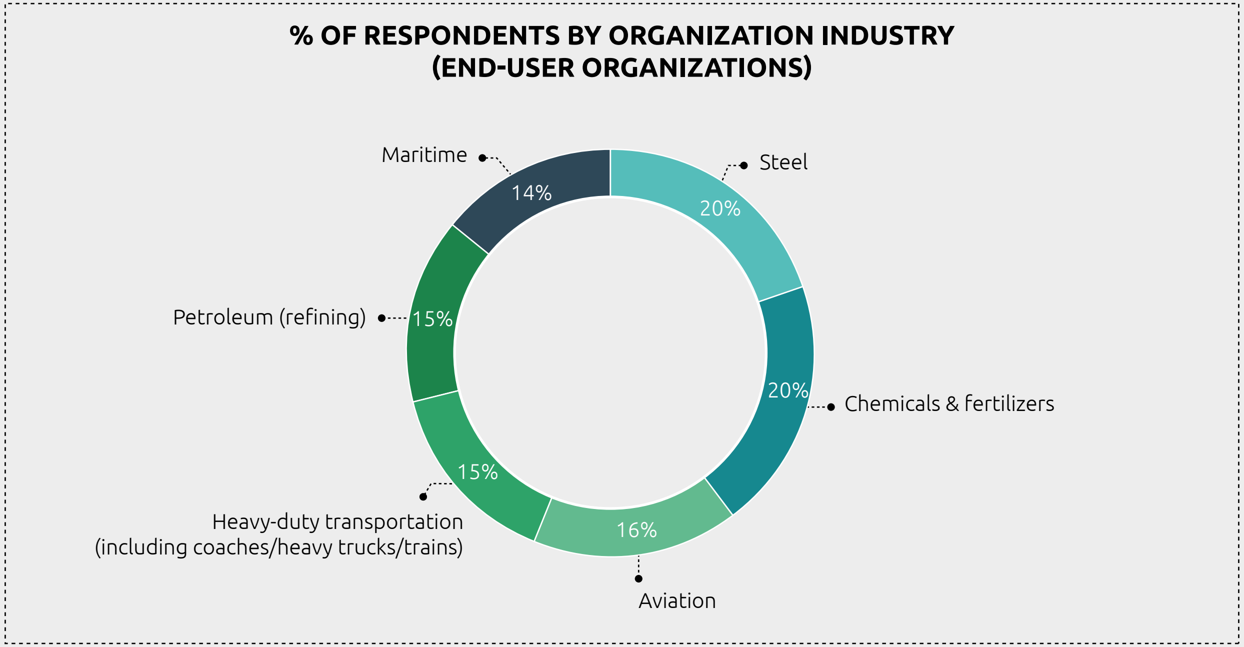

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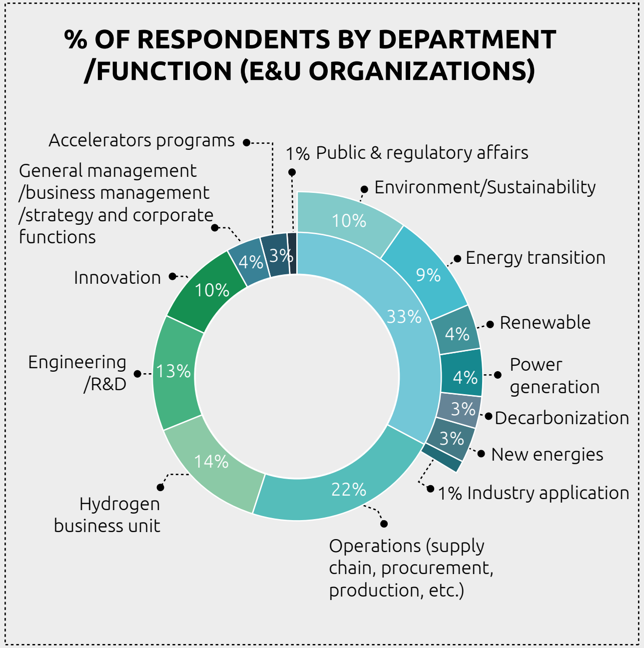

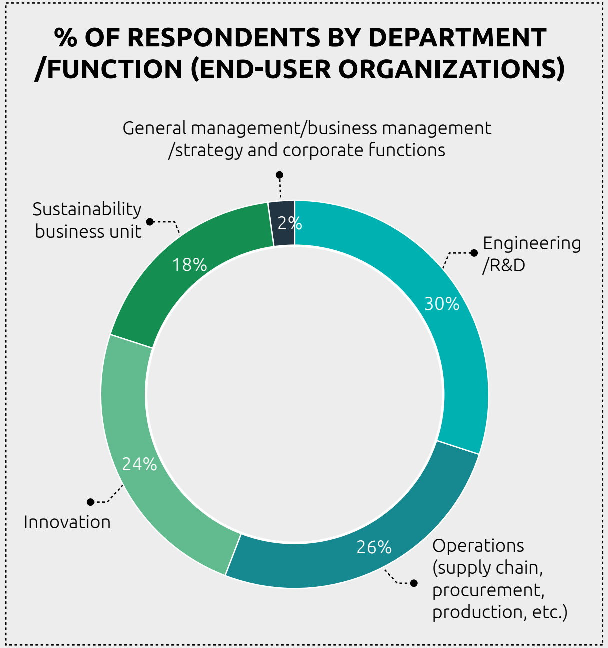

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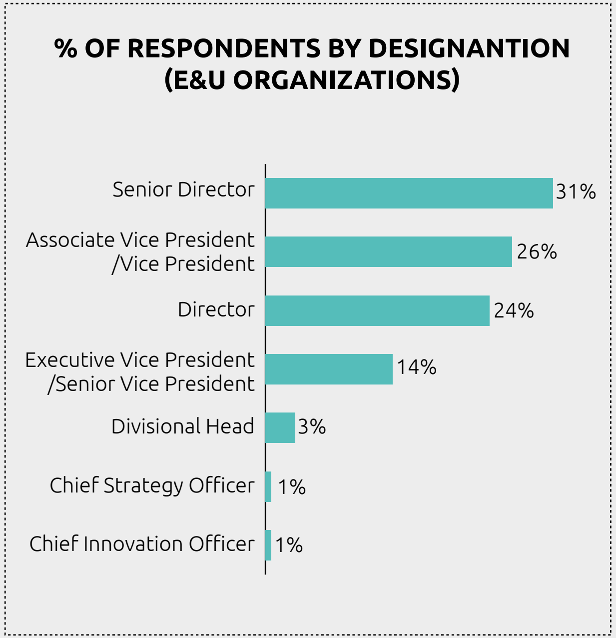

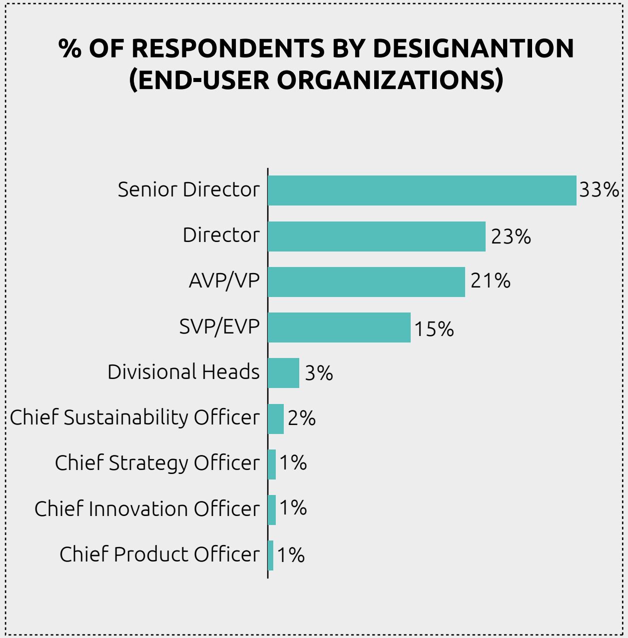

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SELECTION OF CREDENTIALS

- Hydrogen management system digital twin to produce decarbonated carbon
- THySO (Tool for Hydrogen System Optimization)— digital tool to optimize H_2 systems
- Implementation of AI for optimizing supply, quality, and manufacturing
- SISTER project — design of hydrogen storage equipment based on a multi-criteria approach (performance, cost and security)
- Hyprope project— design of a flex gas turbine (heavy mobility)
- CALLISTO project— H_2 specifications for the supply, storage and distribution
- EPC and pre-PM fora liquid hydrogen production plant
- Fuel Cell OEM: Predictive maintenance on hydrogen bus fleet
- Leading electrolyzer manufacturer: design & production process optimization
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Key contributors

James Forrest
EVP, Global and UK Lead Energy, Utilities and Chemicals, Capgemini
james.forrest@capgemini.com

Florent Andrillon
VP, EUC Country Lead, Head of Climate, Energy & Utilities Market Unit, Capgemini Invent
florent.andrillon@capgemini.com

Peter King
VP Global Energy and Utilities Lead, Capgemini Invent
peter.king@capgemini.com

Philippe Vie
VP, Group Global Lead Energy, Utilities and Chemicals, Capgemini
philippe.vie@capgemini.com

Corinne Tresy Jouanny
EVP, Head of Portfolio and Industry Centers of Excellence, Capgemini Engineering
corinne.jouanny@capgemini.com

Richard Biagioni
VP Climate, Sustainability & Ecosystems, Capgemini Invent
richard.biagioni@capgemini.com

Benoit Catalyud
Director Energy Transition, Capgemini Invent
benoit.calatayud@capgemini.com

Alain Chardon
Director Energy Transition, Capgemini Invent
alain.chardon@capgemini.com

Mark Viehman
Principal, Hydrogen and Clean Fuels, Capgemini
mark.viehman@capgemini.com

Jerome Buvat
Head of Capgemini Research Institute
jerome.buvat@capgemini.com

Subrahmanyam KVJ
Senior Director, Capgemini Research Institute
subrahmanyam.kvj@capgemini.com

Nancy Manchanda
Program Manager, Capgemini Research Institute
nancy.manchanda@capgemini.com

Harshada Sambare
Senior Consultant, Capgemini Research Institute
harshada.suresh-sambare@capgemini.com

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For more information, please contact:

James Forrest
EVP, Global and UK Lead Energy, Utilities and Chemicals, Capgemini
james.forrest@capgemini.com

Mike Lewis
VP, Global Leader Energy Transition, Capgemini
mike.lewis@capgemini.com

Peter King
VP Global Energy and Utilities Lead, Capgemini Invent
peter.king@capgemini.com

Laurent Bromet
VP, Global Head of Energy & Utilities, Capgemini Engineering
laurent.bromet@capgemini.com

Richard Biagioni
VP Climate, Sustainability & Ecosystems, Capgemini Invent
richard.biagioni@capgemini.com

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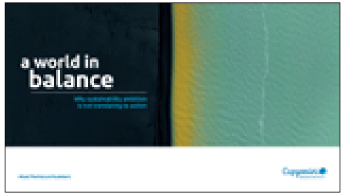

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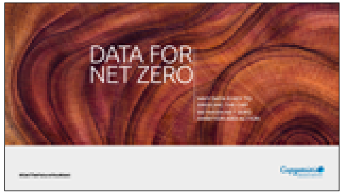

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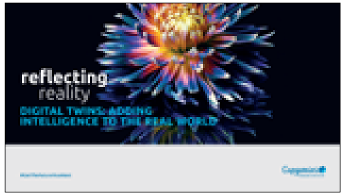

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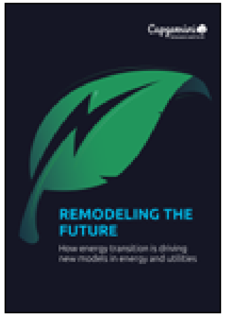

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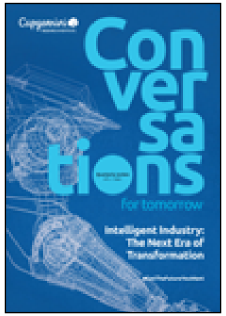

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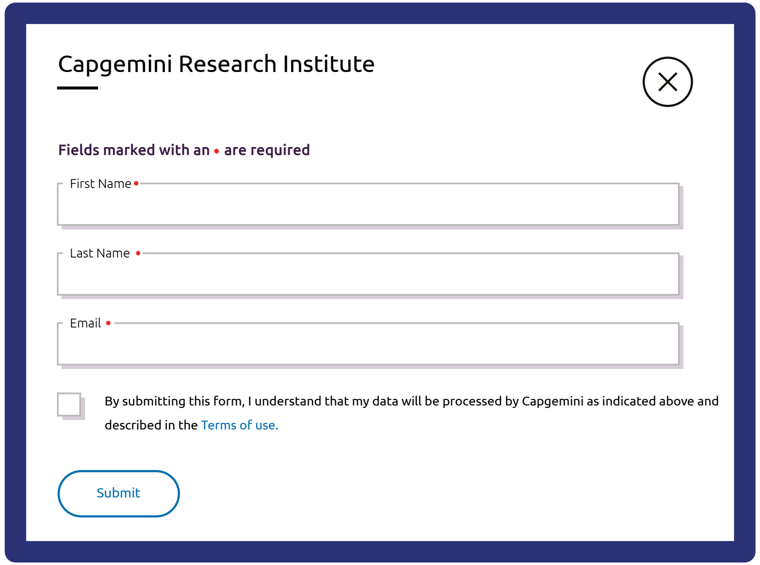
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