

The colours of hydrogen routes

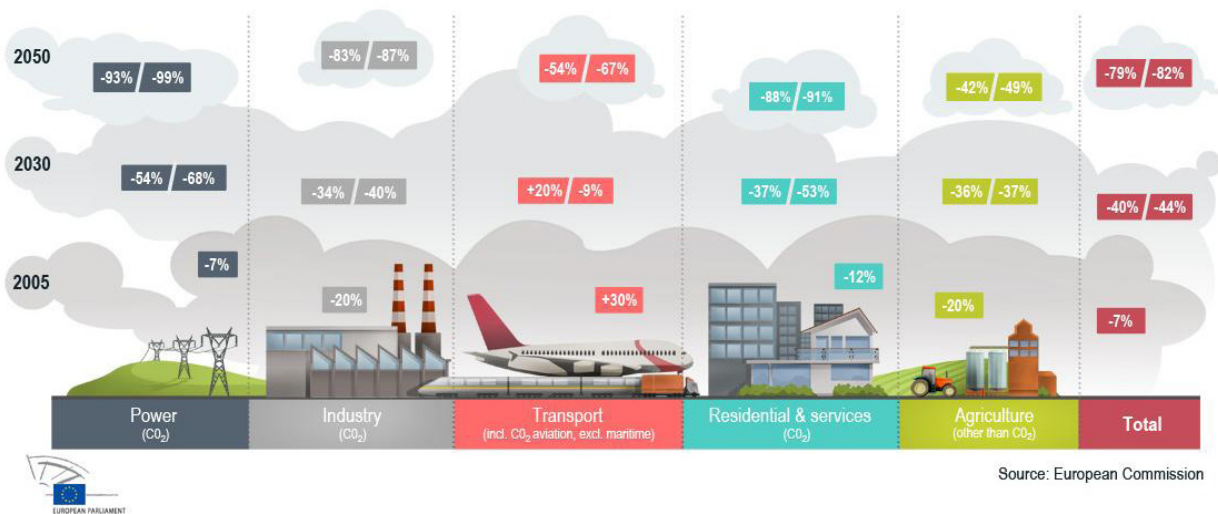
(The many shades of hydrogen)

1. HOW MANY COLOURS OF H₂?

1.1 Intro

The growing need to reduce carbon emissions in all industrial sectors is transforming the current landscape of energy markets and energy carriers. The European Community has set the objective of cutting greenhouse gas emissions by at least 55% by 2030 and sets Europe on a responsible path to becoming climate neutral by 2050. This policy has an important impact in all industrial sectors, and it is expected that the reduction in CO₂ emissions will progressively accelerate. To achieve the target, radical changes in industrial processes and the introduction of new technologies is needed in all sectors of the economy.

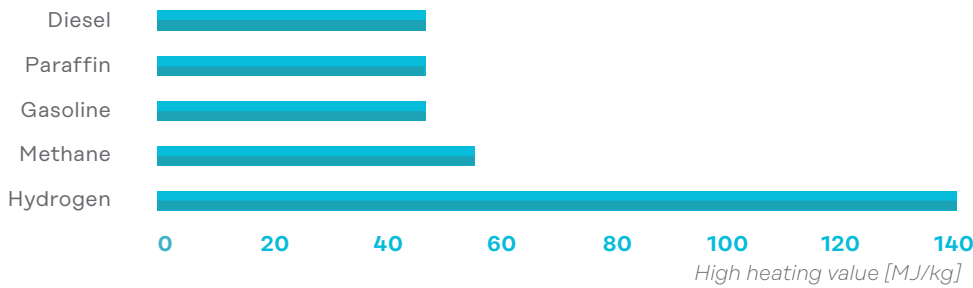
Low-carbon strategy for 2050 Targets compared to 1990 levels



HYDROGEN

Under normal conditions, hydrogen is a flammable, colourless and an odourless gas, and is the most abundant element in the universe, forming up to 75% of matter (based on mass) and able to store enormous amount of energy. It is present at ambient pressure in its gaseous form and can be liquefied at very low temperatures down to -253°C! It is stored either in cylinders at high pressure (normally 350 or 700 bar, but in some cases up to 1000 bar) or as a liquid, to reduce storage volume and be transported in large quantities over distance.

Fuel energy content (per unit mass)

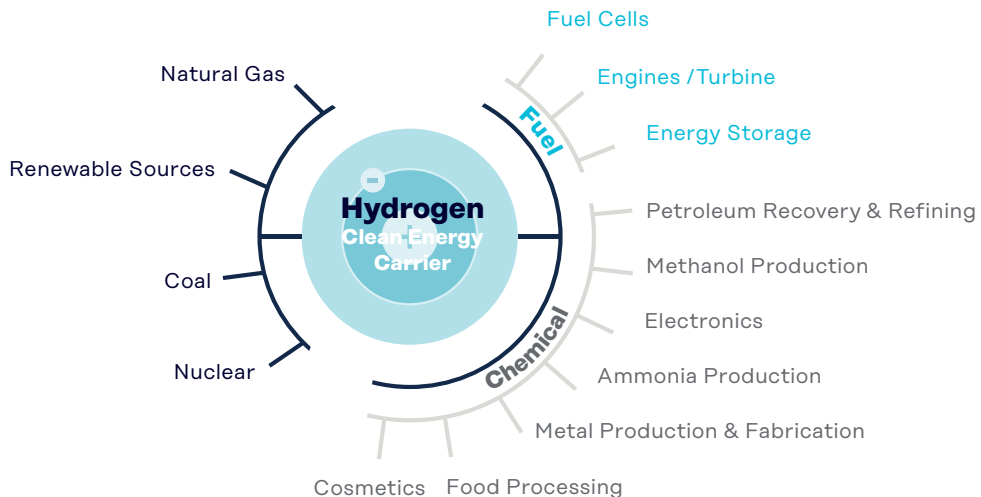


Source: JRC EU Commission

Hydrogen can be produced from almost all energy sources. It is not itself an energy source like natural gas, coal or crude oil, but rather is a flexible energy carrier able to deliver and store huge amount of energy.

One of the most efficient ways to produce hydrogen without CO₂ emissions is through electrolysis. Electrolysis of water takes place by supplying electrical energy to a cathode and an anode from which hydrogen and oxygen will be produced respectively. In the case of renewable energy sources, the process is CO₂-free.

The most important advantage in using hydrogen for the decarbonisation of our society, is that when hydrogen releases energy either through combustion (burning) or as electricity (fuel cells) only water is produced, with no CO₂ emissions. Therefore, replacing traditional carriers with hydrogen in various sectors of the economy such as mobility (using fuel cells), domestic or industrial heating, industrial processes and feedstock can potentially make a major contribution to reducing greenhouse gases.



Source: U.S. Department of Energy Fuel Cell Technologies Office

1.2 Colours of hydrogen

Hydrogen is an energy vector (not a source) that can be produced. Depending on the type of source or process used to produce hydrogen, we can identify it by 'colour'. For each type of hydrogen, a price can be defined according to the source and the efficiency of the technology used. In many cases, the cost of producing hydrogen is linked to the cost of electricity.

Grey hydrogen is extracted from fossil sources such as methane or coal, resulting in the massive production of CO₂ which is then released into the environment without any other use. This is the most widely used method.

Blue hydrogen is produced from sources and processes that release CO₂ into the environment, but which is then captured and stored (and in some cases reused in other processes). In this case we speak of Carbon Capture and Storage (CCS).

Green hydrogen is produced by electrolysis of water, using only electricity from renewable energies. The electrolysis process can split water into hydrogen and oxygen molecules using electric energy. Since production is based on renewable energy, hydrogen is produced without any CO₂ emissions. Today, these three main 'colours' of hydrogen are well known, but pink and turquoise hydrogen are also now appearing.

Pink hydrogen is extracted by electrolysis through electric current produced by nuclear power plants. Nuclear energy is only available in certain countries such as France. Italy has been without proprietary nuclear power for many years and even Germany, which has its own nuclear power plants, is in the process of decommissioning them. It is therefore a type of hydrogen that has a well-defined geographical location. On the other hand, the price of nuclear energy is low (about €50 per MWh, remunerating the investment of the plant which could otherwise drop to €33 per MWh).

Turquoise hydrogen is achieved through pyrolysis, sometimes using catalysts or membranes, which in high temperature reactors (800-900°C) splits carbon and hydrogen from the natural gas molecule or from other sources. This process leads to hydrogen gas and carbon dust without emitting CO₂ into the atmosphere. It is also an energy-intensive process due to the high-temperature requirements and has yet to be efficiently industrialised. However, it has the potential to become a conversion system that can easily be adapted to all the processes that use natural gas today.

1.3 The H₂ value chain

Production

Hydrogen can be generated through different processes, of which the most relevant are Steam Methane Reforming (SMR), intensively used today, and electrolysis, which splits water molecules into hydrogen and oxygen with an efficiency of around 70%. Hydrogen can be used in combustion processes for heating, or in fuel cell to produce electric power. In both cases the only emission is of water (no CO₂ gas or pollutants are present).

Hydrogen produced from renewable sources (biomass, geothermal, solar, or wind) using electrolysis represents an effective way to reduce greenhouse emissions even if it currently comes at a high commercial price. This is the main barrier to the immediate widespread use of hydrogen, and certainly well-targeted investments can have an important effect in the medium and long term.

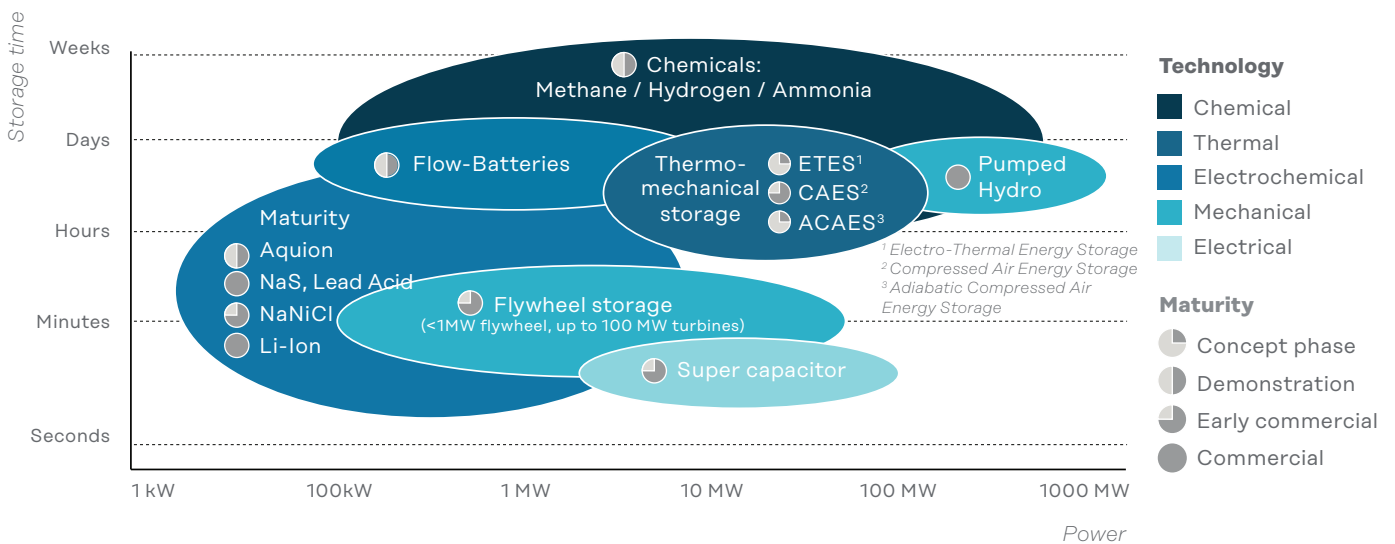
Despite hydrogen having an important role to play in the debate on climate change, today almost 94% is produced from fossil fuels, with significant CO₂ emissions (about 9kg of CO₂ is emitted per kg of hydrogen produced) into the environment. Natural gas is currently the primary source of hydrogen production, accounting for around three quarters of the annual global quota of approximately 75 million tons.

Today the potential of hydrogen remains unexpressed, as only a small amount is produced by electrolysis with renewable energy.

Energy storage and transportation

The first step toward decarbonisation is certainly large scale growth of all renewables energies (solar, wind, wave, geothermal, etc.) to improve the production of electric energy but, since renewable energy availability is not programmable and plants are not necessarily located where the energy is needed, storage and transport are relevant issues. Moreover, not all the processes can be electrified, and in many operative conditions, electrification is uneconomic, especially in thermal processes where temperatures above 1000°C are required. Regarding size and long-term storage, hydrogen represents a competitive solution with respect to the other available technologies, as shown in the picture below. In fact, the high energy density per unit mass and the capability of storing energy for long periods of time makes hydrogen the most useful vector for storing large amounts (MW or even GW) of energy. Batteries have a low energy density and short time range and in case of daily or weekly storage not seasonal as hydrogen.

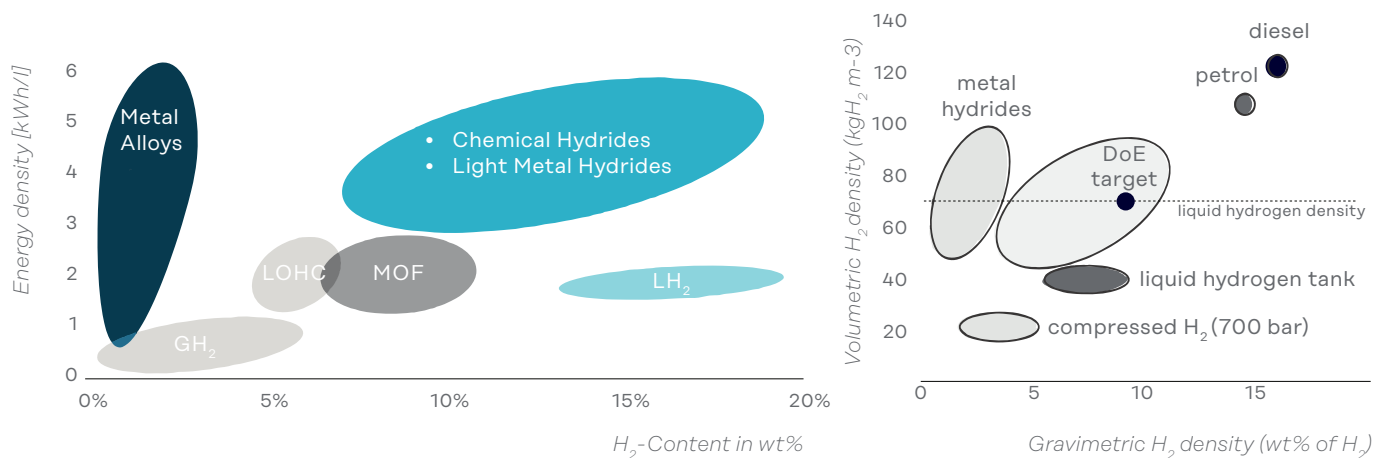
Comparison between different storage technologies



Hydrogen can be stored as a gas, liquid or mixed with other substances to form liquid organic hydrogen carriers (LOHC).

Since hydrogen has low energy density per unit volume, gaseous storage must be carried out at high pressure (300, 700, up to 1000 bar) to limit storage volumes. Many steps forward have been taken in this area, and new storage technologies with high-strength, ultra-lightweight thermoplastic V-type tanks are entering the market. Hydrogen gas can also be stored by means of absorption in foams or porous materials such as hydrates, which allow hydrogen to be absorbed at low pressure (50 bar) and high density, thanks to the properties of specific compounds which reduce molecular repulsion energy. Another storage method is liquefaction, which is characterized by a high energy density but takes place at very low temperatures (-253°C). This storage system is commonly used but is quite costly due to the very low temperatures. Hydrogen can be stored in LOHCs, which are liquid organic substances capable of storing hydrogen through a process of catalytic hydrogenation and dehydrogenation processes over multiple cycles. LOHCs volume energy density is similar to the liquid hydrogen but at room temperature and may contribute to a future hydrogen economy. Moreover, hydrogen can be mixed with natural gas and transported with the existing pipeline network. Both in Europe and in the rest of the world, pipeline grid is widespread, so this solution seems promising for hydrogen transportation. Moreover, the possibility to transport hydrogen via pipeline would allow an integration and interconnection that would go across Europe from North Africa to Belgium, and in this context, Italy would play a central role as an energy hub for Europe.

Nevertheless it must be verified that pipe integrity is not affected by the increasing percentage levels of hydrogen injected in methane. In this respect it is worth mentioning that the maximum percentage of hydrogen that can be transported today via pipeline is 2% when blended with natural gas, but experiments have been carried out up to 5% and 10% without highlighting any criticality. For higher hydrogen percentages, studies on the materials will certainly have to be carried out to verify that there no issue arise related to pipeline integrity or estimated residual life.



Source: Article in Applied Energy, Seasonal storage and alternative carriers: A flexible hydrogen supply chain model

Source: Hydrogen Energy, Article in Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences

In order to be able to transport hydrogen minimizing the storage volumes as required under certain operating conditions (e.g. for long-distance sea transport where weight is not an issue but space on board is at a premium), ammonia may be a solution. Ammonia is “hydrogen 2.0” since it is a molecule that contains hydrogen atoms and yet has about twice the energy density per volume unit, which allows important reductions for storage.

For long distance transportation, that is the common case for renewable energy production, the energy density by volume is a key factor to have economic sustainability and ammonia has nearly the double that of liquid hydrogen. Moreover, hydrogen liquefies at -253° C and ammonia at a significantly higher temperature (e.g. T= -10° C) with a small overpressure. So, when liquid hydrogen is used, very high investment costs are required with a long term payback while when adopting ammonia, the technology for storage and transportation is already in place. Ammonia can be easily stored, burned and new technologies are developing to convert it back into hydrogen for fuel cell applications. Anyway, this is not the end of the story! Because ammonia has a weak point related to its production technology. Nowadays ammonia industrial production is based on the Haber Bosch process that foresees high cost to achieve the plant set up with very long payback time and heavy CO₂ emission.

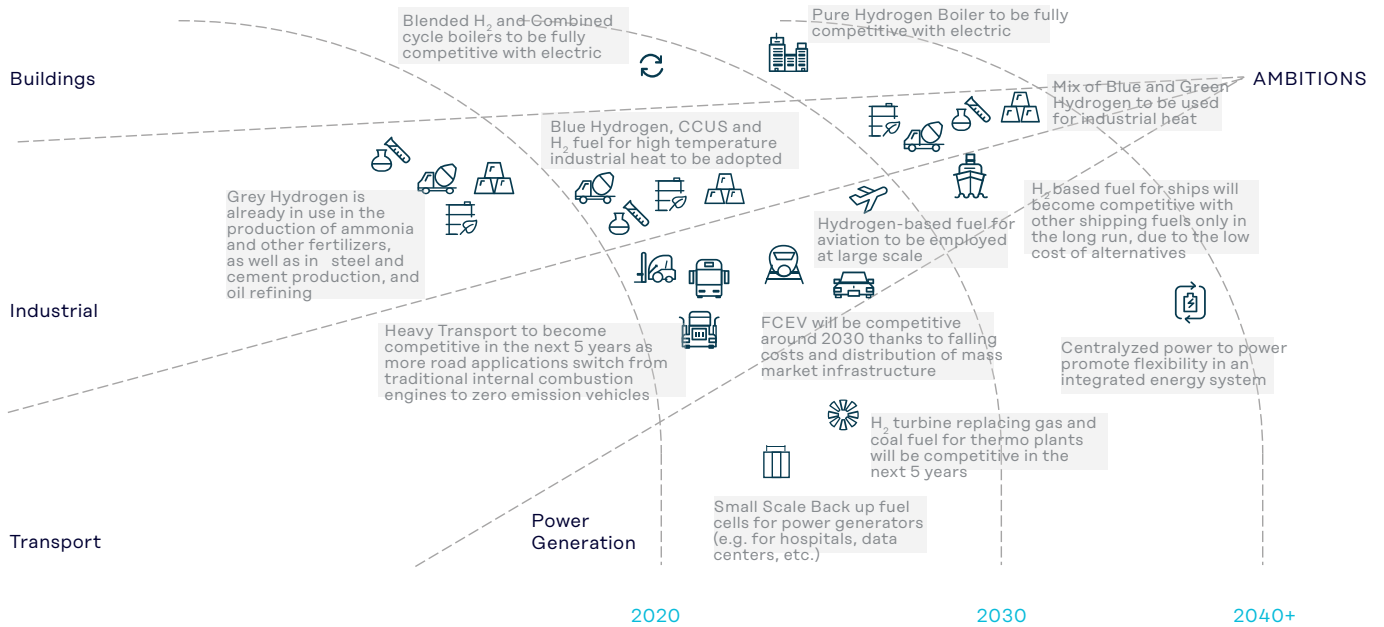
1.4 Current and future market applications

As reported, today hydrogen production is strongly anchored to fossil sources, but the scenario is changing thanks to the directives of the European community. There are two levers that can change the price and therefore the scenario of green hydrogen with a consequent impact on the economy, these are the enhancement in electrolyser technologies (mainly related to the size of the electrolysers) which can have an important effect on the scale of green hydrogen production, and the cost of renewable energy. The first technological theme is one of the objectives of the EU Recovery Plan, in which substantial funds have been allocated to reach targets for hydrogen production capacity through electrolysers. With regard to the second aspect, e.g. the production of renewable energy, all European countries have been active in granting concessions for the exploitation of offshore wind, solar and sea energy in order to make production abundant. Of course, the issue of renewables goes beyond the borders of each country and Europe in general. In fact some geographical areas in the world have abundant renewable energy sources that would make the exploitation economic up to think to transfer renewable energy in the form of hydrogen and ammonia between continents. This is not really absurd if we think of what is being done with LNG, produced in one continent, transported and distributed in another thousands of kilometers away.

As shown in the images below, hydrogen can immediately enter into the decarbonization of various sectors, firstly by decarbonizing existing production processes, such as refineries and ammonia production plant, by supplying green hydrogen reducing drastically the greenhouse gases, then by entering more strongly into all production sectors such as mobility (with hydrogen/ammonia buses, trucks, trains and ships), domestic heating (with blending in gas pipeline network) and finally into hard-to-abate production processes such as steel, glass and ceramics production.

When green hydrogen price will be competitive with fossil fuels many production processes could be decarbonized through hydrogen-based technologies.

In the coming decades hydrogen is expected to expand far beyond its existing industrial uses



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As an example, a ton of steel currently costs €400, €50 of which is for coal. Replacing coal with green hydrogen (at the best market price of €3.6/kg) it would cost €180 (compared to the €50 of coal). This would increase the price of steel by approximately one third. If hydrogen production begins to take place on a large scale, by 2030 the price of hydrogen could halve to €1.8/kg. At this point the difference between CO₂-emitting steel and green steel would be just 10%.

2. THE HYDROGEN MARKET ATLAS

2.1 Current market

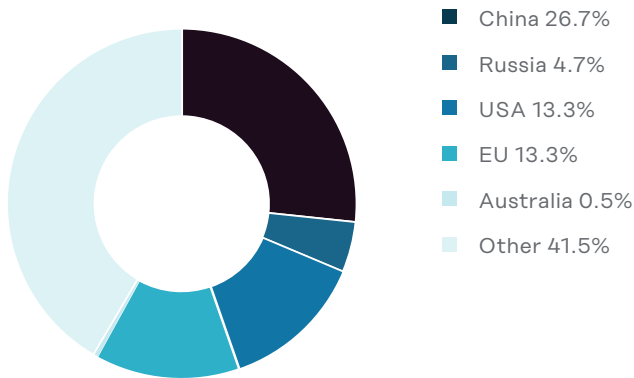
Today, global hydrogen demand has reached 75Mt¹, primarily required for use in the refining and chemical industries, with more than 94% supplied from grey hydrogen, produced from fossil fuel, and is expected to reach between **85 and 110Mt by 2030**.

Europe, through its strategic vision of harnessing the opportunities associated with hydrogen, has developed an ambitious plan of reaching 2 x 40 GW of electrolyzers by 2030². This requires the contribution of fossil fuels as the current dominant production source of hydrogen, but the addition of CCS technology could enable a transition from grey to blue hydrogen.

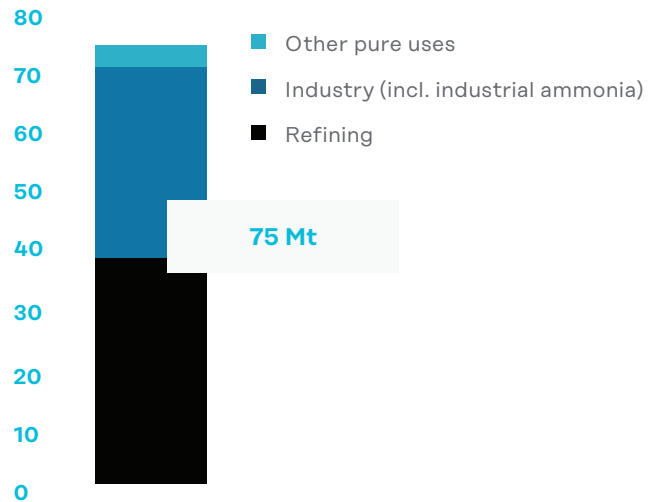
Due to its limited size and population density, **Europe** will likely be unable to meet the demand for hydrogen, and partnerships with renewable energy abundant regions could be required to achieve decarbonisation goals. Leveraging on good renewable sources and consequent lower electricity costs in Northern Africa and the Middle East to produce green hydrogen, and using strategically positioned Southern European countries such as Italy, hydrogen could be transported using existing gas pipelines (up to 10% in the mid-term) that connect Africa directly to Europe, or by ship in pure, compressed or liquefied forms.

These regions are potentially all integral on the European path to decarbonisation, and countries such as Saudi Arabia and the UAE could open up further potential export markets and extend their capabilities by leveraging one of the world's cheapest solar energy sources to produce green hydrogen.

Global H₂ production by country, 2019



Global H₂ demand by sector (MtH₂), 2019



Accenture Analysis

IEA, 2020, Global hydrogen demand by sector in the SDS 2019-2070

Shaping the H₂ Atlas, **American** hydrogen production is today 99% sourced from fossil fuels (95% from natural gas by SMR and 4% by partial oxidation of natural gas via coal gasification), with only 1% of US hydrogen produced by electrolysis. Annually, the US produces approximately 10 Mt of H₂ of which 60% percent is produced in dedicated facilities as their primary product³.

By 2030, the US D.O.E estimates that the local hydrogen economy could represent 17 Mt of fuel consumed every year, 1.2 million Fuel Cell Electric Vehicles (FCEV) sold, 300,000 material-handling FCEVs in the field, and 4,300 fuelling stations operating, attracting an investment of nearly \$8 billion USD per year⁴.

As a potential key player for hydrogen economy growth and the path to decarbonisation within the USA and indeed the entire H₂ Atlas, **Latin American** countries (Argentina and Chile especially) could provide clean energy by leveraging on an ultralow cost of renewable electricity, shipping it as pure hydrogen or converted to other carriers, even if the US would appear to be able to meet its future domestic demand.

On the Asian side of the Atlas, **China**, the largest manufacturer, generates over 20 Mt of H₂ for industrial and chemical processes - equivalent to approximately 1/3 of the world's total production - and is estimated to reach 35 Mt by 2030⁵. Most of China's hydrogen comes from coal, with electrolysis contributing just 3% of the total supply. Only a handful of renewable-to-hydrogen projects exist for research or demonstration purposes, and supply remains of grey hydrogen from coal gasification and as the by-products of the chemical process.

A key lever of China's hydrogen policy has been the promotion of fuel cells, which convert hydrogen back into electricity to power cars, buses and heating. In this area, China is considered a pioneer, and has dedicated targets of 1 million FCEVs and 1,000 Hydrogen Refuelling Stations (HRS) by 2030⁶.

¹IEA, 2020, Global hydrogen demand by sector in the SDS 2019-2070

²Hydrogen Europe, 2020 "Green Hydrogen for a European Green Deal a 2 x 40 GW Initiative"

³US D.O.E. – Hydrogen Strategy: Enabling a Low-Carbon Economy, 2020

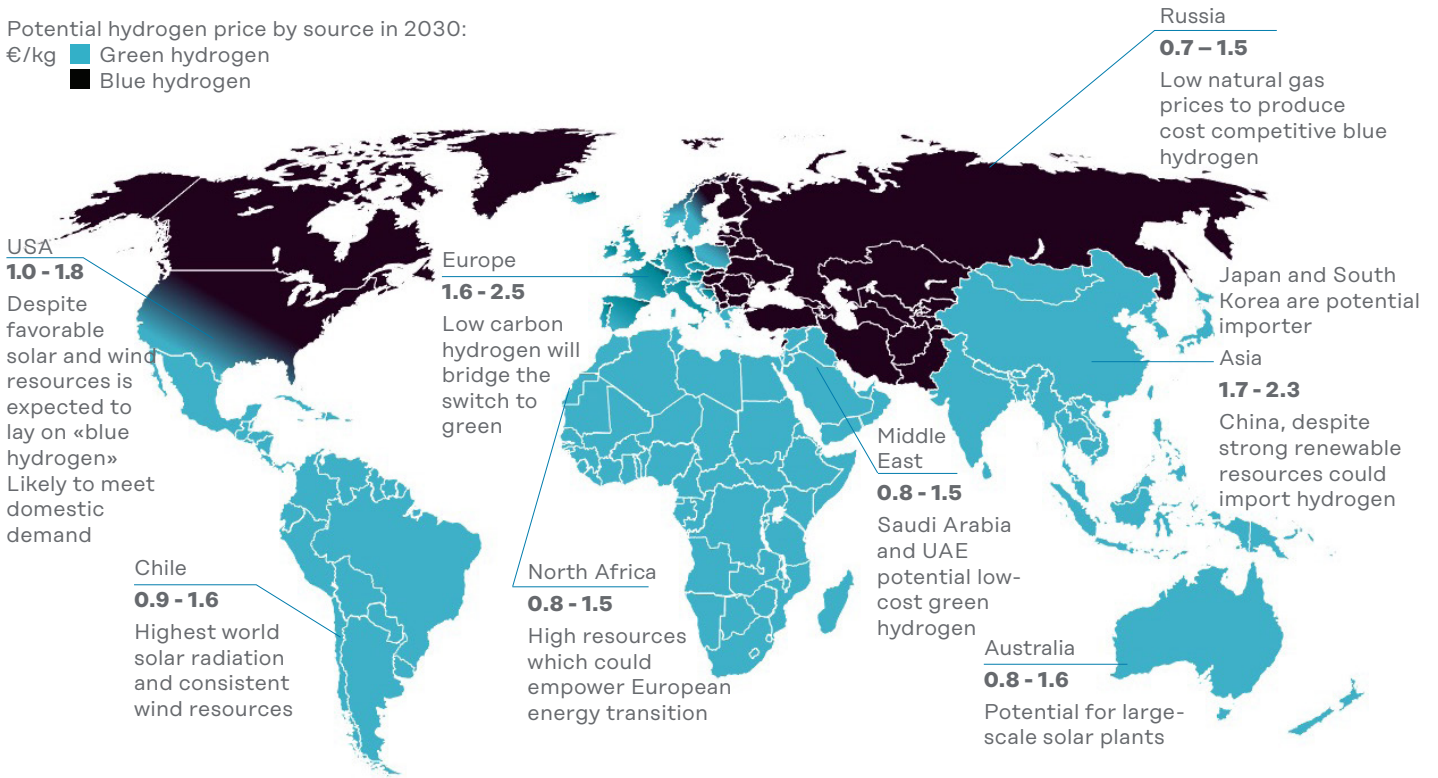
⁴FCHEA, "Roadmap to a US Hydrogen Economy"

⁵Energy Iceberg, Chinese Clean Power Policy Intelligence & Market Insights, 2020

⁶Ifri, 2020 "Prospects of a Hydrogen Economy with Chinese Characteristics"

Hydrogen Production Competitiveness, 2030

Potential hydrogen price by source in 2030:
 €/kg ■ Green hydrogen
 ■ Blue hydrogen



Accenture Analysis on H₂ production cost for selected countries based on analysis of public documents for each country.

With only trace amounts of fossil fuel deposits, **South Korea** is dependent on imports for 98% of its fossil fuel requirements and the government estimates that hydrogen could account for 5% of its expected energy consumption in 2040, if the objectives in its roadmap are achieved⁷.

Japan, whose government set out their “Basic Hydrogen Strategy” in 2017, has the vision to develop hydrogen and fuel cell applications in various sectors (mobility, power generation, industry and residential combined heat & power).

The strategy maps **Australia**’s path to becoming an industry leader by 2030 by developing a clean, innovative, competitive and safe hydrogen industry for both domestic and export use. Large-scale domestic clusters of hydrogen-powered suburbs known as ‘hydrogen hubs’ will help develop the skills and secure the investment required to create a globally competitive hydrogen export industry.

The **Russian Federation** is recently witnessing a growing interest at governmental and industry sector levels in the development of the hydrogen industry and submitted a draft of their roadmap to develop hydrogen energy to the Russian government for review. It provides a timeline for establishing incentive measures for pilot projects on hydrogen production and export, with the ambitious goal of making up 15%⁸ of the global hydrogen market by 2030.

⁷ South Korean efforts to transition to a hydrogen economy, 2020

⁸ CMS, 2020 “Hydrogen in Russia”

2.2 Export hub candidates for the hydrogen challenge

The hydrogen market is expected to change significantly over the coming decade, with increasing demand and the development of green hydrogen promoting the arrival of **new international players and the establishment of new trade routes**. In this way, hydrogen has the potential to become an economic 'bridge' between countries, and it is crucial for those countries interested in developing export hubs to evaluate the infrastructure that will be required to develop their hydrogen ecosystems.

At present, many countries are trying to understand the role hydrogen can play on the energy market and within the energy transition; in some cases, leveraging existing knowledge in similar sectors such as the oil & LNG markets. It is in this context, for example, that **Australia's** availability of land and high-quality renewable energy resources are the kick-start points to allow it to become a **key global hydrogen exporter**. Its well-established reputation for undertaking large-scale projects and being a reliable supplier of conventional energy resources also reduces risks and further reinforces Australia's position as a potential hydrogen trading partner. We estimate a potential of about **1.2 Mt/year of H₂** for export via shipping in 2030 thanks to about 21 GW of renewable energy capacity. The cost of delivery of hydrogen can be less than **€2.8/kg** due to the optimal conditions for renewable energy installations.

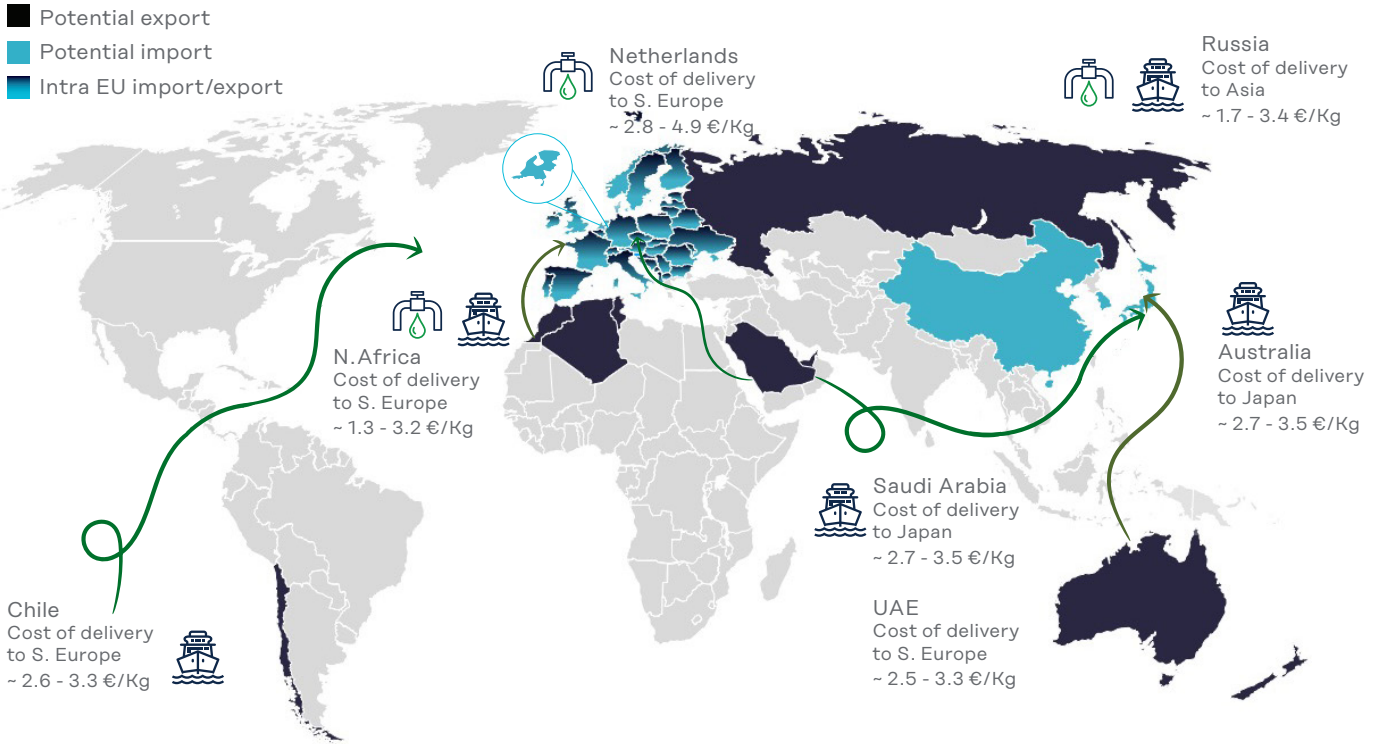
Moreover, three of Australia's top four trading partners, Japan, South Korea and China, have already made clear commitments to using clean hydrogen to decarbonise their energy systems. These nations are highly dependent on imported energy and are focused on clean hydrogen-based fuels as part of the transition from fossil fuels, while ensuring energy security and diversity.

Many actions have already been undertaken by the Australian government through the development of several projects for both blue and green hydrogen production, such as "HESC" (Hydrogen Energy Supply Chain) which aims to produce hydrogen from coal and CCS technologies and transport it after liquefaction, or the 'Intercontinental Energy's Asian Renewable Hydrogen Hub' project to produce hydrogen and ammonia for export.

Chile has the potential to race with Australia to supply hydrogen to Asian countries and to North Africa for Europe. Leaning on the area as the desert of the north, with one of the highest global solar irradiation potentials, and the consistent wind resources of Patagonia, Chile has the renewable energy potential to become one of the cheapest global producers of green hydrogen and has recently announced an ambitious national strategy to develop it, with 5 GW of electrolysis capacity to be under development by 2025 making it one of the top global exporters by 2030. In launching its strategy, Chile will leverage on new renewable energy projects and will exploit its surplus renewable energy capacity with a potential hydrogen production of about **2.5 Mt/year by 2030**. The delivery cost of hydrogen can be less than **€2.7/kg** thanks to the optimal conditions for renewable energy installations (high winds in the south and high solar irradiation in the north).

The competition for exporting hydrogen to Asian countries also takes in **Russia**, which has the internal resources and capacity to produce blue and pink hydrogen for the global market. Its close location to potential importers such as the EU, Japan and China could be also an important advantage. Despite the efforts currently being taken by the Russian government to secure export opportunities for hydrogen (e.g. discussions with Japan in 2019), it is still not fully clear how and where Russian hydrogen will be sold, and ideally such sales should be secured by long-term contracts. However, the prospects for Russia to increase its presence on export markets look more promising (potential of 1.1 Mt of H₂ by 2030) and the delivery cost could be less than **€1.8/kg** thanks to competitiveness of blue hydrogen production.

Mapping of identified future potential global routes and cost of delivery, 2030 Scenario



Accenture Analysis, Costs of delivery include H₂ production, handling, conversion, reconversion, export terminal based on 2030 data. For Shipping routes are considered LH₂, LOHC and Ammonia options.

In the Middle East and Africa, countries as **Saudi Arabia, the UAE, Morocco, Algeria and Tunisia** can leverage on good solar resources, low-cost and price-stable renewable electricity which can contribute to boosting their trading power and enhancing their potential as hydrogen exporters to specific markets, mainly based on current collaboration plans. However, over and beyond meeting domestic demand, these countries also have great potential for green hydrogen export and the European commitment to achieving deep decarbonisation with a constrain on renewable energies due to varying load curves and limited land availability, represents a key factor in promoting partnerships in this respect. **Saudi Arabia** recently unveiled one of the world's largest green hydrogen projects. The completed facility will be operational by 2025 and produce 650 t/day⁹ of green hydrogen (~0.2 Mt/year), which will be shipped as ammonia to Japan. In addition, 'Saudi Vision 2030' forecasts the installation of 55 GW of renewable energy capacity, of which 2/3 can be used to produce hydrogen. We estimate a potential of approximately **0.7 Mt/year of H₂** for export via shipping (ammonia, LH₂ or LOHC) by 2030. The delivery cost could be less than **€2.8/kg**.

The **UAE**, as part of the clean energy movement, is by no means lagging behind and is investing in green hydrogen projects. Recently the solar-driven hydrogen park was announced at the Mohammed bin Rashid Al Maktoum Solar Park, with the capacity to generate 5 GW by 2030, and EU and UAE policy makers and experts discussed hydrogen as the energy carrier of the future during the 'EU Hydrogen Forum in the UAE'. The UAE can play an important role in shaping the H₂ Atlas with a potential production of around **0.4 Mt/year** considering the potential of renewable energy capacity included in their 2017 'Energy Strategy 2050'. The delivery cost could be less than **€2.6/kg**.

Morocco is preparing to create green ammonia as step to building a Power-to-X industry. The country has recently signed a memorandum of understanding with Germany to build Africa's first green hydrogen plant, representing the strong commitment of both countries to move forward in the development of renewable energies and sustainable economic development. Together with Algeria and Tunisia, it creates a large potential H₂ export hub that could change the energy strategy of **Northern Africa** (more insights in the BOX below). We estimate a potential of **1.9 Mt/year of H₂** could be available for export from Northern Africa in 2030 thanks to **46 GW of renewable energy capacity**. The delivery cost in 2030 could be less than **€1.4/kg** thanks to the optimal conditions for solar installations.

⁹ Greentech Media, a Wood Mackenzie subsidiary article, 2020

The potential of Northern Africa in the H₂ Atlas

Europe is embracing hydrogen and it will lead down the path to decarbonisation. The region has committed to transitioning its energy system to an environmentally friendly network, and the success of the transformation will both reduce carbon emissions and boost industrial competitiveness, cutting energy costs and improving living standards.

Reaching these goals will require a profound change in how energy is produced, distributed, stored and consumed. MENA regions - especially Northern Africa due to its proximity to Europe, low cost renewables and existing gas connections - will provide a strong link between regions.

The current European electricity grid was not built with energy transition in mind and needs to be radically modernised. European development of new renewable energy capacity would mean overhead power lines requiring substantial effort and a long time for planning, permitting and construction, especially considering the ambitious plan of connecting several European countries.

Instead of transporting bulk electricity throughout Europe therefore, a more energy and cost-efficient plan would be to transport green hydrogen and rely on a twinned but intrinsically coupled energy system, characterised by the power of electricity and the agility of the hydrogen molecule. New hydrogen gas pipelines could be built by converting existing systems, connecting African renewable energy resources to Europe. Potential ways of exporting H₂ to Europe also include shipping liquid hydrogen or using carriers (ammonia, LOHCs), which would require primary specific import and export terminals and infrastructure conversions.

Building the hydrogen ecosystem requires port facilities to import and export huge quantities of hydrogen.

These include storage tanks to stock the hydrogen molecule in its different states, terminals, loading facilities and equipment, depending on the chosen transportation method. Building a broad port facility generally requires a terminal and storage tanks for liquid hydrogen, a terminal, storage and dehydrogenation plant for LOHCs, a terminal, storage and cracking installation for ammonia and port pipeline infrastructure and multi-modal logistic centres. In that context, areas in Europe with facilities able to receive large quantities of hydrogen need to be identified, with Spain and Italy (and in particular Sicily, thanks to its existing natural gas entry points from Libya and Algeria) potential candidates with strategic positions in Southern Europe. Sicily could also function as a potential export hub with the possibility to supply hydrogen to Malta, which needs to revise its energy strategy by finding an alternative fuel for its current power supply system (LNG via shipping for Delimara Power Station, 537.8 MW of CCGT plant).

The realisation of a hydrogen stream from Northern Africa to Europe, producing around 2.3 Mt of H₂ and potentially transporting **1.9 Mt of H₂ to Europe** via pipelines and shipping would require approximately €69.6 billion, and **46 GW of new renewable energy resources** (31 GW of solar and 15 GW of wind). We estimate that in 2030, **0.4 Mt of H₂ will be destined for internal use** (with green ammonia in particular replacing the current import capacity in Morocco, Algeria and Tunisia).

Estimated Capex (€Bn) to export H₂ from Northern Africa to Europe, 2030 scenario

Renewables (solar & wind)	H ₂ electrolyser	Facility plants	Total
49.4	18.0	2.2	69.6

With the prime hydrogen ecosystem currently in Europe, many European countries are moving forward with their own hydrogen-based economies and are setting out national strategies. One of the main players, the **Netherlands**, has set out ambitious goals for hydrogen including 'NorthH₂', one of the largest green hydrogen projects in the world with a target of 3-4 GW of electrolysis capacity by 2030 using renewable electricity from North Sea offshore wind and plans to further extend it to create a 'Hydrogen Valley'.

The Netherlands is planning to develop a further 1.2 GW of blue hydrogen¹⁰, making it a candidate for an important role in Europe even if its production of hydrogen will mainly be to cover domestic consumption, including the industrial and transport sectors (15,000 FCEVs and 3,000 heavy duty vehicles by 2025 and further 300,000 FCEVs by 2030)¹¹. We estimate potential production of about 0.9 Mt/year of H₂ in 2030 with **0.1 Mt/year** of export capacity.

The delivery costs will be less than **€2.9/kg** thanks to renewable energy capex reduction (offshore wind plants less than €1,900/kW), electrolyser pricing and technology improvements.

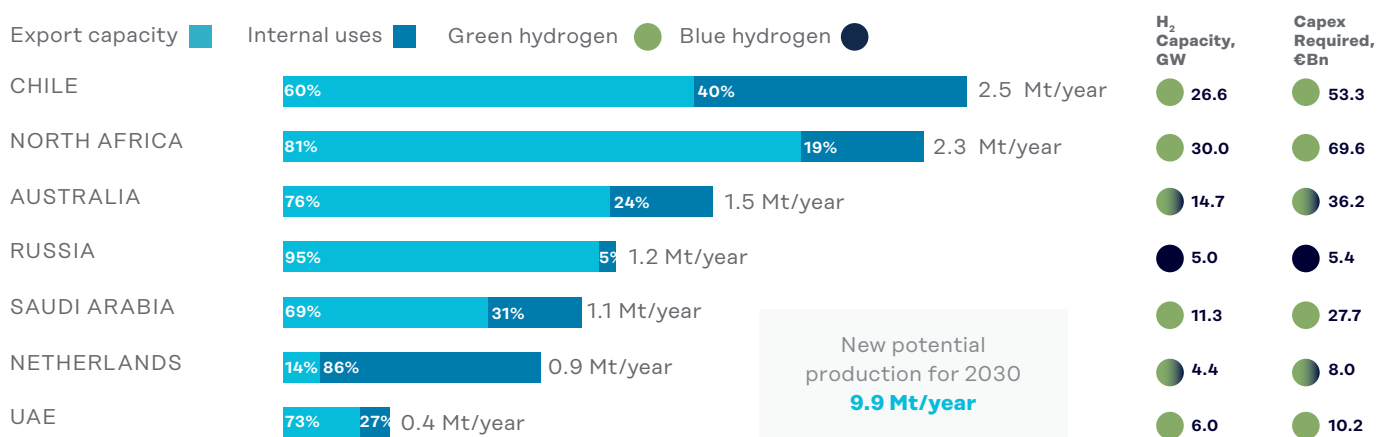
The shape of the hydrogen Atlas will be determined by market needs and countries' competitive edge in production. Supply chains and market models will be created with centralised and distributed production facilities which are expected to be developed in the medium and long term. Distributed production may be the most feasible approach for introducing hydrogen in the short term to supply initial demand, but large central hydrogen production facilities taking advantage of economies of scale are needed in the medium and long terms to meet the greater expected demand, requiring more capital investment in production and transport infrastructures, as well as profound cooperation and the birth of new global partnerships.

In this puzzle, only certain countries have the kind of gamesmanship to become market leaders, based on the specific requirements, with some countries standing out above others. Northern Africa and GCC (Gulf Cooperation Council) countries can export most of their green hydrogen production thanks to good renewable energy sources, lower electricity costs, minor expected domestic requirements and their proximity to Europe - especially if leveraging on the **Italian industry experience of electrolyser manufacturing, hydrogen-related infrastructure and construction services**, which included hydrogen as part of the €100 billion recovery plan funds allocated to the energy sector (about €70 billion for green revolution and ecologic transition, and €30 billion for sustainable mobility and infrastructure¹²) and, as announced by the Minister of Economic Development to be at least €3 billion¹³ for the IPCEI (Important Projects of Common European Interest) for hydrogen, contributing to enhancing hydrogen technology deployment across the world.

Russia, leveraging on its blue hydrogen potential because of large natural gas reserves and low costs, could supply Asian countries such as Japan, China and South Korea.

Apart from Russia, Chile and particularly Australia, because of its multiple existing projects, both characterised by abundant renewable energy sources, could compete to supply hydrogen to Asia. In conclusion, considering those countries analysed, we estimate a potential new **H₂ production of 9.9 Mt/year** to meet demands in 2030, of which **6.8 Mt/year of potential export capacity** from the selected hub.

H₂ Production of potential Export Hubs, 2030, Mt



Accenture Analysis on Value chain model, H₂ production, export and internal uses based on analysis of public documents for each country. Capex required include RES, H₂ plants and export facilities terminals (Ammonia, LOHC and Pipe Options)

¹⁰ Foresight, 2019 "Hydrogen: The Northern Netherlands is ready"
¹¹ CMS, 2020 "Hydrogen in the Netherlands"
¹² International Institute for Sustainable Development, 2020
¹³ Quotidiano Energia, 2020

3. CONCLUSIONS

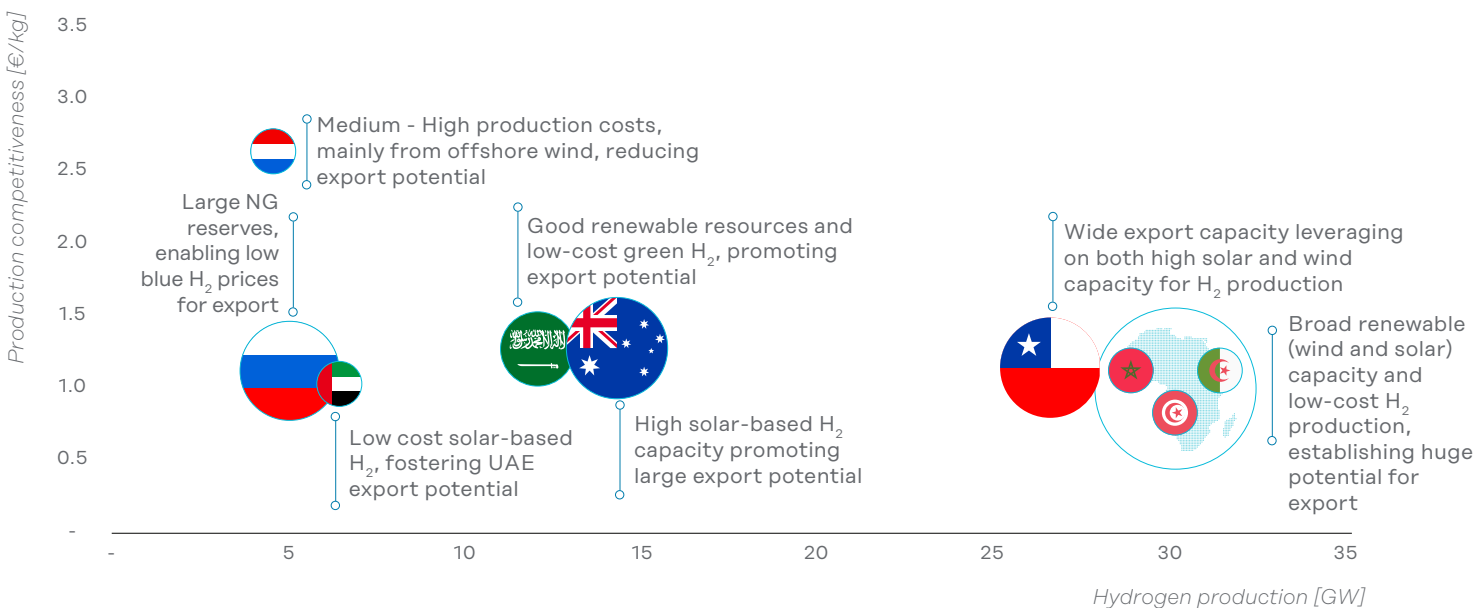
The hydrogen market is expected to develop over the coming years thanks to penetration in sectors where an immediate shift to electrification will be difficult or not feasible. Industries such as steel, chemicals and cement manufacturing represent industrial segments where the use of hydrogen offers low switching costs by decarbonising the fuel used in the manufacturing processes without the need for significant technical or logistical redesigns. Heavy transport (such as ships, trains, trucks, and forklifts) presents an additional opportunity for hydrogen owing to the relatively high cost and impracticality of alternatives such as large-scale electricity and battery storage infrastructure. Hydrogen blending in the European pipeline network has the potential to have an impact on both industrial and domestic usage and also to open up opportunities (such as heating) for transformation in the residential sector.

The countries previously identified have been considered to be export hub candidates based on a series of potential competitive advantages such as geographic location and renewable energy production, as well as certain strategic agreements and existing projects, as discussed in the previous section. However, in order to give a thorough evaluation of each candidate country’s potential, it is necessary to focus on the specific factors which will prove most determinative to the makeup of a new international hydrogen landscape.

Hydrogen competitiveness

The balance of global aggregate hydrogen manufacturing (whether blue, green or pink) will ultimately be determined by how economically competitive individual countries are in producing it. Some potential hubs (e.g. The UAE, Saudi Arabia, several Northern African countries) can exploit large developable land areas to generate solar energy for hydrogen production at competitive prices (**0.8-1.5 €/Kg**). Others (e.g. Australia) are geographically well positioned to serve important potential hydrogen import markets such as Asia, making it economically attractive for some nations to import low-cost hydrogen rather than produce it domestically. Still other countries (e.g. Russia) can take advantage of large natural gas or fossil fuel reserves to produce competitive blue hydrogen via existing low-cost SMR/ATR and other gasification technologies with CCS.

Potential competitiveness of Export Hub in H₂ Atlas, 2030



Bubbles refer to hydrogen export potential capacity.

Accenture Analysis on H₂ generation capacity, production cost and export potential for selected countries based on analysis of public documents for each country.

Use of existing infrastructure

Countries capable of using existing infrastructure (e.g. shipping ports, LNG terminals, gas pipelines, etc.) will be able to reduce final delivery costs and, as a result, increase the overall competitiveness of hydrogen produced for export. Upfront investment in facilities such as import / export terminals can have a significant impact on final delivered hydrogen import costs (1.4-2.2 €/kg) meaning projects integrating existing industrial infrastructure will have notable cost advantages. The possibility of using existing transport infrastructure such as between Italy and Algeria, Russia and Europe, or the soon to be completed connections between Russia and China will be an additional factor to take into consideration.

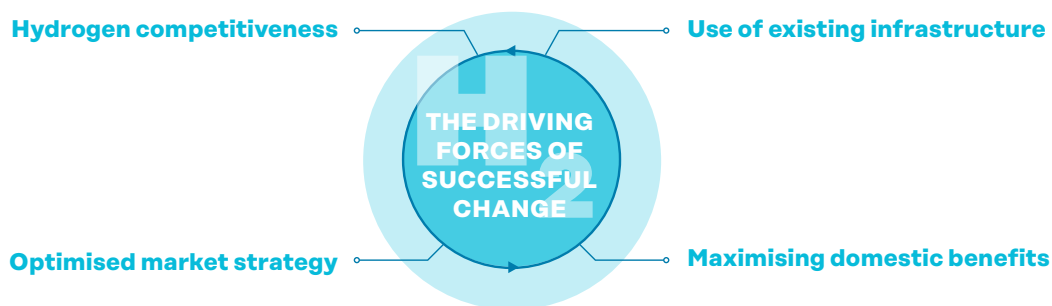
Optimised market strategy

The opportunity for development of long-term cross-sector business strategies and the establishment of one or more leading national players capable of serving as an NHC (National Hydrogen Company) will be fundamental in order to guarantee steady financial earnings and stability in hydrogen export flows. Additionally, large international players aiming to commercialise hydrogen will need to identify optimal contract terms and partnerships, careful to maximise value across the entire value chain. It will be crucial to recognise the correct price signals via medium and long-term contracts from both renewable energy sources and the final hydrogen produced. Finally, the investment risk profile will need to be levelised by way of favourable contract terms for both the NHC and other vendors in the space.

Maximising domestic benefits

There is a distinct competitive advantage to be gained from the development of national industries for hydrogen production which can create significant domestic value in addition to the direct economic benefit of hydrogen export. In some cases (e.g. Morocco, which imports a large share of ammonia), hydrogen production would reduce reliance on the import of other products derived from hydrogen synthesis, delivering further positive impacts on the national trade balance. In other cases, hydrogen manufacturing could produce significant revenue for state governments, particularly in countries currently reliant on oil and gas leasing and royalties, such as Russia and the Middle East.

To proceed with an evaluation of the hydrogen market potential, an analysis framework must be developed to support companies in clearly understanding the effective competitive advantage of each respective country as relates to the dimensions here identified. The more methodologically rigorous the analysis, the greater its potential to interest the largest players to invest in the creation of a new international hydrogen market.



Accenture analysis

The direct competition in the race to become a hydrogen hub will necessarily outline a difference in share of the export market between major hubs, but the expected massive size of the future global hydrogen market will require many actors (NHCs and international players across the value chain) to keep it competitive and ensure its uninterrupted and consistent growth.

To capture the value in hub transformation, companies who want to invest in the hydrogen industry must undertake and work with the four driving forces already mentioned, aiming to build strategic value proposition and optimal business changers.

The race has begun. Players who don't react fast enough will lag behind and only be able to develop the business more later, and at greater expense. The time to act is now.

4. HYDROGEN SERVICES

Accenture and RINA, with the aim of supporting companies in embracing the opportunity to provide a more secure, affordable and sustainable energy system, are committed to bringing their expertise to kick-start hydrogen deployment.

In the statements below, we report our thinking on how our services can help companies investing in a specific country to build a correct value proposition.

THE ACCENTURE OFFER

Scenario analysis on H₂ trends

- Our scenario analysis could help companies to evaluate H₂ cost competitiveness for each area, considering all strategic options along the value chain. We help our clients identify the correct business model to invest in H₂ solutions.

H₂ operational business models

- We support clients evaluating the pros and cons of the organisational and business decision-making process, converting investment into value and evaluating and predicting the impact of possible unexpected changes in the business environment, identifying opportunities and outcomes. We can support clients in building consortiums and long-term partnerships with the aim of creating a 'Hydrogen Valley'.

Go-to-market strategy

- Leveraging on our market-leading capabilities and combining our deep functional expertise in sales, marketing and pricing, we help clients address key organisational issues.

Data-driven modelling

- Providing advanced innovation and business agility with cloud, applied intelligence and analytics leveraging on data generated by people, organisations and things, helping companies to advance on their journey to becoming data-driven enterprises, maximising the value of data and enabling data as a strategic asset.

Digital capital project engineering and financial management

- Accelerating the entire capital project process through Accenture end-to-end digital capabilities reducing planning, permitting and construction times, leveraging on ground-breaking innovation for the engineering and construction industry, optimising the capital project lifecycle and guaranteeing transparency across the value chain.

THE RINA OFFER

Market end technology scenario

- Providing consulting engineering services for Strategic Market Intelligence related Renewables sources, Hydrogen and Ammonia market scenario and Port Infrastructure optimization for Cold Ironing solutions.
- Development of studies applicable to the entire Energy, Hydrogen and Ammonia supply chain including Logistics simulation and Vessels occupancy and optimization of size and route.
- Coordinating and actively participating in Research and Development financed projects as Coordinator or Consortium Member.
- Supporting customers in Green Project Financing Setup and Advisory Services for Investors.

Project development, distribution and transmission network

- Accelerating the energy transition providing Environmental and social studies, permitting consultancy services,

Sustainability studies, Environmental & Social Impact Assessment (ESIA) and HSE, Loss prevention and Process Safety (HAZID, HAZOP, QRA, RAMS), Engineering services (Conceptual and Feasibility Studies & FEED), full Performance assessments and technical due diligence.

- Assisting customers during Construction and Installation phases monitoring progress and quality aspects and providing Project Management Services, Asset Certification and Classification.

Asset management

- Leveraging on our industrial know-how and Laboratories capabilities for Materials and Components Performance assessment in H₂ Environment (small scale testing), Full scale test for Experimental Validation and relevant procedures set-up, assessment and qualification for Material for Storage and Material for Transportation in high pressure gaseous H₂ and Industrial Burner capable of handling H₂ / N₂-NG mixtures, Fitness for Services and Repurposing assessment of existing pipelines for H₂ and CO₂ transportation.
- Supporting in the definition of Guidelines and assistance for Asset Integrity Management system implementation.

Digital services

- Providing Virtual assets modeling, Smart & Remote inspection, measurement sensors layout set-up, data remotization on Rina CUBE cloud and Remote visualization with dedicated dashboards.

5. CONTACTS

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