THOUGHT LEADERSHIP

Partnering for our energy future — strengthening the hydrogen value chain

Forward

The use of hydrogen (H_2) as an energy carrier and feedstock has been well known for centuries, but in recent years its ability to reduce carbon emissions has made it a popular topic in energy and industrial circles. There have been some exciting projects, from production facilities that operate on renewable energy to novel applications of hydrogen fuel cells, but much remains to be done for H_2 to scale up and become a key component of a more sustainable economy and energy system.

The hydrogen industry is mature, but its future is predicated on moving from production methods that rely on fossil fuels (both as fuel and as feedstock) to zero-carbon electrolysis powered by renewable energy sources. Getting there will be a challenge. Reducing cost is paramount, as is placing a value on carbon in order for markets to make the right investment signals. For industry players, it is vital to strengthen the entire hydrogen value chain, and to approach the development of the sector from a holistic perspective.

Within these broad objectives are myriad details that will determine the success of any given H_2 project. ABB has a unique perspective as a global leader in automation and electrification with more than a century of experience in process industries. This paper assesses the current state of play in the sector and offers a roadmap for the hydrogen industry to realize its full potential.

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Peter Terwiesch

“Our customers in the process, hybrid, energy and transportation industries continue to look for better ways to increase safety and productivity, and the environmental sustainability of their operations. We help them achieve these goals, combining economic outcomes with a positive impact on society.

Throughout ABB, we are collaborating with customers and partners to build the new ecosystem for hydrogen – from a new production facility in France, transportation between Australia and Japan, and novel end-uses such as fuel cells to power marine vessels. We are proud to partner with our customers in their efforts to help the world operate and grow more sustainably.”

Dr. Peter Terwiesch, President of ABB’s Industrial Automation business

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Brandon Spencer

“We are in the midst of an exciting transformation – energy is transforming to cleaner, more sustainable sources and uses. As one of the world’s largest technology suppliers to energy industries, ABB has had a clear view of the growing interest in hydrogen. Hydrogen is capturing the imagination of innovators around the world for its potential to help us reach our climate goals, improve the reliability and resiliency of energy systems and to enable new business models that are sustainable in a low-carbon future.

ABB is committed to helping our customers transition to a clean energy future. We are all working together to make a world of difference – by enabling safer, smarter and more sustainable use of our planet’s resources.”

Brandon Spencer, President, ABB Energy Industries division

Introduction

As one of the world's largest technology suppliers to the process industries, ABB has had a front-row seat from which to observe the groundswell of interest in hydrogen. If there is one word to describe the industry, it might well be "promise." H_2 holds tremendous potential to help reach our climate goals, to improve the reliability and resiliency of energy systems and to enable new business models that are sustainable in a low-carbon future.

There are several challenges facing the sector, but perhaps the most critical is the need for a holistic approach. Consider this assessment by Atkins in a technical report[1] entitled Engineering Net Zero (2020) (emphasis added):

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"The complex interfaces of a hydrogen economy are also technically challenging, with the potential to result in a disjointed or (worse) redundant system. Furthermore, each interface represents a potential commercial transaction and risk. Without a clear hydrogen strategy backed by Government policy and commitment, there is a risk that the hydrogen economy will simply not develop.

To counter this risk, the use of hydrogen in all applications… **requires the overarching energy system architecture to coordinate the sub-system components.**"

The make-or-break relationship between primary systems – in H_2 production, but also in transport, storage and end use – and the supporting energy (i.e., electrical) infrastructure can't be overstated. In its June 2019 report[2], "The Future of Hydrogen," produced for the G20 in Japan, the International Energy Agency (IEA) notes that, "other clean energy technology opportunities have greatly improved recently, most importantly solutions that directly use electricity, which means that the future for hydrogen may be much more one of integration into diverse and complementary energy networks."

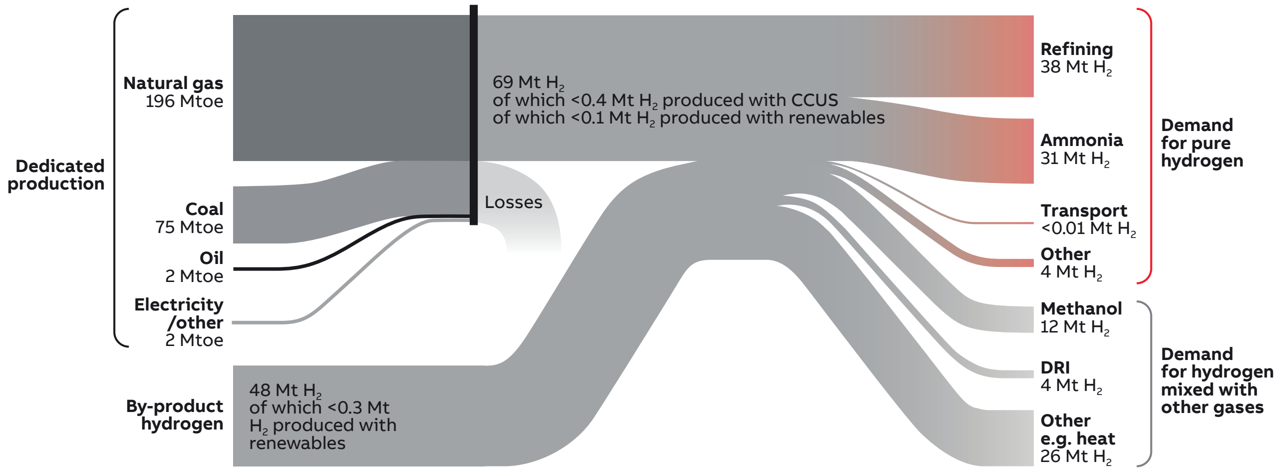
Still, public policy around the world is increasingly being leveraged to support the development of a hydrogen industry based on low-carbon production and a wide range of applications. Growing such an industry will rely on strengthening interface points between power and production, between complementary use cases and between the production, transport, storage and end use segments. To realize hydrogen's potential, the industry should work to bolster the entire value chain to lower costs, create demand and expand markets for H_2. In particular, would-be players in the hydrogen economy should:

- Identify and exploit low-hanging fruit (e.g., adding H_2 to gas networks)
- Look for synergies between use cases and business models in industry sub-sectors
- Drive economies of scale, especially in production
- Emphasize integration, holistic design and long-term value in new build facilities

This paper provides ABB's assessment of where the hydrogen industry stands today, illustrated with some examples of the company's contributions. We then move on to where hydrogen might go in the near future, and how the industry can work to ensure its continued success.

"Maximizing the potential long-term promise of hydrogen depends on moving beyond the existing industrial uses of hydrogen, and on the development of a strong case for its use as a versatile fuel in various new sectors. This case rests largely on its ability to help diversify the fuel mix and, if produced from low-carbon sources, support the transition to a cleaner energy system."

The Future of Hydrogen, IEA



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01 Value chains of today's global hydrogen industry (source: International Energy Agency)

Hydrogen background
Hydrogen is an excellent store and carrier of energy. It has three times the energy per unit of mass of gasoline, but it has low energetic volume density so more of it must be transported to deliver the same energy (e.g., three times as much as natural gas). The hydrogen industry produces around 70Mt of pure H_2 each year, globally, and another 45Mt as part of mixtures with other gases. The vast majority of production (85%) takes place on-site where the H_2 will be consumed, so the industry is highly localized.

Most of the world's hydrogen production is used in just three applications:
- 33% in oil refining as a desulphurization agent
- 27% in the synthesis of ammonia, mainly for use in production of fertilizers
- 11% in production of methanol, a common feedstock for other chemicals

Hydrogen supply for these applications is based on mature technologies and well-established markets. High-profile "green" uses, such as in fuel cell electric vehicles (FCEVs), use only a small fraction of the H_2 supply, though these segments are growing and could represent significant future demand (e.g., if long-haul trucking shifts to electric drive using fuel cells). Figure 1 illustrates the inputs and outputs of the H_2 industry.

H_2 is produced most often by reforming fossil fuels using thermo-chemical reactions, the most common of which is steam methane reforming or SMR. This is the least expensive pathway, but it entails substantial carbon emissions. Alternatively, H_2 can be produced by electrolysis of water, using energy to "split" water molecules and collect the freed hydrogen. When coupled with a zero-carbon energy source, there is no CO_2 released in the production process, but the electrolysis process requires significant energy, not to mention water.

The cost of producing H_2 varies widely by location and is dependent on the cost of inputs (gas, coal, electricity), transport distances, and local regulatory constraints. Hydrogen produced in the US costs around $1/kg, whereas Europe produces H_2 at around $2.30/kg, the difference due largely to the availability of plentiful and cheap natural gas in the US.

According to IEA data, electrolysis costs twice as much as SMR. To be cost-competitive, it requires electricity prices of between $10 and $40 per MWh, plant operation at full load between 3,000 and 6,000 hours per year, and the capture and use/storage of the CO_2 released during the SMR process. In short, carbon must be valued for market forces to properly value green hydrogen (see below, "The colors of hydrogen").

The "colors" of hydrogen

Electrolytic hydrogen was a major source of industrial hydrogen from the 1920s to 1960s, using water and hydropower from rivers, before being displaced by natural gas. More recently, industry observers have coined a series of terms to provide a shorthand for differentiating the various methods for producing hydrogen.

- **Green** – derived from renewables, no CO_2 byproduct (electrolysis)
- **Blue** – derived from natural gas with CCUS (reforming)
- **Gray** – derived from natural gas without CCUS (reforming)
- **Brown** – derived from coal/lignite with CCUS (gasification)
- **Black** – derived from coal without CCUS (gasification)
- **Pink** – derived using power and/or waste heat from nuclear (electrolysis, reforming)

Adding carbon capture and use/storage (CCUS) to the SMR process increases capital costs by 50% and operating costs by 100%, again according to IEA. However, the best suited regions could still produce H_2 at $1.50/kg with SMR+CCUS.

The environmental impact of H_2 production is substantial. Globally, hydrogen production consumes 2% of the world's primary energy every year and 6% of the natural gas supply. The production process is responsible for 830Mt of CO_2 emissions annually, which is equivalent to those of Indonesia and the United Kingdom combined. Electrolytic hydrogen uses 9 liters of water per kg of hydrogen produced, and obviously is only as climate-friendly as the electricity supply used to operate the electrolyzer.

Hydrogen: ready for disruption

Hydrogen is a stable, mature industry, but looking ahead even to just the near term reveals a sector that is ripe for disruption. First, there are several structural changes taking place in the larger energy industry including a push to develop electric power transmission and distribution systems, notably in Europe, an emphasis on decentralization of electric power (e.g., using microgrids), a renewed focus on reliability and resiliency of energy systems, and a diversification away from fossil fuels. Hydrogen's selling points as an energy storage option and a low-carbon fuel (i.e., in fuel cells) put it in an excellent position to support these broad objectives.

"Hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications across industry, transport, power and buildings sectors. Most importantly, it does not emit CO2 and almost no air pollution when used. It thus offers a solution to decarbonize industrial processes and economic sectors where reducing carbon emissions is both urgent and hard to achieve."

A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020.

Public policy supporting hydrogen varies. The European Union has identified hydrogen technologies as a strategic value chain for EU industrial policy and designated it an "Important Project of Common European Interest". This title is given to high value-added projects with a high R&D content and involving multiple EU member states to realize full-scale industrial deployment.

Most EU countries as well as Australia, New Zealand and others have established strategies for hydrogen development. While the US lacks a national strategy for H_2, some US states have their own initiatives such as California's Low Carbon Fuel Standard, which subsidizes hydrogen production, incentivizes H_2 vehicle purchases and funds the construction of a network of H_2 refueling stations.[3] Governments are especially keen on funding green hydrogen projects to bring the cost of electrolytic H_2 down.

From a strictly regulatory standpoint, hydrogen is subject to the rules applicable to the chemical industry. It falls under the Seveso III Directive (EU) on the storage of chemical substances above certain thresholds, for example. However, a number of barriers remain in the way of a thriving hydrogen sector, as noted by HyLaw in its 2019 EU policy paper.[6] The group identifies several areas where European regulations are out of step with where the hydrogen industry is going. Examples of these include:

- No distinction between production methods
- Absence of simplified rules and processes for small quantities
- Unintentionally relegating H_2 refueling stations with on-site production to industrial areas

Rules in these areas inhibit not only the growth of the industry but also the cost of delivered H_2 and the impact hydrogen has on carbon emissions. Even so, hydrogen is growing, driven by a range of applications that extend into vast, but as yet largely untapped markets such as transportation and energy. In response, supporting technologies are advancing, especially electrolyzers in production and fuel cells in end use. As of 2019, there were 40 water electrolysis plants operating in Europe, according to IHSMarkit. These plants are less than 10MW in size, but manufacturers are already offering electrolyzers ten times that.

H_2 project economics
Industry observers agree there is tremendous growth potential for hydrogen, but the business case is anything but easy to make. Managing cost of energy used for production, in particular natural gas or electricity, is critical. As more regions put a price on carbon, greenhouse gas (GHG) emissions can lead to additional costs via carbon trading systems or tax. This will take on even greater significance if/when US policy changes to drive the development of electrolysis.

Finally, there is the cost of capital. If H_2 projects can't find financing—or if financing is limited to a handful of large investors—it will hamper the industry's growth. If on the other hand capital is readily available from a variety of sources, it will hasten hydrogen's development.

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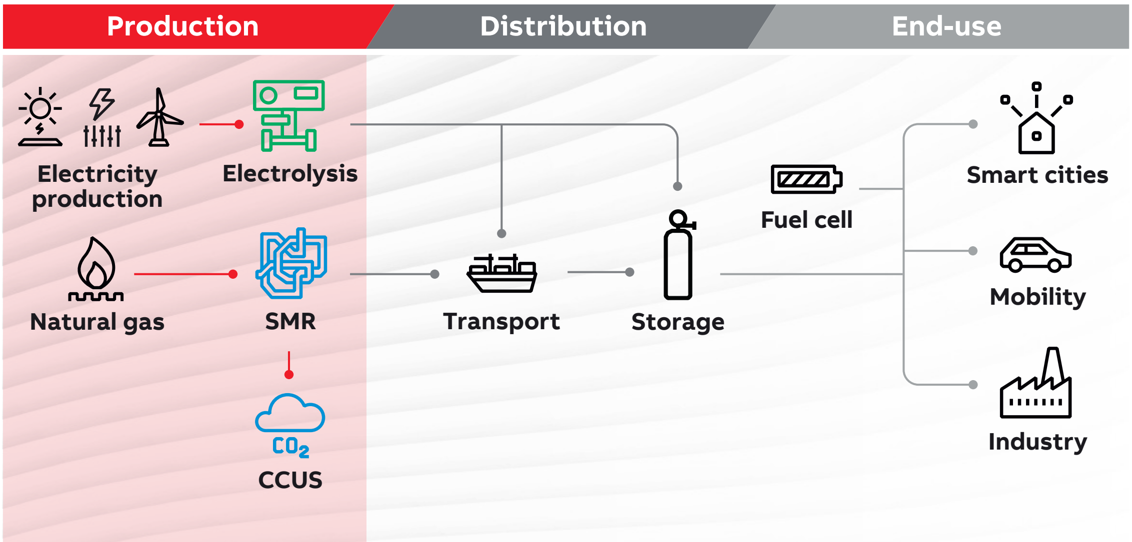
02 Overview of the hydrogen value chain



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Hydrogen production
Currently, most of the global supply of hydrogen is produced through thermo-chemical reactions to reform fossil fuels—typically natural gas—into hydrogen and by-products like CO_2. SMR is the cheapest and most commonly used process and has a large installed base, accounting for around 75% of global production. High-temperature steam is combined with methane to yield hydrogen gas, carbon monoxide and a small amount of CO_2. Propane, gasoline and even ethanol can substitute as feedstock.

SMR is energy-intensive because you need a great deal of heat to create the reaction. Heat can be generated from a number of sources, but today it's largely done through the combustion of fossil fuels. In the end, one kilogram of hydrogen produced via SMR produces 9.3 kg of CO_2 on average, slightly more than that released in the production of a gallon of gasoline (9.1 kg).

Partial oxidation (POX) is a similar process that uses exothermic oxidation (i.e., burning) of some of the input gas to create the needed heat. It's mostly used to extract hydrogen from coal or heavy oil such as that found in Canada's oil sands.

Autothermal Reforming (ATR) combines the steam reforming reaction and fuel oxidation into a single process. As with POX, exothermic oxidation provides heat for the reforming process, but ATR is more efficient and yields more hydrogen than POX. It also produces lower emissions than either POX or SMR, and the emissions are contained and thus easier to mitigate.

ABB scope in H_2 production:
- Grid and factory electrical and automation infrastructure
- Rectifier
- Energy optimization models
- Asset management including condition monitoring & predictive maintenance
- Safety & security management
- Gas analyzers & instrumentation

Another technology used to isolate hydrogen from input fossil fuels is gasification, which is already used in some advanced coal-fired power plants. The coal feedstock is converted via chemical reaction into a synthetic gas or “syngas” that is then separated into pure hydrogen and CO_2, which can be captured and stored or sent on to other use such as enhanced oil recovery. Given the capital cost associated with a gasification plant, it’s likely this technology would only be useful in a multiple use case scenario such as producing both hydrogen and electric power with CCUS.

Electrolytic processes use energy (i.e., electric power) to split water molecules into their component hydrogen and oxygen. The process is 60-80% efficient using current technology, but as noted earlier the cost is twice that of SMR and is almost entirely dependent on the price of electric power at the location of production. Electrolysis’ green credentials are also only fully valid if the input power is generated from carbon-free sources, which to date have included hydropower, solar PV and wind.

PROJECT EXAMPLE

Lhyfe: automation for green H_2 production at industrial scale

French company Lhyfe is committed to developing green hydrogen production. For their new plant in Bouin, in the Vendée region, the firm turned to ABB for process control and manufacturing operations management (MOM) using ABB’s Freelance DCS and the ABB Ability Manufacturing Operations Management (MOM) digital platform. The system controls all aspects of production with improved efficiency, safety and productivity across the operation.

Matthieu Guesne’, founder of Lhyfe: “Around the world, ABB’s innovative solutions are improving industrial efficiency, productivity and quality, while minimizing environmental impact. In addition, ABB is already very active in the world of hydrogen and renewable activities. Their experience and broad portfolio will hopefully mean we are in a position to partner on future projects. We are pleased to be working with a business so committed to renewable energy.”

The Bouin plant, Lhyfe’s first, will produce 400kg of hydrogen per day when it opens in 2021 and aims to increase to >1 ton per day.

There are other technologies emerging that are bit further down the road in terms of development and market readiness. Methane splitting is a hydrogen production technology that is still in the R&D stage but offers some tantalizing advantages. Using methane as a feedstock and electric power to provide heat, the process yields hydrogen gas and solid carbon but no CO_2 emissions. It also requires three to five times less energy input than electrolysis. Given these characteristics, methane splitting could become a game changer in hydrogen production if it can be replicated at scale.

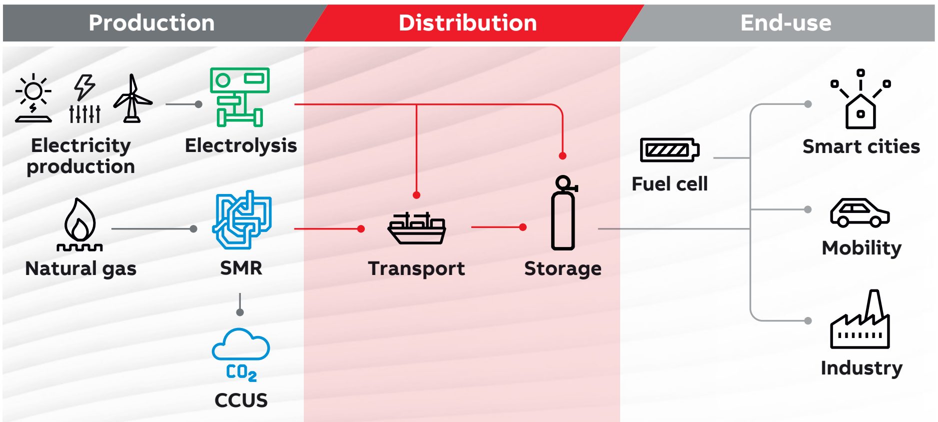
Key challenges in H_2 production

Assuming a long-term shift toward low-carbon or carbon-free H_2 production, there are several considerations for operators of both electrolysis and reforming facilities. The first applies to both: increasing performance, efficiency and safety while reducing costs, which admittedly is applicable to most any industrial process.

In the case of electrolysis, it means scaling up electrolyzers toward multi-MW installations, improving round-trip efficiency and seeking out locations for new build plants with access to inexpensive and ideally carbon-free power. That likely implies building some amount of on-site generation and thus co-locating H_2 and power production. At the very least it means engineering the power system to accommodate the particular requirements of electrolytic production across the full range of operational conditions.

SMR will continue to make up the bulk of hydrogen plants for the foreseeable future, so the industry will likely look to mitigate these facilities’ environmental impact through the addition of CCUS and fine-tuning of process controls. However, CCUS will come at a substantial price and is probably not feasible for many plants. In the meantime, SMR plants could migrate to using ATR in order to boost efficiency and more easily capture carbon by-products.

Saudi Arabia’s vast Sadara complex offers a vision of what full-scale hydrogen production might look like in the future. Sadara comprises 26 separate petrochemical plants operated by 18 distributed control systems (ABB™ Ability™ 800xAs) that monitor and control more than 150,000 data points. Operations are conducted from five redundant control rooms that can each see into any phase of the operations. The facility produces H_2 as a feedstock for other processes, co-locating the production with related processes, which will likely be an imperative for the H_2 business case for the foreseeable future.



Hydrogen distribution
Hydrogen's low energy density and very low boiling point make it more challenging to transport and store than methane, which is three times as energy-dense. In fact, according to the IEA, moving hydrogen to where it's needed can add as much as three times the cost of producing it to the end price of delivered H_2. No wonder that almost all hydrogen today is used at the same location it is produced.

Pipelines represent the most economical means of inland transport of hydrogen gas in bulk, but for longer distances and for overseas shipping, hydrogen will need to be either liquified or converted into some other carrier to be economical. Liquefaction requires energy equivalent to as much as 35% of the initial amount of H_2, far more than the natural gas. Converting hydrogen to ammonia takes less energy – between 7% and 18% according to IEA data. However, a similar amount of energy is needed to extract the hydrogen again at the destination. Ammonia is also toxic and environmentally harmful, so using it as a carrier comes with additional risk.

It's also possible to hydrogenate other substances to make liquid organic hydrogen compounds (LOHCs) that can then be shipped using similar techniques to those used for liquid fuels without the toxicity of ammonia. The process of making LOHCs is energy intensive, requiring 30-40% of the input hydrogen's energy, but the end-to-end cost is lower. In fact, IEA estimates that the cost of converting and moving hydrogen 1500km by ship comes to $0.6/kg for LOHCs, $1.20/kg for ammonia and $2.00/kg for liquid hydrogen. The cost of conversion can also vary depending on how pure the hydrogen needs to be.

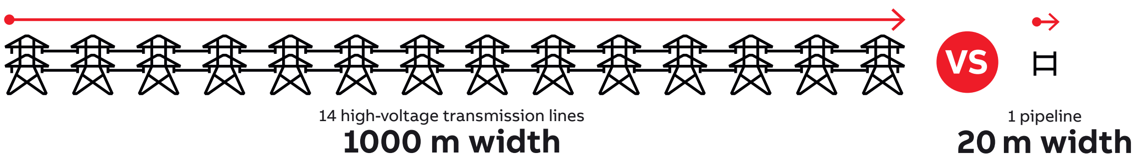
ABB scope in H_2 distribution:
- Containerized, modular electrical and automation infrastructure
- Tank farm automation and optimization
- Remote monitoring and operation
- Compressor and pumping stations
- Pipeline security monitoring
- Leak detection
- Fuel cells

Challenges in hydrogen transport and storage
Safety is obviously paramount, particularly when dealing with gases stored at high pressure. Pipelines begin with collection systems and tanking facilities to store hydrogen before it is sent on through the pipeline network. Managing these facilities and optimizing terminal operations requires specialized technology and deep expertise. There is also the challenge of siting new industrial installations like tank farms, which will need to be constructed en masse to accommodate hydrogen at scale.

Atoms vs. electrons

Moving energy can be accomplished by transmission of electric power or by transport of an energy carrier like hydrogen, ammonia or other compounds. While it might be appealing to leverage the power grid, it actually takes less infrastructure to move hydrogen as a gas via pipeline. Moving 42GW of power, for example, would require 14 high-voltage transmission lines occupying a right-of-way a kilometer in width. Moving hydrogen at the same throughput requires a single pipeline using 20m right-of-way. So, while there may be advantages to moving energy in the form of electrons, the power grid would need to scale up to preposterous levels to accommodate a robust hydrogen industry's transport requirements.

Moving 42GW of energy using power grid vs. hydrogen gas through a pipeline



PROJECT EXAMPLE

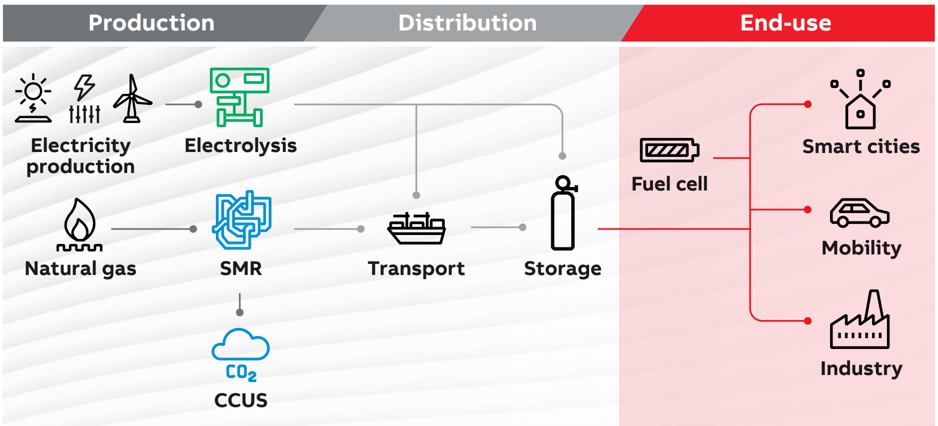
HESC: a global first in hydrogen transport and trade

A cooperative project dubbed the Hydrogen Energy Supply Chain (HESC) will produce hydrogen via gasification of brown coal (lignite) in Australia that will then be liquefied and shipped to Japan in the world's first specialized H_2 carrier ship.

"ABB is excited to collaborate on this world-first pilot to commercialize technology for liquefying and transporting hydrogen from Australia and deliver clean energy to Japan, while also reducing emissions," said Peter Terwiesch, President of ABB's Industrial Automation business.

This will be Australia's first hydrogen liquefaction terminal, and the project as a whole represents one of the world's first efforts to commercialize technology to liquefy and transport hydrogen. ABB will provide electrification and instrumentation solutions as well as end-to-end engineering, project management and commissioning services for production and liquefaction in Australia. The company will also provide the automation system for the regasification plant in Japan.

Construction of the small-scale pilot facilities at Australia's Port of Hastings commenced in 2019, and the pilot phase will operate for approximately one year from 2020. The project has the potential to create $1.4 billion in exports nationally, positioning Australia as a global leader in hydrogen production.



Hydrogen end uses

Current and future use cases for hydrogen reflect the flexibility of this fuel/energy carrier. One of the most discussed applications is in supporting power grids both in energy storage and in power generation. Today's gas turbines can already accommodate a mix of 5% hydrogen to 95% methane$_2$; higher concentrations could be handled with new designs. IEA further suggests that "at the low capacity factors typical of flexible power plants, hydrogen costing under $2.50/kg has good potential to compete" as a generation fuel. Displacing natural gas (or even better, coal) would improve air quality and public health. Hydrogen can also provide backup systems to bolster resilience.

One of the most appealing applications of hydrogen in a storage context lies in using excess renewable power generation (e.g., wind) to produce hydrogen during off-peak hours. Germany is already experimenting with marrying H_2 production to offshore wind power.

Perhaps the most compelling use case for H_2 in the energy sector involves using it in existing gas networks. Household appliances such as gas stoves can accept up to 30% hydrogen without any ill effects. Industrial processes vary widely in this respect, but simply replacing 5% of a gas pipeline network's volume with H_2 represents very low hanging fruit and would dramatically increase hydrogen demand globally. That would, in turn, stimulate investment in H_2 production and provide the impetus for more innovative multi-use applications.

ABB scope in H_2 end-use:

- Modular, containerized electrification and automation infrastructure
- Condition monitoring
- Usage optimization across network
- Fueling infrastructure for H_2-powered mobility
- CHP (combined heat & power)
- Turbine automation
- Fuel cells

In transportation, hydrogen has much to offer, mostly in the form of H_2-powered fuel cells linked to electric motors. Fuel cells are already available in cars and offer greater range than lithium-ion batteries due to their greater energy density. Fleets are prime candidates for early adoption of FCEVs—with demand from refueling on-site, the cost of H_2 stations would come down, making them less expensive for consumer use.

Fuel cells are potentially a replacement for diesel power in shipping as well, and here there may be a developing business case for an H_2 tanker using electric propulsion powered by fuel cells fed by the ship's cargo. With the signing of a memorandum of understanding with Hydrogen de France (HDF) and fuel cell maker Ballard Power, ABB is now partnering with both firms on a megawatt-scale power and propulsion system for ocean-going vessels. The consortium expects to have a working prototype in the next few years.

FLAGSHIPS

PROJECT EXAMPLE

FLAGSHIPS: hydrogen power on the Rhone

The world's first H_2-powered river vessel will operate on the Rhone river in France using hydrogen produced from renewable energy—hydropower from the river itself. FLAGSHIPS is an EU-funded initiative to deploy commercially operated zero-emission vessels for inland and short sea operations. The river boat project is led by Finnish research organization and project coordinator VTT.

"CFT has been an inland waterways innovator for more than half a century. Powering river transport in a sustainable way is a new type of challenge, but it has become vital that we cut emissions on Europe's inland waterways and specifically in the city centers. With this project, we aim to highlight that emission-free operation is both feasible and commercially viable," said Matthieu Blanc, COO at CFT.

The vessel design, which incorporates ABB's Azipod propulsion system with on board fuel cells, is near complete. The boat is expected to enter service in mid-2021.

Smaller scale marine applications like the FLAGSHIPS project (see inset) are already in the pilot stage, and electric propulsion is even being used in small workboats. As reported in Motorship, "the Evoy is a fully-electric fish farming boat. It was designed by Leif A. Stavøstrand, a Norwegian fish farmer who wanted to design a new type of electric boat for his industry (…) In normal operation at speeds up to 25 knots, the onboard rechargeable batteries will allow Evoy-1 to operate for around one hour. At much lower speeds of 4 to 5 knots, the operating time increases to several hours. The boat can be fully charged in 30 minutes using a high-speed charger."[4]

In stationary applications, fuel cells are already widely used to provide heat and power, particularly to critical infrastructure like hospitals. Costs for residential-scale systems remain high, but that segment of the market represents enormous potential for hydrogen, if costs fall as a result of technological advances and investment spurred by H_2 demand from other sectors.

Hydrogen has long been used in a multitude of applications in the chemical and process industries and use in this segment is set to grow by nearly 30% by 2030 according to IEA. It is used both as a feedstock and as a fuel for process heat. As noted earlier, ammonia, methanol and petroleum refining account for most of the hydrogen use in chemicals today, but they could still grow further. As public policy continues to favor low-carbon fuels, hydrogen could be used to reduce the sulfur content and CO_2 emissions of petroleum fuels.

Most refineries are equipped with SMR facilities already. Adding CCUS would likely make more sense than switching to electrolytic H_2, which is why reforming is likely to remain the dominant hydrogen production pathway for many years. Oil refining and petrochemical operations offer an example of complementary use cases for H_2. While petrochemical steam crackers tend to generate a surplus of hydrogen, the low-value fuel gases produced by refineries can be used in steam crackers. Co-locating such plants would represent a win-win.

Imperial College London

Carbon capture at Imperial College, London

Capturing carbon from industrial processes—and either storing or using it in some other application—is seen as essential to reducing the amount of CO2 released from the use of fossil fuels. In 2012, Imperial College of London, UK, constructed a carbon capture pilot system at their South Kensington campus that relies on wireless control technology from ABB. The plant is the most advanced of its kind in the world and serves as a learning opportunity for the further development of carbon capture technology.

The preceding examples illustrate just how broad hydrogen's reach is, even today. Moving forward, hydrogen can:

- **Support industrial competitiveness and innovation** by facilitating distribution of energy across many sectors and geographies, and reducing the cost of secondary products by lowering cost of H_2 feedstock via economies of scale
- **Enhance public health and safety** by reducing emissions of CO_2, NO_x, other pollutants associated with fossil fuels
- **Boost energy system resiliency** via diversification away from fossil fuels, especially in on-site, critical power applications
- **Decarbonize energy and transport systems** by absorbing excess power, displacing natural gas in existing pipeline networks, and supplanting fossil fuels for heating and mobility. These are some of the most difficult sectors in which to abate GHG emissions.

Realizing hydrogen's promise will require the right mix of public policy and private investment. The following section outlines ABB's vision for a thriving hydrogen economy.

How we get there: strengthening the hydrogen value chain

ABB's H_2 supply chain vision is based on development of integrated renewable energy systems and an emphasis on multi-use case projects supported by advanced digital systems.

Starting with production, it's important to understand that all hydrogen production technologies will be needed to advance the industry. SMR is likely to remain the dominant production method due to its vast installed base. So, hydrogen producers should explore ways to optimize SMR process efficiency and reduce energy consumption as well as cost while low-carbon alternatives (i.e., electrolysis) can be further developed and commercialized.

Existing plants may also look to add CCUS in order to address emissions, particularly if carbon capture will be mandated under new regulations. This will require the given plant to revisit the supporting power system to ensure the new process—essentially, a new chemical plant—will operate efficiently, safely and reliably next to the production process.

In terms of new electrolysis plants, hydrogen producers face a number of challenges at the design stage. Selecting an electrolyzer technology (i.e., proton exchange membrane vs. alkaline), sizing the system, opting for parallel production lines—all of these have implications, in particular for plant electrification. It's important for H_2 producers to look for modular solutions that will allow them to scale up production while maintaining safety and reliability. Ultimately, standardization of the final plant concept covering systems, equipment and engineering will reduce costs on subsequent projects.

Designing a robust yet economical electrical distribution system is vital. Operators must account for operational flexibility in the electrical design, for example, as it impacts system stability. Also, operating large rectifiers will require handling harmonics to maintain power quality. Managing the intermittency of renewable energy sources will be key. This implies the use of battery storage and a control philosophy supported by robust algorithms. All of these factors must be considered and optimized in the final design.

There are also large differences between suppliers in electrolyzer topology, so the interface between the electrolyzer and the power system must be optimized for the chosen approach. For this reason and to address the preceding points, it's essential for hydrogen producers to seek out an expert partner for the electrical balance of plant. That portion of a project accounts for around 1/3 of total capital cost, but is critical to ensure long-term reliability, operational flexibility and plant performance.

While hydrogen production is not a new technology per se, producing it at scale is. Some vendors not used to delivering large projects may not be attuned to some of the issues that arise when there is no clear answer. For example, it's not straightforward how to optimize the rectifier-electrolyzer interface at large scale today. Each project must be engineered to suit the specific requirements and operating constraints.

It's also important to look beyond the hardware and control logic. Service throughout the lifecycle of the project is also vitally important. Choosing a partner that can support pre-design/FEED through installation, commissioning and ongoing support will ensure continuity over the life of the project.

ABB service throughout project lifecycle

Engineering

- H_2 demand assessment
- Storage needs optimization
- Electrolyzer technology sourcing
- Grid connection requirements
- Safety & security concept

Construction

- Equipment supply
- System integration
- Commissioning services

Operation

- Energy input optimization
- SCADA system management
- Asset management

Maintenance

- Electrolyzer maintenance
- Stack replacement

Sale

- Hydrogen sale (primary revenue stream)
- Grid services (secondary revenue stream)

Strengthening H_2 transport/storage
Pipelines are likely to carry the vast majority of H_2 produced, especially in the early stages of the industry build-out. Pipeline operators can take advantage of lessons learned from gas pipeline operations and can leverage existing assets. While the capital cost of a newly built dedicated hydrogen pipeline will be 10-50% more expensive than its natural gas counterpart, the cost of repurposing existing gas pipelines is only 10-25% that of building new dedicated hydrogen pipelines.[5]

There are operational and maintenance concerns. For example, H_2 can accelerate pipe degradation through hydrogen embrittlement, but this can be addressed in construction/retrofit with coatings or more ductile steel pipe and/or in operation and maintenance with regular pigging and maintaining steady pressure.

Gas network compressor stations may not be able to be re-purposed for H_2 due to its properties and requirements for more throughput than gas. In gas pipelines, powering compressor stations with electric motors offers advantages over gas-fired engines due to maintenance costs and environmental impact, but in a hydrogen network it may be advantageous to use the H_2 itself to power turbines.

There is also a balance that must be struck in a hydrogen pipeline project between designing a single pipeline that will be operated at higher pressure and throughput vs. opting for two lower pressure lines. There is some evidence that the former may be more expensive to build, and there is a benefit in redundant pipelines in terms of reliability and security of supply. There is no one-size-fits-all answer—each project will have to be evaluated individually.

Pipelines have a unique role to play in the development of a broader H_2 industry in that they represent a ready use case for H_2 by adding it to existing natural gas networks. This is perhaps the single best way to drive demand for hydrogen and stimulate investment in supply technologies without the cost and risk associated with new builds.

Strengthening H_2 end use
Improving efficiencies and reducing cost in end uses for hydrogen will drive demand and stimulate investment upstream in the value chain. Fuel cells offer a good example. Current costs are in the range of $250/kw with state-of-the-art technologies bringing the cost down to $180/kw. To bring costs down further, fuel cell design must advance, but major cost savings can be achieved through economies of scale in fuel cell production.

According to IEA, “about half of the system cost is in the bipolar plates, membranes, catalyst and gas diffusion layers. These could be reduced by 65% by increasing plant scale from 1,000 to 100,000 units per year.” That would bring total system cost down to $50/kW.

Similar economies of scale could be realized in hydrogen refueling stations for FCEVs. In those facilities, the compressor and storage tanks account for up to 60% of total installed cost. Increasing the station’s capacity from 50 to 500kg/day could reduce capital cost per kg of hydrogen dispensed by 75%.[2]

A growing industry with growing pains
There is of course the chicken-and-egg problem of hydrogen production and consumption, each relying on the another to spur investment. But, as we've noted here, there are opportunities for first movers. Adding hydrogen to gas networks is the most obvious and perhaps most feasible in the short term. Co-locating complementary processes makes sense, but such projects are likely to be limited to massive installations where both the synergies between processes and economies of scale can be maximized.

Early project successes will rely on effective partnerships. Players with broad capability across power systems and process control will simplify the project by reducing the number of cooks in the kitchen. Expertise in managing complex projects and integrating single and multi-vendor systems is smart. Experience in specific sectors like pipelines, renewable power and shipping will also be valuable.

Throughout this paper, certain themes recur: integration, optimization at the design stage and an emphasis on stacking use cases. These imperatives demand a holistic approach to hydrogen projects, whether in production, transport, storage or end use. This is especially important as an already well- established hydrogen industry undergoes a mid-life metamorphosis to become the cornerstone of a low-carbon economy.

iea

"Maximizing the potential long-term promise of hydrogen depends on moving beyond the existing industrial uses of hydrogen, and on the development of a strong case for its use as a versatile fuel in various new sectors. This case rests largely on its ability to help diversify the fuel mix and, if produced from low-carbon sources, support the transition to a cleaner energy system."

"The Future of Hydrogen," IEA

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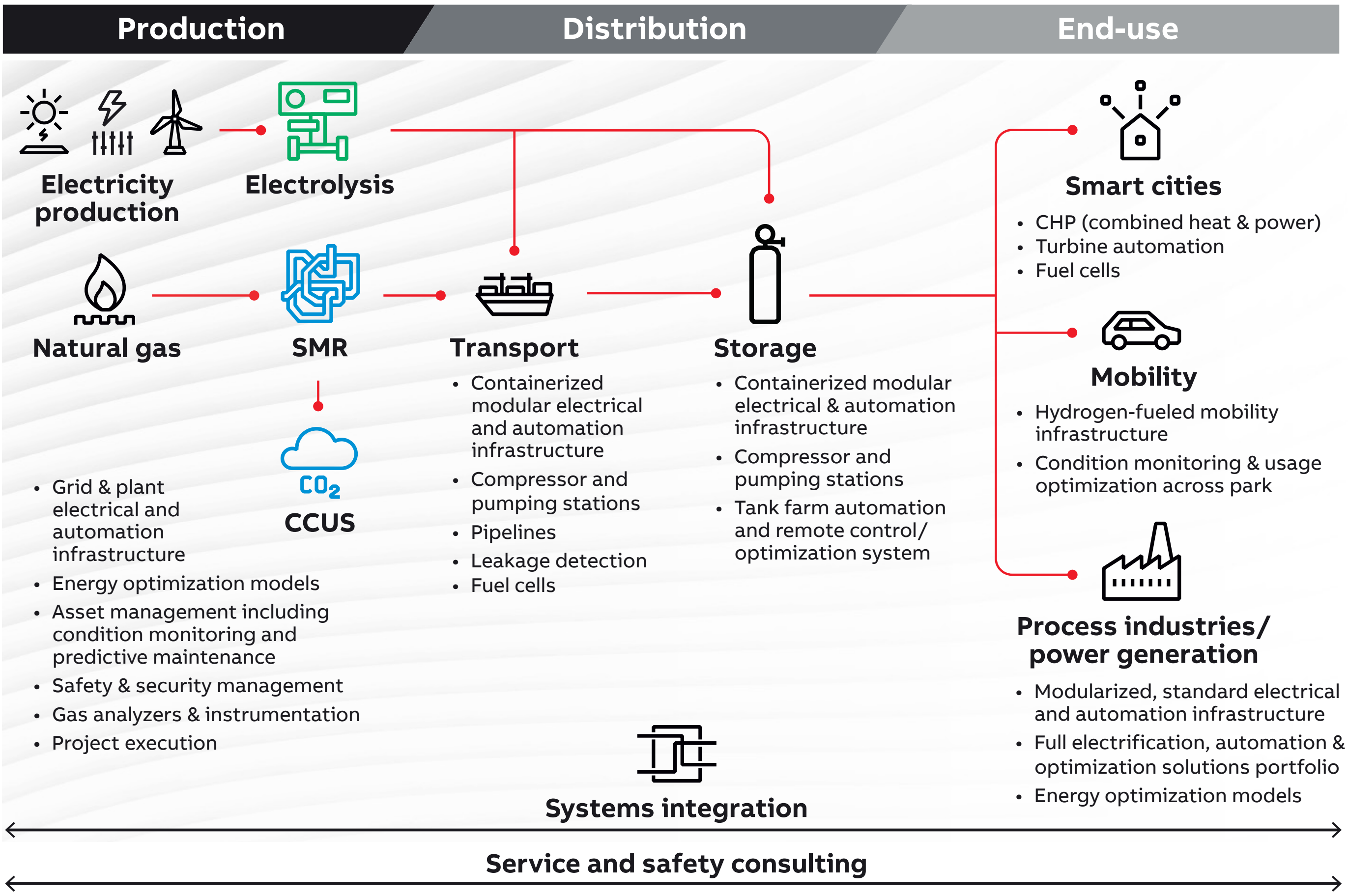
03 Overview of ABB's contribution to the hydrogen value chain



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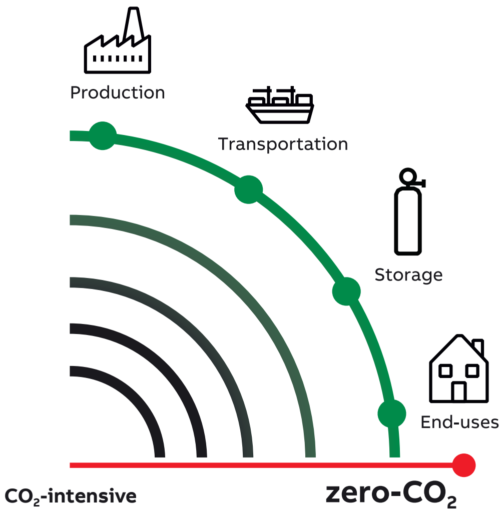
03

About ABB

Sustainable transformation requires process expertise with an evolution roadmap that is ambitious yet realistic, providing an immediate but gradual transition plan. For the transformation of an energy value chain from CO_2-intensive to zero-CO_2 operations, you need partners that understand all of the steps involved – from primary energy generation to creating the optimal energy mix all the way to the point of sales – and can offer and integrate a solutions portfolio to match.



ABB's broad scope encompasses the full hydrogen value chain from production, transportation, storage to distribution and end-uses. We are collaborating with partners to create the new Hydrogen ecosystem. We believe a sustainable, economically-vibrant ecosystem depends on active collaboration with experts throughout the value chain; experience and expertise in actual and related uses and applications; and importantly, an integrated, holistic view of the solutions and approaches that can shape the value chain.

ABB brings a unique combination of experience, expertise and vision to the hydrogen industry, from 130 years of innovation, 110,000 employees in over 100 countries, and 50+ years in the energy sector:

- **Pioneering technology,** enabling energy efficient and low carbon operations across traditional industries
- **Proven integration and project execution expertise,** leveraging technology and engineering partners on complex projects globally
- **New models,** supporting development of new and renewable energy models
- **Committed to a clean energy future,** with strong capabilities in delivering renewables projects and a solid commitment to helping all customers transition to cleaner energy future

ABB is a leading global engineering company that energizes the transformation of society and industry to achieve a more productive, sustainable future. By connecting software to its electrification, robotics, automation and motion portfolio, ABB pushes the boundaries of technology to drive performance to new levels.

For more information on ABB and/or to contact a representative, please visit our website at **www.abb.com/hydrogen**.

Endnotes

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