MOVE THE WORLD FORWARD MITSUBISHI HEAVY INDUSTRIES GROUP

HYDROGEN – POWERING A NET ZERO FUTURE

THE TECHNOLOGIES TO GET US THERE

MITSUBISHI HEAVY INDUSTRIES

EXECUTIVE SUMMARY

Hydrogen has two key roles to play as the world seeks to achieve net-zero CO_2 emissions by 2050: enabling greater use of renewable electricity; and decarbonizing every part of the global economy, including those CO_2-intensive sectors that are difficult to decarbonize using renewables.

For both roles, there are technologies that are either already available or in advanced stages of development to make use of hydrogen in several key applications.

When it comes to enabling greater use of renewable electricity, hydrogen can play a role in two key areas:

1. As a form of energy storage for renewable electricity

2. As a cleaner source of reliable power generation to complement variable renewables

Building hydrogen to the scale needed to fulfil these functions will require the intermediate step of decarbonizing traditional hydrogen production through carbon capture, utilization and storage (CCUS) until production from electrolysis powered by renewables becomes commercially viable.

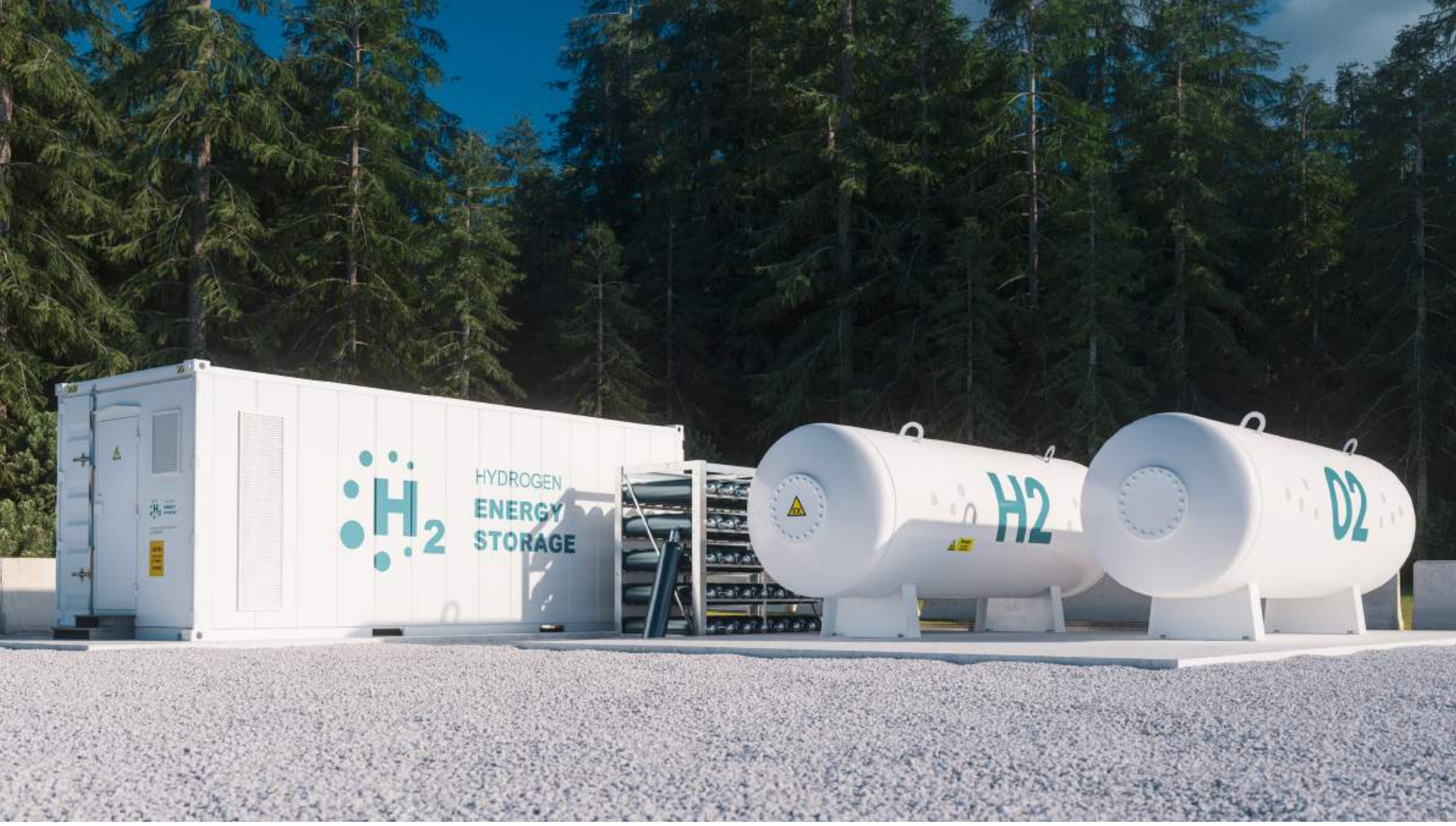
For hydrogen's second role of decarbonizing the CO_2-intensive "hard to abate" sectors, there are three areas where it can help reduce CO_2 emissions:

1. Reduction of CO_2 emissions from heavy industry by being used both as a feedstock in production processes and as a source of industrial heat

2. Cutting CO_2 emissions in long-haul and heavy transportation applications such as shipping, where electrification through batteries is currently unviable

3. Decarbonizing power and heating of residential and commercial buildings

Developing and commercializing solutions in all of these areas is essential for establishing a robust and viable market for hydrogen over the coming decade.



INTRODUCTION

Hydrogen is building momentum as a key energy carrier in the global effort to reach net-zero CO_2 emissions by 2050. In 2019, it rose to the top of the discussions between global leaders at the G20 summit in Japan. This event was supported by a comprehensive report from the International Energy Agency (IEA) that declared "unprecedented momentum" as hydrogen was "increasingly a staple of mainstream energy conversations in almost all regions"[1] . In total, there were over 50 policies globally supporting investment in hydrogen by mid-2019. These included initiatives under way in 11 countries from the G20 and the EU, plus the U.S. state of California[2].

The momentum that built up in 2019 has continued into 2020, with January alone seeing German chancellor Angela Merkel highlighting the importance of hydrogen for decarbonizing her country's steel sector[3] and the U.K. starting its first trial of injecting hydrogen into its gas grid for domestic heating[4].

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[1] IEA, The Future of Hydrogen - Seizing today's opportunities, June 2019
[2] Spectra, CCUS: The Key to Making Hydrogen Energy Work Today, December 2019
[3] World Economic Forum, Special Address by Angela Merkel, Chancellor of the Federal Republic of Germany, January 2020
[4] Hydeploy, UK's first grid-injected hydrogen pilot gets underway,, January 2020

Vattenfall's Magnum Power Plant in the Netherlands

It is clear that – at policymaker level at least – it is well understood that hydrogen as a clean fuel can play two key roles in the global drive to reach net-zero CO_2 emissions by 2050:

1. **Enabling greater use of renewable electricity**
2. **Decarbonizing CO_2-intensive sectors**

What is needed now is the evidence that the demand for hydrogen will grow. This will be required by both policymakers and by those companies considering investing in hydrogen production capacity – which will need to be between seven and 11 times greater by 2050[5] if it is to play these two major roles in cutting CO_2 emissions. Governments and corporations need to know that the technologies exist, or are at advanced stages of development, and that the demand is there – in other words there are industries prepared to make the switch to hydrogen as a cleaner fuel.

This eBook sets out some of the applications that can help hydrogen fulfill its two key decarbonization roles. Mitsubishi Heavy Industries (MHI) group, through its work with the Japanese space program, has a long history of working with hydrogen. Its group companies are now working to develop the technologies and processes that will enable hydrogen's transition from powering rockets to being the clean fuel that will drive a net-zero future.

[5] The Energy Transitions Commission, Reaching Net Zero Carbon Emissions: Mission Possible, 2018


Offshore Wind Turbines by MHI Vestas Offshore Wind

SECTION 1: ENABLING GREATER USE OF RENEWABLES

1.1: ENERGY STORAGE

An almost symbiotic relationship is emerging between hydrogen and renewables. As wind turbines and solar PV panels become cheaper, so does the cost of producing green hydrogen from renewables through electrolysis. At the same time, the IEA[6] points out that as renewables begin to account for a high proportion of the energy mix, their variability poses a challenge. This means the need for large-scale energy storage to smooth out differences between supply and demand becomes more pressing.

Hydrogen offers the potential for energy storage on a much greater scale than the battery solutions currently being used to provide flexibility to the grids. This is a particular advantage when there are large seasonal variations in the level of electricity generated by renewables, and can help capture energy that might otherwise be wasted. For example, hydrogen storage could be used to capture the excess electricity generated by offshore windfarms during the North Sea's fierce winter winds, or it could take advantage of the longer summer days and additional electricity generated by solar PV farms in regions of the U.S. such as Utah (see box below).

[6] IEA, The Future of Hydrogen - Seizing today's opportunities, June 2019

Gas turbine by Mitsubishi Hitachi Power Systems

The Hydrogen Council estimates that by 2030, 250 to 300 terawatt hours (TWh) of surplus renewable electricity could be stored in the form of hydrogen[7] – that's more than the entire annual amount of electricity generated by many major advanced economies, including Australia and Italy[8].

In addition to this theoretical storage potential, independent research commissioned by the Japanese government shows that projected demand for green hydrogen as a fuel, rather than just as a form of storage, could require up to 16TWh of renewable power generation by 2050[9].

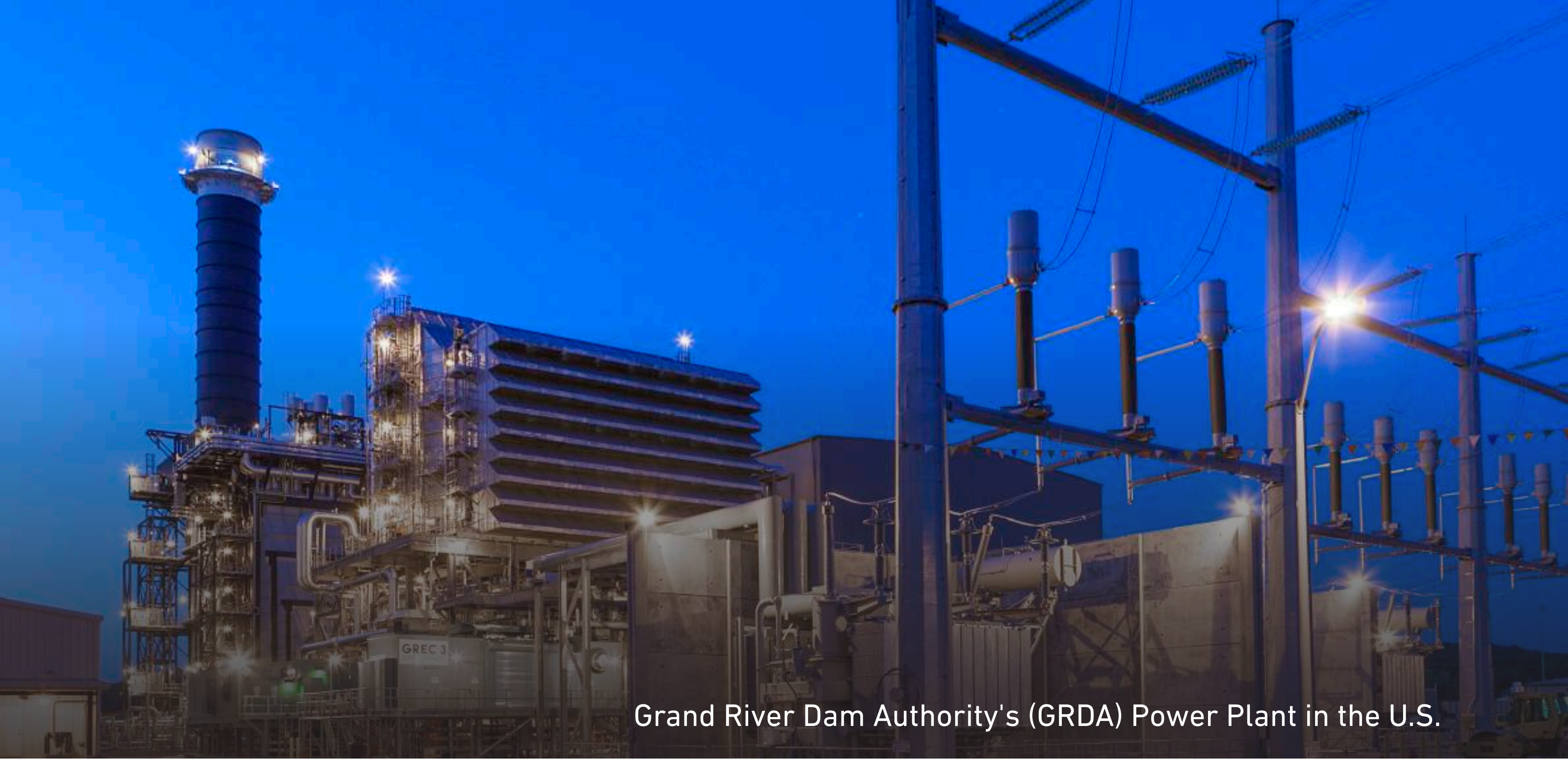
[7] Hydrogen Council, Hydrogen, scaling up, November 2017
[8] BP, Statistical Review of World Energy - Electricity, 2019
[9] International Renewable Energy Agency, Hydrogen: A Renewable Energy Perspective, 2019

THE MHI SOLUTION

Mitsubishi Hitachi Power Systems (MHPS), in partnership with Magnum Renewable Development, is building the world's largest renewable energy storage project, called ACES (Advanced Clean Energy Storage) in Utah[10] in the United States. Renewable hydrogen will be produced from excess renewable energy and stored in a series of underground salt caverns. One cavern at the ACES project will store enough renewable hydrogen to provide 150,000 MWh of clean energy storage.

The location of the project is important for two reasons. First, it sits on salt caverns that can be used for compressed hydrogen and compressed air energy storage. Second, it's being built next to the Intermountain Power Plant, a 1.8GW coal-fired power plant that supplies one-fifth of Los Angeles' electricity[11] and is due for retirement in 2025. This location means the project will be able to easily connect with the existing electricity transmission infrastructure. It also potentially removes the need for long-distance hydrogen pipelines, as the Intermountain Power Renewal Project will be adjacent to ACES[12].

[10] MHPS, World's Largest Renewable Energy Storage Project Announced in Utah, 2019
[11] Los Angeles Times, Los Angeles wants to build a hydrogen-fueled power plant. It's never been done before, 2019
[12] Los Angeles Times, Los Angeles wants to build a hydrogen-fueled power plant. It's never been done before, 2019



Grand River Dam Authority's (GRDA) Power Plant in the U.S.

1.2: POWER GENERATION

Using hydrogen as an effective form of renewable power storage relies on the ability to convert the gas back into electricity.

This requires power plants capable of using hydrogen fuel and generating a steady supply of electricity. As well as realizing the stored hydrogen's potential, these plants could help stabilize grids where there are high proportions of variable renewables in the system.

The Hydrogen Council claims that more than 200TWh could be generated from hydrogen in large power plants[13].

Japan's Basic Hydrogen Strategy targets commercialized hydrogen power generation by 2030[14], and in response MHPS took the first step in 2018 by inventing and successfully testing a gas turbine combustor capable of utilizing a fuel that is 70% liquefied natural gas (LNG) and 30% hydrogen (see box below).

[13] Hydrogen Council, Hydrogen, scaling up, November 2017
[14] MHPS, Hydrogen Power Generation Handbook, November 2019

Hydrogen gas turbine by Mitsubishi Hitachi Power Systems

The advantage of this solution is that existing power plants can be renewed to low-carbon or CO_2-free power generation just by converting burners and associated equipment. MHPS is now working with Vattenfall to deploy this technology at its Magnum power plant in the Netherlands. This project aims to convert one of the three existing MHPS units, which house M701F gas turbines (440MW/unit), to be 100% hydrogen-firing by 2025.

THE MHI SOLUTION

After successfully demonstrating 30% co-firing, MHPS is moving into the next phase of its program to achieve gas turbines running on 100% hydrogen. It is doing this by using DryLowNOx (DLN) hydrogen combustion. Based on conventional DLN technology – which reduces nitrogen oxide emissions – this solution is aimed at preventing flashback. This is a phenomenon where the flames inside the combustor travel up the incoming fuel and air mixture and burn too close to the nozzle section causing hardware damage. Since hydrogen burns at a faster rate than natural gas, the potential for flashback increases as the concentration of hydrogen rises. MHPS' solution is the creation of what it calls a "multi-cluster combustor". It uses a greater number of smaller fuel nozzles, which create smaller sprays being released in a high velocity region within the combustor. This reduces the likelihood of a flame travelling up the fuel's flow path and damaging the nozzles. MHPS has targeted completing its rig test of 100% hydrogen firing at its facility in Takasago, Japan by 2025.

On a smaller scale, hydrogen can also be used as a distributed energy source via solid oxide fuel cell (SOFC) technology. SOFCs developed by MHPS can replace diesel generators as cleaner power backups in places such as commercial buildings, using either hydrogen or natural gas to generate both electricity and heat (see 2.3 Heating).

1.3: SCALING HYDROGEN TO GO GREEN

HYDROGEN COLOR	PRODUCTION PROCESS AND ENERGY SOURCE
GREEN	Electrolysis using electricity from renewable sources.
BLUE	Conventional CO_2-intensive methods such as SMR combined with carbon capture technologies, electrolysis using electricity from grid (energy from a mix of renewable and conventional power plants), or byproducts from existing chemical factories.
GRAY	Conventional CO_2-intensive methods of hydrogen production from fossil fuels.

Production of green hydrogen from renewables offers a tantalizing solution to the storage challenges of power sources such as wind and solar. Western states in the U.S. such a California and Utah are already creating green hydrogen and plan to scale it over the coming years.

However, not all regions and industries are ready to make the transition directly to green hydrogen. Analysis by McKinsey on behalf of the Hydrogen Council reveals that even though the costs of producing renewable green hydrogen will fall 60% in the next decade, it will take until the mid-to-late 2030s before it can rival conventional "gray" methods of hydrogen production from coal and natural gas[15].

Blue hydrogen, on the other hand, is much more likely to be commercially viable in the near future. This type of hydrogen uses conventional carbon-intensive methods of production, but couples it with CCUS technology to ensure CO_2 emissions from the production process are not released into the atmosphere.

McKinsey's analysis predicts that with the addition of carbon pricing, blue hydrogen will be cost competitive with gray hydrogen by 2030. Dependent on local natural gas prices, blue hydrogen may already be cheaper than gray hydrogen in some parts of the world: the IEA identifies hydrogen production from coal with CCUS as the cheapest form of clean hydrogen production[16] in China today, cheaper even than hydrogen from natural gas without CCUS.

There are 19 CCUS plants operational around the world today, with a further 32 planned or under construction. The largest facility is in Texas and uses Mitsubishi Heavy Industries Engineering (MHIENG) technology[17]. CCUS represents the best hope for scaling up hydrogen production in the short-to medium-term. Using blue hydrogen to establish supply chains and growth in demand for the gas will ensure that by the time green hydrogen projects become commercially viable, they have a ready-made market to sell into. Blue gets us to green.

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[15] McKinsey & Company/Hydrogen Council, Path to Hydrogen Competitiveness, January 2020
[16] IEA, The Future of Hydrogen - Seizing today's opportunities, June 2019
[17] MHI, CO^2 Capture Plant, N/A

Petra Nova Carbon Capture Plant

THE MHI SOLUTION

The Petra Nova Carbon Capture Plant in Thompson, Texas is the world's largest post-combustion carbon capture facility. Owned and operated by Petra Nova (a joint venture of NRG and JX Nippon Oil & Gas Exploration), the facility captures more than 90% of the CO_2 from a 240MW power plant. Operational since the end of 2016, in its first 10 months it captured more than 1 million short tons of carbon[18]. This captured CO_2 is used in enhanced oil recovery (EOR) that has boosted production at the West Ranch oil field in Texas significantly[19].

Petra Nova uses MHIENG's carbon capture technology, called the Kansai Mitsubishi Carbon Dioxide Recovery Process (KM-CDR Process™), jointly developed with Kansai Electric Power Co., Inc. It employs a specially developed amine-based solvent called KS-1™ to absorb CO_2 from the flue gas, cleaning the plant's emissions. The CO_2-rich solvent is then moved to a regenerator, where steam separates the CO_2 from the solvent. This 99% pure CO_2 is sent to a compressor to be transported via pipelines and used for EOR. The CO_2-free solvent, meanwhile, is recycled and used in the process all over again.

[18] NRG, Petra Nova - Petra Nova - Carbon capture and the future of coal power, N/A
[19] Spectra, Carbon Capture Technology for an Evolving Energy Landscape, May 2018

SECTION 2: DECARBONIZING CO_2-INTENSIVE SECTORS

2.1: INDUSTRY

Hydrogen's other great role in the race to net-zero emissions is its potential to decarbonize those CO_2-intensive industries and forms of energy use considered "hard to abate".

These are sectors that rely on fossil fuels either as the raw materials for their products, or for energy. Quite often the energy application comes in the form of extreme levels of heat, which cannot be simply electrified. In 2018 industry accounted for 29% of energy consumption and 42% of direct CO_2 energy-related and process emissions[20], according to the IEA.

Along with CCUS and alternative fuels such as biogas, hydrogen can be used both as a feedstock for industry's raw materials and in heat applications to help decarbonize sectors such as chemicals, cement and steelmaking.

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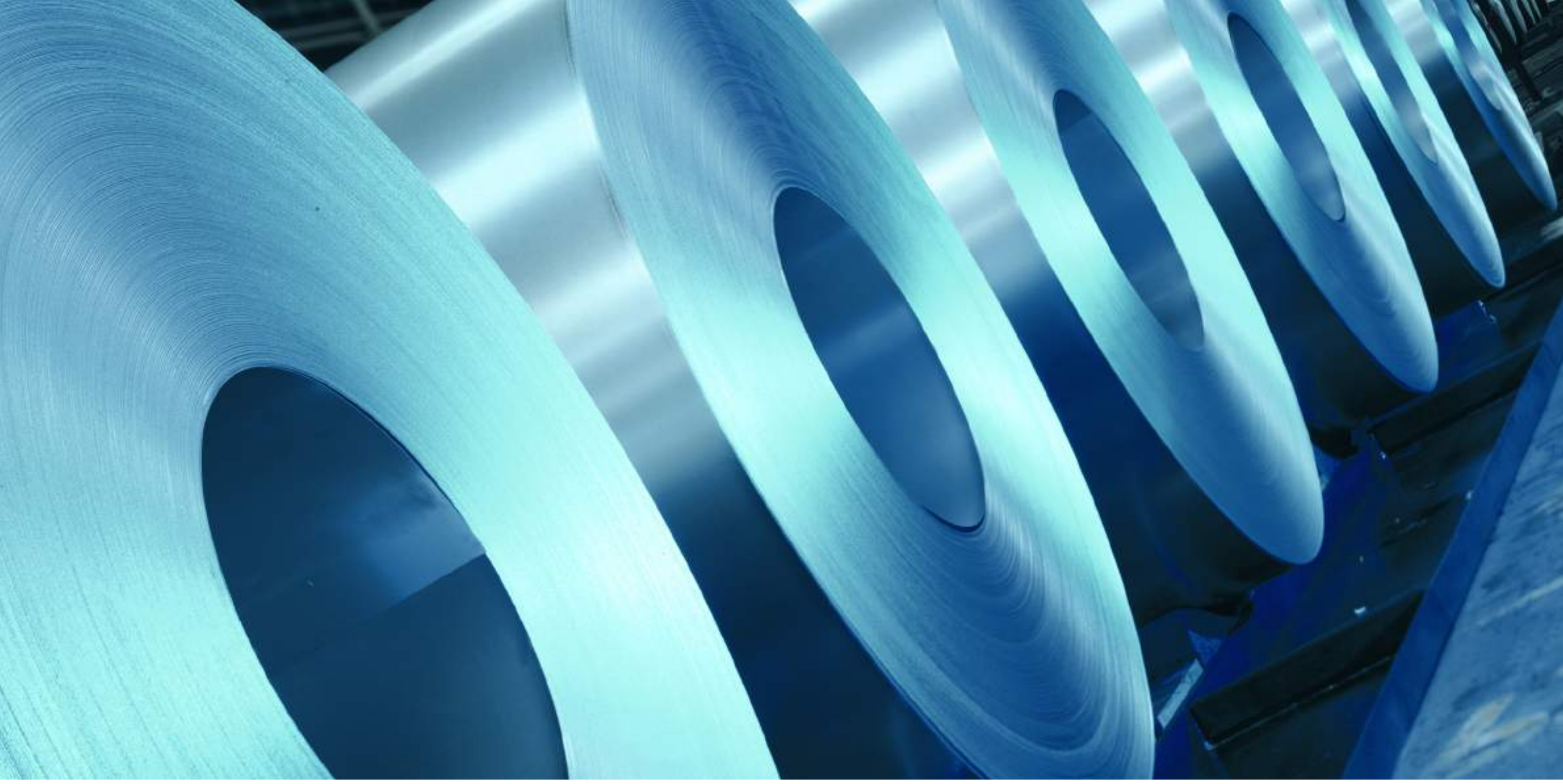
[20] IEA, World Energy Outlook, November 2019



The steel industry, for example, is so carbon intensive it actually produces more CO_2 than steel[21]. Roughly 1.8 tonnes of CO_2 are released into the atmosphere for every tonne of liquid steel. And this is based on calculations that assume an average, modern blast furnace operated in OECD Europe – many plants around the world emit three or more tonnes of CO_2 per tonne of steel[22]. In total, this one industry is responsible for anything between 7% and 10% of global CO_2 emissions.

With such high emissions levels, the industry is already feeling the pinch from carbon pricing in some parts of the world. In Europe, for example, CO_2 pricing rose sixfold between 2017 and 2019, and is expected to continue to rise as new rules in the EU Emissions Trading System come into place in 2021 that tighten the supply of emissions credits.

In anticipation of such regulatory measures and market pressures, steel producers around the world are racing to deploy new technologies aimed at reducing carbon intensity in iron and steelmaking. ArcelorMittal, for example, has set a target of its European operations being carbon neutral by 2050[23]. Merely shifting production from coal and coke-based blast furnaces to processes such as direct reduction (see box) based on natural gas will be insufficient for reaching such ambitious targets. The industry will need to develop other energy sources without a direct carbon footprint, such as hydrogen, to a commercial scale and in a manner that is economically feasible.

[21] Spectra, Swapping carbon for hydrogen, and how the steel industry can do it, October 2019
[22] Primetals Technologies, The Winding Road Toward Zero-Carbon Iron, January 2020
[23] BusinessGreen, Steel giant ArcelorMittal targets carbon neutral European operations by 2050, June 2019

Hydrogen-based steelmaking will drastically cut carbon emissions from the industry

THE MHI SOLUTION

MHI Group company Primetals Technologies is developing a process using hydrogen in place of coking coal as a reduction agent for iron ore. The solution, called hydrogen-based fine-ore reduction (HYFOR), is the world's first direct-reduction process for iron-ore concentrates that removes traditional pre-processing treatments of the material. As of today, most of the iron in the world is produced using coal to generate the high levels of heat required by the process and to remove the oxygen in the ore. HYFOR, on the other hand, uses hydrogen as a primary reduction agent, replacing carbon emissions with water vapor. Depending on the source of the hydrogen, this leads to a low or even zero CO_2 footprint for the resulting direct-reduced iron. The HYFOR plant features a modular design with a minimum rated capacity of 250,000 tonnes per module per year, making it suitable for all sizes of steel plants. A pilot plant for testing purposes is being constructed at the Stahl site of Austrian steelmaker Voestalpine, and is due to be commissioned by the end of 2020.

2.2: SHIPPING AND TRANSPORTATION

When the general public hears about hydrogen, it is usually in reference to hydrogen fuel-cell electric vehicles (FCEVs). And while sales of these vehicles are predicted to rise, hydrogen is actually forecast to have a far greater impact in long-haul freight, shipping, public transportation and potentially aviation, where the limited range and efficiency of the batteries of battery-powered electric vehicles (BEVs) are unsuitable[24].

Many parts of the world are already embracing hydrogen-fueled public transportation. In 2018, Germany began the operation of two hydrogen trains[25] and many cities across the globe are using hydrogen fuel cell buses, including Tokyo, where they will provide the transportation for spectators and athletes at the 2020 Games[26].

For long-haul freight, either on road or by sea, hydrogen is predicted to be able to play a role either directly, in the form of FCEV trucks, or indirectly by being converted into ammonia as a shipping fuel[27](see box). Similarly, the IEA identifies hydrogen-based synthetic fuels as a potential solution for lowering emissions in aviation[28]. A project under consideration in the Netherlands would build a 60MW electrolyzer powered by North Sea offshore wind farms to create hydrogen that would be converted to methanol and combined with cooking oil to produce 100,000 tonnes of aviation biofuels per year[29].

[24] The Energy Transitions Commission, Reaching Net Zero Carbon Emissions: Mission Possible, 2018
[25] DW, World's first hydrogen train rolls out in Germany, September 2019
[26] Bloomberg, This Bus Filling Station Is Latest in Japan's Hydrogen Quest, January 2020
[27] The Energy Transitions Commission, Reaching Net Zero Carbon Emissions: Mission Possible, 2018
[28] IEA, The Future of Hydrogen - Seizing today's opportunities, June 2019
[29] Nouryon, Nouryon and Gasunie study scale-up of green hydrogen project to meet aviation fuels demand, May 2019

LCO_2 Carrier Cool Blue by Mitsubishi Shipbuilding

THE MHI SOLUTION

The UN's International Maritime Organization (IMO) has set a target for the international shipping industry to halve its greenhouse gas emissions by 2050[30]. With battery technology currently only a viable solution for short journeys such as ferry crossings, alternative approaches are being sought to decarbonize the sector. MHI Group believes that the IMO's emissions targets will drive demand for ammonia as a low-carbon shipping fuel.

Ammonia can be made from hydrogen and is a denser gas, providing a potential solution for the shipping of hydrogen in large volumes. If pressurized at room temperature, ammonia becomes a liquid in the same manner as liquefied petroleum gas (LPG). This means that it is relatively easy to design and build new ships to handle either LPG or ammonia. Mitsubishi Shipbuilding has already built a multi-gas carrier capable of holding LPG and ammonia. It is also developing a concept ship – the LCO_2 Carrier Cool Blue – capable of carrying liquefied CO_2 captured by carbon capture facilities, making carbon capture possible in places where there may not be any suitable storage sites.

[30] IMO, Low carbon shipping and air pollution control, N/A

2.3: HEATING

The heating of buildings, water and use of heat in industry accounts for more than half of global energy use[31]. In Europe, heat and hot water account for 79% of energy use by EU households[32]. The vast majority of European homes rely on natural gas boilers for heat, and hydrogen offers a potential alternative that could make use of existing gas infrastructure. In the U.K., work is underway to test this theory. The H21 project is testing gas infrastructure's potential to carry a 100% hydrogen heating network, with a live trial scheduled to take place in either 2021 or 2022[33]. Meanwhile, Keele University began feeding a 20% blend of hydrogen into the natural gas used by buildings on campus[34].

Elsewhere, in Japan a demonstration scheme has been running since 2009 installing hydrogen fuel cells to provide heat and electricity for homes and businesses. The ENE-FARM program is expected to reach 300,000 installed units in 2020, and has a goal of installing 5.3 million units by 2050. At present, ENE-FARM units reform natural gas or liquefied petroleum gas in-situ to feed a fuel cell with hydrogen. According to the IEA, the use of fossil fuels leads to limited CO_2 reduction benefits, but aids delivery of cost reductions that will help to pave the way for low-carbon hydrogen distribution once it becomes economically attractive[35]. Fuel cell technology also offers a lower carbon alternative to diesel generators for back-up power and heat supply (see box).

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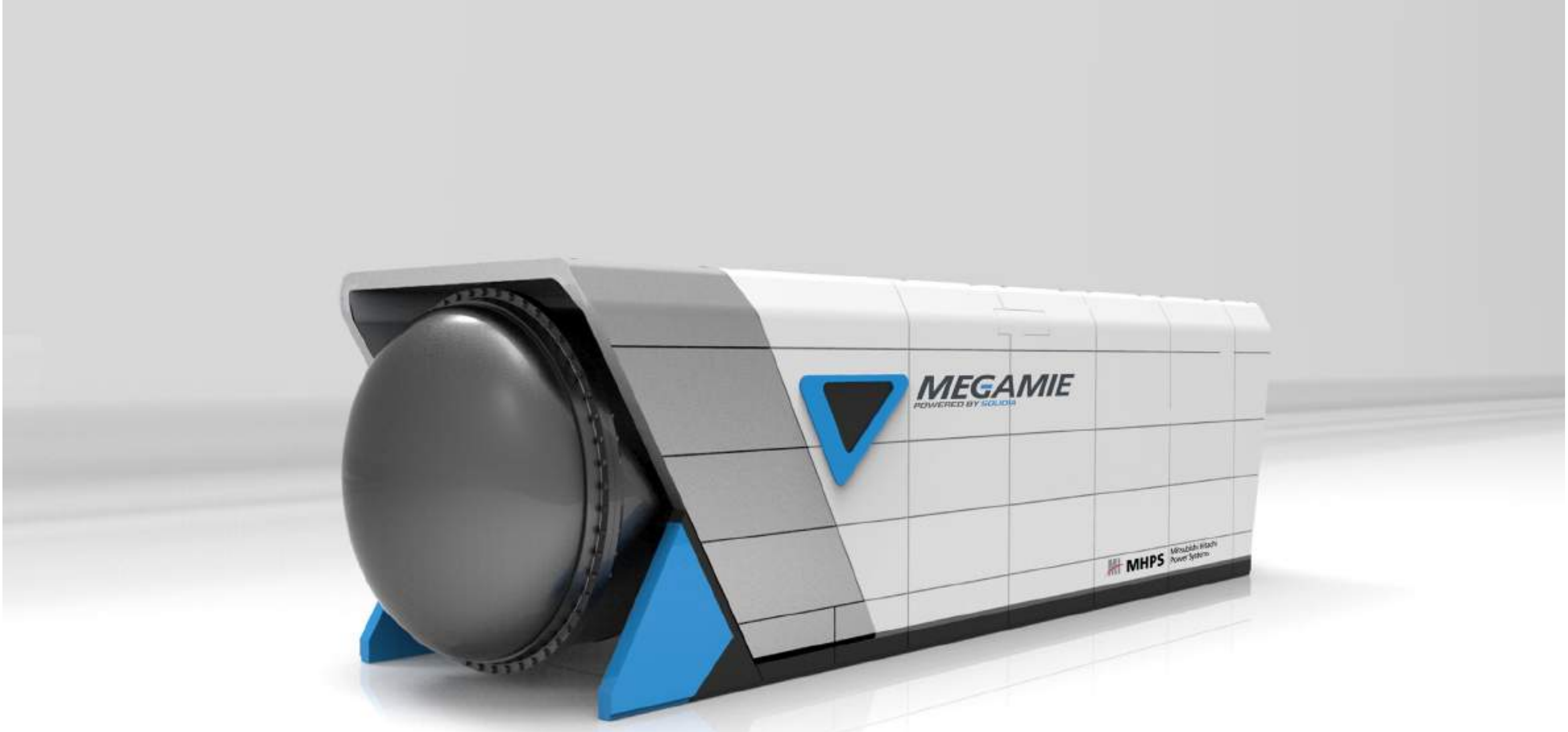
[31] IEA, Renewables, 2018
[32] MHI, Hydrogen - The Next Step In Energy Evolution, June 2019
[33] H^{21}, About H^{21}, N/A
[34] Hydeploy, UK's first grid-injected hydrogen pilot gets underway, January 2020
[35] IEA, The Future of Hydrogen - Seizing today's opportunities, June 2019



MEGAMIE, solid oxide fuel cell (SOFC) by Mitsubishi Hitachi Power Systems

THE MHI SOLUTION

MHPS produces a 250kW class solid oxide fuel cell (SOFC) unit called MEGAMIE, which combines fuel cell technology with a gas turbine to generate both electricity and heat. The unit is currently used in university campuses, factories and commercial buildings, and it can run on LNG, biogas or hydrogen as a fuel. If LNG or biogas is used, the methane from the gas is combined with recirculated water vapor from the exhaust to create hydrogen and carbon monoxide (CO). The SOFC generates electricity from the chemical reaction between oxygen in the air and hydrogen and carbon monoxide extracted from the fuel. The emissions are water and CO_2, but at 47% lower than the CO_2 emissions from conventional power generation, including the benefit of heating. Using green hydrogen as the fuel drops CO_2 emissions to zero. Of the eight sites currently using this technology in Japan, two are currently using hydrogen in their SOFC fuel mix. MHPS is currently testing a new 1MW capacity version of the SOFC.

SECTION 3: CONCLUSION

Hydrogen has found a way to the top table of global discussions about CO_2 emissions as policymakers realize that simply decarbonizing through renewable electricity will be insufficient to get us to the goal of net zero by 2050.

As its visibility continues to rise, it is clear that hydrogen can complement renewables and help decarbonize those parts that renewables cannot reach.

There is now a global effort across many industries and sectors to make hydrogen commercially viable for a range of applications. MHI Group companies are doing their part to deliver the technologies and solutions that will realize this potential, and help establish a viable market with robust demand for hydrogen over the next decade.