Hydrogen's Decarbonization Impact for Industry

Near-term challenges and long-term potential

Insight Brief

January, 2020

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Key Insights

- When considering what a global energy system on a 1.5°C or 2°C pathway will look like by 2050, hydrogen consistently plays a critical role as a low-carbon fuel. In fact, for several of the hydrogen application areas discussed in this Insight Brief, there are no other viable pathways to decarbonization.
- The abatement impact of hydrogen depends strongly on both the specific use case where it is implemented and the way it is produced.
- Hydrogen produced with grid power at the global average carbon intensity – or even with coal gasification – could be used to reduce carbon emissions in steelmaking today.
- Despite lower CO_2-intensity than most power grid-based hydrogen sources, there is no long-term role for steam methane reform (SMR) in decarbonizing industry sectors unless successfully fitted with carbon capture and storage (CCS).
- In the near-term, electrolysis using Chinese and Indian grid power is less CO_2-effective than coal gasification, and EU and US grid power is less efficient than SMR.
- In natural gas-based economies like the United States, the predominantly SMR-based existing hydrogen production plants are quickly on track to become less CO_2-efficient than electrolysis.
- Because electrolysis production with grid power will be at parity with SMR within the next 5-year period, EU and US policy should exclusively focus on electrolysis until CCS is a viable and scalable technology.
- Given the long lifetime of hydrogen generation assets, even in coal-heavy economies (such as China and India), any build-out of coal gasification has to be motivated with the belief in CCS retrofit in the 2030 – 2040 timeline.
- Near- and medium-term outlooks for power grid CO_2 intensity should be leveraged and implemented as a leading indicator for hydrogen policy.
- The alignment of high-potential for CO_2 reduction and the large-scale of off-takers in sectors like steel and shipping, where demand is naturally aggregated in ports, provides a pathway for policy makers to achieve demand at scale. This can significantly accelerate the cost reduction of electrolysis technologies.

Hydrogen's Role in the Energy Transition

When considering what a global energy system on a 1.5°C or 2°C pathway will look like by 2050, hydrogen consistently plays a critical role as an energy carrier. The industrial processes used in the production of things like steel, cement, glass, and chemicals all require high-temperature heat. Currently, this heat is produced by burning fossil fuels. For these hard-to-abate sectors, there is essentially no way to reach net-zero emissions at the scale required without using hydrogen.

Renowned institutes like the International Renewable Energy Agency, the Energy Transitions Commission, and the Hydrogen Council anticipate as much as 18 percent of final consumption to be provided by hydrogen by 2050.[i,ii,iii] Other, more opportunity-oriented assessments claim that hydrogen could emerge as a serious heads-on competitor to natural gas, which would open up a $1 trillion market driven by fundamental market economics, even without the help of having emission reduction policies in place.

How Green Is Hydrogen?

The Basics of Hydrogen's Abatement Impact

The abatement impact of hydrogen is determined by the combination of the CO_2 footprint of how it is produced and the emissions from the activity in which the hydrogen is being used.

The CO_2 emissions associated with producing hydrogen are closely linked to the technology used and the structure of the electricity grid providing power to the process. There are basically two categories of hydrogen production processes: one that extracts the hydrogen from water with electricity (i.e. electrolysis), and one that leverages fossil fuels as a source of energy and/or hydrogen.

When extracting hydrogen with or from a fossil fuel, such as natural gas, oil or coal, the emissions are anchored in the chemical reaction that is being catalyzed. In the case when electricity is used to run an electrolysis process, the associated emissions are caused by the CO_2 intensity of the electricity source.

Hydrogen from fossil fuel sources is often referred to as "gray" hydrogen, unless the facilities are equipped with Carbon Capture and Storage (CCS), in which case the hydrogen is called "blue" hydrogen. CCS on hydrogen assets has a capture rate range of as high as 90%,[iv] making this production route quite effective from a greenhouse gas perspective. Hydrogen produced with electrolysis is generally called "green" hydrogen, under the assumption that the supplied electricity is generated with renewable resources.

Today the absolute majority of hydrogen, 96%, is produced with fossil fuels, and virtually none of this production capacity is fitted with CCS. Only 4% is electric, claiming to source its power from renewables.

However, when designing policies and markets to achieve abatement, it is arguably relevant to look at the whole energy system, not just at a specific subsector. In the global energy transition, with the major thrust of decarbonization happening between now and 2050, we have to replace today's electricity production of 24,000 TWh with renewables,[v] and growth in population and wealth will add additional 23,000 TWh that needs to be generated from renewables.* This means we will essentially double our global electricity consumption in the next 30 years even without hydrogen. Successfully growing the green hydrogen economy would add another 20,000 TWh* to the challenge, effectively requiring us to build additional renewable capacity almost at the scale of the total current global electricity system—just to produce hydrogen.

If you operate under the assumption that all electricity will be carbon-free by 2050, and your policy and market goals are 30 years out, the current low share of green hydrogen is not a concern. However, in order to keep global warming below 1.5°C, we need to start reducing emissions immediately. Additionally, the argument that hydrogen production can absorb and consume otherwise curtailed electricity from renewables is weak as it assumes that no other industrial applications could leverage this market arbitrage.

It is also important to consider that when it comes to offsetting emissions, there is a range of use cases for hydrogen that are distinctly different. You often see hydrogen compared to fossil fuels by the use of gasoline gallon equivalents (GGE) or diesel gallon equivalents (DGE). However, this is not an apples-to-apples comparison. These conversion factors compare the thermal energy content of fuels. However, for the most obvious application of replacing diesel or gasoline in an internal combustion engine (ICE), the comparison fails to acknowledge that the powertrain of an ICE has an efficiency of around 20%, compared to 50% or higher efficiency for a fuel-cell electric powertrain.

And for the scenario for which this conversion makes sense—when fossil fuels are burned to produce heat—you are most likely displacing natural gas or coal, which means GGE and DGE are still not accurate comparisons. But there are also applications for hydrogen where it acts as a catalyst for a chemical reaction, in which the equation looks completely different.

CO_2 Intensity of Hydrogen Applications

Understanding the abatement impact of hydrogen on a level that provides useful guidance for policy makers requires a deeper understanding of different end uses where hydrogen could be used to displace fossil fuels. Across the five use cases we have analyzed, the CO_2 reduction effectiveness of a kilogram (kg) of hydrogen varies quite dramatically, by more than a factor of three. Figure 1 shows an overview of the analyzed cases.

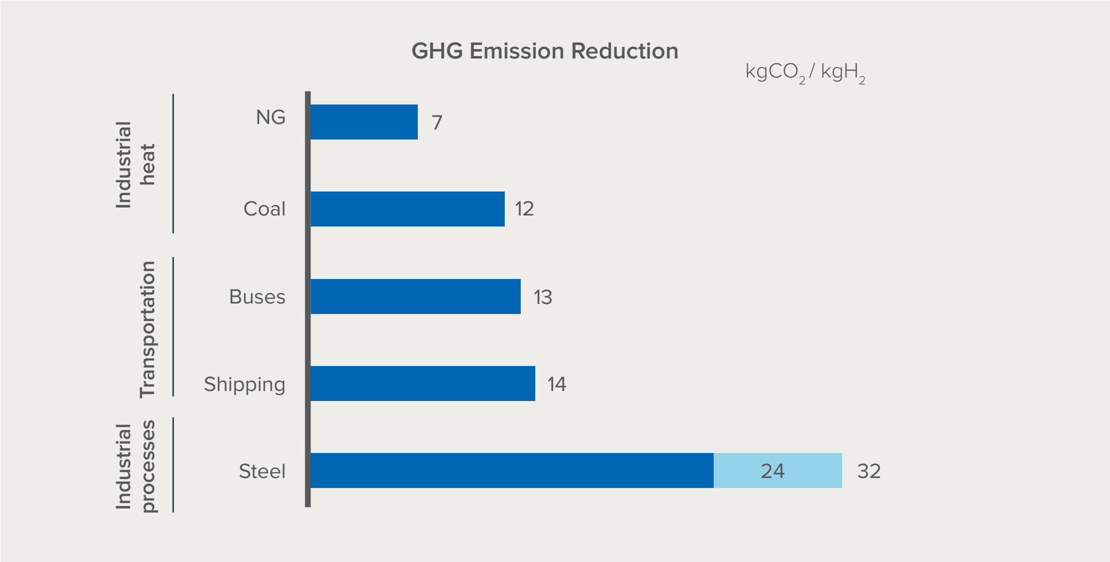
Steel Production

Using hydrogen for steel production is a technology currently in the late research and development stage, with the first pilot facilities being constructed. The objective is to replace the blast oxygen furnace (BOF) process, which is the prevailing technology for primary steelmaking and uses coking coal as both a source of heat and to reduce oxygen from the iron ore, with a process called direct reduction of iron (DRI).

* For this calculation we assume that a future efficiency of 45 kWh of electricity is required per kg of hydrogen produced, based on Pareek, Alka, Rekha Dom, Jyoti Gupta, Jyothi Chandran, A.Vivek and Pramod H.Borse "Insights into renewable hydrogen energy: Recent advances and prospects," Materials Science for Energy Technologies, January 2020, **https://www.sciencedirect.com/science/article/pii/S258929912030001X?via%3Dihub**

FIGURE 1

Achieved CO_2 emission reduction for each consumed kilogram of hydrogen



One of the pioneering companies developing the hydrogen-based DRI process, HYBRIT, has assessed the end-to-end energy consumption associated with both the new supply chain setup and the reference case of a blast furnace. The company's analysis also includes the mining activities to extract the iron ore from the ground. According to Hybrit's research, a blast furnace emits 1,600 $kgCO_2$ from the combustion of coking coal and oil to produce one ton of crude steel. The DRI route only emits 25 $kgCO_2$ while consuming approximately 50 kg of hydrogen, in turn using 2,633 kWh of power. This suggests an emission reduction effectiveness of 32 $kgCO_2$ per kgH_2.

But while this is an accurate calculation of achieved emission reduction for the consumed hydrogen, the DRI process creates an interim sponge iron product that needs to be processed in an electric arc furnace (EAF) to produce crude steel, the end product of BOF. To normalize the comparison with other end uses of hydrogen, the electricity consumption in the EAF of 855 kWh per ton of crude steel could have been used to produce another 16 kg of hydrogen, implying a normalized effectiveness of 24 $kgCO_2$ per kgH_2.

Transportation

The abatement efficiency of hydrogen used for transportation is impacted not only by the technology used to "consume" the hydrogen in the vehicle – either fuel cells or internal combustion – but also by how the hydrogen is carried to the point of consumption. For example, in shipping, it is likely that ammonia (NH_3) is a more practical carrier of hydrogen, since it is easier to transport and store, with a significantly higher energy volume density than hydrogen in its molecular form. Ammonia can be produced from hydrogen and can therefore be considered to be a hydrogen-based fuel.

Studies that look at total electricity consumption of fueling large fleets of vehicles with hydrogen have been leveraged to assess end-to-end efficiencies of using hydrogen to displace fossil fuels in transport sectors. For fuel cell-operated buses, the European public-private partnership The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has looked at the CO_2 emissions from replacing diesel buses in a number of European economies.[vi] Combining this assessment with the European Commission's database on CO_2 grid intensities for member countries enables the reconstruction of the line in Exhibit 1 representing buses.

For shipping, the European Federation for Transport and Environment looked at the electricity required to decarbonize European bunker consumption across a number of on-board technologies.[vii] While the results were rather similar, the line in Exhibit 1 represents on-board internal combustion engines operating with ammonia. In the analysis, the baseline footprint of bunker consumption is 300 $MtCO_2$ and the hydrogen route requires 1,190 TWh of electricity.

It is not surprising that the use cases for fuel cell buses and large ships are quite similar in Exhibit 1, arguably within the error margin of this analysis, since they both represent the use case of replacing fossil fuel with hydrogen to perform kinetic work.

Industrial Heat

Hydrogen can also be burned to generate heat, by many considered one of the few low-carbon options to achieve really high temperature process environments. In these applications, a direct comparison of thermal content of the different fuels applies, contrasted with the CO_2 emissions of the displaced fossil fuel.

Combustion of one mmbtu of coal leads to the emission of 95 kg of CO_2. In order to displace one mmbtu of coal, you need 8.07 kg of hydrogen, which in turn will require 440 kWh or electricity. The equivalent carbon emissions from the combustion of natural gas is 53 kg of CO_2 per mmbtu.

CO_2 Intensity of Hydrogen Production

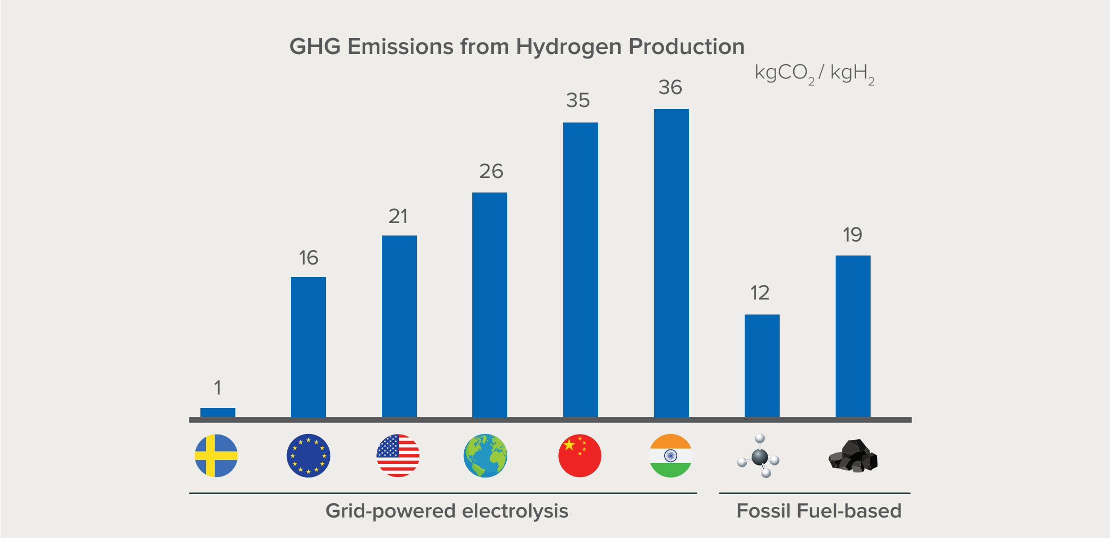
Traditionally, the absolute majority of all hydrogen in the market has been produced using fossil fuels, predominantly methane (CH_4) through Steam Methane Reform (SMR). Conveniently, SMR has some hydrogen embedded in the fuel in addition to what is stripped from water (H_2O), making the process significantly more effective from a greenhouse gas perspective compared to coal gasification. Depending on the cost of feedstock, it is generally the lowest-cost production route, also leveraging the benefit that large petrochemical complexes where hydrogen is both produced and consumed have access to natural gas.

Electrolysis

Producing one kilogram of hydrogen with electrolysis requires 50–55 kWh of electricity. This power consumption leads to indirect CO_2 emissions, the level of which varies according to the sources of electricity used. Exhibit 2 shows how the CO_2 intensity of power grids vary widely across markets, with the global average being around 0.48 kgCO2/kWh, India around 0.67 $kgCO_2$/kWh and Sweden at 0.02 $kgCO_2$/kWh or lower, depending on how emissions are allocated to power or heat production in combined heat and power plants.

FIGURE 2

Emitted CO_2 in the production process of hydrogen



Fossil Fuel-Based Hydrogen

The emissions of CO_2 from hydrogen production are independent of the grid intensity of the location, since the process requires a negligible amount of electricity. But an SMR plant emits between 8 and 12 kg of CO_2 for each kg of hydrogen produced, while coal gasification results in 18 – 20 kg CO_2 per kg hydrogen. Noticeably, fossil fuel-based production is a rather CO_2-effetive way of producing hydrogen with the current generation mix in many grids. Specifically, SMR is more effective than grid-powered electrolysis in both the United States and Europe, while coal gasification is more effective in China and India.

Policy and Market Implications

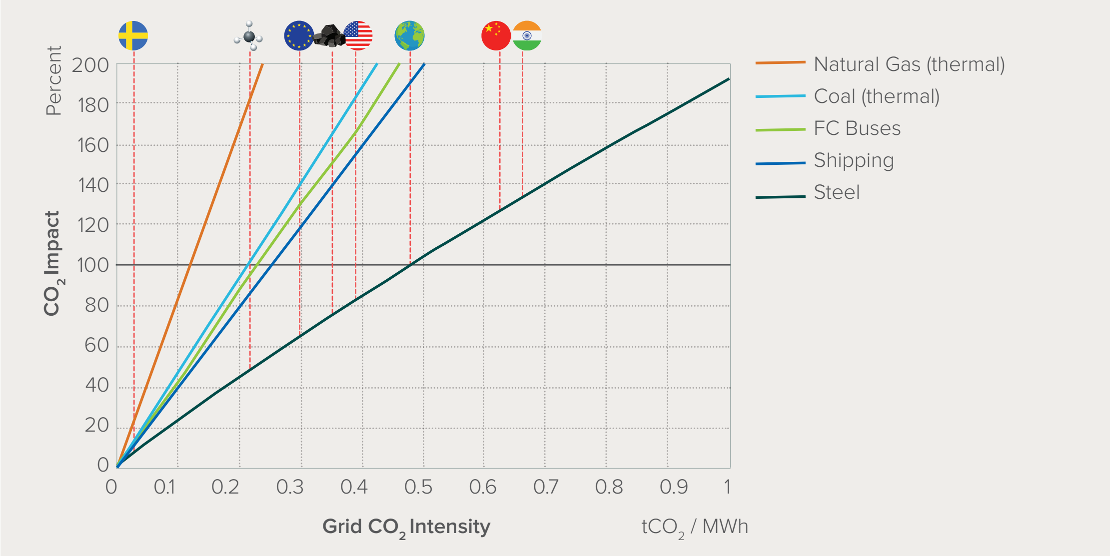
Effective policy and market design to facilitate decarbonization takes into account both the effectiveness of the production route and the impact for the sectors where the transition to hydrogen is supported. As shown above, there are many factors influencing both aspects of the transition, making it a rather complex regulatory topic.

Exhibit 3 shows an overview of five selected applications that are often discussed in the context of hydrogen's role in the future energy system. Since the emission intensity measures of the different use cases are related to different outputs (passenger miles, ton-km goods transported, tons of steel produced or mmbtu of heat provided), the graph has normalized the y-axis to an index of 100 = current emissions. The x-axis represents the CO_2 intensity of the power used to produce the hydrogen with an electrolyzer, assuming an efficiency of 55 kWh per kg of hydrogen.

Each line in the graph represents a use case, where the achieved abatement for a specific electricity efficiency can be read as the difference between the index line and the use case. If the line is in the lower half of the graph, using hydrogen leads to a lower CO_2 footprint, otherwise it will lead to increased emissions.

FIGURE 3

GHG impact of shifting to hydrogen for selected use cases and production routes



Fundamental Rationale for Hydrogen

For several of the hydrogen application areas, it is important to remember *that there are no other viable pathways to decarbonization*. Therefore the dilemma for policy making is similar to what has been acknowledged for battery electric vehicles (BEVs): that waiting for electricity to be clean enough to achieve immediate decarbonization as drivers abandon conventional cars will unacceptably delay the timeline of the transition.

The same is true for hydrogen. If we delay the fuel shift in heavy industry, shipping, heavy transport or other sectors, by the time there is a supply of green hydrogen at scale, we will already be overshooting a 1.5°C pathway.

Also, early demand is critical to stimulate investments in the technologies that provide low-carbon hydrogen, whether it’s renewably-powered electrolysis or CCS, which will allow them to come down in cost to a point where they are competitive for end users.

With all that said, there is still value in considering the near-term dynamics of the supply chain. With policy intended to guide us towards a 2050 outcome, this will implicate business and investment decisions made today.

Steel, the No-Regret Sector

With quite a broad margin, using hydrogen for steel making has the highest decarbonization impact of the analyzed use cases. This is because the hydrogen is not only used for heat but also as a catalyst in the process where prevailing technology uses coal, generating water vapor (H_2O) instead of carbon monoxide (CO) and carbon dioxide (CO_2).

Figure 4(a) shows only the steel curve in our synthesis framework, calling out the impact of hydrogen from different production routes. It's worth highlighting that:

- Using global average grid power for electrolysis, using hydrogen instead of coke will significantly lower the carbon intensity of the steel-making process.
- In many developed economies where power grids have less CO_2-intensive generation sources, electrolysis can immediately start decarbonizing this "hard-to-abate" industry.
- For economies with a large portion of coal power in their grid, like India and China, hydrogen can still reduce emissions in the steel industry, even if produced via coal gasification.

In summary, from a CO_2 abatement perspective, there is no reason to wait with transitioning the steel industry from BOF to HDRI technology. By the time new steel-making technologies are available at commercial scale around 2030, the immediate impact for each replaced blast furnace will be immediate and significant.

SMR, the Zero-Impact Route

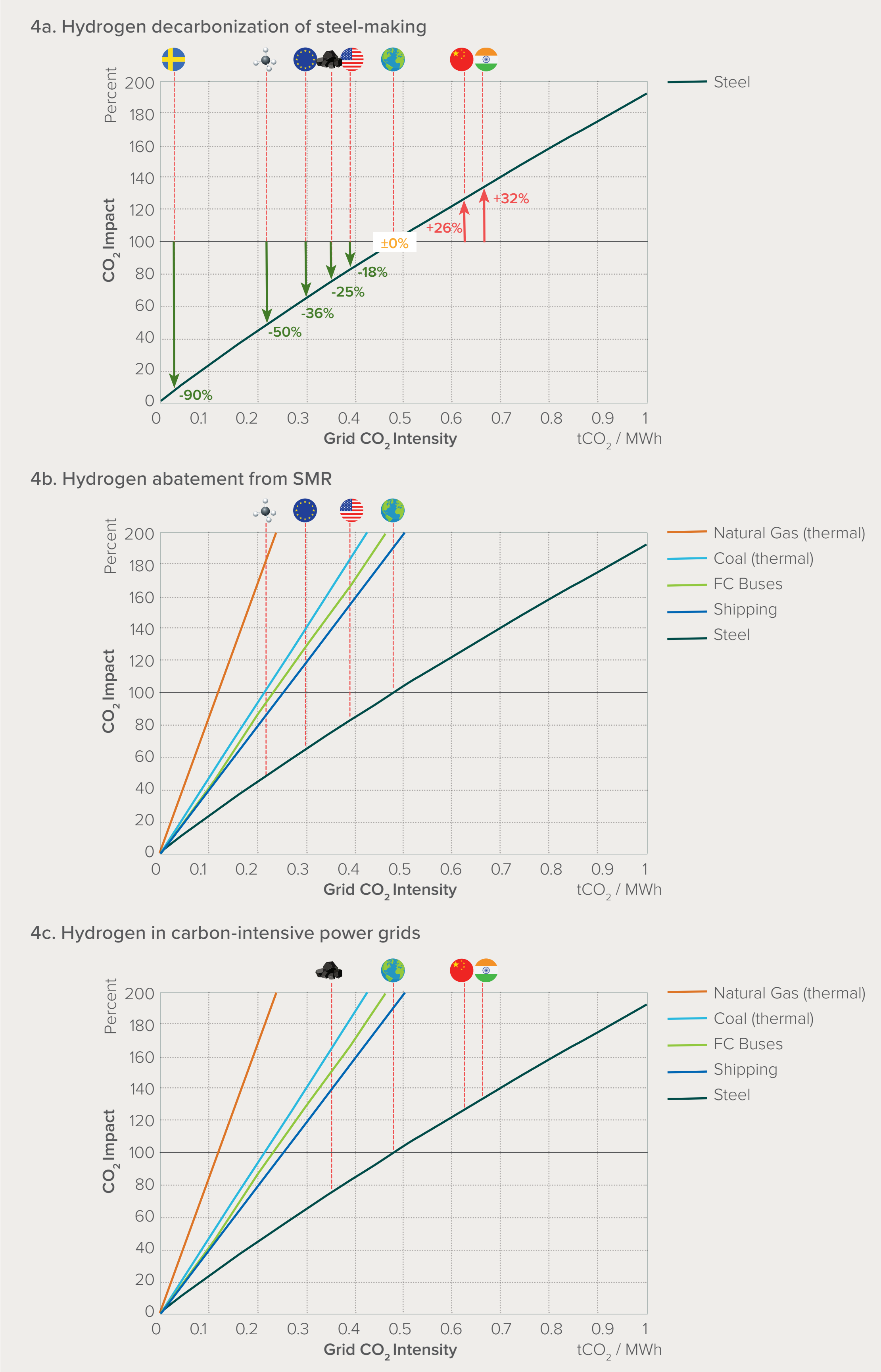
At first glance steam methane reform (SMR) comes across as comparably attractive from a CO_2 reduction perspective, with better performance than for example electrolysis using either current European or United States grid power. However, as Figure 4(b) shows, there are not many use cases where the hydrogen produced with SMR will actually reduce the CO_2 emissions from the application. A few observations:

- It is not surprising that combusting hydrogen generated with methane to replace combustion of natural gas – which is in essence methane – is not effective.
- Transportation applications, both shipping and fuel cell buses, are at break even with SMR hydrogen.
- While steel making with hydrogen from SMR reduces emissions by approximately 50%, the same emissions reduction can be achieved by using natural gas directly in a Direct Reduction process, avoiding the added cost of transforming the methane to hydrogen.
- SMR is more CO_2-efficient than using grid-powered electrolysis in most economies, but in contrast to electrolysis, the CO_2 intensity of SMR is constant, while electricity grids gradually improve over time.

All in all, while not having a negative effect on greenhouse gas emissions, SMR produces hydrogen with at best break-even performance. Therefore unless Carbon Capture and Storage (CCS) technologies are installed on the SMR assets, there are no scenarios or use-cases where CO_2 emissions are reduced. Generating hydrogen with SMR (without CCS) simply has no abatement impact.

FIGURE 4

Interpreting the abatement impact of Hydrogen



Coal Gasification Beats Coal Power

Figure 4(c) highlights one of the more controversial insights that can be extracted from this analysis: Hydrogen produced through coal gasification has a lower CO_2 footprint than electrolysis using power from a grid that is dominated by coal power (e.g., China and India). Thermodynamically this is not a major surprise, given the significant heat losses that an average coal power plant experiences, operating at efficiencies around 45%.

Practically, this provides an opportunity to start decarbonizing steel making, a heavy industry sector that is considered one of the hardest to abate, without waiting for the build-out of renewables in these economies. It also provides an opportunity for a smoother transition for the coal industry.

Planning Ahead for Effective Transition

The CO_2 intensity of power generation has been changing rapidly in the last decade, a trend that is projected to accelerate. This is particularly true in the outlooks that are adhering to global warming well below 2°C. As Figure 5 shows, some of the insights from the static view of current emission intensities will be obsolete already within the next 5 years, which in many cases is less than the implementation timeline for new policies.

Specifically, the EU and the United States are anticipated to have grid power that enables electrolysis to produce hydrogen more effectively than SMR in 2023 and 2027, respectively. This also means that hydrogen from electrolysis can be used to decarbonize thermal use of coal in industry on the same timeline.

The transportation sector can be targeted for decarbonization with hydrogen in the early to mid 2020s in the EU and the United States, and in the mid 2030s in China and India. It will take another ten years, until 2029, for both India and China to have clean enough power supply to beat coal gasification from a CO_2 perspective. However, every economy that we analyzed will be able to generate hydrogen that is more CO_2 effective than natural gas for industrial thermal use before 2040.

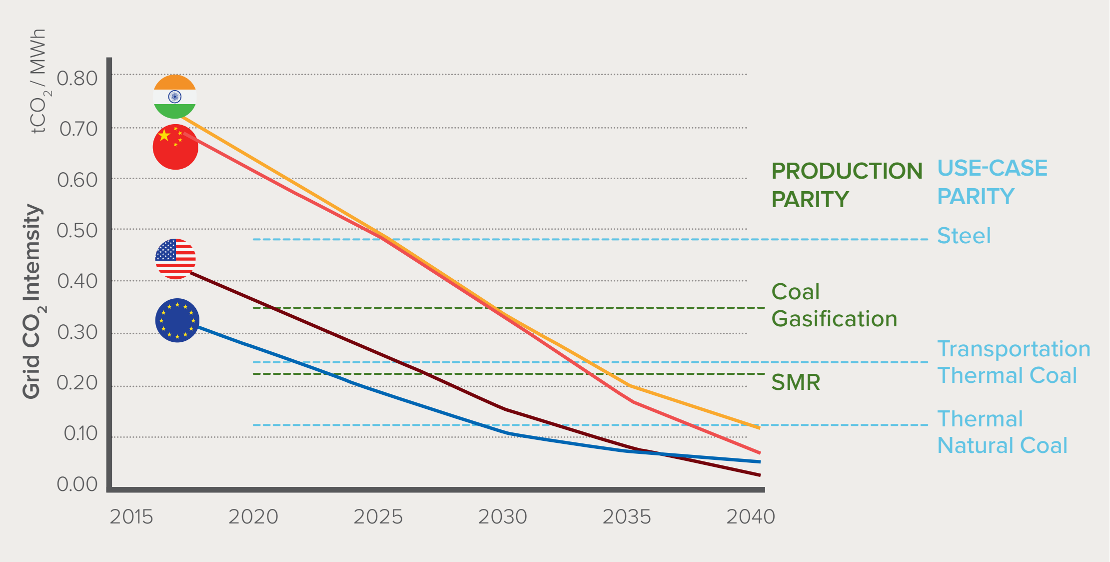
Practically, this means that the efforts of building a hydrogen-based energy system in Europe and the United States should likely focus exclusively on electrolysis, given that the production parity with SMR is achieved before 2025, which is arguably on a timeline comparable with the project development timeline of large-scale industrial capacity build-out combined with the timeline of implementing policy. While SMR is competitive from a CO_2 performance within this 5–10 year period, policy makers should keep in mind that investments made in this period will lead to assets with 20–30 year lifetimes or more.

For economies with a power supply that relies more heavily on coal power plants, like China and India, there seems to be a role for SMR, or even coal gasification, in the period up until 2030. However, hydrogen production plants, like most other heavy industry assets, have an anticipated productive lifetime of more than 20 years, which means that they will quickly become a burden to the CO_2 footprint of these countries within their lifetime.

Policy makers should take into account for their system cost analysis that a retrofit of CCS technology on these assets will be required to stay on the lowest-CO_2 pathway, in order to avoid this outcome.

FIGURE 5

Projected CO2 intensity of power in sustainable development scenarios



The current installed base of hydrogen production capacity is predominantly (>90 percent) based on SMR and coal gasification technologies. With the outlooks of IEA and other energy transition scenarios, these assets are looking at being outperformed by electrolysis in major economies within the next 5 years, also in markets like the United States that are relying heavily on natural gas for energy.

Keeping in mind that these scenarios are often not great projections of actual outcomes beyond 5–10 years, policy making should be aligned around the intent of steep decarbonization across utility markets and industrial energy use. It would also be wise to use the power intensity of the grid as a leading indicator for policy implementation. This is particularly true in markets like India where the anticipated development of the power system follows steep outlooks which imply significant shifts in trends from progress to date.

Balancing Production and Fuel-Shift Incentives

The hydrogen opportunity exists in a dynamic market context, where the impact of different technologies is a moving target and the current asset base is soon expected to be underperforming. Generally, in setting decarbonization policies for energy systems, there is a tendency to regulate the production assets, whether through carbon taxes or investment subsidies. However, for hydrogen there is arguably a case to be made for regulating the consuming sectors more actively, for two main reasons:

1. There is value in promoting transition in the sectors where CO_2 impact is the highest ahead of others, while the production base is still evolving.

2. Consumer regulation effectively sets a higher price in the traded marketplace for hydrogen, instead of subsidizing emerging technologies to be competitive at a low price point. Counterintuitively this can benefit a smooth transition by enabling existing assets and near-term investments to service debt and achieve financial returns in a timeline where they will need to be decommissioned or retrofitted with CCS.

There is not a strong case for exclusively implementing either demand-side or production-side policies for hydrogen. Instead, it is a market-by-market consideration that will evolve over time from a focus on achieving demand uptake, to accelerating deployment of low-carbon technology. As there is more demand for hydrogen, we will need less regulatory intervention.

Achieving Scale

Reducing the cost of emerging technologies for hydrogen production, in particular electrolyzers, is a critical enabler of hydrogen adoption. This is true whether it's supported by demand- or supply-side policy. As for many technologies, two of the main drivers of cost reduction are:

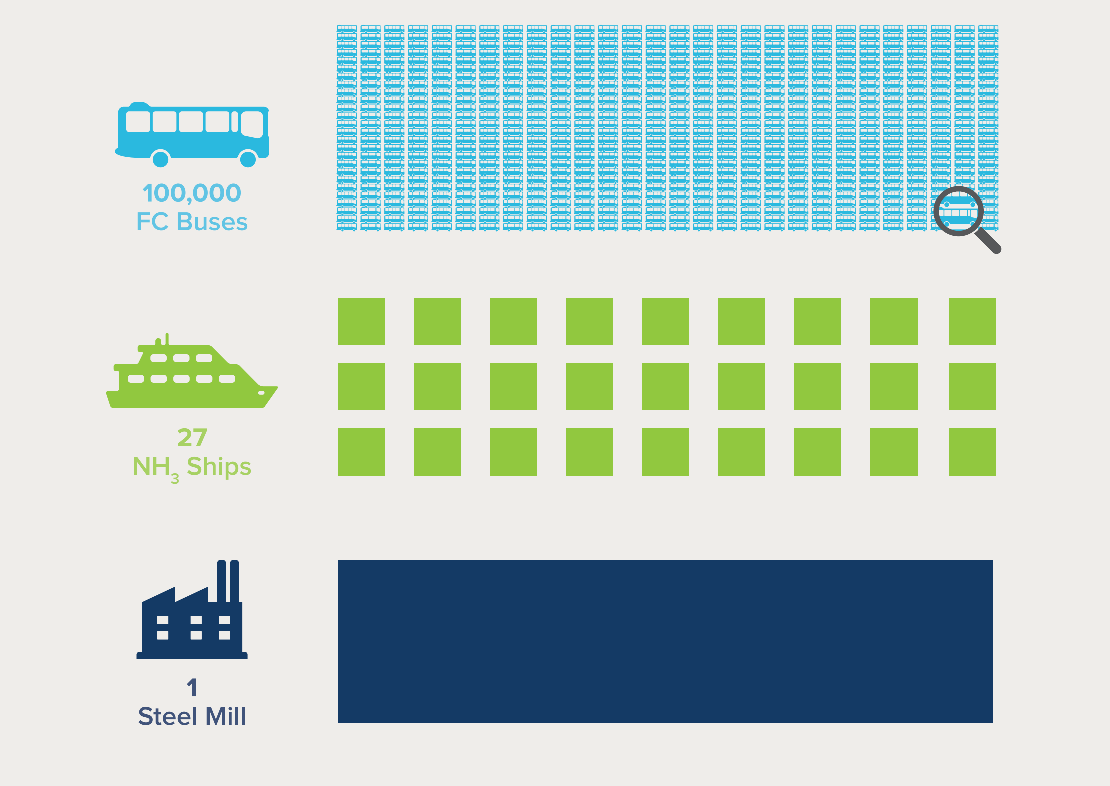
1. Supply-chain learning from a growing market and installed base
2. Scale of production assets, monetizing economies of scale in both construction and operations

For both of these drivers, regionally concentrated scale is critical. While many market speculators are betting on a future with global seaborne trade of hydrogen, such an end state will require significant lead time. Also, regional infrastructure, such as pipelines and other distribution options, will not be available immediately. This means that production capacity will be highly contingent on local and regional demand.

Figure 6 visualizes the relative unit-level demand of hydrogen applications, which varies by as much as five orders of magnitude. Specifically, replacing a typical blast furnace requires the same amount of hydrogen as 100,000 fuel cell buses, which in turns can be compared with the equivalent demand of 27 large 8,000 twenty-foot equivalent unit container ships.

FIGURE 6

Supplied units from 1 GW of electrolysis capacity in selected sectors



Given the complexity of emerging hydrogen opportunities it is helpful from a policy perspective that there seems to be some alignment between the sectors with the highest CO_2 reduction impact and where the scale of demand is highest per off taker. The specific cost competitiveness that market-level policies will need to catalyze is highly dependent on other regional factors, such as natural gas and electricity prices, and will in any case need to be analyzed and tailored to each market's needs.

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