TECHNICAL REPORT FEBRUARY 2025

Hydrogen Guardrails

Guiding Hydrogen Deployment for Industrial and Heavy Transport Decarbonization

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Executive Summary

Hydrogen is an indispensable industrial feedstock for many crucial industries such as fertilizers (ammonia), fuel production, and clean steel production. Hydrogen consumption is expected to reach 100 Mt in 2024, yet its production remains predominantly from fossil fuels, mostly through natural gas followed by coal, which are carbon-intensive processes with significant climate impact. Hydrogen's annual emissions amount to ~1.3 Gt of CO_2eq, or ~2.5% of global emissions. Only a symbolic volume of hydrogen, less than 1%, is produced from renewable electricity or with carbon capture and storage (CCS). According to the IEA, a fourfold increase in hydrogen demand is expected by 2050 if it is used throughout the economy. As it is so energy intensive to produce, hydrogen does not lead to energy security; therefore, it should first be deployed in those sectors in which it is needed as an indispensable feedstock (fertilizers, steel, or fuels production) i.e. in industries that already consume hydrogen today, before considering novel sectors and uses.

All low-carbon or renewable hydrogen production pathways come with challenges pertaining to scalability, cost, and/or energy consumption, resulting in less than 5% of announced renewable hydrogen projects in 2024 receiving final investment decisions (FID). Additionally, hydrogen faces upstream challenges in handling, transport, and storage. The current natural gas infrastructure is incompatible with pure hydrogen streams, and low emissions savings would be achieved if hydrogen were to be blended with natural gas. Finally, hydrogen is not a drop-in fuel that can replace other hydrocarbon fuels in all applications. Hydrogen is more prone to explosions and fires, takes up more storage space, provides lower energy per unit volume, and differs in its flame properties when compared to hydrocarbon fuels.

As clean hydrogen will continue to remain scarce in the near future, and the main green production pathway is dependent on clean electricity, hydrogen must first be prioritized for sectors that are currently or will be dependent on it as a feedstock, such as refineries, chemicals, and steel.

Hard-to-abate sectors with limited direct electrification potential, such as aviation and shipping, should receive priority access to clean hydrogen once hydrogen-dependent sectors have transitioned to clean hydrogen or when clean hydrogen is available in such abundance that it allows including these sectors.

Sectors where electrification will deliver the most effective decarbonization solution, such as road transport, buildings, and power generation, should be excluded from hydrogen deployment strategies or public funding support as direct electrification brings about the most effective emissions savings with the lowest carbon abatement costs in these cases.

This report provides policymakers with guardrails for the development and deployment of clean hydrogen to decarbonize industrial processes and heavy transport. It aims to encourage clean hydrogen use where it can achieve significant emissions reductions or serve as an essential industrial feedstock. The report recommends key parameters for consideration, such as techno-economic analyses and lifecycle greenhouse gas emissions assessments, to evaluate hydrogen's effectiveness against other climate solutions. These insights are intended to inform public policy design and ensure subsidy schemes for clean hydrogen that result in the most efficient use of public funds.

Recommendations

1. Decarbonize current hydrogen uses

- Clean hydrogen's critical role in facilitating emissions reductions in sectors such as refining, chemicals, and steel must be prioritized. A facts-based allocation of scarce resources, such as renewable electricity and green hydrogen, that prioritizes sectors currently dependent on hydrogen is key. Ramping up renewable electricity deployment to bring down green hydrogen costs and supplementing supply with low-carbon and novel hydrogen sources can help reduce bottlenecks. It is necessary to assess the feasibility of decarbonizing existing hydrogen production assets through the deployment of carbon capture and storage paired with strict methane emissions control.

2. Prioritize hard-to-abate sectors

- Clean hydrogen will play a key role in sectors where direct electrification is not a viable decarbonization option, such as long-haul aviation and shipping. In these sectors, hydrogen will be used as a feedstock for the production of sustainable alternative fuels. Clear national strategies for clean hydrogen deployment that prioritize hard-to-abate sectors, with targets that provide long-term visibility for hydrogen and alternative fuels coupled with incentives to close the commercialization gap, are needed.

3. Abandon incompatible sectors

- Science-based guardrails are needed to prevent the use of hydrogen in sectors where other more effective and efficient decarbonization strategies can be deployed (e.g., road transport, heating). To this end, national strategies should exclude hydrogen-incompatible sectors and avoid technology openness in sectors where effective decarbonization solutions, such as direct electrification, have been established. Awareness must be raised amongst all stakeholders on the challenges and limitations of clean hydrogen.

4. Invest in RD&D

- Investing in RD&D is crucial to closing the commercialization gap and ramping up clean hydrogen production to help meet current and future hydrogen needs. It is crucial to fund commercially viable clean hydrogen production pathways, invest in innovative supplementary pathways, and accelerate RD&D to overcome upstream challenges, and ensuring public funds are invested in hydrogen projects that will supply hydrogen to industries where it is an indispensable feedstock or fuel.

Guardrails for Hydrogen Deployment in Non-Priority Sectors

When designing public policy frameworks to support hydrogen development and deployment in sectors beyond the highest priority areas, the following guardrails should be applied. If these criteria reveal that hydrogen results in the highest total carbon abatement cost and an inefficient use of clean energy, policymakers should avoid allocating public funds to hydrogen in those sectors, as this would lead to a wasteful use of both public resources and decarbonized energy.

Buildings

A techno-economic analysis, based on the levelized cost of hydrogen (LCoH), lifecycle GHG emissions reductions, and the total carbon abatement cost of deploying hydrogen versus heat pumps should be included in any public policy framework that seeks to support hydrogen deployment to decarbonize buildings.

Road transport

A detailed analysis, based on the total cost of ownership of the vehicle, lifecycle analysis, and the total carbon abatement cost of deploying hydrogen versus direct electrification should be included in any public policy framework that seeks to support hydrogen deployment to decarbonize road transport.

Electricity generation

A techno-economic analysis, based on the levelized cost of electricity (LCoE), lifecycle emissions reduction, and the total carbon abatement cost of deploying hydrogen versus direct electrification should be included in any public policy framework that seeks to support hydrogen deployment to decarbonize the grid of the economy.

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Introduction

In 2022, 95 Mt of hydrogen were produced, mainly for use in refining and industry, with production predicted to reach 100 Mt in 2024 [1] [2]. As seen in Fig 1., most of the hydrogen produced today is still generated from fossil fuels through high-polluting pathways. Currently, 62% of hydrogen is produced from natural gas via steam methane reforming (SMR), while 37% is produced from coal and byproducts [1] [2]. These two main production pathways are carbon-intensive, with natural gas releasing 10 – 17 kg of CO_2eq and coal releasing 15 – 30 kg of CO_2eq per kg of H_2 produced [3]. Less than 1% of the hydrogen produced today is generated with renewable electricity or carbon capture and storage (CCS) [1] [2]. These clean pathways have the potential to reduce CO_2eq emissions to <10 kg per kg of H_2 produced, with higher emissions savings if renewable electricity is deployed [3].

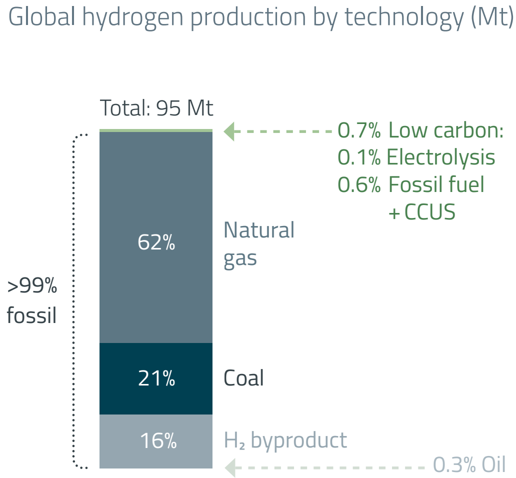

Figure 1: Total hydrogen production in 2022 with a breakdown based on production method from FCA's hydrogen factsheet, based on IEA data [2] [4].

Currently, hydrogen production is responsible for 1.3 Gt (~2.5%) of global CO_2eq emissions annually [5]. 2050 scenarios estimate a fourfold[1] increase in hydrogen demand compared to today's levels, as seen in Fig 2., which makes decarbonizing existing and future hydrogen production of the utmost importance [6].

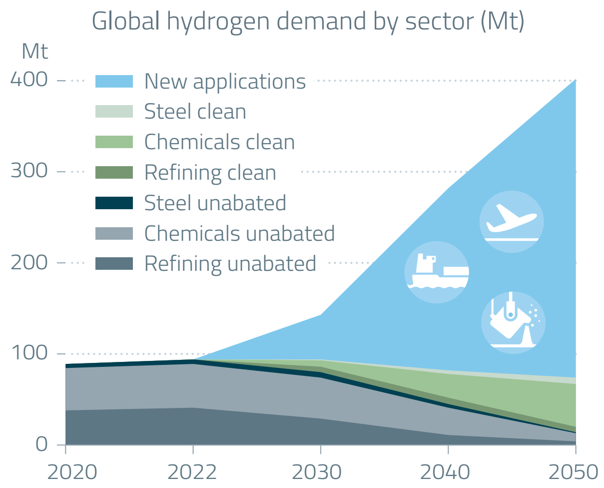

Figure 2: Current and projected global hydrogen demand by sector from FCA's hydrogen factsheet, based on IEA data [4] [6].

Producing hydrogen is an energy and carbon-intensive process that is still heavily reliant on fossil fuels. Therefore, efforts must first prioritize the decarbonization of current hydrogen uses before allocating clean hydrogen[2] to new sectors. Even if hydrogen is produced using clean processes, it should not be deployed in all sectors of the economy. Policies that support the development and deployment of hydrogen should exclude sectors where direct electrification is a viable technical and economic option, such as power generation and road transportation.

Clean hydrogen should only be deployed where it is needed as an indispensable feedstock (fertilizers, chemicals, steel, or in refining) or where there are no other technically viable or cost-effective solutions to reduce emissions effectively.

The State of Hydrogen in Europe

Over 550 hydrogen production sites are currently operational in Europe, with a total production capacity of 10.8 Mt/year. More than 95% of that is produced from fossil fuels [7]. Over 50% of this production is concentrated in six EU countries: Germany, Netherlands, Poland, Spain, Italy, and France [8]. Germany is Europe's largest hydrogen consumer and producer, with an estimated demand of approximately 1.4 Mt per year in 2023 [8]. Total hydrogen demand in Europe has decreased in recent years, falling ~3% to ~7.9 Mt/year in 2023[3], relative to 2022, which amounts to ~9% of global demand [7] [8]. Hydrogen is an indispensable industrial feedstock, predominantly used in refineries (~58% of European demand), ammonia production – mainly for fertilizer synthesis – (~25%), and methanol and other chemicals (~11%) [7] [8]. Hydrogen demand for ammonia has decreased by 36% relative to 2020 levels due to high natural gas prices, which has forced the closure of numerous ammonia plants, in addition to leading existing ones to operate at low-capacity factors [7]. However, ~96% of hydrogen produced in Europe

[1] This fourfold increase includes projected demand across all sectors of the economy. However, this demand increase should be critically assessed to ensure that hydrogen is not deployed in regret sectors, as this would lead to higher clean hydrogen demand than necessary and inefficient use of clean energy.

[2] For the purpose of this report, "clean hydrogen" refers to hydrogen produced through pathways that achieve significant greenhouse gas emissions reductions across the entire value chain compared to fossil-based hydrogen. The clean hydrogen lifecycle emissions methodology should account for upstream and embodied emissions (e.g., methane leaks). The European Union has defined renewable and low-carbon hydrogen under the Renewable Energy Directive and the Decarbonised Gas and Hydrogen Package, enacted in 2024. The methodology for calculating the lifecycle emissions reductions of low-carbon hydrogen will be detailed in a Delegated Act under the Gas Package.

[3] This includes the EU27, United Kingdom, Norway, Iceland, Liechtenstein, and Switzerland.

is still from unabated fossil fuels, mainly through natural gas, and its production process is emissions intensive, making up ~3% of the EU's annual emissions [7] [9].

In a decarbonized world, in addition to current industrial uses, clean hydrogen will be needed in larger quantities as a feedstock for producing primary steel and for novel uses in the production of alternative fuels, such as sustainable aviation fuels (SAFs).

Prioritizing clean hydrogen production is necessary, whether for decarbonizing existing hydrogen applications or supporting emerging sectors. Additionally, identifying and excluding sectors where hydrogen is not the most effective decarbonization solution is key to ensuring this scarce resource is allocated to the sectors where its carbon abatement potential is optimal. This is crucial as hydrogen can divert clean electricity deployment from sectors where it could deliver higher emissions abatement at lower cost.

Hydrogen Production

Currently, more than 99% of hydrogen is still produced from fossil fuels, including byproduct production from refinery processes [2]. Clean means of producing hydrogen include low-carbon or blue hydrogen produced from natural gas coupled with carbon capture and storage (CCS), which should be paired with strict methane leak controls; biogenic hydrogen, using biogenic methane with or without CCS; and renewable hydrogen (green), from water electrolysis using renewable electricity.

All low-carbon solutions come with challenges. Blue hydrogen requires additional capital expenditure for the capture units and energy consumption, thereby increasing the levelized cost of hydrogen (LCoH) compared to unabated fossil hydrogen. While the technology for biogenic hydrogen production is mature, the process requires scarce feedstock in the form of biomethane. Green or renewable hydrogen is energy-intensive due to the strong chemical bonds in the water molecule that need to be broken and the inefficiencies in the electrolysis process. Novel electrolyzers have reported efficiencies above 80%, but even with an ideal 100% efficiency, thermodynamic limitations require a minimum of 33 kWh/kg of H_2 produced to break the chemical bond of water and produce the required hydrogen [10].

Aside from challenges in procuring clean hydrogen, handling, transporting, and storing hydrogen poses challenges as well. With hydrogen being the lightest gas, and both colorless and odorless, it spreads quickly and is hard to detect in case of leaks. Additionally, hydrogen's wide flammability range and high flame speed mean that the hydrogen could easily ignite and spread in case of a leak [11] [12].

While hydrogen can be blended with natural gas up to a certain limit, its lower energy content per unit volume (1/3 that of natural gas) leads to lower emissions savings. Blending 20% hydrogen with 80% natural gas leads to only 7% emissions savings per unit volume [12] [13]. Additionally, hydrogen cannot replace natural gas in existing pipelines for multiple reasons: hydrogen is the smallest molecule and thus can permeate throughout a material leading to embrittlement. Hydrogen also requires higher compression rates, as it is transported at higher pressures than natural gas and is prone to leaking [11] [14].

Contrary to popular belief, hydrogen is not a 'drop-in' alternative for hydrocarbon fuels, as is shown in Fig. 3. Its lower density means larger storage space is required, and its lower energy density means larger volumes of hydrogen are needed to achieve the same energy output (three times relative to natural gas) [12]. Additionally, hydrogen flames do not generate radiative heat transfer as hydrocarbon flames do and thus would not be suited for applications where high radiative heat transfer is required, such as in a cement kiln [11].

Finally, clean hydrogen is more expensive than conventional hydrogen, whether it is produced from fossil fuels with CCS or from renewable electricity, as can be seen in Table 1. Therefore, the green premium on clean hydrogen must be reduced to facilitate its increased uptake. There are, however, limitations: blue hydrogen incurs additional capital expenditure (CAPEX) and operating expenditure (OPEX) relative to unabated fossil-based or grey hydrogen, as equipment and clean energy is required to capture CO_2 from a conventional hydrogen production process. For green hydrogen, OPEX costs are key. This is due to the high electricity requirements in hydrogen electrolysis, which alone are the largest contributor to the LCoH at ~40% or higher [7] [15]. These high electricity requirements lead to a high LCoH that can be more than six times the cost of fossil hydrogen.

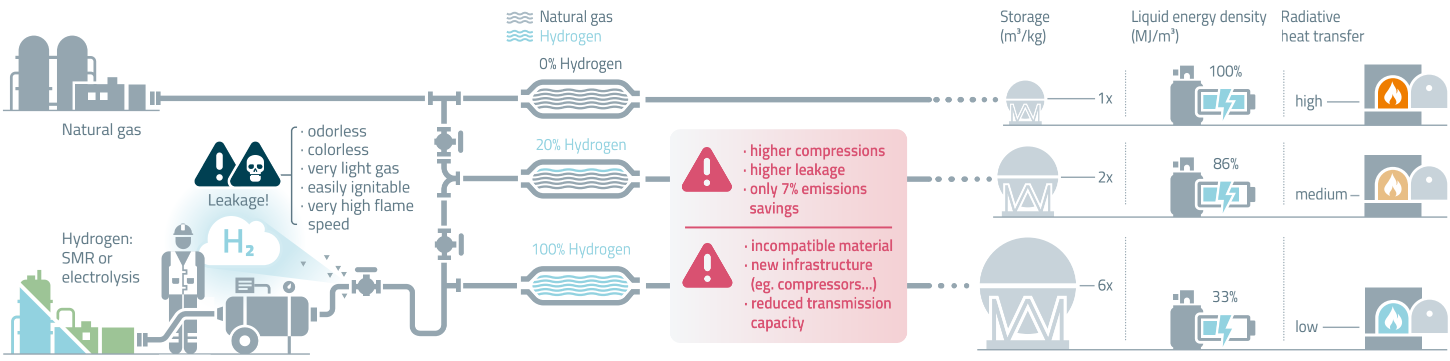

Figure 3: A comparison of storage requirements, liquified specific energy, and radiative heat transfer for a 100% natural gas stream, 80% natural gas 20% hydrogen blend, and a 100% hydrogen stream from FCA's hydrogen factsheet [4] [11] [12].

Table 1: Global average levelized cost of hydrogen (LCoH) for grey, blue, and green hydrogen from BNEF and TNO [15] [16].

Grey hydrogen	1 – 3 $/kg
Blue hydrogen	2- 5 $/kg
Green hydrogen	5 – 15 $/kg

The State of hydrogen projects

Box 1

As was seen in Fig. 2, a fourfold increase in hydrogen demand is expected by 2050, but production today is still predominantly from fossil fuels. In 2024, ~37 Mt/year of renewable hydrogen production projects have been announced globally, but <5% of those have received a final investment decision (FID), while ~25% have been received for fossil + CCS projects [2]. Announced projects by 2030 amount to ~66 Mt/year of low-carbon hydrogen. If all are successful, they will only be able to satisfy less than 50% of the projected needs for 2030 [2]. However, it is unlikely that all announced projects will reach FID given the historical trends of <10% FID [2]. As for the EU, 14.4 Mt of clean hydrogen production projects have been announced, but only 4% are currently under construction [7]. Therefore, it is important to prioritize the sectors with the most urgent need for hydrogen and eliminate those sectors with more effective decarbonization solutions, as will be discussed in the coming sections. **Policymakers must create an adequate policy framework to ensure that hydrogen will be deployed where it will be an indispensable feedstock and where it will deliver significant emissions reductions at the lowest cost of abatement.**

High- and Medium-Priority Sectors

Chemical industry

Ammonia and methanol production are some of the largest consumers of hydrogen currently and are responsible for ~50% and ~27% of the total hydrogen consumption globally and in Europe, respectively [2] [7] [8]. Most of this hydrogen is currently produced on-site, where it is ultimately used as a chemical feedstock to synthesize ammonia and methanol.

Ammonia

Currently, the main use for ammonia is in fertilizers (70% of global demand, 80% of which is in the form of urea) [17]. Ammonia is a building block for all mineral nitrogen fertilizers and therefore is of the utmost importance for Europe's agricultural sector and food security. The remaining 30% of ammonia is deployed in various industrial applications, such as plastics, explosives, or cleaning products [17]. In nearly all ammonia applications, ammonia is a precursor to final products. Only 2% of the ammonia currently produced is used as a final product [17].

Global ammonia production today requires 32 Mt of hydrogen and directly emits 450 Mt CO_2 annually (~1.3% of global annual energy-related CO_2 emissions). It is thereby the largest emitter in the chemicals sector [2] [17]. ~ 400 Mt CO_2 or ~90% of the emissions are due to unabated hydrogen production mainly from natural gas [2]. Based on global averages, the production of ammonia is very carbon intensive, at 2.4 t CO_2/t. For comparison, steel's carbon intensity is 1.4 t CO_2/t and cement's is 0.6 t CO_2/t, as shown in Fig. 4 [17].

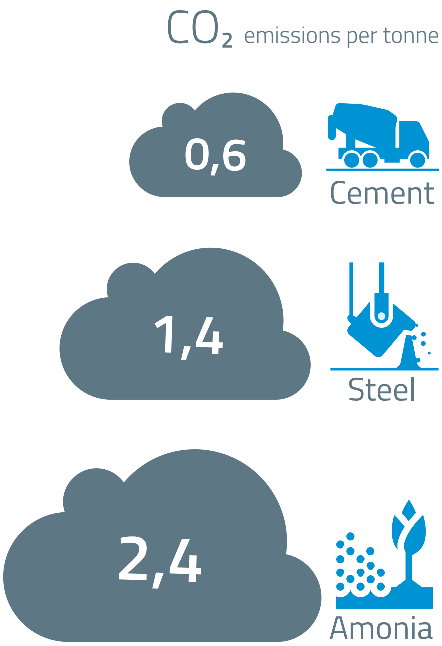

Figure 4: Graphic comparison of the carbon intensity of producing one tonne of ammonia, steel, and cement [17].

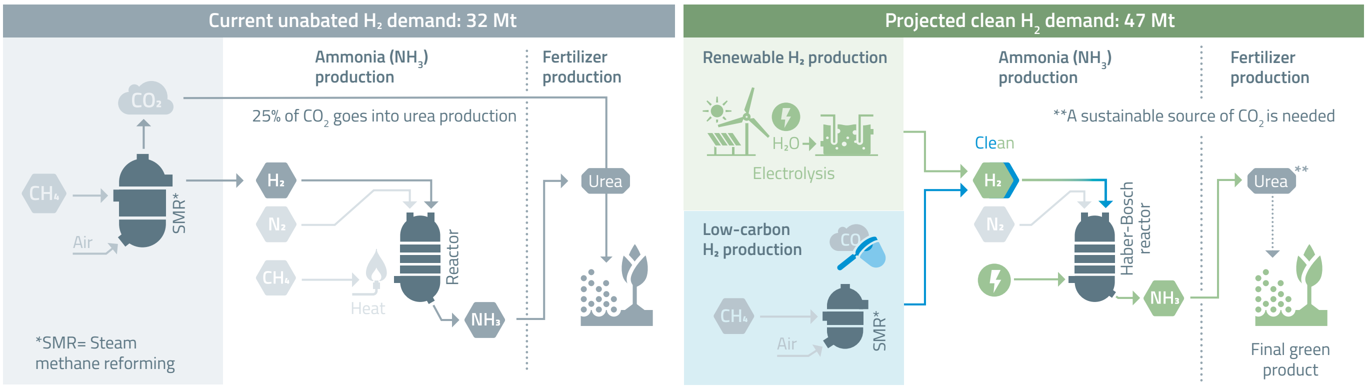

Figure 5: The current ammonia production process (left) and methods for using low-carbon hydrogen to produce ammonia and fertilizers (right) from FCA's hydrogen factsheet, based on IEA data [4] [17].

Figure 5 above shows that steam methane reforming (SMR) with natural gas is still the main route for generating hydrogen for ammonia synthesis. 40% of the natural gas used is as feedstock, while the remainder is used to generate the required energy in the form of heat for the process [17]. On average, ~30% of the CO_2 emissions from global ammonia production are captured and used in producing the fertilizer urea [17]. However, this CO_2 is then released when urea is used in the soil and contributes to the indirect CO_2 emissions from the sector. Currently, only ~2% of the CO_2 emitted globally from ammonia production is captured and stored [17].

Synthetic ammonia-based fertilizers keep food production rates high enough to sustain 50% of the global population and are thus indispensable [18]. Demand for this feedstock is only going to rise as the world's population continues to increase, and by 2050, 47 Mt of hydrogen is projected to be needed for ammonia production alone [19]. Additionally, the majority of the CO_2 emissions from this chemical are related to hydrogen production. Policy mechanisms that incentivize clean hydrogen production should designate ammonia a high-priority industry, also because no direct substitutes exist for the hydrogen utilized for ammonia-based fertilizers.

As shown in Fig. 5, one option for decarbonizing ammonia includes green hydrogen from electrolysis. However, a sustainable source of carbon would need to replace the CO_2 currently captured and utilized to make urea. **One option would be Direct Air Capture (DAC). This pathway provides the highest lifecycle GHG emissions savings, but is both energy-intensive and costly, costing approximately 1000$/t of CO_2 captured, which is 10 times more expensive compared to point source CO_2 captured** [20]. Another option to decarbonize urea production would be to couple natural gas with carbon capture and storage (CCS) and capture all the CO_2 that does not go into urea synthesis or to utilize biomethane, which provides a sustainable source of CO_2 from the SMR process.

Methanol

Methanol is a key product of the chemicals industry and is a versatile molecule that can be used both as an organic feedstock for chemical derivatives and fuels or as a final product used across a variety of sectors, from pharmaceuticals to construction and transport [21]. It is used to manufacture everyday products, for instance plastics, paints, polyester, gloves, and masks. The most common methanol derivative is formaldehyde, a ubiquitous chemical found in glues, dyes, textiles, disinfectants, and car parts.

Methanol production emits ~260 Mt of direct CO_2 (the second largest in the chemicals sector after ammonia), with China being both the largest consumer and producer globally, consuming over 50% of global demand annually [22] [23]. 60% of this methanol is consumed in the chemicals industry [24]. The main feedstocks to manufacture methanol remain fossil fuels, with more than ~65% from natural gas and less than 1% from renewable sources [24]. Even though the synthesis gas (a mixture of H_2, CO_2, and CO) that is produced as a result of natural gas SMR is used for methanol synthesis, direct emissions still arise from both the process and combustion. Thus, the production of methanol remains carbon-intensive, emitting up to ~0.75 t CO_2/t of methanol [25].

The ubiquitous nature of methanol and its varied uses designate it as a high-priority sector for clean hydrogen, similarly to ammonia. Methanol requires both a source of hydrogen and carbon for its synthesis. If green hydrogen is opted for the necessary carbon would need to be sourced either from DAC or carbon capture and utilization (CCU). Alternatively, biomethane or blue hydrogen with high CO_2 capture rates and strict methane emissions control could be opted for. However, as biomethane is also a scarce and expensive resource, its use must be limited to sectors where it is optimal to use from a process, cost, and emissions perspective.

Oil refining

Hydrogen is an indispensable feedstock in refining processes, particularly in hydrocracking and hydrotreating. It enables the upgrading of intermediate streams into final products such as fuels, the production of less-polluting fuels with lower sulfur content[4] (which is responsible for acid rain), and petrochemical feedstock. As with decarbonization progresses, dependence on fossil fuels will diminish, and thus the amount of hydrogen needed for refinery processes will drop. The need for conventional fuels, such as diesel, gasoline, heavy fuel oil, will decrease due electrification efforts in road transport and adoption of sustainable fuels in aviation and shipping; however, the need for other

[4] Reducing sulfur content is essential because it is responsible for acid rain (coming mostly from coal-based power plants). Additionally, the catalytic converter that reduces NOx emissions from a car contains precious metals that degrade when exposed to sulfur.

refinery products, such as asphalt and petrochemical feedstock, will continue to grow. Finally, there are emerging viable uses for hydrogen in refineries to decarbonize the fuel gas system of these facilities to generate low-to-medium temperature heat processes [26]. Today, residual hydrogen from refinery processes, which makes up a small portion of the hydrogen used in the refineries, is downgraded to the fuel system where it is mixed with other gases and combusted to generate low-to-medium heat. Therefore, the need for hydrogen in refinery processes will remain.

Refineries are some of the largest consumers of hydrogen, as depicted in Fig. 6, respectively requiring ~45% and ~57% of global and European hydrogen demand annually [2] [7] [8]. Globally, refineries produce 80% of the hydrogen they need, known as captive hydrogen, through onsite unabated production mostly from natural gas SMR (45%) and byproduct from the refinery processes themselves (35%), while the remaining 20% is purchased from merchants [2]. In Europe, 22.2% of the hydrogen production capacity is from byproduct production, which amounts to a maximum of 2.4 Mt/year [7]. Because hydrogen is a byproduct in refineries, hydrogen-related emissions range 250-400 Mt of CO_2, based on the emission allocation for byproduct hydrogen [1].

As shown in Fig. 6, due to the refineries' configuration, a combination of green and low-carbon hydrogen will be needed to achieve deep decarbonization. **Green or blue hydrogen can replace merchant hydrogen and dedicated on-site hydrogen. CCS can be coupled to the unabated hydrogen produced on-site. Finally, a portion of the hydrogen will continue to be supplied as a byproduct, as long as the units producing the byproduct hydrogen continue to be needed. For this sector, hydrogen is both a feedstock and a fuel (i.e., to potentially decarbonize high-temperature heat process).**

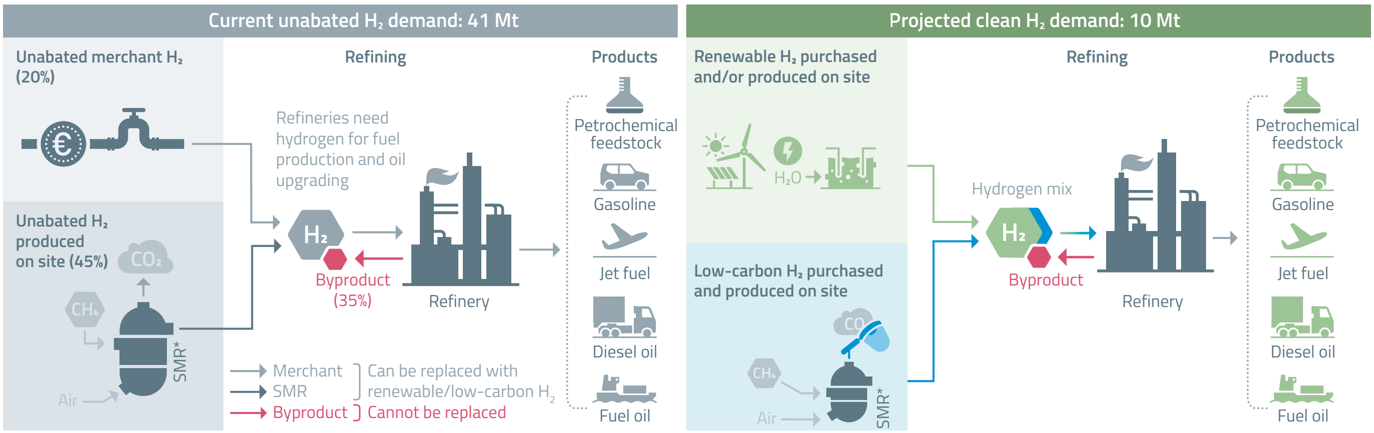

Figure 6: Current hydrogen requirements in refineries (left) and methods for using low-carbon hydrogen in refineries (right) from FCA's hydrogen factsheet, based on IEA data [2] [4].

Primary steel production

Hydrogen is a promising feedstock for primary steel via the Direct Reduced Iron (DRI) pathway, currently a secondary pathway in steel manufacturing requiring 5 Mt of hydrogen globally, though not yet used at scale in the EU [2]. Today, steel production is responsible for 2.6 Gt/year or ~5% of $CO_{2\,eq}$ emissions [27]. Steel is dependent on coal to meet 75% of its energy and feedstock needs, making it a carbon-intensive sector emitting 1.4 t CO_2 /t [17] [28]. Primary steel will continue to play a major role in steel production, as current scrap collection rates are at 85% and insufficient to meet the current and projected global steel demand [28]. Additionally, with steel being a building block of modern society, demand is expected to continue growing even after implementing material efficiency to optimize steel usage, increasing ~11% in 2030 relative to 2022 production [28].

Globally today, 92% of steel is produced through a blast furnace (BF) with coal and iron pellets as inputs [28] [29]. Pig iron from the BF and scrap are introduced into a basic oxygen furnace (BOF) to produce crude steel. CO_2 is released from both the BF and BOF. In Europe, 60% of production is via this route, while the remaining 40% is through a secondary route utilizing scrap directly in an electric arc furnace (EAF) to produce crude steel, with no primary iron involved [29]. Currently, unabated steel from DRI is the secondary route, making up 8% of global production, a route dependent on hydrogen rather than carbon as the reductant for iron ore [29]. Both hydrogen and carbon monoxide, known as synthesis gas from natural gas SMR, are currently used as reductants, as shown in Fig. 7. Therefore, while lower CO_2 emissions are emitted through this route compared to coal, CO_2 emissions are not eliminated from the furnace.

However, as depicted in Fig. 7, green hydrogen from electrolysis can be used as the sole iron ore reductant in a shaft furnace to produce sponge iron. In this case, no CO_2 is produced in the shaft furnace. Hydrogen is not yet used on a large scale as the sole reductant in steel production; however, several pilot projects and early industrial initiatives—such as HYBRIT in Sweden and Thyssen Krupp trials in Germany—are actively demonstrating its potential. As demand for hydrogen for steel production through the DRI route increases, this sector is expected to require 49 Mt of hydrogen in 2050 [19]. Sponge iron is then passed to an EAF and combined with scrap to produce liquid steel. The EAF would still require a source of carbon, but at a low concentration between 0.002% and 2% which then comes out of the EAF as CO_2, representing a much lower concentration compared to the current conventional BF and BOF route with coal [29]. **European steel demand is expected to reach 140 Mt in 2024. To decarbonize all this demand with hydrogen through the DRI route, at minimum 7.5 Mt of hydrogen would be required, which is equivalent to 95% of current European hydrogen consumption. The steel sector should therefore be considered as high priority for hydrogen use** [7] [30] [31].

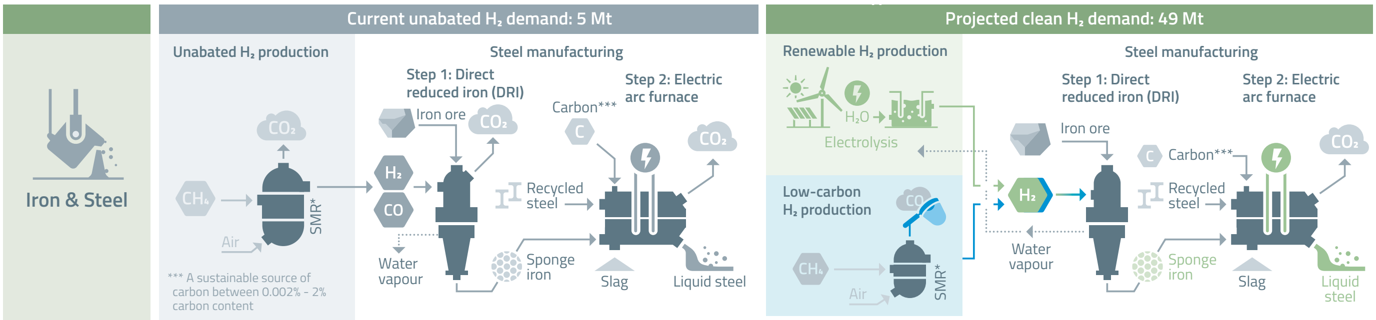

Figure 7: The current secondary steel production process (left) and methods for using low-carbon hydrogen to produce steel (right) from FCA's hydrogen factsheet, based on Roland Berger data [4] [29].

Aviation and shipping

The following sectors are considered medium priority (nascent sectors) where hydrogen will be deployed directly as a fuel or as a feedstock to produce sustainable aviation and maritime fuels [32] [33].

In 2022, the aviation sector was responsible for 2.5% and 4% of global and EU annual CO_2 emissions, respectively [34] [35]. Aviation's contribution to annual emissions is expected to rise further as the sector continues to recover from the impacts of COVID-19 and is poised for a full recovery by 2025 at the latest. Over 99% of the fuel used in aviation is high-polluting, fossil-based, conventional jet fuel [36]. One of the main solutions put forth to help tackle the sector's emissions by 2050 are Sustainable Aviation Fuels (SAF), which are considered 'drop-in' fuels that can be used in airplane engines today without the need for modifications. SAFs can be produced from bio- or synthetic (e-fuels) fuel routes, both of which require hydrogen to be produced.

In 2022, the shipping sector was responsible for ~2.4% and ~4% of global and EU annual CO_2 emissions, respectively [37] [38]. Over 99% of the fuel used in shipping is high-polluting bunkering fuel such as heavy fuel oil (HVO) and marine diesel [39]. One of the main solutions put forth to help tackle the sector's emissions by 2050 are sustainable shipping fuels, both bio and synthetic, as well as alternative fuels, such as methanol and ammonia. International shipping is the most cost-effective and efficient means of transporting goods and is responsible for ~80% of global trade by volume [40]. As most shipping emissions stem from international trade, regional, and international efforts are necessary to decarbonize this crucial sector of our economies and achieve net zero by 2050.

Globally, clean hydrogen required to produce sustainable aviation and shipping fuels is projected to reach 115 Mt by 2050, ~18% more than the entirety of global annual demand [2] [19]. Major airlines are devoting efforts to transition to SAFs and hydrogen, while shipping companies are focusing on fuels such as synthetic or biofuels, e-methanol, or green ammonia as part of their decarbonization strategies, as depicted in Fig. 8.

Figure 8 shows that hydrogen is currently used in refineries in processes such as hydrocracking and hydrotreating to upgrade the feedstock into the final usable form of the fuel, such as jet fuel or heavy fuel oil. Producing biofuels for aviation and shipping will undergo similar hydroprocessing and will require ~0.03 kg H_2/kg of fuel used in biorefineries [41]. To produce e-fuels fuels and alternative hydrocarbon fuels for shipping such as e-methanol, both sustainable or direct air-captured CO_2 and green hydrogen are needed, which in turn require renewable electricity for their production. These fuels require hydrogen as a feedstock because they are produced starting from the building blocks of hydrocarbon fuels, i.e. H_2 and CO_2. While other alternative fuels, such as green ammonia, do not require CO_2, they do require H_2 and nitrogen sourced from the air. The amount of hydrogen needed in these pathways is an order of magnitude higher than in the biofuel pathway. Raw biofuels already contain most of the H_2 atoms needed for the final product while H_2 is one of two essential feedstocks in the production of e-fuels. For example, in a pathway optimized for jet fuel production, ~0.52 kg H_2/kg of fuel is needed [42]. As for e-methanol and green ammonia, ~0.2 kg H_2/kg of fuel is required [43] [44]. While the H_2 required is within this order of magnitude, it varies based on the specific pathway chosen to produce synthetic jet fuel, green ammonia, or e-methanol.

ReFuelEU Aviation's 2050 targets are taken as an example to contextualize the amount of hydrogen that will be needed to produce these fuels. FCA conducted a technical analysis to assess the feasibility of meeting the regulation's target of synthetic jet fuels making up 35% of the final fuel mix by 2050, finding that ~13.2 Mt of green hydrogen will be needed [45]. For comparison, Europe's entire hydrogen demand currently amounts to ~7.9 Mt [7]. ~870 TWh of additional renewable electricity is required to produce this amount of synthetic jet fuel, which amounts to 95% of the EU's total renewable electricity production in 2022 [45] [46]. 80% of this renewable electricity is needed solely to produce the green hydrogen required to make the e-fuels, while the remainder is for DAC [45].

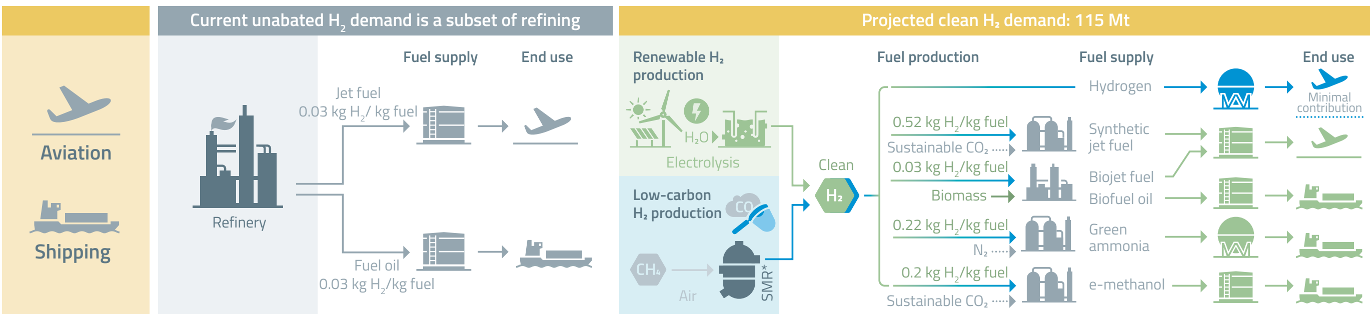

Figure 8: Current hydrogen requirements in refineries to produce jet fuel and fuel oil (left) and methods for using low-carbon hydrogen to produce sustainable aviation and shipping fuel in the future (right) from FCA's hydrogen factsheet [4].

It is important to consider that there is no business case for these fuels yet, with the green premium still high relative to both conventional bunkering and jet fuel as well as conventional ammonia and methanol, as shown in Table 2. It must be noted that the ship's engine must be retrofitted to operate with alternative fuels and new safety arrangements for transport, handling, and storage of these new fuels are required.

EU decisionmakers should commission a comprehensive and realistic feasibility analysis of clean hydrogen production until 2050, globally and in the EU. The available clean hydrogen must first be prioritized to decarbonize existing hydrogen needs in refining and chemical production and for use in emerging technologies in steel manufacturing.

The amount of clean hydrogen that can be dedicated to aviation and shipping for use partly as the final fuel, but mainly as a feedstock for synthetic jet fuel and alternative fuel production, must then be identified. Therefore, these two sectors should be designated as medium priority for clean hydrogen deployment to maximize the amount that can be made available for aviation and shipping. This will then give visibility to the possibility of achieving targets such as those of ReFuelEU Aviation, FuelEU Maritime, the International Civil Aviation Organization's (ICAO's) long-term aspirational goals (LTAG) of net-zero aviation by 2050, and the International Maritime Organization's (IMOs) GHG emissions cut targets by 2050.

Table 2: Costs of conventional and sustainable aviation and shipping fuels per gallon BE, for ammonia from S&P, and for methanol from the methanol institute and S&P [47] [48] [49] [50].

Aviation				Shipping			
Conventional jet fuel	2.2$	Conventional bunker fuel	1.3$	Grey Ammonia	1.5$	Methanol	1.3$
Advanced biojet fuel	5.35$	Advanced biofuel	5.5$	Blue Ammonia	1.7$	Bio-methanol	2.4$
E-fuels	8.8$	E-fuels	9.1$	Green Ammonia	2.6$	E-methanol	4.2$

Sectors such as buildings, road transport, and power generation do not currently consume hydrogen but are projected to demand 157 Mt of hydrogen by 2050 [19]. However, these sectors have more effective and readily available decarbonization solutions that should be opted for to maximize emissions savings and ensure hydrogen is prioritized for those essential and hard-to-abate sectors outlined in the previous sections.

Buildings

Direct emissions from buildings, both residential and commercial, amounted to ~3 Gt of CO_2 globally in 2022 [51]. However, more than double these emissions come from the electricity and heat generation used in buildings, which lead to an additional ~6.8 Gt of indirect CO_2 emissions [51]. Combined, emissions from buildings are responsible for ~26% of global annual CO_2 emissions [51] a ~40% of the EU's annual energy consumption is from buildings, most of which goes to heating, cooling, and hot water, thus contributing to more than 33% of the block's GHG emissions annually [52].

There are several ways to provide heating in buildings, with district heating, fossil fuel boilers and central heating, and heat pumps being some of the most common. Today, natural gas boilers remain the most prevalent heating source for buildings and account for 23% of the energy consumed by buildings globally [51]. Hydrogen is not used as a source of heating in buildings today and should not be considered as a potential decarbonization option for this sector when other more effective alternatives are readily available. Technically, hydrogen could be used to supply heat to buildings in several ways. One option could be blending with natural gas, which provides minimal savings. As mentioned above, 20% hydrogen blending by volume leads to only approximately 7% emissions savings [13]. Another option could be hydrogen boilers; however, this requires retrofits to existing boilers and the installation of a hydrogen infrastructure that come with their own costs and challenges. Globally, natural gas prices are currently ~3.2$/MMBtu, equivalent to 0.011 $/kWh and 0.063 €/kWh in Europe [53] [54]. Per unit mass, hydrogen has ~2.25 times the specific energy of natural gas. However, even after accounting for this difference, natural gas is still approximately five times cheaper than grey hydrogen per unit energy, considering global average costs of grey hydrogen shown in Table 1. Therefore, switching from natural gas boilers to hydrogen boilers incurs CAPEX costs as well as higher OPEX due to the higher costs of hydrogen relative to natural gas (see Table 1). Both air-to-air (AAHP) and air-to-water heat pumps (AWHP), on the other hand, could be competitive on a Levelized Cost of Heating (LCoH) compared to gas boilers across Europe and the United States [55]. Heat pumps in Sweden and Denmark are 60% and 15% cheaper than gas boilers, respectively [55]. In the US and Italy heat pumps are ~15% cheaper than gas boilers due to CAPEX subsidies and in France, subsidies help make the AWHPs ~25% cheaper [55]. Therefore, the LCoH of a boiler operating with hydrogen would have to contend with even higher OPEX and CAPEX compared to a natural gas boiler in these countries, resulting in an even higher LCoH compared to heat pumps. These costs aren't expected to come down by 2050, with hydrogen boilers predicted to remain ~50% more expensive for EU homes compared to heat pumps [13].

From an efficiency point of view, as shown in Fig. 9, hydrogen boilers cannot compete with heat pumps. With a coefficient of performance (COP) of 3, and an electricity transmission and distribution efficiency of 90%, the overall efficiency of generating heat from electricity through a heat pump is 270% [13]. However, when using hydrogen, an extra conversion step is required as electricity is converted to hydrogen which is then used in a boiler to generate heat for the buildings, leading to

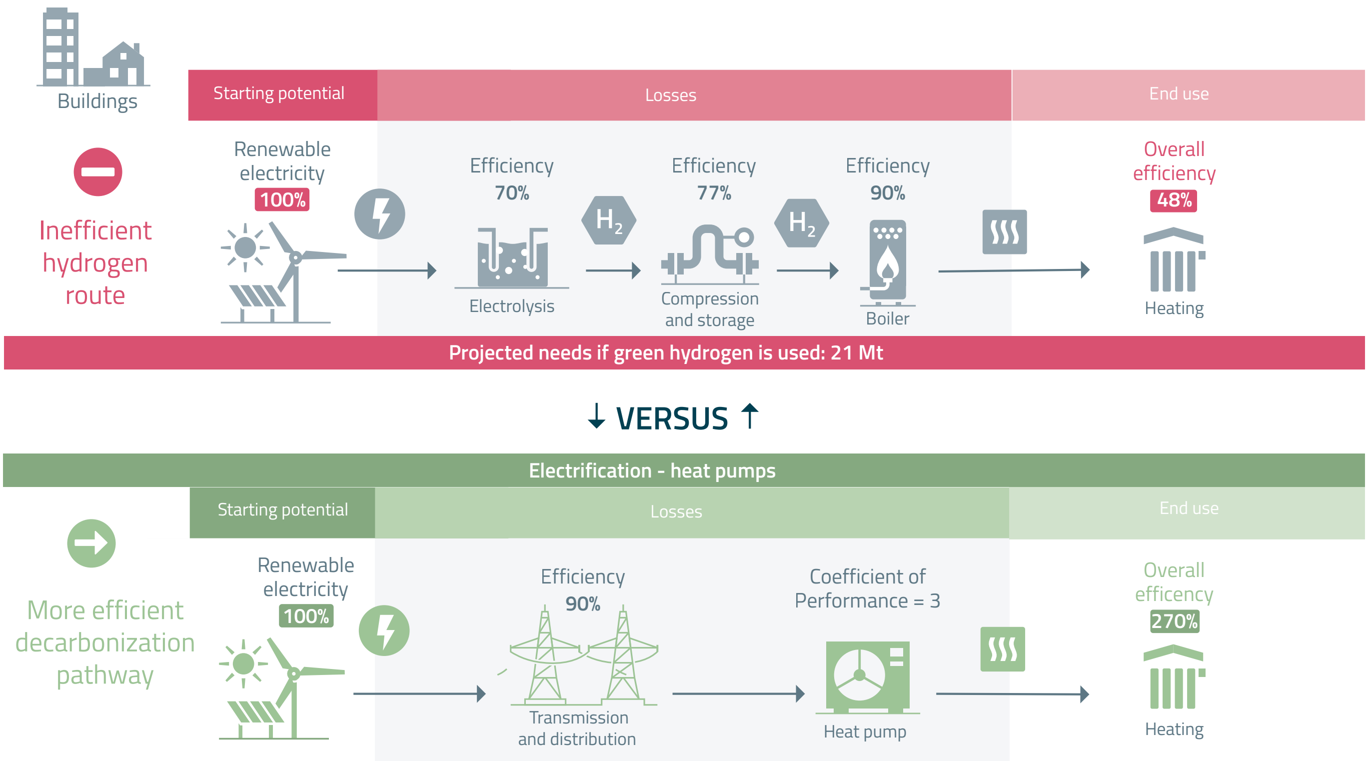

Figure 9: Process efficiency if hydrogen is used to produce heat for buildings (left) compared to heat pumps (right) from FCA's hydrogen factsheet, based on data from the Hydrogen Science Coalition [4] [13].

major losses along the value chain. Electrolysis is only ~70% efficient, transmission and storage incur losses of ~23%, and the boiler incurs ~10% losses leading to an overall efficiency of 48% [13]. A meta-review of 54 independent studies of hydrogen used in buildings for heating revealed that there is no business case, with heating from hydrogen being more costly and less efficient compared to heat pumps [56].

As 1 kWh of renewable electricity leads to 0.48 kWh of heat if a hydrogen boiler is used, and 1 kWh of electricity leads to 2.7 kWh of heat if a heat pump is used, hydrogen is at an approximate sixfold disadvantage when it comes to both cost and emissions. Requiring 0.37 kWh of electricity from heat pumps and 2.08 kWh for hydrogen leads to emissions of 15.54 g CO_2eq/kWh and 87 g CO_2eq/kWh of heat generated, respectively. This is solely based on the average lifecycle GHG emissions of electricity from wind and solar [57]. This gap in GHG emissions will only grow further when accounting for additional emissions to quantify the full lifecycle GHG emissions of these two pathways. With heat pumps, the electricity is transmitted and used directly to transfer heat. However, with hydrogen, the electricity is first converted to hydrogen, stored and transported, and then converted into heat. Emissions from equipment processing and manufacturing, transport and distribution, and the end-use phase will all contribute to the lifecycle GHG emissions.

Hydrogen guardrails for buildings
For this sector, a techno-economic analysis based on the LCoH, lifecycle GHG emissions reductions, and the total carbon abatement cost of deploying hydrogen versus heat pumps should be included in any public policy framework that seeks to support hydrogen deployment to decarbonize buildings.

Road transport

Road transport is the single largest emitter in the transport sector and was responsible for ~5.9 Gt of CO_2 emissions in 2022 [37]. In the EU, road transport is responsible for ~25% of annual emissions, with 15% of the EU's emissions coming from light-duty vehicles alone [58]. When looking at lifecycle greenhouse gas (GHG) emissions, efficiency, and the total cost of ownership (TCO), there is no competitor for electric vehicles (EVs) in road transport. Additionally, hydrogen in road transport would require the roll out of a hydrogen distribution infrastructure. Finally, hydrogen fuel cell vehicle (HFCV) sales remain extremely low, representing only 0.02% of global passenger vehicle sales in 2022 compared to 13.7% for EVs [59].

A comparative assessment by the International Transport Forum (ITF) revealed that the lifecycle GHG emissions were consistently the lowest for battery electric vehicles (BEVs), especially when electricity is sourced from renewables [60]. While hydrogen fuel cell vehicles offer zero-emission transportation at the point of use (i.e., zero tank-to-wheel emissions), their upstream production, processing, and transport emissions contribute to their lifecycle GHG emissions. This applies to all road vehicle types: medium cars, SUVs, buses, trucks, etc. Finally, as shown in Fig. 10, hydrogen vehicles cannot compete with BEVs from an efficiency perspective, which have overall efficiencies of 73% compared to 22% for HFCVs [13]. With BEVs, electricity is used to charge the battery that directly powers the electric motor. However, with HFCVs, electricity is first converted to and stored as hydrogen. This hydrogen is converted back into electricity onboard the vehicle and is used to power an electric motor. This additional conversion step comes with higher losses and lower overall efficiency.

While BEVs incur higher vehicle costs, from a TCO perspective, they are even more economical than internal combustion engine vehicles (ICEVs) due to their lower operating and maintenance costs over a vehicle's lifetime [61]. For HFCVs, production costs of the vehicle, including the high-pressure onboard hydrogen storage as well as the fuel cell, lead to higher upfront vehicle costs. Additionally, the installation of a hybrid transport and pump distribution network needs to be constructed. Finally, average costs of green hydrogen remain high, with average global costs at 5 – 12 $/kg and even higher prices in Europe of 12 – 14 €/kg [15] [16].

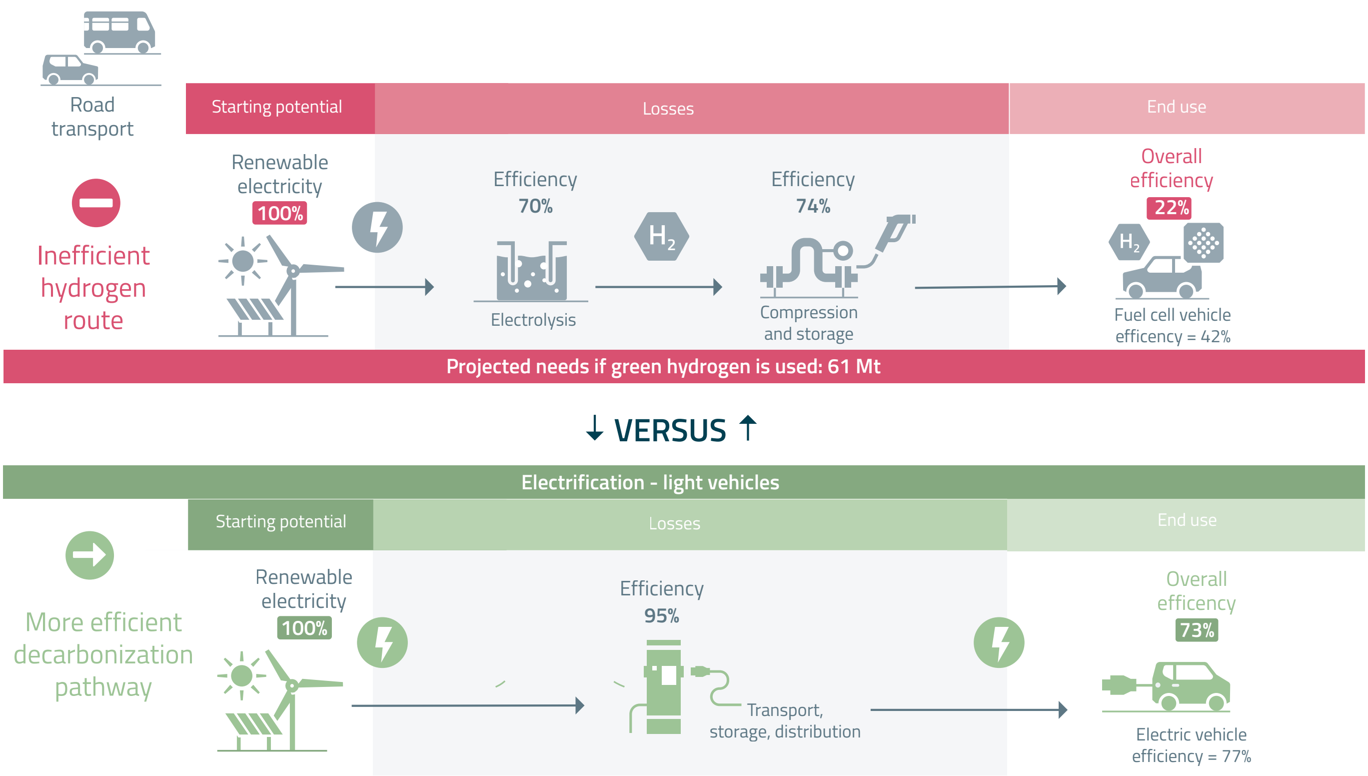

Figure 10: Process efficiency if hydrogen is used to power vehicles (left) compared to electrification (right) from FCA's hydrogen factsheet, based on data from the Hydrogen Science Coalition [4] [13].

Subsidies can help to artificially lower costs; however, if a technology cannot eventually achieve cost parity while simultaneously offering lower emissions savings and sub-optimal efficiency, then public funds should be allocated elsewhere. Policymakers should preclude from enacting policy mechanisms that will promote the uptake of hydrogen or other solutions for road transport that will incur the inefficient allocation of public funds for the decarbonization of road transport.

Hydrogen guardrails for road transport
For this segment of the transport sector, a detailed analysis based on the total cost of ownership of the vehicle, lifecycle analysis, and the total carbon abatement cost of deploying hydrogen versus direct electrification should be included in any public policy framework that seeks to support hydrogen deployment to decarbonize road transport.

Electricity generation

Both globally and in the EU, electricity and heat production combined are the largest contributors to annual CO_2 emissions [62]. Today, electricity supply still comes from a combination of renewable and non-renewable sources. Coal remains the largest supplier of electricity globally at more than ~33%, followed by natural gas at more than 20%, nuclear at ~10%, and hydropower as the single largest source of renewable electricity [63]. In the EU, approximately 55% of electricity production comes from non-renewable sources and nuclear [46]. Renewable electricity's contribution to the final electricity mix has been increasing over the past 20 years and now supplies over 30 % of the electricity globally and in the EU [46] [63]. In the EU, ~45% of electricity comes from renewables and biofuels [46]. Hydrogen is not currently used as a source of power generation and should not be considered for such a sector where direct electrification is a viable technical and cost-efficient option. Europe is still in the process of decarbonizing its electricity grid and renewable hydrogen deployment for the power sector delivers very limited climate benefits while the grid is not fully decarbonized. Only in the case of a fully decarbonized grid could hydrogen be considered as an option as a long-duration chemical storage solution [64] [65].

Figure 11 shows that when renewable hydrogen is deployed to produce electricity, there is an approximate 25% round trip efficiency, meaning 75% of the energy is "lost" in the process.

This means that if four units of renewable electricity are produced, only one unit of electricity can be used in downstream sectors. Additionally, for hydrogen to provide high emissions savings, it would need to be green hydrogen which requires electricity for its production as blue hydrogen delivers limited emissions reduction when deployed to generate electricity [65]. Therefore, electricity would be needed to generate the hydrogen that is then converted back into electricity for consumption. Direct electrification from renewable sources, on the other hand, is approximately 90% efficient, owing merely to transmission and distribution losses, and leads to lower lifecycle GHG emissions.

Renewable sources of electricity such as wind and solar have average lifecycle GHG emissions of ~34 g CO_2eq/kWh and ~50 g CO_2eq/kWh [57]. Hydrogen, on the other hand, would emit 116 g CO_2/kWh[5], which only increases when accounting for manufacturing, transport, and use phase emissions further down the value chain from hydrogen transportation, storage, and conversion back to electricity. Additionally, as renewable electricity is transmitted and used directly (instead of being converted to hydrogen which is then converted back to electricity in a turbine), hydrogen for power generation incurs additional CAPEX and OPEX costs that make it impossible to compete with direct electrification in terms of levelized cost of production (LCoP).

Hydrogen guardrails for electricity generation
For this sector, a techno-economic analysis, based on the levelized cost of electricity, lifecycle emissions reduction, and the total carbon abatement cost of deploying hydrogen versus direct electrification should be included in any public policy framework that seeks to support hydrogen deployment to decarbonize the grid.

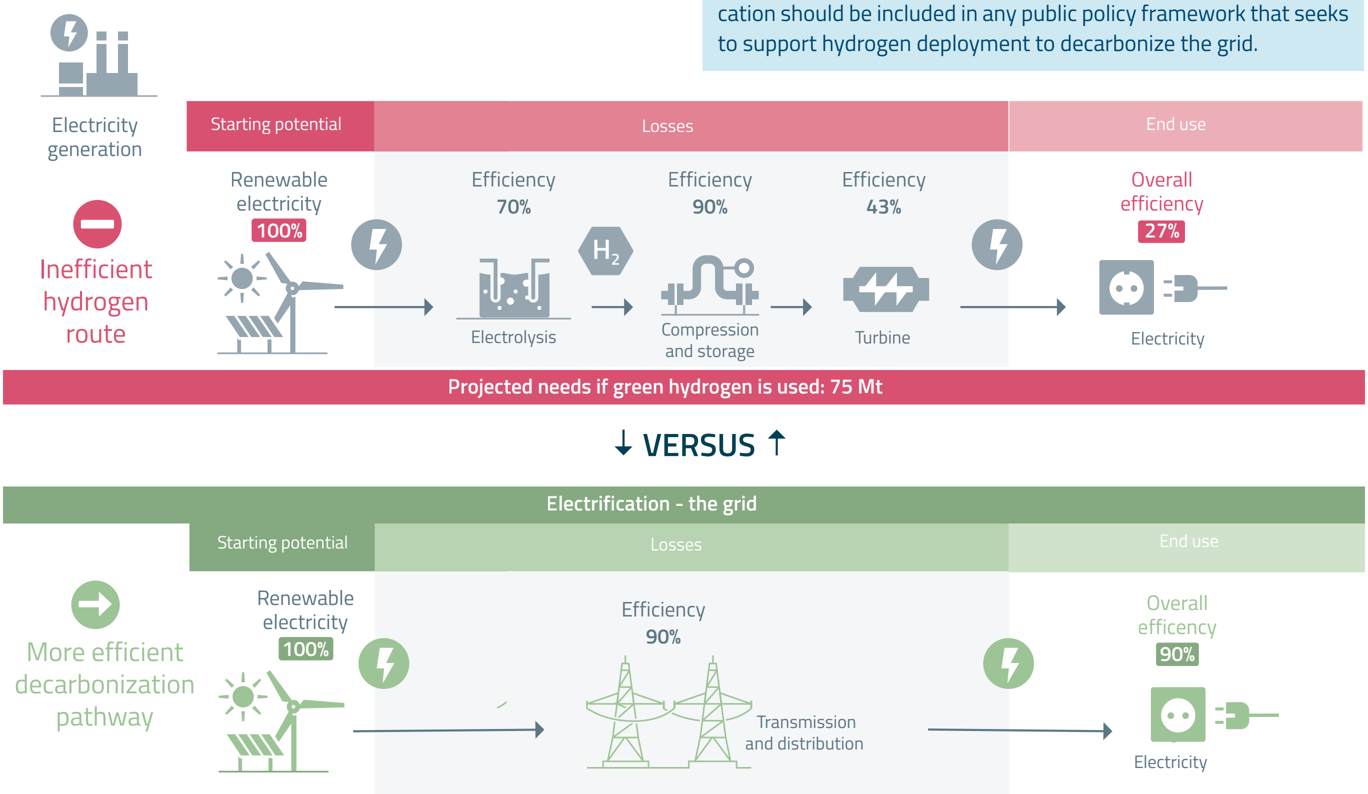

Figure 11: Process efficiency if hydrogen is used for power generation (left) compared to direct electrification (right) from FCA's hydrogen factsheet, based on data from CATF [4] [65].

[5] Green hydrogen production from solar and wind has average lifecycle CO_2 emissions of ~1500 g CO_2/kg H_2, which when transported and burned in a turbine, will generate ~13 kWh of electricity [66]. Thus, on a kWh basis, hydrogen would emit 116 g CO_2/kWh.

Recommendations

1. Decarbonize current hydrogen uses

Current essential hydrogen applications must be decarbonized before branching into novel hydrogen uses. Clean hydrogen's critical role in facilitating emissions reductions in sectors such as refining, chemicals, and steel must be prioritized.

- Implement a facts-based allocation of scarce resources, such as renewable electricity and green hydrogen, which are subject to cross-sectoral competition. Both direct electrification and electricity as a feedstock for e-fuel production will play a major role in decarbonization efforts; thus, estimating scale-up in renewable electricity production and its allocation to the various sectors of the economy will be paramount to quantifying the amount of green hydrogen that can be realistically produced.

- Prioritize available clean hydrogen for indispensable sectors that are dependent on hydrogen, such as ammonia, methanol, refining, and steel, before introducing novel applications on a large scale.

- Ramp-up renewable electricity deployment, including novel sources such as advanced geothermal and concentrated solar power, to eliminate bottlenecks and drive down green hydrogen costs.

- Consider low-carbon hydrogen from natural gas with CCS as a supplement to renewable hydrogen in the short-to-medium term only if strong upstream methane leak controls are implemented. Additionally, assess the feasibility of decarbonizing high-polluting existing hydrogen production assets expected to operate for decades to come, by deploying CCS paired with strict methane emissions control. Finally, develop biogas SMR with and without CCS for those sectors where both H_2 and CO_2 streams are needed and where the carbon abatement potential is higher than using the biogas directly, for example, the production of urea.

2. Prioritize hard-to-abate sectors

Hydrogen should be positioned as a decarbonization enabler for hard-to-abate sectors alongside its role as an indispensable industrial feedstock. Hydrogen will play a key role in sectors where direct electrification is not a viable decarbonization option, such as aviation and shipping.

- Develop clear national strategies with guardrails for clean hydrogen deployment that prioritize hard-to-abate sectors dependent on hydrogen for decarbonization.

- Close the commercialization gap through dedicated funding, Contracts for Difference (CfDs), incentives such as the Dutch SDE++ mechanism, and permitting for hydrogen projects, with prioritization for projects aiming to develop clean hydrogen and alternative fuels such as e-methanol, green ammonia, and synthetic jet fuels for hard-to-abate sectors.

- Provide long-term visibility for hydrogen and alternative fuels through national energy and climate plans (NECPs) based on the targets defined in regulations such as the Renewable Energy Directive (REDIII). These targets should also include effective mechanisms to prioritize hydrogen in sectors where it has the highest carbon abatement potential and stimulate off-take agreements.

3. Abandon incompatible sectors

Science-based guardrails are needed to prevent precious and scarce renewable electricity from being inherently lost in the production and use of hydrogen in sectors where other more effective and efficient decarbonization strategies, such as direct electrification, can be deployed.

- Ensure national strategies include hydrogen end-use criteria and remove incompatible sectors such as road transport, power generation, and buildings from these strategies, as they lead to ineffective allocation of public funds.

- Avoid technology openness strategies in sectors where direct electrification is the most efficient, cost-effective, and environmentally friendly solution. For example, road transport, where BEVs are the most effective decarbonization solution from a lifecycle GHG emissions reductions, efficiency, and TCO perspective.

- Raise awareness with all stakeholders, from policymakers to industry, on the limited availability of renewable and low-carbon hydrogen and the challenges in its sourcing, transportation, and storage, necessitating the need to restrict its use to hard-to-abate sectors.

4. Invest in RD&D

Clean hydrogen remains a scarce and costly resource. Investing in RD&D is crucial to closing the commercialization gap and ramping up production to help meet current and future clean hydrogen needs.

- Increase funding in commercially viable alternative clean hydrogen production pathways to ramp-up supply for sectors without any viable alternatives, such as those that require hydrogen as a feedstock or cannot directly electrify.

- Ensure that public funds are prioritized for innovative hydrogen production projects with clear downstream allocation of hydrogen utilization. For example, allocating funds for clean hydrogen projects aimed to produce hydrogen as a feedstock for the chemical sector or for alternative fuel production over projects without a clear indication of the hydrogen's downstream utilization.

- Invest in innovative supplementary hydrogen production pathways, such as thermochemical, to diversify the supply chain and reduce dependence on renewable electricity for electrolysis.

- Accelerate RD&D, investment, and scaling in hydrogen sourcing, infrastructure, and storage to overcome upstream challenges and avoid bottlenecks in supply for indispensable sectors as demand rises, for example to develop the hydrogen transport and distribution infrastructure for 100% hydrogen streams, which are not compatible with the current natural gas infrastructure.

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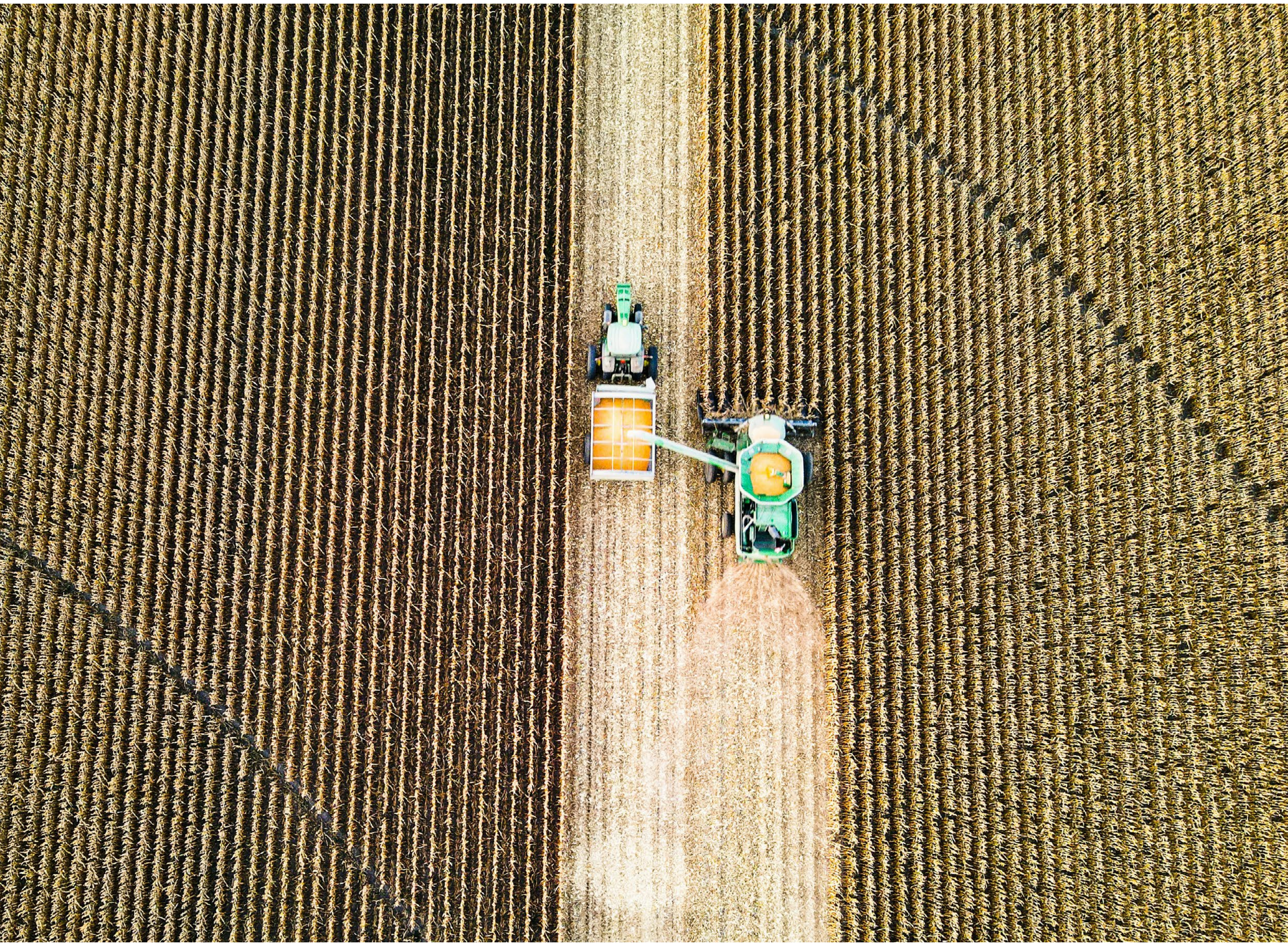

Figures and Tables

Figures

Tables

References

[1] IEA, "Global Hydrogen Review 2023," IEA, Paris, 2023. https://www.iea.org/reports/global-hydrogen-review-2023.

[2] IEA, "Global Hydrogen Review 2024," IEA, Paris, 2024. https://www.iea.org/reports/global-hydrogen-review-2024.

[3] B. Parkinson et al., "Levelized cost of CO_2 mitigation from hydrogen production routes," Energy & Environmental Science, vol. 12, no. 1, pp. 19 - 40, 2019, doi: 10.1039/C8EE02079E.

[4] Future Cleantech Architects, "Hydrogen and climate change - all you need to know," 2024. https://fcarchitects.org/content/future-cleantech-factsheet-hydrogen/.

[5] IEA, "Hydrogen," 2023. https://www.iea.org/energy-system/low-emission-fuels/hydrogen.

[6] IEA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach," IEA, Paris, 2023. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

[7] Hydrogen Europe, "Clean Hydrogen Monitor 2024," 2024. https://hydrogeneurope.eu/wp-content/uploads/2024/11/Clean_Hydrogen_Monitor_11-2024_V2_DIGITAL_draft3-1.pdf.

[8] European Hydrogen Observatory, "Hydrogen Demand," 2023. https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/end-use/hydrogen-demand.

[9] European Environment Agency, "Total net greenhouse gas emission trends and projections in Europe," 2024. https://www.eea.europa.eu/en/analysis/indicators/total-greenhouse-gas-emission-trends.

[10] IEA, "Electrolysis," 2023. https://www.iea.org/energy-system/low-emission-fuels/electrolysers.

[11] Hydrogen Tools, "Best Practives: Hydrogen Compared To Other Fuels," 2024. https://h2tools.org/bestpractices/gaseous-gh2-and-liquid-h2-fueling-stations/hydrogen-compared-to-other-fuels.

[12] Clean Air Task Force, "Hydrogen for Decarbonization A Realistic Assessment," 2023. https://www.catf.us/resource/hydrogen-decarbonization-realistic-assessment/.

[13] Hydrogen Science Coalition, "Putting facts into perspective on hydrogen's role in the energy transition," 2024. https://h2sciencecoalition.com/data-resources.

[14] MIT Climate Portal, "Can we use the pipelines and power plants we have now to transport and burn hydrogen, or do we need new infrastructure?," 2023. https://climate.mit.edu/ask-mit/can-we-use-pipelines-and-power-plants-we-have-now-transport-and-burn-hydrogen-or-do-we-need.

[15] TNO, "Evaluation of the levelised cost of hydrogen based on proposed electrolyser projects in The Netherlands: Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET)," TNO, Amsterdam, 2024. https://repository.tno.nl/SingleDoc?find=UID%20e5e1ab2e-ff69-48fb-8564-75f56282378c.

[16] K. Schelling, "Green Hydrogen to Undercut Gray Sibling by End of Decade," BloombergNEF, 2023. https://about.bnef.com/blog/green-hydrogen-to-undercut-gray-sibling-by-end-of-decade/.

[17] IEA, "Ammonia Technology Roadmap Towards more sustainable nitrogen fertiliser production," IEA, Paris, 2021. https://www.iea.org/reports/ammonia-technology-roadmap.

[18] H. Ritchie, "How many people does synthetic fertilizer feed?," Our World in Data, 2017. https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed

[19] IEA, "Global hydrogen demand in the Net Zero Scenario, 2022-2050," IEA, Paris, 2023. https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-in-the-net-zero-scenario-2022-2050

[20] L. Limb, "World's largest air capture plant opens in Europe. Is it really a 'misguided scientific experiment'?," Euronews, 2024. https://www.euronews.com/green/2024/05/09/worlds-largest-air-capture-plant-opens-in-europe-is-it-really-a-misguided-scientific-exper

[21] Methanol Institute, "Essential Methanol Infographic," 2024. https://www.methanol.org/essential-methanol-infographic/

[22] IEA, "Chemicals," 2023. https://www.iea.org/energy-system/industry/chemicals.

[23] M. Avarao, "The changing face of the global methanol industry," Methanol Institute, 2016. https://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf.

[24] IRENA and Methanol Institute, "Innovation Outlook: Renewable Methanol," International Renewable Energy Agency, Abu Dhabi, 2021. https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol.

[25] Methanol Institute, "carbon footprint of methanol," 2022. https://www.methanol.org/wp-content/uploads/2022/01/CARBON-FOOTPRINT-OF-METHANOL-PAPER_1-31-22.pdf.

[26] Future Cleantech Architects, "Decarbonizing High-Temperature Heat in Industry: Technology assessment and policy recommendations for Europe," 2024.

[27] IEA, "Industry," 2023. https://www.iea.org/energy-system/industry.

[28] IEA, "Steel," 2023. https://www.iea.org/energy-system/industry/steel.

[29] A. Ito, "Europe's steel industry at a crossroads," Roland Berger, 2020.https://www.rolandberger.com/en/Insights/Publications/Europe%27s-steel-industry-at-a-crossroads.html.

[30] EUROMETAL, "EU steel demand to recover in 2025: worldsteel," 2024. https://eurometal.net/eu-steel-demand-to-recover-in-2025-worldsteel/.

[31] World Steel Association, "Hydrogen (H2)-based ironmaking," 2022. https://worldsteel.org/publications/fact-sheets/.

[32] Future Cleantech Architects, "The Basics & The Gaps - Aviation," 2023. https://fcarchitects.org/content/the-basics-the-gaps-aviation/.

[33] ITF, "The Potential of E-fuels to Decarbonise Ships and Aircraft," OECD/ITF, Paris, 2023, doi: 10.1787/3d96e0d9-en.

[34] H. Ritchie, "What share of global CO_2 emissions come from aviation?," Our World in Data, 2024. https://ourworldindata.org/global-aviation-emissions#article-citation.

[35] European Comission, "Reducing emissions from aviation," 2024. https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-aviation_en.

References

[36] IEA, "Aviation," 2023. https://www.iea.org/energy-system/transport/aviation.

[37] IEA, "Transport," 2023. https://www.iea.org/energy-system/transport.

[38] European Comission, "Reducing emissions from the shipping sector," 2024. https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en.

[39] IEA, "Energy consumption in international shipping by fuel in the Net Zero Scenario, 2010-2030," 2023. https://www.iea.org/data-and-statistics/charts/energy-consumption-in-international-shipping-by-fuel-in-the-net-zero-scenario-2010-2030-2.

[40] ITF, "Navigating Towards Cleaner Maritime Shipping," OECD/ITF, Paris, 2020, doi: 10.1787/ab3d3fbc-en.

[41] Fuel Cells and Hydrogen Observatory, "Chapter 2: 2021 Hydrogen supply and demand," 2021. https://observatory.clean-hydrogen.europa.eu/sites/default/files/2023-05/Chapter-2-Hydrogen-Supply-and-Demand-2021.pdf.

[42] K. Atsonios, J. Li and V. J. Inglezokis, "Process analysis and comparative assessment of advanced thermochemical pathways for e-kerosene production," Energy, vol. 278, 2023, doi: 10.1016/j.energy.2023.127868.

[43] S. Sollai et al., "Renewable methanol production from green hydrogen and captured CO_2: A techno-economic assessment," Journal of CO_2 Utilization, vol. 68, 2023, doi: 10.1016/j.jcou.2022.102345.

[44] G. Pagani , Y. Hajimolana and C. Acar, "Green hydrogen for ammonia production – A case for the Netherlands," International Journal of Hydrogen Energy, vol. 52, pp. 418 - 432, 2024, doi: 10.1016/j.ijhydene.2023.06.309.

[45] Future Cleantech Architects, "ReFuelEU Aviation's Targets: A Feasibility Assessment," 2024. https://fcarchitects.org/content/refueleu-targets-sustainable-aviation-fuels-report/.

[46] Eurostat, "Electricity and heat statistics," 2023. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics.

[47] Breakthrough Energy, "Where to Innovate First: The Green Premium," 2022. https://www.breakthroughenergy.org/our-approach/the-green-premium/.

[48] S&P Global, "Interactive: Platts Ammonia price chart," 2024. https://www.spglobal.com/commodity-insights/en/news-research/latest-news/energy-transition/051023-interactive-ammonia-price-chart-natural-gas-feedstock-europe-usgc-black-sea.

[49] Methanol Institute, "Methanol Price and Supply/Demand," 2024. https://www.methanol.org/methanol-price-supply-demand.

[50] S&P Global, "Renewable methanol drives maritime industry decarbonization: institute CEO," 2023. https://www.spglobal.com/commodity-insights/en/news-research/latest-news/chemicals/021523-renewable-methanol-drives-maritime-industry-decarbonization-institute-ceo.

[51] IEA, "Buildings," 2023. https://www.iea.org/energy-system/buildings.

[52] European Comission, "Energy Performance of Buildings Directive," 2024. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.

[53] Investing.com, "Natural Gas Futures," 2024. https://www.investing.com/commodities/natural-gas.

[54] Eurostat, "Natural gas price statistics," 2024. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics.

[55] IEA, "Levelised cost of heating for air-to-air and air-to-water heat pumps and gas boilers for selected countries, and sensitivity to fuel prices, H_1 2021 - H_1 2022," 2022. https://www.iea.org/data-and-statistics/charts/levelised-cost-of-heating-for-air-to-air-and-air-to-water-heat-pumps-and-gas-boilers-for-selected-countries-and-sensitivity-to-fuel-prices-h1-2021-h1-2022.

[56] J. Rosenow , "A meta-review of 54 studies on hydrogen heating," Cell Reports Sustainability, vol. 1, 2024, doi: 10.1016/j.crsus.2023.100010.

[57] D. Nugent and B. K. Sovacool, "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey," Energy Policy, vol. 65, pp. 229-244, 2014, doi: 10.1016/j.enpol.2013.10.048.

[58] European Comission, "Road transport: Reducing CO_2 emissions from vehicles," 2024. https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles_en.

[59] L. Collins, "Hydrogen car sales are so low that we are unable to make long-term forecasts': BloombergNEF," Hydrogen Insight, 2023. https://www.hydrogeninsight.com/transport/hydrogen-car-sales-are-so-low-that-we-are-unable-to-make-long-term-forecasts-bloombergnef/2-1-1464843.

[60] ITF, "Cleaner Vehicles: Achieving a Resilient Technology Transition," OECD/ITF, Paris, 2021, doi: 10.1787/08cb5e7e-en.

[61] IEA, "Electric Vehicles: Total Cost of Ownership Tool," 2022. https://www.iea.org/data-and-statistics/data-tools/electric-vehicles-total-cost-of-ownership-tool.

[62] IEA, "Energy Statistics Data Browser," 2023. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=EU27_2020&fuel=CO2%20emissions&indicator=CO2BySector.

[63] IEA, "Electricity," 2023. https://www.iea.org/energy-system/electricity.

[64] Future Cleantech Architects, "Long Duration Energy Storage for the Power System," 2023. https://fcarchitects.org/content/the-basic-the-gaps-ldes/.

[65] Clean Air Task Force, "Hydrogen in the Power Sector: Limited Prospects in a Decarbonized Electric Grid," 2024. https://www.catf.us/resource/hydrogen-power-sector/.

[66] L. Rosa and M. Mazzotti, "Potential for hydrogen production from sustainable biomass with carbon capture and storage," Renewable and Sustainable Energy Reviews, vol. 157, 2022, doi: 10.1016/j.rser.2022.112123.

About Future Cleantech Architects:
We are a climate innovation think tank. We exist to close the remaining innovation gaps to reach net-zero emissions by 2050. To reach this objective, we accelerate innovation in critical industries where sustainable solutions are still in very early stages.

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