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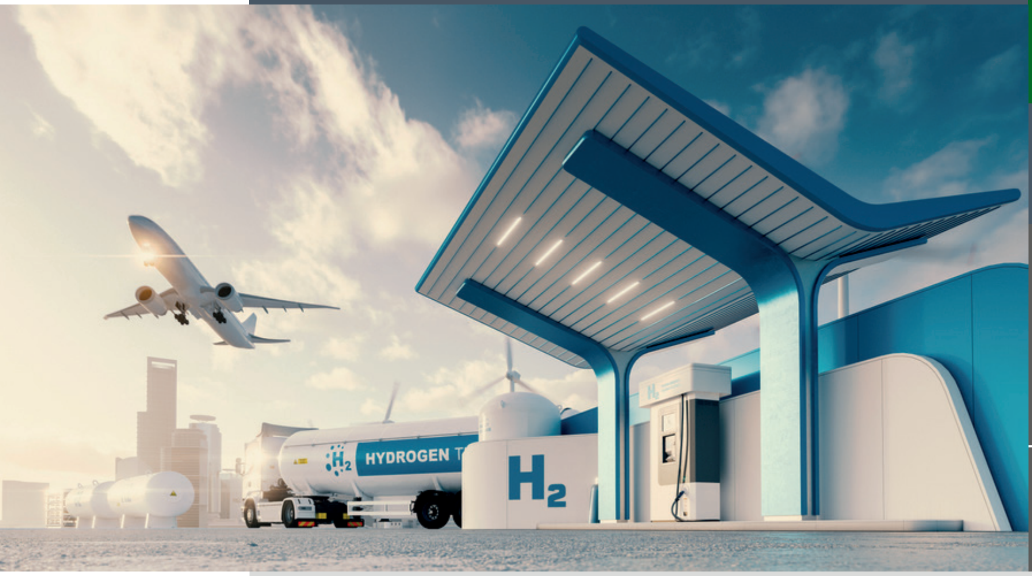

After the Hydrogen Bubble Bursts

The Factors Shaping and Possibly Unfolding International Hydrogen Value Chains

Cédric PHILIBERT

Key Takeaways

- The laws of physics and the geographic realities will prevail over the myths of hydrogen (H_2) : it will essentially be delivering carbon-neutral feedstocks to the chemical and steelmaking industries, carbon-neutral fuels to shipping and aviation, and eventually ensuring security in fully decarbonised power grids.
- Blue or turquoise H_2 produced from natural gas in either electrified steam methane reformer or plasma methane crackers may have a transitory role to play, sparing scarce renewable electricity before sufficient electricity-generating capacities get deployed globally to replace fossil-based electricity and direct fossil fuel use in buildings, industries, and transports.
- Blue and turquoise H_2 would best be produced next to the point of use. Green H_2-based feedstocks and fuels would be produced at lower costs in countries with bountiful renewable resources and exported to regions with high energy demand density.
- Rather than deploying domestic green H_2 production forcefully, European governments should help more renewables-blessed countries engage in the supply of green H_2-based feedstocks and fuels. H_2 production in European countries may grow much less than often claimed, or even shrink, as it gets decarbonised globally.
- The deployment of renewables and the electrification of almost everything remain the highest priorities.

AN EXUBERANCE POSSIBLY LESS IRRATIONAL THAN IT SEEMS

The spectacular infatuation surrounding hydrogen, notably after the publication of the famous International Energy Agency's *Future of Hydrogen* report in June 2019, looks largely irrational. Every knowledgeable expert understands that the characteristics of dihydrogen (H_2) can only limit its use as an energy carrier. Indeed, its combustion or its use in fuel cell does not generate carbon dioxide (CO_2) formation, as the H_2 molecule contains no carbon. H_2 has a high energy per unit mass, but a rather low energy per unit volume, even when liquefied or heavily pressurised. It gets liquefied at -253°C: reaching and maintaining such temperature level is complex and energy intensive. Its storage and transport are affordable in saline cavities and pipelines, but rather costly in steel tanks, and aboard ships, trains and trucks. As Ulf Bossel, the Founder of the German Solar Energy Society, once put it, "*compared to natural gas or liquid fuels, much more energy is required for the marketing of hydrogen*".[1] With current technologies, the efficiency of using hydrogen from a low-carbon source of electricity to move a vehicle is of ~25%, three times less than using a battery electric vehicle. Its efficiency rises to ~50% for delivering heat from the same source of electricity, vs. ~90% with resistive heating, and an apparent ~300% efficiency (150 to 500%) with heat pumps – a ratio of one to six.

From a decarbonation perspective, there are five major uses of hydrogen that appear necessary: producing low-carbon or carbon-neutral feedstocks (or process agents) to the chemical and steelmaking industries, delivering low-carbon or carbon-neutral fuels (ammonia and synthetic kerosene) to the great majority of planes and ships that cannot be electrified. These matter a lot: steelmaking is responsible for 7% of global greenhouse gas (GHG) emissions, aviation and maritime transportation for about 3% each, and these shares will only grow as other activities get decarbonised.

There are five major uses of hydrogen

Finally, hydrogen will likely be needed as a long-duration storage option in power systems dominated by variable renewables such as solar and wind. This need is further discussed at the end of this briefing.

Low-carbon hydrogen may find other uses, though, but the perspectives are far from clear-cut. For ground transportation, notably long-range heavy-duty, hydrogen may play a role to complement the more energy-efficient direct electrification, possibly in so-called "range-extenders", but as is discussed below this can take several forms.

Another often-quoted use of hydrogen would be to deliver heat, which represents half the global energy demand. However, delivering from hydrogen low and even medium temperature heat to buildings and industries is a quite inefficient proposition by comparison with heat pumps. The United Kingdom (UK) Hydrogen Strategy, generally very aggressive, remains cautious on heating, consumers' safety not being the least

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[1] U. Bossel, "Does a Hydrogen Economy Make Sense?", *Proceedings of the IEEE*, Vol. 94, October 10, 2006.

concern.[2] The case for delivering high-temperature heat to industries looks somewhat better but low-carbon hydrogen would have to compete here with biomass and a breadth of direct electric heat technologies, backed by emerging efficient and compact high-temperature heat storage technologies.

From these perspectives indeed, the current hype is largely excessive.[3] It can only be explained by the fact that hydrogen is a promise for all energy interests – fossil fuel producers and retailers to avoid stranded assets, nuclear and renewable developers to extend low-carbon electricity productions further. Some gas transport companies even pretend to simultaneously deploy the production of blue hydrogen and the methanation of hydrogen with captured CO_2. However, steam methane reforming and methanation are exact reverse operations,[4] with no climate benefit compared to simply burning natural gas and storing captured CO_2; instead, doing both increases emissions and costs from unavoidable energy losses. Adding to this the enthusiasm of the few companies specialised in handling industrial gases, that of a few large automakers and truck manufacturers, and hundreds of start-ups of all sizes that have invested in the development of hydrogen-consuming technologies, one obtains an interest that is much wider than hydrogen deserves. From these companies' perspectives, this exuberance has nothing irrational, especially if it is financially backed by policy makers lured by the promise of a new industrial development and jobs going hand in hand with the perspective of a carbonless, apparently non-controversial, "energy". To them, hydrogen proves the green growth like the eating proves the pudding.

The current hype is largely excessive

As a result, many applications that would not pass a simple test relative to the implied GHG emissions or the economic efficiency get largely financed, public finances helping raise additional funds from investors fearing to miss the boat, fuelling the hydrogen bubble further. Grand plans are made with gigawatts (GW) of electrolysers and ubiquitous pipeline networks.[5] Hydrogen is "the new oil" and the "geopolitics of hydrogen" are promising to reshape international relations.[6] A symbol is how the German government signs memoranda of understanding all over the world, lately with Namibia. Caution alerts from well-informed analysts and realistic industry leaders are still ignored.[7] However, sooner or later all bubbles burst against the reality wall.

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[2] L. Collins, "Using Clean Hydrogen for Domestic Heating and Transport is 'Nonsensical', qSays Enel CEO", *Recharge*, July 13, 2021, available at: www.rechargenews.com; HM Government, *UK Hydrogen Strategy*, London, 2021.

[3] For more detailed analyses, see C. Philibert, "*Perspectives on a Hydrogen Strategy for the European Union", Études de l'Ifri*, Ifri, April 2020, available at: www.ifri.org.

[4] Steam methane reforming: $CH_4+H_2O \rightarrow H_2 + CO_2$. Methanation: $H_2+CO_2 \rightarrow CH_4+H_2O$.

[5] See Enagás *et al.*, *European Hydrogen Backbone*, Guidehouse, 2020; Creos *et al.*, *Extending the European Hydrogen Backbone*, Guidehouse, 2021.

[6] T. Lepercq, *Hydrogène : le nouveau pétrole*, Paris : Le Cherche Midi, 2019.

[7] See, e.g., M. Liebreich, "Separating Hype from Hydrogen", *Bloomberg*, October 16, 2020, available at: https://about.bnef.com.

This memo takes a sober look at economic and environmental realities of hydrogen, identifies indispensable developments in Europe and determines factors that will shape, and possibly unfold, international value chains.

THE LOW-CARBON HYDROGEN RAINBOW: GEOGRAPHY AND TIME SEQUENCING MATTER

Some say one should only speak of "low-carbon" hydrogen and define criteria respective to the GHG emissions implied in producing hydrogen; however, the use of "colors" remains a convenient shortcut. Black and grey hydrogen are made from coal and natural gas, blue hydrogen is the same with carbon dioxide capture and storage (some add "use" as an alternative to storage, but this creates some confusion). Green hydrogen is made from water electrolysis running on renewable electricity, some add pink or yellow hydrogen made from nuclear power.

Turquoise is the color of hydrogen from methane pyrolysis, which generate solid carbon, not CO_2, as a by-product, and is being developed throughout the world.[8] Plasma methane pyrolysis consumes only about a fifth of the electricity that electrolysis of water would require, but uses more gas, not less, than standard methane reforming.

The use of "colors" remains a convenient shortcut

Upstream methane leaks must be accounted for in a life-cycle analytic comparison of technologies. Recently, two scientists have claimed that total carbon dioxide equivalent emissions for blue hydrogen are only 9%-12% less than for grey hydrogen and over 20% greater than burning gas or coal for heat, due to higher fugitive methane emissions.[9]

However, their calculations rest on the disputable choice of a 20-years' time-horizon for the Global Warming Potential instead of the United Nations Framework Convention on Climate Change (UNFCCC)-preferred 100-years' time horizon, as well as other disputable assumptions relating to the rate of upstream methane leaks and the efficacy of carbon capture. Still, this paper shows, despite itself, that electrifying methane reformation combined with carbon capture leads to a much better environmental outcome.

Electrification reduces by one third the consumption of natural gas, and thus the upstream methane leaks, as well as the CO_2 formation. Furthermore, it delivers only a concentrated flux of CO_2, much easier to capture and store. The electricity the process requires is only about a fourth of that of electrolysing water. It allows conceiving extremely compact reactors.[10] In the case of ammonia production, an additional option could be to co-electrolyse air and steam in more efficient solid oxide electrolysers, benefitting from the

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[8] See, e.g., S.B. Harrison, "Four More Technologies for Turquoise Hydrogen", H2-View, September 13, 2021, available at: www.h2-view.com; C. Philibert, "Methane Splitting and Turquoise Ammonia", *Ammonia Energy*, May 14, 2020, available at: www.ammoniaenergy.org.

[9] R.W. Howarth and M.Z. Jacobson, "How Green is Blue Hydrogen?", *Energy Science & Engineering,* July 26, 2021.

[10] S.T. Wismann *et al.*, "Electrified Methane Reforming: A Compact Approach to Greener Industrial Hydrogen Production", *Science,* Vol. 364, No. 6442, May 24, 2019, available at: www.science.org.

waste heat of the ammonia synthesis, and suppressing the need for an air separation unit to provide the nitrogen.[11] Compared with methane pyrolysis, electrified reformers do produce some CO_2 in need of storage, but entail only about half upstream methane leaks – and both could be considered mixes of green and blue.

Green hydrogen would best be produced in areas with bountiful renewable resources with low energy demand or already fully decarbonised electric grids. In areas with high energy demand density and milder renewable resources, such as most of Europe, Korea or Japan, renewable electricity is usually on the rise but still far from displacing most of fossil fuel-based electricity generation. The priority is then to deploy more renewables to deliver electricity in its current and novel uses in buildings, industry and transports.

The priority is then to deploy more renewables

Deploying too quickly large electrolyser capacities and dedicated renewable energy capacities in such areas might delay, not accelerate, emission reductions. Although this may seem paradoxical, the urgency of mitigating climate change does not allow this. On the other hand, technology development, learning and economies of scale fully justify an accelerated deployment of hydrogen production and transformation technologies, if only where and for which usage they make real sense.

There might thus be a window of opportunity for blue or green-blue hydrogen, which most analysts assess will be the cheapest low-carbon source in this decade (unless gas prices are too high), while after 2030 green hydrogen would progressively become more competitive (unless gas prices crash as demand stalls).

NEW RENEWABLE ENERGY TRADE

Forty years ago, the German engineer Reinhard Dahlberg was first to propose exporting green hydrogen or ammonia from regions with bountiful solar resources to the industrialised nations. The idea resurfaced in the International Energy Agency (IEA) work in 2017.[12] In 2021, hardly a week passes without some spectacular announcement from some government or consortium of companies that another GW-scale investment in renewables and electrolysers will soon be made for producing and exporting hydrogen – in most cases as ammonia.

The largest such project so far is the HyDeal project, by which a large consortium intends to build eventually up to 93 GW of photovoltaic (PV) capacity in Spain, running 67 GW of electrolysers and exporting 3.7 million tons per year (Mt/y) hydrogen to France, then Germany and the rest of Europe. The developer initially intended to mix the H_2 gas with natural gas and stored the mix in an underground cavern in the south of France, where it would feed a large hydrogen combined cycle

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[11] J.B. Hansen, *Solid Oxide Cell Enabled Ammonia Synthesis and Ammonia Based Power Production*, Presentation at the American Institute of Chemical Engineers Annual Meeting, Minneapolis, Minnesota, 2017.

[12] R. Dahlberg, "Replacement of Fossil Fuels by Hydrogen", *International Journal of Hydrogen Energy,* Vol. 7, No. 2, 1982, pp. 121-142; C. Philibert, "Renewable Energy for Industry", *IEA Insights Paper*, IEA, 2017.

gas turbine (CCGT). The early hydrogen production will more likely be piped to a Spanish steelmaker for direct iron reduction.

Next are the large intents expressed by Kazakhstan (50 GW), and the Western Renewable Energy Hub (50 GW solar and wind, ~29 GW electrolysers) and the Asian Renewable Energy Hub (26 GW solar and wind, 14 GW electrolysers), both in Western Australia, both developed by InterContinental Energy and CWP Global. The Australian Fortescue Metal Group wants to build up to 235 GW solar and wind capacities dedicated to hydrogen in a variety of countries, and has signed memoranda of understanding with some, notably Mauritania (for 30 GW solar and wind) and Pakistan. Chile plans 25 GW of renewable capacities for hydrogen exports. Argentina, Brazil, Canada, Kuwait, Mexico, Namibia, Morocco, Oman, Paraguay, Russia, Saudi Arabia, South Africa, Ukraine, and other countries (or stakeholders in these countries) are also considering jumping on the bandwagon.

Importing low-carbon fuels and feedstocks looks like a solution

On the demand side, three countries have expressed an intent to import massive amounts of hydrogen or hydrogen-based feedstocks and fuels: Germany, Japan and the Netherlands. Japan intends to massively co-combust imported ammonia with coal in its thermal power plants (1.7 Mt NH_3 by 2030… and over 50 Mt/y by 2050). While Japan possibly underestimates the potential of floating offshore wind power, or overestimate its future costs, Germany and the Netherlands can credibly measure the difficulties they have begun to face in deploying enough renewables to fully replace fossil fuels in their power systems, not to mention other uses. In this decade at the minimum, but possibly long afterwards, importing low-carbon fuels and feedstocks (from synthetic alcohols or hydrocarbons for the chemical industry to direct reduced iron for steelmaking) looks like a solution outcompeting local production based on green hydrogen.

Relatively short pipelines or networks of pressurised hydrogen exist, notably in the Gulf of Mexico and the north of Europe (one linking France, Belgium and the Netherlands, another one in Germany). They may further develop and support some international trade of dihydrogen. Transport by ships of liquefied dihydrogen seems much less likely, and the use of liquid organic hydride or ammonia as pure hydrogen carriers, of which the whole dihydrogen would be extracted at the receiving end, seems barely credible: the capital costs and energy losses of all options are too high. Ammonia stands out precisely because it is used as an industrial feedstock and already an internationally traded commodity, transported in pipelines and ships; and it can be burned directly in gas turbines, internal combustion engines, or used in some types of fuel cells.

The point is, dihydrogen is likely to remain produced relatively close to the point of consumption, while hydrogen-based feedstocks and fuels are more likely to travel long distances, and thus support a significantly larger international trade. Meanwhile, China, France, the UK and the United States, among others, are developing both production and uses of low-carbon hydrogen and assume self-sufficiency or, as the UK Strategy puts it, fear “over-reliance on imports”.

VARIATIONS AROUND A NO-REGRET APPROACH FOR EUROPE

Can one try and estimate the amounts of hydrogen that will be produced within the European community in the decades to come? A recent study by the European gas companies concludes that the European Union (EU) and the UK could see a hydrogen demand of 2,300 terawatt-hours (TWh) (2,150-2,750 TWh) or 69 Mt/y[13] by 2050, i.e., 20-25% of EU and UK final energy consumption by then.[14]

Of this, 1,200 TWh would be for industry, including just over 200 TWh for medium and high temperature industrial process heat, vs. 650 TWh of demand for dispatchable electricity production, 300 TWh in transport and 150 TWh for buildings, among a total of low-carbon gas for buildings of 600 TWh – the 450 TWh difference assumed to come in as biomethane. Unfortunately, the 1,200 TWh figure for industrial hydrogen "*includes hydrogen needed to produce hydrogen-derived synthetic fuels in aviation*". Inadvertently or on purpose, this blurs the picture significantly and it seems difficult to accept this overall figure lightly, even though it seems in line with global estimates produced by global hydrogen supporting consortia such as the Hydrogen Council.[15]

The European Commission, for its part, targets the production of up to 10 Mt/y renewable hydrogen by 2030, and considers that "about a quarter of renewable electricity might be used for renewable hydrogen production by 2050".[16]

A more cautious, "no-regret" approach is proposed

A more cautious, "no-regret" approach is proposed by the German think-tank Agora Energiewende.[17] It leaves aside the most controversial uses of hydrogen – for private cars and in buildings, and focuses on "where there is much more consensus", the so-called "hard-to-decarbonise" or "hard-to-abate" applications: "ammonia production, methanol production, iron ore reduction, production of petrochemicals for plastics and fuels and plastics recycling".

The underlying assumption is moderate growth in all sectors. Hydrogen demand from refineries would vanish by 2050, but demand from steel plants and the chemical industry would increase. Overall, less than 300 TWh of low-carbon hydrogen will be required to reduce process emissions in the industrial sector: by 2050, 123 TWh for steel, 96 TWh for ammonia, 42 TWh for chemical plastics recycling and 10 TWh for methanol."

Contrary to common wisdom, the Agora Energiewende's analysis does not factor in demand from process heat: besides heat pumps, "eight mechanisms for electric heating are commercially established, of which six can produce heat in excess of 1,000 Celsius degrees", with a much greater efficiency than hydrogen, and offering several side benefits.

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[13] 1 TWh is the low heating value of 30,030 tons of H_2.

[14] Gas for Climate, *Analysing Future Demand, Supply, and Transport of Hydrogen*, Guidehouse, June 2021.

[15] Hydrogen Council, *Hydrogen Decarbonisation Pathways*, January 2021.

[16] European Commission, *A Hydrogen Strategy for a Climate-Neutral Europe*, COM(2020) 301 final, 2020.

[17] Agora Energiewende and AFRY Management Consulting, *No-Regret Hydrogen: Charting Early Steps for H2 Infrastructure in Europe*, 2021.

Hydrogen could offer a flexibility advantage for continuous industrial processes, where it can be stored cheaply in underground salt caverns. Nevertheless, “power-to-heat technologies should be considered before thinking about producing heat from hydrogen”.

Considering then the possibilities of hydrogen production from solar and/or (mostly offshore) wind power in Europe, Agora Energiewende then identifies four “no-regret pipeline corridors”. One stands out by the large assumed industrial demand, spanning over north of France and Germany, Belgium and the Netherlands – precisely where the unique international hydrogen pipeline network is already operating.

Would the corresponding investments in electrolysers, additional renewable energy capacities, hydrogen storage and pipelines be actually “no regret”, i.e., “resilient to future levels of hydrogen demand”? Agora Energiewende assumes that synthetic naphtha, like synthetic hydrocarbon fuels, would likely be imported from areas with better renewable resources and more space. The study also refers to the vision of the German Energy Agency, which assumes that trade in synthetic hydrocarbons might eclipse trade in hydrogen.[18] For example, instead of using pressurised H_2 in fuel cells as “range-extenders” for electric trucks, one could use synthetic gasoline in motors. While the overall efficiency would be even lower than with hydrogen due to additional conversions, the fuel costs would be close if the production takes place in areas with much better resources, while the cost of vehicles would be lower, and the distribution could use existing networks and refilling stations.

But why would low-carbon methanol and ammonia not be imported as well?

Ammonia will be produced next to where hydrogen is produced

Arguably, the cost of transport is higher for ammonia and methanol than for hydrocarbons, due to their lower energy density, plus in case of ammonia the need to keep it safely cooled during storage and transport. Still, whether fuel or feedstock, ammonia will be produced next to where hydrogen is produced – and green hydrogen will mostly be produced in areas with bountiful energy resources and transported. Over time however, while the costs of green electricity and hydrogen plumet, the regional cost disparities will shrink and stop covering the long-distance transport costs – as early as 2030 according to a recent study.[19]

Somewhat surprisingly, the Agora Energiewende “no-regret” study does not consider the forthcoming important demand for ammonia as a fuel for maritime transportation. If it is assumed to be imported rather than produced locally, one may wonder why ammonia as an industrial feedstock would instead be assumed to be produced locally.

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[18] *Powerfuels in a Renewable Energy World,* LUT University and Deutsche Energie-Agentur GmbH (Dena), 2020.

[19] M. Fasihi *et al.*, “Global Potential of Green Ammonia Based on Hybrid PV-Wind Power Plants”, *Applied Energy,* Vol. 294, July 15, 2021, assuming all hydrogen storage can be underground, contrary to modelling work based on expensive steel tanks (J. Armijo and C. Philibert, “Flexible Production of Green Hydrogen and Ammonia from Variable Solar and Wind Energy: Case Study of Chile and Argentina”, *International Journal of Hydrogen Energy*, Vol. 45, No.3, pp. 1541-1558, January 13, 2020.

For all hydrogen-based fuels but ammonia, one needs a source of "fresh" atmospheric carbon, via direct air capture, presumably a costly option, or biomass: recycling fossil carbon from industries or from combusting fossil fuels does not seem optimal from a net zero emission path perspective. There is thus little justification for situating methanol or Fisher-Tropsch installations next to industrial facilities.[20] CO_2 captured from calcinating limestone in cement factories might be an exception.

If green ammonia and methanol are imported from abroad, the large remaining hydrogen demand are for steelmaking and plastics recycling. However, the demand for hydrogen from plastics recycling appears poorly documented; to the opposite, the reduction of plastic waste is usually presented as a possible source of hydrogen production. With respect to green steelmaking, the possibility of importing hydrogen-reduced iron as hot briquetted iron (HBI) instead of iron ores should be considered seriously.[21]

Except in Sweden and, to a lesser extent, Norway and Austria, there is little iron ore mining in Europe, which imports over 90% of its needs, notably from Brazil and Ukraine – a country in which the EU intends to develop green hydrogen production. Exactly like aluminium plants have long been sited next to vast hydropower resources, iron ore reduction may be relocated in countries with abundant and cheap solar and wind power resources – and possibly at the same time closer to growing steel markets such as Africa and South-East Asia. In the long term, the possibility of reducing iron ores with electricity directly, such as with the Siderwin process under development by Arcelor Mittal, represents another threat for the European production of hydrogen for green steelmaking.

CONCLUSION: DEPLOYING RENEWABLES, THE REAL PRIORITY

Assessing the real "no-regrets" investments for locally produced green hydrogen in Europe appears quite challenging in the medium term, with the competition from "green-blue" hydrogen from methane pyrolysis or electrified steam methane reformers on one side, and from imported green hydrogen-based fuels and feedstocks on the other.

In a somewhat longer term, an important need may arise from achieving the decarbonisation of the power systems. The issue is to replace natural gas in balancing power plants while preserving sufficient energy security to face "dark doldrums" of ~10 days will low sun and low wind, possibly separated by episodes of excess supply too short for sufficiently refilling the energy storages. In the case of Germany, this may

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[20] However, direct air capture would cost less if installed where large surface areas and large volumes of wasted heat can be made available simultaneously, a rare occurrence, except close to nuclear power plants.

[21] The same applies to the iron ore exports from Australia to China. See D. Gielen *et al.*, "Renewables-Based Decarbonisation and Relocation of Iron and Steel Making", *Journal of Industrial Ecology,* March 6, 2020.

require ~22% of electricity from fully dispatchable capacities,[22] which dihydrogen or carbon-neutral derivatives could fuel – preferably ammonia (NH_3), which contains no carbon atom.

The whole hydrogen discussion should be reconsidered

Here again, a balance may be struck between imports of ammonia as a fuel, and local hydrogen production and storage, assuming that existing or greenfield gas turbines can be adapted to combust either fuel. An important aspect may weigh in favour of local production: flexible electrolyser production in the European grid can help integrate more variable renewable while not contributing to demand peaks, thereby reducing the need for dispatchable electricity. However, this is unlikely to be required before 2035 at the earliest.[23]

The question here again is the capacity of European countries to significantly accelerate the deployment of solar and wind power, and the direct electrification of end-use sectors. The whole hydrogen discussion should be reconsidered from this perspective, and policy makers throughout the continent should clearly define these deployments as the most urgent and important priority – rather than the deployment of hydrogen itself.

__Cédric Philibert__ is an independent consultant and senior analyst of energy and climate issues, with a focus on renewable energy for industry and transports, the roles of electrification and hydrogen in decarbonizing the global economy. He is also an associate fellow of the Ifri Center for Energy and of the Australian National University.

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[22] O. Ruhnau and S. Qvist, "Storage Requirements in a 100% Renewable Electricity System: Extreme Events and Inter-Annual Variability", *Working Paper*, ZBW – Leibniz Information Centre for Economics, 2021.

[23] Réseau de transport d'électricité (RTE), *Futurs énergétiques 2050 : Bilan de la phase I*, June 8, 2021.

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27 rue de la Procession
75740 Paris cedex 15 – France

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