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True Colors: What Role Can Hydrogen Play in the Transition to a Low-Carbon Future?

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True Colors: What Role Can Hydrogen Play in the Transition to a Low-Carbon Future?

By John Treat

Producing hydrogen through steam methane reforming (SMR). Photo courtesy Air Liquide Engineering & Construction.

Introduction

Recent years have seen a surge of interest in hydrogen, especially as part of efforts to meet the climate challenge by decarbonizing the use of energy and whole economies. Even people who are not following these debates closely have probably heard references to "clean hydrogen," or to hydrogen categorized as "blue" or "green." Terminology like this can leave the impression that the issues around hydrogen are relatively simple or that the important issues should be relatively easy to sort out. This could hardly be further from the truth.

Debates around energy technologies and options can be politically polarized, and hydrogen is no exception.[1] For some, "clean" hydrogen is seen to have enormous potential—both to advance decarbonization and to protect or create jobs—and should be developed as quickly and extensively as possible. For others, the emphasis on hydrogen is a "false solution" that merely distracts from other options they consider more promising, or other tasks they see as more urgent.

Trade unions are already engaged in the discussions and debates around hydrogen as part of decarbonization strategies and as a potential source of jobs—in the UK,[2] Germany[3] and elsewhere. But many unions are not engaged at all, although many trade union activists concerned about climate change are trying to follow the discussions and developments. Those outside the energy sector may feel especially reluctant or unable to participate in such debates, much less formulate a position with confidence and advocate for it.

In general, private interests and mainstream policy voices drive and frame the debates over hydrogen without seriously questioning, let alone challenging, current policy and ownership patterns. As a result, the debates often take place as if the priority is to choose among technology options, without considering what would need to change in order for *any* of those options to be deployed in ways that truly address the climate and energy emergency. As TUED has argued elsewhere, the policies that have been pursued over the past two decades or so in an attempt to "incentivize" the wider energy transition have resoundingly failed to do so, leading not to an energy *transition*, but rather an energy *expansion*, in which the use of essentially *all* forms of energy continues to rise.[4] This failure must be kept sharply in view in order to avoid trying to answer the wrong questions, such as, "What color of hydrogen should unions advocate, if any?" while leaving the right questions, such as, "What do we have to do in order to free all decarbonization options from the imperatives of profit?" unasked.

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1 See for instance, Nikolaus J. Kurmayer, "Summer controversy illustrates polarisation of hydrogen debate," EURACTIV.com, August 27, 2021, https://www.euractiv.com/section/energy-environment/news/summer-controversy-illustrates-polarisation-of-hydrogen-debate/.

2 See for instance, Unite the Union, "A Plan for Jobs in UK manufacturing," February 1, 2021, https://www.unitetheunion.org/campaigns/a-plan-for-jobs-in-uk-manufacturing/;

GMB Union, "Unions back hydrogen jobs boom," 25 Jun 2020, https://www.gmb.org.uk/news/unions-back-hydrogen-jobs-boom; Unison, "Unlocking the potential of Hydrogen," February 21, 2019, https://www.unison.org.uk/motions/2019/energy/unlocking-the-potential-of-hydrogen/.

3 Kerstine Appunn, "German trade union calls for use of "blue" hydrogen, European industry power price," *Clean Energy Wire*, November 9, 2020, https://www.cleanenergywire.org/news/german-trade-union-calls-use-blue-hydrogen-european-industry-power-price.

4 Sean Sweeney, John Treat and Daniel Chavez, *Energy transition or energy expansion?*, TUED and TNI, October 22, 2021, https://www.tni.org/en/publication/energy-transition-or-energy-expansion.

Why Hydrogen?

Interest in hydrogen as a technology to support decarbonization rests on several factors. Hydrogen is a useful and flexible "energy carrier," allowing it to play potentially a wide range of important roles in energy-using systems.[5] It can be used to produce electricity chemically through fuel cells, which can power vehicles or be fed into electrical grids. It can also be used as a fuel for heat or to drive gas turbines, or can be converted into ammonia or other fuels. Hydrogen has an energy density triple that of gasoline or diesel,[6] and over a hundred times that of current lithium-ion batteries.[7] This makes hydrogen far more suitable for use in larger, heavier vehicles and for longer distances, where the additional weight of batteries required to provide adequate range or power would be prohibitive. It can be pumped as quickly as gasoline or diesel, allowing for refueling much more quickly than electric batteries can be "recharged." Hydrogen burns at a temperature comparable to that of "natural gas,"[8] making it a potentially vital source of heat for heating or industrial uses.[9] Perhaps most importantly, in principle hydrogen can be produced from "carbon-free" sources and used as a fuel in ways that produce only water as "waste." And although hydrogen is a combustible (and potentially explosive) fuel that requires appropriate handling, it has several features that make it safer than many more common fuels, including being both nontoxic and significantly less likely to result in dangerous fires.[10]

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5 It is important to keep in mind that hydrogen is not an energy source (like coal, crude oil, wind or sunlight), but what is commonly called an energy "carrier" or "vector" (like gasoline, or electricity). An energy carrier is the product of some transformation of a primary energy source, and typically has important advantages over the primary source from which it is derived: it is often easier to transport or store for later use, or can be used in ways for which the primary source isn't suitable. Both pure hydrogen (whether liquid or gas) and the ammonia or other synthetic fuels that can be produced from it are "energy carriers"—and potentially important ones. It should also be kept in mind that even many of what are commonly thought of as "energy sources"—such as coal or crude oil—are technically also energy "carriers," in the sense that they effectively hold millions of years of sunlight in decayed and compacted organic matter. See: IEA, *The Future of Hydrogen: Seizing today's opportunities*, June 2019, https://www.iea.org/reports/the-future-of-hydrogen, 32.

6 *Engineering ToolBox*, "Fossil and Alternative Fuels—Energy Content," 2008, https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html.

7 Clean Energy Institute, "What is a lithium-ion battery and how does it work?" University of Washington, https://www.cei.washington.edu/education/science-of-solar/battery-technology/.

8 We will use the term "natural gas" in this paper for the mixture of (mainly) methane and other fossil compounds that is commonly referred to by that name, but it should be noted that the name has a complex and checkered history, and is increasingly being challenged as playing into gas-industry "greenwashing" spin, with calls that it be replaced by "fossil gas," "methane gas," or some other term—as articulated for instance at: Rebecca Leber, "The end of natural gas has to start with its name," *Vox*, February 10, 2022, https://www.vox.com/22912760/natural-gas-methane-rename.

9 Michael Liebreich, "Separating Hype from Hydrogen—Part One: The Supply Side," *BloombergNEF*, October 8, 2020, https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/.

10 *Power Magazine*, "Lessons Learned from a Hydrogen Explosion," May 1, 2009, https://www.powermag.com/lessons-learned-from-a-hydrogen-explosion/; see also, Christian Tae, "Hydrogen Safety: Let's Clear the Air," NRDC, January 14, 2021, https://www.nrdc.org/experts/christian-tae/hydrogen-safety-lets-clear-air.

Hydrogen already plays a crucial role in many applications. Large quantities of hydrogen are used in refining petroleum, in the production of steel, ammonia and other chemicals (including synthetic fuels) and as a coolant in power stations. Global demand for hydrogen has more than tripled since 1975 and continues to rise.[11] In 2020, roughly 87 million tons of hydrogen were produced to meet this rising demand.[12]

But in addition to its many established uses, hydrogen is increasingly being presented in mainstream energy transition scenarios as having a crucial and much-expanded role: in decarbonizing heavy industry, shipping and transport; in heating homes; and in tackling the challenges of electrical grid balancing and storage, as power systems incorporate more "variable" sources of generation like wind and solar. One key point of debate is whether "blue" hydrogen (produced from fossil fuels, with the resulting emissions "captured" and thus prevented from being released to the atmosphere) can play a significant role as, in effect, a "bridge" technology (as natural gas has sometimes been proposed as a "bridge fuel") toward full decarbonization, relying on "green" hydrogen (produced from wind- or solar-generated electricity and with effectively no carbon emissions released during the process). Understanding whether and how hydrogen can play the roles envisaged for it, and under what conditions, may be crucial for unions working to develop a technically sound, shared vision for the transformation of our energy systems and economies to more sustainable and just forms.

It is important to emphasize the dual nature of the task involved in realizing hydrogen's potential for decarbonization. First, in order for hydrogen to play a meaningful role in decarbonization, its application must be *expanded into sectors where it is currently hardly used at all*—into more industrial applications, as well as more widely into transport, power generation and more. Second, *its own production must also be decarbonized*—either by "capturing" the emissions generated during its production, or by producing it through processes that do not generate significant emissions to begin with.

It should also be kept in mind that, for "green" hydrogen and the power sector, these two tasks are deeply intertwined. The challenge of producing "green" hydrogen from electricity (which must ultimately be generated from renewable or other zero-carbon sources) and the challenge of turning the resulting "green" hydrogen back into useful power for those same grids need to be resolved at the same time—while also ensuring sufficient "green" hydrogen to meet the many other requirements envisaged for it in future,

11 IEA, *The Future of Hydrogen: Seizing today's opportunities*, June 2019, https://www.iea.org/reports/the-future-of-hydrogen.
12 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, May 2021, https://www.iea.org/reports/net-zero-by-2050.

decarbonized energy systems. We will have much more to say about this in Part Three below.

Hydrogen and the Case for Public Ownership

We think a serious consideration of the facts and technical challenges involved in scaling up hydrogen in line with meeting the decarbonization challenge leaves little doubt that this is highly unlikely to be achieved without a dramatic shift in approach—a shift away from trying to "incentivize" private investors, and toward a planned, coordinated mobilization under public ownership and control. The speed and scale of investment and deployment required to bring hydrogen production and storage in line with mainstream scenarios for reaching "net zero," and the technical challenges involved in hydrogen's production, storage and use, call for levels of planning, coordination and cooperation that private interests are not suited to provide. This includes development of the infrastructure required for hydrogen to play a role not only in enabling the full decarbonization of the power sector but also in powering essential industrial, transportation and other processes that cannot realistically be electrified.

"Incentivizing" and "de-risking" investment for private actors has not produced the results that were hoped for in relation to wind and solar power; we see no reason to believe the results will be different in relation to hydrogen. We need a different approach to solving the formidable challenges that must be faced in driving forward the transition to genuinely sustainable future energy systems.

To be clear, "public ownership" is hardly sufficient on its own to ensure making the changes required. We must also ensure that the transition is carried out in a way that's consistent with the social, ecological and other goals of the trade union movement and its allies. Achieving that broader but essential set of aims will also require robust democratic accountability that can keep the risk of any state-led "extractivist" expansion of energy exploitation and use in check. Only such an approach can ensure that *any* technological decisions are based on a rigorous (and ongoing) assessment of their social, environmental and economic merits.

Although it seems likely that hydrogen will play a very important role in future energy systems, given the difficulty in decarbonizing crucial sectors and processes in other ways, it is essentially impossible at this point to know how large a role that might be, since the answer would depend on an enormous number of prior decisions—about industrial production, transportation modalities, conservation efforts and much besides. But unions and their allies should be skeptical in the meantime of claims coming from (or supported by) industry voices. Whatever role hydrogen can and should play in future energy systems, our focus should be on developing a robust, alternative, technically informed political vision of public ownership and democratic control of energy, and on formulating the political strategy necessary to make that vision real.

Goals and Structure

This paper aims to help unions and their allies make a more informed and more widely shared assessment of the options being advanced, and make clear the conditions that need to be met in order for hydrogen's potential to be realized. It takes a critical view of mainstream proposals for the scaling up of hydrogen—based on both the enormity of change required in order to meet agreed targets for decarbonization, and a sober consideration of the policy approaches that are proposed in order to bring about that change.

In particular, this paper argues that considerations of ownership must be kept centrally in view in the debates over hydrogen (as with other technological choices). This can help to place public research and a scientific discourse back at the center of international cooperation for future decisions and choices. A "pro-public" approach allows for the possibility of making decisions around technologies that are based on a rigorous (and ongoing) assessment of their social, environmental and other merits, without being constrained by the additional imperative of generating profits for investors.

This paper is structured as follows:

In Part One, we look at hydrogen in the context of the decarbonization challenge. This includes introducing some conventional terminology and technical information, and about the overall role hydrogen is anticipated to have under major mainstream scenarios for the energy transition.

In Part Two, we look in more detail at specific sectors and applications where hydrogen is being promoted as having a crucial role to play in supporting decarbonization efforts. The main aim here is to provide a better sense of the potential importance of hydrogen in providing, maintaining and improving modern infrastructure and services, as well as protecting and expanding high-quality jobs, and thus to reinforce the need to formulate a vision and political strategy that can enable it to play that role.

In Part Three, we look at the key options and technical challenges involved in decarbonizing hydrogen production at scale. As noted previously, expanding the role of hydrogen into industrial, transport and other sectors is only part of what needs to happen in order for hydrogen to play a serious role in decarbonization. The production of hydrogen for use in those ways also needs to be decarbonized. Here, our aim is to make clearer the formidable nature of the technical challenges involved in scaling up hydrogen production for use as envisaged in mainstream scenarios.

Finally, in the conclusion, we summarize key lessons from the paper and suggest how an alternative, pro-public approach grounded in decommodification and demarketization may be the only hope for tapping into hydrogen's potential for the future decarbonized energy systems we urgently need.

Part One: Hydrogen and the Decarbonization Challenge

In Part One, we look at hydrogen in the context of the decarbonization challenge. This includes introducing some conventional terminology and technical information, and about the overall role hydrogen is anticipated to have under major mainstream scenarios for the energy transition.

Hydrogen Production and the Hydrogen Color Spectrum

Despite being the most abundant chemical element in the universe—making up nearly three-quarters of all known mass[13]—pure hydrogen does not occur naturally on Earth in significant quantities. Instead, it mainly exists as part of other chemical compounds—mostly water, but also methane, and in smaller quantities in nearly all other organic chemical compounds. So in order to be available for use, hydrogen has to be extracted from these other compounds. Doing so requires a lot of energy, and as currently carried out releases large quantities of greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA), hydrogen production globally is responsible for CO2 emissions of roughly 830 million tons per year—an amount "equivalent to the CO2 emissions of the United Kingdom and Indonesia combined."[14]

By convention, hydrogen is called by various color names based on the methods of its production, although there is not always consensus on the use of these color terms: Some are used fairly consistently, while others can

13 https://imagine.gsfc.nasa.gov/ask_astro/stars.html#961112a.
14 IEA, *The Future of Hydrogen*.

vary by country and even change over time.[15] We will have much more to say about some of these "colors" of hydrogen later in this paper, but introducing the conventional terminology here can help make sense of what follows.

"Gray" Hydrogen

Nearly three quarters of hydrogen today is produced from natural gas through a highly emissions-intensive process known as "steam methane reforming" (SMR). In color terms, the resulting hydrogen is usually labeled "gray." This gray hydrogen production accounts for roughly 6% of global natural gas consumption,[16] and production of one kilogram (kg) of gray hydrogen results in the release of roughly 9.3 kg of CO2—slightly more than what is released (9.1 kg) from the combustion of one gallon of gasoline (which contains roughly the same amount of energy as one kg of hydrogen).[17]

"Black" and "Brown" Hydrogen

Coal accounts for most of the remaining quarter of global hydrogen production, mainly due to its use in China to produce hydrogen through a method called "coal gasification."[18] This method is both highly emissions intensive and highly polluting, releasing large amounts of both CO2 and carbon monoxide. In color terms, the resulting hydrogen is usually labeled "black" or "brown," depending on the type of coal used as the source ("black" for bituminous coal; "brown" for lignite). According to the IEA, hydrogen production from coal accounted for 2% of global coal consumption as of 2019.[19]

"Blue" Hydrogen

The color "blue" is generally used to refer to hydrogen that would otherwise be termed "gray," "black" or "brown," but where emissions are "captured" and then prevented from release to the atmosphere either by being "stored" or "sequestered" (thus "carbon capture and storage/sequestration," abbreviated "CCS" in either case) or by being "used or "utilized" in some way (thus "carbon

15 "The hydrogen colour spectrum," National Grid, https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum, accessed August 26, 2021.
16 IEA, *The Future of Hydrogen*.
17 Robert Rapier, "Estimating the Carbon Footprint of Hydrogen Production," *Forbes*, June 6, 2020, https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/.
18 IEA, *The Future of Hydrogen*.
19 Ibid.

capture and usage/utilization," abbreviated "CCU" in either case).[20,21] Although not yet deployed at scale, blue hydrogen is held up by some (including major fossil fuel companies) as a promising form of "low carbon" hydrogen. Of course, the potential of this type of hydrogen will depend very largely on the effectiveness of the CCUS technology involved—an issue of considerable consequence, since CCUS has yet to be deployed at significant scale and faces significant hurdles.

"Green" Hydrogen

Much of the recent interest in hydrogen for decarbonization focuses on "green" hydrogen, which is generated using electricity from renewable sources to "split" water into hydrogen and oxygen using "electrolyzers." This method releases effectively no CO2 emissions during production.

Although not yet deployed at scale, the production of "green" hydrogen holds special promise for a decarbonized future since it can in principle use "surplus" electricity (when generation exceeds demand, or "load") to generate hydrogen, which can then be used in turn to generate electricity when supply falls short. This could help solve serious storage and balancing challenges resulting from the large-scale deployment of variable or intermittent sources of electrical power like solar PV and wind. Offshore wind in particular often generates substantial power at night that would otherwise go to waste, making the production of hydrogen (or ammonia, one of hydrogen's important synthetic derivatives) potentially well suited as a complement to offshore wind installations. Ammonia is also significantly easier to store and transport than pure hydrogen, and the infrastructure for doing so is much better developed. We will also return to consider these issues later in this paper.

20 "Carbon capture and storage" (sometimes also called "carbon capture and sequestration," abbreviated "CCS" in either case) refers to the process of capturing, compressing, transporting and storing carbon dioxide (CO2) emissions that would otherwise be released into the atmosphere. Both capture and storage can be accomplished using various chemical or physical processes. Storage is usually intended to be for very long periods of time—decades or centuries—and is most often envisaged to take place in deep geological formations. The physical and chemical characteristics of such formations are highly site-specific, often leaving questions about their suitability for long-term storage, including importantly the risk of leakage. In principle, the captured CO2 can also be put to use in various ways, including the production of synthetic fuels; see for instance, David Roberts, "These uses of CO2 could cut emissions—and make trillions of dollars," *Vox*, November 27, 2019, https://www.vox.com/energy-and-environment/2019/11/13/20839531/climate-change-industry-co2-carbon-capture-utilization-storage-ccu. To date, however, captured CO2 has only seen significant use in what is called "enhanced oil recovery," in which it is injected into oil-bearing rock formations to make the oil easier to extract. Of course, the use of captured CO2 emissions for the purpose of extracting even more fossil fuels is widely viewed by climate and environmental campaigners, including in the labor movement, as extremely problematic.

21 This whole range of possibilities is often grouped together under some version of the general term "carbon capture, usage/utilization, and storage/sequestration," abbreviated "CCUS." For the purposes of this paper, we will use this general term "CCUS" except where the context requires something else.

Other "Colors" of Hydrogen

Current debates around hydrogen focus mainly on what are called "gray," "blue" and "green" forms, but there are many other possibilities for producing hydrogen beyond those. Some of these could offer real potential for use in decarbonization, at least if their development could be pursued outside of the imperatives of profitability and commodification, in order to minimize or eliminate the kinds of social, ecological or other problems that might accompany them under expansionary, for-profit dynamics. Two examples may help illustrate the kinds of options and issues that are involved:

- **Biomass:** Hydrogen can be produced from biomass through various processes (gasification, steam reforming, and even fermentation). Although some of these processes have been in use for some time, the emissions depend on many other factors (kind of biomass used, effectiveness of CCS, etc.) and hydrogen from biomass has not been assigned a consistent color.[22] Of course, the production of biomass at scale also raises serious issues about land use and rights.

- **Nuclear Electrolysis:** Hydrogen can also be generated using nuclear power, making use of both the electricity and the steam generated in the process to produce hydrogen through "high temperature steam electrolysis," which is significantly more efficient than the more typical electrolysis at lower temperatures.[23] Hydrogen produced in this way is labeled "yellow" by the influential financial advisory firm Lazard[24] (which produces regular analyses of energy cost comparisons), but "pink" by the UK's National Grid (which notes that it may also be termed "purple" or "red")[25] as well as by "Energy Cities," an association of cities focusing on the energy transition.[26]

Hydrogen's Role in Major Decarbonization Scenarios

In order to get a sense of the scale of the role hydrogen is expected to play in decarbonization, it is useful to consider the major scenarios for decarbonization

22 Shayne Willette, Guidehouse Insights, "Don't Forget About Biomass Gasification for Hydrogen," *Forbes*, April 22, 2020, https://www.forbes.com/sites/pikeresearch/2020/04/22/dont-forget-about-biomass-gasification-for-hydrogen/.

23 Badwal, S. Giddey & C. Munnings (2012). *Hydrogen production via solid electrolytic routes*. Wiley Interdisciplinary Reviews: Energy and Environment, 2(5), 473–87. doi:10.1002/wene.50.

24 Lazard, *Levelized Cost of Hydrogen*, October 19, 2020, https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/.

25 The hydrogen colour spectrum, National Grid.

26 Sara Giovannini, "50 shades of (grey and blue and green) hydrogen," *Energy Cities*, November 13, 2020, https://energy-cities.eu/50-shades-of-grey-and-blue-and-green-hydrogen/.

from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). Before doing so, however, it is important to clarify and emphasize a few things about those mainstream scenarios.

First, these key mainstream scenarios are based on the idea of reaching "net zero" by mid-century: a state in which any greenhouse gases (GHGs) being released *into* the atmosphere are matched by GHGs being taken *out of* the atmosphere. At its most basic level, the idea of "net zero" simply expresses a recognition of the need to reach a state in which human actions are no longer contributing to rising atmospheric levels of GHGs—a state that needs to be reached before potential climate "tipping points" are passed, beyond which certain natural processes that could release GHGs may accelerate beyond human control.[27]

Second, it should be kept in mind that this idea of "net zero" as an end state to be reached is not the same as any particular "scenario" or "pathway" for reaching that state. The IEA and IRENA's scenarios represent specific pathways to "net zero," based on modeling exercises. Alternative proposals for reaching a state of "net zero" in time to avoid passing climate "tipping points" might focus on a much more radical vision of energy conservation or even "degrowth."

Third, it should also be kept in mind that the way in which the concept of "net zero" has come to be used in mainstream policy debates has been criticized from many sides, including some climate scientists. For instance, in mid-2021, James Dyke (Senior Lecturer in Global Systems, University of Exeter), Robert Watson (Emeritus Professor in Environmental Sciences, University of East Anglia) and Wolfgang Knorr (Senior Research Scientist, Physical Geography and Ecosystem Science, Lund University) collectively called the very concept of net zero a "dangerous trap."[28] As they wrote:

> We have arrived at the painful realisation that the idea of net zero has licensed a recklessly cavalier "burn now, pay later" approach which has seen carbon emissions continue to soar. It has also hastened the destruction of the natural world by increasing deforestation today, and greatly increases the risk of further devastation in the future….
>
> The tragedy is that [academics'] collective efforts were never able to mount an effective challenge to a climate policy process that would only allow a narrow range of scenarios to be explored.[29]

27 Robert McSweeney, "Explainer: Nine 'tipping points' that could be triggered by climate change," *Carbon Brief*, February 10, 2020, https://www.carbonbrief.org/explainer-nine-tipping-points-that-could-be-triggered-by-climate-change.

28 James Dyke, Robert Watson and Wolfgang Knorr, "Climate scientists: Concept of net zero is a dangerous trap," *The Conversation*, April 22, 2021, https://theconversation.com/climate-scientists-concept-of-net-zero-is-a-dangerous-trap-157368.

29 Ibid.

Finally, it needs to be kept in mind that the levels of investment and deployment necessary to reach "net zero" on the IEA and IRENA's scenarios are substantial, and would be enormously challenging to meet. Alternative pathways drawing much more heavily on energy conservation—and much less on technological fixes aimed at *avoiding* the need for conservation—might offer a way forward that poses less of a challenge to investment and deployment, but quantifying just how much "easier" such a pathway might be than the mainstream scenarios is far beyond the scope of the present paper. Such an approach would also pose its own formidable political *challenges*, and seems highly unlikely outside of a decisive shift toward public ownership.

In essentially all of the major scenarios for tackling the climate and emissions challenge, the vast majority of decarbonization is expected to be achieved through a combination of: (1) electrification of activities and processes that currently rely on other forms of energy; and (2) shifting electricity generation away from fossil fuels to exclusively "low-carbon" sources. But many of these projections also see an important role for hydrogen, because of its potential to tackle, in the words of the IEA, "critical energy challenges" while reaching agreed Paris targets for emissions reductions.[30]

It should be kept in mind that such scenarios are not predictions of what will happen, but essentially modeling exercises outlining one or more "pathways" for achieving some predetermined goal (for instance, keeping average global warming to no more than 1.5°C above pre-industrial levels, or reaching a state of "net zero" emissions by 2050). Such modeling exercises inevitably make a range of assumptions; they are therefore perhaps best understood as indicators of the *general nature and scale* of what needs to happen in order for the goals on which they are based to be reached.

The IEA's scenario for reaching "net zero" emissions by 2050 anticipates a crucial role for hydrogen in decarbonization. In a major May 2021 report titled *Net Zero by 2050: A Roadmap for the Global Energy Sector*, the IEA identified "low-carbon hydrogen" (including hydrogen‐based fuels) as one of the "key pillars of decarbonisation of the global energy system," especially in heavy industry and shipping, but also eventually in essentially all energy-using sectors.[31]

30 IEA, "International action can scale up hydrogen to make it a key part of a clean and secure energy future, according to new IEA report," June 14, 2019, https://www.iea.org/news/international-action-can-scale-up-hydrogen-to-make-it-a-key-part-of-a-clean-and-secure-energy-future-according-to-new-iea-report.

31 IEA, *Net Zero by 2050*, 55, 64. The IEA's other major pillars are energy efficiency, changes in behavior, electrification, renewables, bioenergy and "carbon capture, utilization and storage" (CCUS).

In the IEA's Net Zero by 2050 scenario ("NZ50"), global hydrogen use needs to expand from less than 90 million metric tons (Mt) in 2020 to more than 200 Mt in 2030, while the share of "low-carbon hydrogen" rises from 10% of all hydrogen in 2020 to 70% in 2030.[32] By 2050, the IEA projects that hydrogen and hydrogen-based fuels (including ammonia and synthetic liquids and gases) need to account for nearly 30% of total energy consumption, compared to essentially 0% in 2020.[33]

In this scenario, global hydrogen use is projected to more than double in the current decade. The proportion of this hydrogen that is "low carbon" is set to grow from 10% to 70% by 2030.[34] By 2050, the share of hydrogen used in transport is projected to exceed that for industry: 207 Mt (39%) and 187 Mt (35%) respectively out of a total 528 Mt.[35] According to the IEA's projections, nearly two-thirds (62%) of the hydrogen required to meet this projected demand will come from renewable sources ("green" hydrogen) and most of the rest from natural gas or coal with CCS ("blue" hydrogen), with additional smaller amounts from nuclear power and other processes.[36]

Like the IEA, IRENA also sees a major role for hydrogen in reaching decarbonization targets. In its June 2021 report, *World Energy Transitions Outlook: 1.5°C Pathway*, IRENA finds that hydrogen (and the fuels produced from it) should account for 12% of global final energy use by 2050. At that time, according to IRENA, 30% of global electricity needs to be dedicated to the production of hydrogen and its derivatives (including ammonia and synthetic methanol). For IRENA, "green and blue hydrogen production grows from negligible levels today to over 74 exajoules (EJ) (614 Mt) in 2050."[37]

IRENA also sees an important role for hydrogen in helping to achieve net zero CO2 emissions in sectors like steel, chemicals, long-haul transport, shipping and aviation. Hydrogen can also "play fundamental roles in balancing renewable electricity supply and demand by absorbing short-term variations as well as acting as an option for long-term storage to help balance renewable variability across seasons."[38]

32 Ibid., 75.
33 Ibid., 61.
34 Ibid., 75.
35 Ibid., 76.
36 Ibid., 195.
37 IRENA, *World Energy Transitions Outlook: 1.5°C Pathway*, June 2021, https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook
38 Ibid.

Speed and Scale

It is important to emphasize the speed and scale of development of hydrogen that is envisaged by the mainstream scenarios—while keeping in mind that these scenarios are not the only possible pathways forward, and may not fully reflect what a trade union decarbonization agenda might look like.

With that qualification in mind, in order to put the mainstream figures in context, it should be recalled (as noted above) that 2020 saw the production of 87 million tons of hydrogen in total—nearly all of it "gray" or "brown" (i.e., produced from natural gas and coal with no capture of the resulting emissions).[39] This means that the IEA's NZ50 scenario requires growth in the production of low-carbon hydrogen of roughly 66% every year until 2030, and then 23% every year from 2030 to 2050.[40] The increase in production of hydrogen gas from 2020 and 2030 in the NZ50 scenario is thus "twice as fast as the fastest 10-year increase in shale gas production in the United States."[41] The overall increase in electricity consumption—both from end-use sectors being electrified and from hydrogen production—means that "overall annual electricity demand growth is equivalent to adding an electricity market the size of India every year."[42]

Since the production of hydrogen through electrolysis requires large amounts of electricity, meeting projected future needs for hydrogen via this method would require much more additional renewable generation capacity. According to the IEA's NZ50 scenario, production of green hydrogen would require roughly 3,850 terawatt hours (TWh) of electricity per year by 2030—slightly more than the total US consumption of electricity in 2020.[43] By 2050 it would require roughly 14,500 TWh[44]—nearly four times as much as in 2030, and roughly 20% of global electricity supply (71,164 TWh).[45]

IRENA estimates that producing hydrogen at these scales will consume nearly 21,000 TWh annually by 2050.[46] According to IRENA's projections, hydrogen production just from renewable electricity needs to reach 19 Exajoules per

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39 IEA, *Net Zero by 2050*.
40 Ibid., 195.
41 Ibid., 59.
42 Ibid., 60.
43 Statista, "Total electricity end use in the United States from 1975 to 2020," https://www.statista.com/statistics/201794/us-electricity-consumption-since-1975/.
44 IEA, *Net Zero by 2050*, 111.
45 Leigh Collins, "A wake-up call on green hydrogen: The amount of wind and solar needed is immense," *Recharge*, March 19, 2020, https://www.rechargenews.com/transition/a-wake-up-call-on-green-hydrogen-the-amount-of-wind-and-solar-needed-is-immense/2-1-776481.
46 IRENA, *Green Hydrogen Supply: A Guide to Policy Making*, May 2021, https://www.irena.org/publications/2021/May/Green-Hydrogen-Supply-A-Guide-To-Policy-Making.

year in 2050 (roughly 5,300 TWh).[47] For comparison, Japan's total primary energy consumption in 2020—the fifth largest in the world—was 17 Exajoules (roughly 4,700 TWh).[48] In the words of one industry observer:

> Annual growth rates for wind and solar are increasing, but nowhere near fast enough for the world to be in line with Paris Agreement goals. Terawatts of renewable energy will be needed to produce green hydrogen, but that seems secondary to the demand from the rapidly growing electricity sector, which needs to decarbonise while simultaneously powering ever-larger shares of the heating and transport sectors.[49]

According to the IEA, fulfilling the role of green hydrogen foreseen in its NZ50 scenario would require a total electrolyzer capacity of 850 gigawatts (GW) by 2030, and 3,000 GW by 2045.[50] IRENA foresees a need for nearly 5,000 GW capacity of hydrogen electrolyzers by 2050—up from just 0.3 GW today.[51]

Although details vary across these different scenarios, they are broadly comparable in terms of the speed and scale of change involved. According to the IEA, from 2030 onward, fulfilling the role of clean hydrogen in the "net zero" scenario requires adding 2 GW of electrolyzer-based hydrogen production capacity, *and* replacing three fossil-fuel-based industrial plants with hydrogen-based plants *every month* until 2050.[52] The IEA warns that producing this electrolyzer capacity at the pace required for NZ50 "is a key challenge given the lack of manufacturing capacity today, as is ensuring the availability of sufficient electricity generation capacity."[53]

How Much Investment Will Be Required?

Scaling up hydrogen in line with its projected role in reaching decarbonization targets will also require major new investment over the next few decades in order to realize the expansion of production, distribution and usage infrastructure seen to be necessary under "net zero" and similar scenarios.

47 IRENA, *Innovation Landscape Brief: Renewable Power-to-Hydrogen*, 2019, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-Hydrogen_Innovation_2019.pdf, 9.

48 BP, *Statistical Review of World Energy 2021*, July 2021, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf, 10; cited at Statista, "Primary energy consumption worldwide in 2020, by country," https://www.statista.com/statistics/263455/primary-energy-consumption-of-selected-countries/.

49 Leigh Collins, "A wake-up call on green hydrogen."

50 IEA, *Net Zero by 2050*, 20.

51 IRENA, *World Energy Transitions Outlook*.

52 IEA, *Net Zero by 2050*, 19.

53 Ibid., 76.

According to the IEA's *Global Hydrogen Review 2021*, published in October 2021, "realising government climate ambitions will require significant ramp-ups across the entire production, end-use and infrastructure value chains."[54] To achieve "net zero emissions" by 2050, according to the IEA, "global cumulative investments [in hydrogen-based technologies] must increase to USD 1.2 trillion by 2030 and USD 10 trillion by 2050."[55]

Investment in electrolyzers needs to be USD 7 billion per year until 2030 (roughly 30 times the highest recent levels) as well as USD 4 billion in fuel-cell electric vehicles (14 times the highest recent levels).[56] According to the IEA's NZ50 scenario, the required rollout of just the core enabling infrastructure for scaling up hydrogen envisaged must increase from its current level of roughly $1 billion per year to around $40 billion per year by 2030.[57]

While these amounts may seem manageable in the context of current overall levels of investment in renewable energy—roughly $300 billion per year in recent years[58]—the *rate* of annual growth required to achieve a 40x increase in a decade (nearly 45% per year, every year for 10 years) far exceeds the year-on-year growth of investment in renewable generation capacity, which has stalled in recent years.[59] This strongly suggests that reaching the levels of investment and scaling up needed will require a very different approach than mainstream policies of recent decades, which have relied on using incentives and special protections to encourage private investment, but which have failed to generate anything like the scales of investment required—and which seem incapable of doing so.[60]

Part Two: Hydrogen's Role in Decarbonizing Key Sectors

In Part Two, we look in a bit more detail at specific sectors and applications where hydrogen is being promoted as having a crucial role to play in supporting decarbonization efforts. The main aim here is to provide a better sense of the

54 IEA, *Global Hydrogen Review 2021*, October 2021, https://www.iea.org/reports/global-hydrogen-review-2021.
55 Ibid.
56 Ibid.
57 IEA, *Net Zero by 2050*, 22.
58 IRENA, *Global Landscape of Renewable Energy Finance 2020*, November 2020, https://www.irena.org/publications/2020/Nov/Global-Landscape-of-Renewable-Energy-Finance-2020.
59 IEA, *World Energy Investment 2021*, June 2021, https://www.iea.org/reports/world-energy-investment-2021.
60 Sean Sweeney and John Treat, *Working Paper #10: Preparing a Public Pathway: Confronting the Investment Crisis in Renewable Energy*, Trade Unions for Energy Democracy, November 2017, https://unionsforenergydemocracy.org/resources/tued-working-papers/tued-working-paper-10/.

potential importance of hydrogen in providing, maintaining and improving modern infrastructure and services, as well as protecting and expanding high-quality jobs, and thus to reinforce the need to formulate a vision and political strategy that can enable it to play that role.

In the power sector, the potential role of hydrogen mainly pertains to helping solve serious issues of seasonal storage for power grids. The issue here is that, for regions with a large variation between summer and winter in the amount of sunlight and wind available for conversion to electricity, ensuring adequate power during the cold, dark months requires either vast "overcapacity" of generation capacity, or some form of storage that can provide weeks or months of backup power—something that is far beyond what electrochemical batteries (such as lithium-ion batteries) are currently suited to provide.

But low-carbon hydrogen is also seen as having a crucial role to play in decarbonizing sectors that do not lend themselves easily to electrification, and for which emissions are therefore "hard to abate"—for instance, steel production and transport—as well as in home heating.

According to Columbia University's Center on Global Energy Policy, heavy industry (including steel, cement and chemicals) produces roughly 22% of global CO2 emissions, and roughly 40% of that (10% of total emissions) is the direct product of combustion to generate high-quality heat, almost entirely based on fossil fuels.[61] According to data published by Climate Watch and the World Resources Institute,[62] iron and steel production alone account for 7.2% of total emissions. Freight transport accounts for 6.5% of all emissions. Aviation and shipping are responsible for 1.9% and 1.7% of total emissions respectively. Together these "hard to abate" sectors account for more than a third (34.3%) of total GHG emissions.

Steel

In 2020, the global steel industry produced 1.86 billion metric tons of steel, generating more than 3 billion tons of CO2—roughly 7% to 9% of all greenhouse gas emissions from human activity, according to a 2021 report from the World Steel Association.[63] In the words of Mark Peplow, a science journalist and former editor of the British weekly scientific journal *Nature*,

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61 Julio Friedmann, Zhiyuan Fan and Ke Tang, "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs," Center on Global Energy Policy at Columbia University, October 7, 2019, https://www.energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today.

62 Hannah Ritchie, "Sector by sector: where do global greenhouse gas emissions come from?" *Our World in Data*, September 18, 2020, https://ourworldindata.org/ghg-emissions-by-sector.

63 World Steel Association, *Climate change and the production of iron and steel*, 2021, https://www.worldsteel.org/publications/position-papers/climate-change-policy-paper.html.

"If the steel industry were a country, its carbon dioxide emissions would rank third in the world, below the US and above India."[64] With global steel demand projected to grow by more than a third by 2050—to 2.5 billion tons per year—limiting emissions from steel production consistent with the 2°C Paris target would mean the steel industry's annual emissions would need to fall to roughly 500 million metric tons of CO2 per year. This change would require a drop in carbon intensity from about 1.85 tons of CO2 per metric ton of steel to just 0.2 tons. Again in Peplow's words, such a change would require "nothing less than a revolution in steelmaking technology, backed by hundreds of billions of dollars in investments."[65]

One potentially promising alternative makes use of hydrogen in place of traditional fossil or synthetic fuels to carry out "direct reduction" of the iron ore—in other words, the removal of oxygen from the solid ore using chemicals and heat, rather than melting it in a blast furnace. Although not in use at large scale, the technology of direct reduction itself is relatively mature but relies on natural gas, synthetic gas or coal to produce the "reducing agents" required for the process (carbon monoxide and hydrogen). Efforts are underway to rely on hydrogen alone. If successful, that may be able to reduce CO2 emissions across all stages of production and see to their virtual elimination from a crucial step in the steel production process—provided the hydrogen could itself be produced from decarbonized sources.[66]

Although only limited data are available at this stage, Christopher Goodall—an energy analyst at Carbon Commentary—has concluded that the process will offer not only emissions reductions but also energy efficiency gains over traditional steelmaking. On Goodall's estimates, one ton of finished "new" steel produced through "direct reduction" will require roughly 4.25 MWh to produce, as compared to the 6 MWh required for coal-based production.[67] At today's levels of steel production, that would equate to electricity required to create the hydrogen needed on the order of 5,700 Terawatt hours (TWh)—roughly one quarter of total world electricity production.[68] If that hydrogen were made using electricity from wind (and assuming a capacity factor for wind of 40%), global steel production would require roughly 1,600 to 1,650 GW of additional wind turbine capacity—"well over two and a half times the currently installed amount

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64 Mark Peplow, "Can industry decarbonize steelmaking?" *Chemical & Engineering News*, June 13, 2021, https://cen.acs.org/environment/green-chemistry/steel-hydrogen-low-co2-startups/99/i22.
65 Ibid.
66 Wood Mackenzie, "How green can steel go—and what does it mean for coal and iron ore?" May 21, 2020, https://www.woodmac.com/news/opinion/how-green-can-steel-go--and-what-does-it-mean-for-coal-and-iron-ore/.
67 Chris Goodall, "How much hydrogen will be needed to replace coal in making steel?" *Carbon Commentary*, November 4, 2020, https://www.carboncommentary.com/blog/2020/11/4/how-much-hydrogen-will-be-needed-to-replace-coal-in-making-steel.
68 Ibid.

of wind power globally," with the figure for solar PV roughly double that level.[69]

Another possibility for decarbonizing steel production using hydrogen, although one that for many is likely to be more controversial, is through the use of nuclear power in "nuclear hydrogen cogeneration systems" (NHCS).[70] Such systems could take advantage of the ability of high-temperature gas-cooled nuclear reactors to provide large quantities of heat, electricity and hydrogen in order to decarbonize steel production.[71] According to a study from the Royal Society, nuclear cogeneration also "enables a nuclear plant to be used more flexibly, by switching between electricity generation and cogeneration applications."[72] Of course, whatever its technical potential, such an option may not be able to overcome the significant political obstacles it would face, given public resistance to nuclear energy in many countries.

No matter what processes are involved, shifting to steel production based on low-carbon hydrogen would likely involve the extensive relocation of that steel production. According to one industry expert, the next 10 to 15 years will see a "radical transition" in where steel (and other metals) are produced and processed, which will be "dictated by proximity to sources of generation of hydropower, nuclear and green hydrogen production."[73]

Transport

In the transport sector, expectations for hydrogen have shifted in recent years, increasingly away from small passenger vehicles and toward long-haul trucking, shipping and aviation.

Where some years ago it may have been an open question whether electric-battery-powered or hydrogen-fuel-cell-powered electric vehicles (FCEV) would come to dominate for passenger transport, at this point it seems likely that the former have won out. This is in part due to the efficiency losses involved in the production and use of hydrogen. As *The Economist* reports, according to the UK's Committee on Climate Change (CCC), "a battery-powered car charged with electricity from a wind turbine converts 86% of the turbine's

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69 Ibid.

70 D. H. Salimy, D. Priambodo, A. Hafid, Sriyono, I. D. Irianto, R. Kusumastuti, and Febrianto, "The assessment of nuclear hydrogen cogeneration system application for steel industry," AIP Conference Proceedings 2180, 020038 (2019) https://doi.org/10.1063/1.5135547.

71 Ibid.

72 The Royal Society, "Nuclear cogeneration: civil nuclear energy in a low-carbon future," Policy Briefing, October 2020, https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/nuclear-cogeneration/.

73 Diana Kinch, "Metal, steel production must relocate near renewable energy to decarbonize: Forum," SPG Global, June 22, 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/metals/062221-metal-steel-production-must-relocate-near-renewable-energy-to-decarbonize-forum.

output into forward motion on the road. For a fuel-cell car, it is 40-45%."[74]

Hydrogen-powered cars also cannot realistically be refueled at home, unlike their battery-powered equivalents. However, as of January 2021, there were less than 50 hydrogen vehicle refueling stations in the United States, nearly all of them in California.[75] Hydrogen refueling infrastructure faces a "chicken and egg" problem: New stations are unlikely to become common any time soon, since the vehicles needing them also remain few and far between.[76]

But refueling with hydrogen could more readily be carried out for fleet vehicles with designated end-points to their routes. Hydrogen refueling can also be carried out much more quickly than battery-powered vehicles can be charged, allowing for faster turnaround times.

For such reasons, FCEV technology is still expected to play a major role in long-haul transport, aviation and shipping, where the weight of the required batteries and charging times make all-electric power impractical.[77] The IEA's NZ50 scenario projects more than 15 million hydrogen fuel cell vehicles on the road by 2030.[78] By 2050, hydrogen and hydrogen-based fuels will potentially account for nearly 30% of transport energy consumption (up from essentially nothing in 2020)—mainly long-haul trucks—although this is "contingent on policy makers taking decisions that enable the development of the necessary infrastructure by 2030."[79]

Despite the challenges, some believe it is too soon to discount even hydrogen-based passenger vehicles. Growing awareness of the environmental damage and potential costs associated with production of key metals used in batteries for EVs like cobalt and nickel could also play a role in driving the development of FCEVs, and some major automakers—notably Honda, Hyundai and Toyota—are still pursuing FCEV passenger vehicles as part of their production lines.[80]

Hydrogen is also seen as a promising technology for long-haul trucking, where the weight of batteries required for all-electric power trains may significantly reduce cargo capacity, and where the time required to refuel with hydrogen

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74 *The Economist*, "After many false starts, hydrogen power might now bear fruit," July 2, 2020, https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit.

75 EIA, "Hydrogen explained—Use of hydrogen," updated January 7, 2021, https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php.

76 *The Economist*, "Hydrogen power might now bear fruit."

77 IRENA, *Hydrogen: A Renewable Energy Perspective*, September 2019, https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

78 IEA, *Net Zero by 2050*, 75.

79 IEA, *Net Zero by 2050*, 76.

80 Felicity Bradstock, "Hydrogen Fueled Cars Are Making A Comeback," *Oil Price*, September 23, 2021, https://oilprice.com/Energy/Energy-General/Hydrogen-Fueled-Cars-Are-Making-A-Comeback.html

may be many times faster than that required to recharge batteries—by as much as 15 times for a long-haul, Class 8 truck with a 100-kilogram hydrogen tank, according to an analysis by Thomas Walker, Senior Fellow for Transportation Technology at the Clean Air Task Force.[81]

For aviation, hydrogen may also play a significant role in decarbonization. Again here, the weight of batteries required for all-electric flight poses a major challenge. By contrast, hydrogen contains a lot of energy by *weight*—triple the "specific energy" of commercial jet fuel, and more than a hundred times that of lithium ion batteries—although its energy density by *volume* is just a quarter that of jet fuel, meaning that its use in flight would require much larger storage tanks.[82]

Hydrogen can also be used to generate ammonia, which is considered a promising alternative fuel by the shipping industry, to replace emissions-intensive "bunker fuel," which currently accounts for the vast majority of marine transport fuel.[83] Ammonia can be produced from hydrogen and nitrogen using electricity, produces no CO2 when combusted, can be much more easily transported and stored than hydrogen (and the infrastructure for doing so is better established), and has an energy density sufficient for many shipping applications, even if it is lower than current, carbon-intensive marine fuels.[84] The IEA projects that by 2050, hydrogen‐based fuels will provide more than 60% of total fuel consumption for shipping. Ammonia produced from hydrogen will account for most of this, meeting 45% of total fuel consumption.[85]

Heating

Hydrogen is considered by some to be a solution for heating, especially in locations far from the equator. In Europe, aggressive emissions reductions targets could force the adoption of hydrogen in place of electrification for heating in some locations, such as Germany. According to Eva Hennig, head of EU energy policy for Thuega, a network of local German utilities, "If Europe adopts a 55% emission reduction target for 2030, Germany would have to reduce its

81 Thomas Walker, "Why the future of long-haul heavy trucking probably includes lots of hydrogen," June 15, 2021, *GreenBiz*, https://www.greenbiz.com/article/why-future-long-haul-heavy-trucking-probably-includes-lots-hydrogen.

82 Caspar Henderson, "The hydrogen revolution in the skies," BBC Future Planet, April 7, 2021, https://www.bbc.com/future/article/20210401-the-worlds-first-commercial-hydrogen-plane.

83 Maersk, "Maritime industry leaders to explore ammonia as marine fuel in Singapore," March 10, 2021, https://www.maersk.com/news/articles/2021/03/10/maritime-industry-leaders-to-explore-ammonia-as-marine-fuel-in-singapore; Riley E. J. Schnurr, Tony R. Walker, "Marine Transportation and Energy Use," *Reference Module in Earth Systems and Environmental Sciences*, Elsevier, 2019, https://doi.org/10.1016/B978-0-12-409548-9.09270-8.

84 Charles Haskell, "Decarbonising shipping—could ammonia be the fuel of the future?" *Lloyds Register*, May 6, 2021, https://www.lr.org/en/insights/articles/decarbonising-shipping-ammonia/.

85 IEA, *Net Zero by 2050*, 76, 107.

heating emissions by half…. That is impossible with realistic renovation rates and just electricity. You will have to decarbonize gas for heating."[86]

This vision for hydrogen in home heating is being put forward with significant support from private interests, including the organization "Hydrogen4EU," financed by the oil and gas industry.[87] Hydrogen4EU promotes "the merits of blue hydrogen," promising "savings worth €2 trillion across Europe by 2050 if existing gas infrastructure is reused or repurposed to carry hydrogen."[88]

But since the vast majority of hydrogen currently available is produced from methane—currently "gray" in the prevailing color terminology, but with the aim to shift to "blue" as soon as possible, and then eventually to "green"—such moves are seen by many in the climate movement, including the climate think-tank E3G, as risking "locking in users with existing carbon-intensive infrastructure."[89]

Indeed, hydrogen for home heating has been criticized as a "survival option" for oil and gas companies, to take advantage of the fact that hydrogen is still currently produced overwhelmingly from natural gas.90 Such an approach, according to energy analyst Simon Pirani, "stands opposed to the approach recommended for years by housing policy experts and architects: to use insulation to slash the amount of heat needed, and install electric pumps which work like fridges in reverse."[91]

Of course, undertaking the kind of extensive electrification program being offered as the alternative to hydrogen for heating would also likely only be accomplished by way of a massive, coordinated public works program of the kind many unions would support.

Although in principle the use of hydrogen for home heating could rely on any "color" of hydrogen, the most developed proposals focus on "blue" hydrogen in the near term. We will return to consider the prospects for blue hydrogen—which depend on the prospects of CCS/CCUS—in Part Three below, where we look in more detail at some of the issues and challenges involved in the decarbonization of hydrogen production.

86 Sonja van Renssen, "The hydrogen solution?" *Nature Climate Change*, Volume 10, August 27, 2020, https://www.nature.com/articles/s41558-020-0891-0.
87 Nikolaus J. Kurmayer, "Summer controversy illustrates polarisation of hydrogen debate," EURACTIV.com, August 27, 2021, https://www.euractiv.com/section/energy-environment/news/summer-controversy-illustrates-polarisation-of-hydrogen-debate/.
88 Ibid.
89 Ibid.
90 Simon Pirani, "Hydrogen homes is a terrible idea," *The Ecologist*, November 3, 2020, https://theecologist.org/2020/nov/03/hydrogen-homes-terrible-idea.
91 Ibid.

The Power Sector

In the power sector, much of the decarbonization potential of hydrogen lies in the fact that it can serve as backup storage for electricity generated from intermittent sources like wind and solar. In certain ways, hydrogen is better suited to long-term storage of electricity than most battery technologies, potentially offering a solution to the daunting challenge of balancing seasonal variation in the amount of usable power available from sun and wind.

For the IEA's NZ50, hydrogen and hydrogen-based fuels are seen to play a small but significant role in the power sector, contributing roughly 2% of total electricity generation in 2050. Despite this small share, the IEA notes, "this translates into very large volumes of hydrogen and makes the electricity sector an important driver of hydrogen demand."[92] Even more importantly, in this scenario hydrogen provides "an important low-carbon source of electricity system flexibility."[93] But notably, this contribution is anticipated to come mainly through blending hydrogen with natural gas.

Although currently at minimal levels, hydrogen is already in use to generate electricity, and more often for dedicated, site-specific use than for feeding into power grids. According to the US Energy Information Administration (EIA), as of October 2020, there were 161 fuel cells operating at 108 facilities in the United States, with a total generation capacity of roughly 250 megawatts (MW). The largest of these is the Red Lion Energy Center in Delaware, which has roughly 25 MW total electric generation capacity and uses hydrogen produced from natural gas to operate the fuel cells.[94] Of the 530 Mt of hydrogen the IEA's NZ50 scenario anticipates being produced in 2050, one quarter is expected to be produced within industrial facilities (including refineries) for use in generating electricity on-site.

The relationship between "green" hydrogen and the power sector is especially complicated, since unlike other "end use" sectors, hydrogen production and use by and for the power sector are deeply intertwined. Because of this complexity, and the importance of the power sector in essentially any future decarbonization scenarios, we will return to look at this in more detail in Part Three below.

92 IEA, *Net Zero by 2050*, 76.
93 Ibid.
94 EIA, "Hydrogen explained—Use of hydrogen," updated January 7, 2021, https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php.

Part Three: Decarbonizing Hydrogen Production: Options and Challenges

In Part Three, we look in more detail at the key options and technical challenges involved in decarbonizing hydrogen production at scale. As noted previously, expanding the role of hydrogen into industrial, transport and other sectors is only part of what needs to happen in order for hydrogen to play a serious role in decarbonization. The production of hydrogen for use in those ways also needs to be decarbonized. Here, our aim is to make clearer the formidable nature of the technical challenges involved in scaling up hydrogen production for use as envisaged in mainstream scenarios.

Blue Hydrogen: A Fate Tied to CCS

Fundamentally, the potential of "blue" hydrogen to contribute to decarbonization depends on the effectiveness and availability of CCS/CCUS. In the words of one analyst with the Oxford Institute for Energy Studies, "Given that hydrogen production from gas is relatively mature technology, it is the CCS part of the supply chain that requires the most attention." As he writes:

> There are an increasing number of CCS projects worldwide. However, several key elements are still lacking: scale of activity, development of one-size-fits-all technology, [etc.]…. Broadly speaking, if blue hydrogen is to become a major player in global energy systems, far-reaching success is also needed with CCS.[95]

Blue hydrogen has received a great deal of support from major fossil fuel companies. The Hydrogen Council—a "global coalition of CEOs committed to accelerating the energy transition with hydrogen,"[96] launched at the Davos World Economic Forum in 2017—is a virtual "who's who" of fossil fuel, transport and heavy industry players, with more than 100 corporate members as of January 2021.[97] Shell, BP, Repsol and others have announced plans and projects involving hydrogen, focusing especially (although not exclusively) on possibilities for turning "gray" hydrogen (produced from fossil fuels without

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95 Adam Hawkes, "Opportunities and Challenges for Hydrogen in a Decarbonized Energy System," in *The Role of Hydrogen in the Energy Transition—Forum: A Quarterly Journal for Debating Energy Issues and Policies*, Oxford Institute for Energy Studies, May 2021: Issue 127, https://www.oxfordenergy.org/publications/oxford-energy-forum-the-role-of-hydrogen-in-the-energy-transition-issue-127/.

96 Hydrogen Council, "Hydrogen Council Reaches 100+ Members as Hydrogen Industry Enters Next Stage of Growth," January 12, 2021, https://hydrogencouncil.com/en/newmemberannouncement2021-1/.

97 Ibid.

carbon capture) to "blue" hydrogen (adding carbon capture to contain those emissions).[98] Such plans and projects have drawn considerable financial support in the form of government subsidies.[99]

The fact that large oil and gas interests are promoting "clean" (usually "blue") hydrogen has understandably helped feed suspicions in some quarters that "blue" hydrogen is simply a "lifeline for the gas industry."[100] Such suspicions were only heightened in August 2021, when Christopher Jackson, then chair of the UK Hydrogen and Fuel Cell Association, resigned from his position, calling blue hydrogen an "expensive distraction" that "risks locking [the] UK into reliance on fossil fuels."[101,102]

In recent years, there has been significant growth in the number of CCUS demonstration projects being developed around the world. This growth follows a period of declining numbers for several years leading up to 2018. The IEA reports that 2021 has seen a significant increase, with more than 100 new CCUS facilities announced (as of late November).103 The IEA attributes this "unprecedented" growth to, among other things, "the growing interest in producing low-carbon hydrogen," which "has resulted in almost 50 facilities under development to capture CO2 from hydrogen-related processes."[104]

It is too soon to say whether this recent burst of growth will lead to the kind of commercial-scale CCUS projects required under the IEA's NZ50 or similar scenarios. The IEA itself acknowledges that CCUS's track record raises serious questions about its future prospects. As the IEA notes, "previous hopes that CCUS was about to fulfill its potential have petered out," and that the past decade "saw high-profile project cancellations and government funding programs that failed to deliver." Although it also believes that "the combination

98 Giulia Petroni and Dieter Holger, "Major Energy Companies Bet Big on Hydrogen," *Wall Street Journal*,

October 22, 2020, https://www.wsj.com/articles/major-energy-companies-bet-big-on-hydrogen-11603392160; see also, John Parnell, "Who Will Own the Hydrogen Future: Oil Companies or Utilities?" August 3, 2020, https://www.greentechmedia.com/articles/read/utilities-on-both-sides-of-atlantic-follow-oil-majors-hydrogen-lead.

99 Justin Mikulka, "As Subsidies Roll in, the Fossil Fuel Industry Is Winning Efforts to Cast Blue Hydrogen as a 'Clean' Fuel," *DeSmog Blog*, August 23, 2021, https://www.desmog.com/2021/08/23/subsidies-blue-hydrogen-natural-gas-pr-clean/.

100 Ibid.

101 *Fuel Cells Works*, Christopher Jackson Announces His Retirement as Chair of UKHFCA," August 18, 2021, https://fuelcellsworks.com/news/christopher-jackson-announces-his-retirement-as-chair-of-the-ukhfca/.

102 It should be noted, however, that Jackson remains a supporter of green hydrogen.

103 Samantha McCulloch, "Carbon capture in 2021: Off and running or another false start?" IEA, November 24, 2021, https://www.iea.org/commentaries/carbon-capture-in-2021-off-and-running-or-another-false-start.

104 Ibid. The other two "key developments" behind the recent growth in CCUS projects are "a growing recognition that CCUS is necessary to meet national, regional and even corporate net zero goals" and the fact that the "investment environment" for CCUS "has substantially improved as a result of new policy incentives."

of strengthened climate goals, an improved investment environment and new business models have set the stage for greater success in coming years."[105]

Trade Unions for Energy Democracy (TUED) has written previously about the technical as well as economic problems that confront CCS (which was the main option for "carbon capture" under consideration at the time) as it applies to coal-fired power generation.[106] That analysis showed that, even if CCS were deployed at scale on the basis of commercial incentives and the policy imperative of continuing growth in energy exploitation and use, the "energy penalty" (i.e., losses) associated with its use seemed likely to lead to even greater extraction per unit of energy generated, with the negative health and other impacts one would expect. That paper invited unions to consider an alternative scenario for the deployment of CCS under public ownership, while challenging the imperatives of growth. It argued, "The only conceivable route for truly essential CCS development (such as for specific industrial purposes) lies completely outside of the neoliberal framework that currently sets the parameters for what's possible within the narrow terrain of the market."[107] Since the publication of that paper, nothing has changed that we think challenges that conclusion.

"Green" Hydrogen: Confronting Some Technical Realities

In order to understand how and why "green" hydrogen may only really be able to make a meaningful contribution toward achieving agreed climate targets, we need to look in more detail at some of the technical realities involved in its production and use. In particular we take a look at the inner workings of "curtailment"—when "excess" electrical power must be "wasted" to preserve system stability—and the "power-to-hydrogen-to-power" ("H2P2P") cycle.

Relying on "Curtailed" Wind and Solar Energy

As the share of intermittent energy sources like wind and solar rises in power systems, their intermittency has to be managed in order to avoid destabilizing grids. On current estimates, as the share of intermittent sources rises above roughly 30%, grids require additional flexibility.[108] In the absence of the

105 Ibid.
106 Sean Sweeney, *TUED Working Paper #5: The Hard Facts about Coal*, October 2015, http://unionsforenergydemocracy.org/resources/tued-publications/tued-working-paper-5-the-hard-facts-about-coal-landing/.
107 Ibid.
108 Torbjørn Egeland-Eriksen, Amin Hajizadeh, Sabrina Sartoria, "Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives," *International Journal of Hydrogen Energy*, Volume 46, Issue 63, September 13, 2021, 31,963-83, https://www.sciencedirect.com/science/article/pii/S0360319921025064.

ability to absorb intermittently excessive power, it will be simply wasted, or "curtailed." For example, California producers "curtailed enough wind and solar energy last year to fuel 200,000 vehicles for a full year, had that energy been converted to hydrogen."[109]

Curtailment rates are affected by a wide range of factors, including geography and weather, and vary considerably (and often unpredictably): from day to day, season to season, and year to year. The uncertainty also generally rises with increasing capacity of "variable renewable" sources like wind and solar power feeding into grids.

According to a major review of the costs and impacts of integrating variable renewables into power grids—authored by researchers at the Imperial College of London's Centre for Environmental Policy and published in the journal *Nature Energy* in November 2020—median values for the share of variable renewable output curtailed ranged from 0.5% to 8.87% over the period analyzed. With penetration levels up to 65% of energy from variable sources, the median value was 5% or less; if data for penetration levels above that were included, the median value rose to 12.5%.[110] The study also noted that data are scarce for relatively high penetration levels requiring more research.

A separate study looking at land-based wind power in the US found curtailment of wind in 2020 of 3.4%, and "generally rising over the last five years" and with some regions seeing rates of 4.6% and 5.0%.[111] Another study looking at wind curtailment in China found "an overall upward trend since 2014," and averaging 7% as of the end of 2018, which saw 277 TWh of wind power curtailed.[112] A study of solar PV curtailment in 2018 in several countries and several US States found curtailment ranges from a low of 0.3% in Germany to 8.4% in Texas.[113]

These percentages may seem modest, but these are substantial amounts of

109 Emma Penrod, "What's the biggest role for hydrogen in a clean energy economy? It depends who you ask," *Utility Dive*, March 25, 2021, https://www.utilitydive.com/news/whats-the-biggest-role-for-hydrogen-in-a-clean-energy-economy-it-depends/597316/.

110 Philip J. Heptonstall and Robert J. K. Gross, "A systematic review of the costs and impacts of integrating variable renewables into power grids," November 2, 2020, *Nature Energy*, Volume 6, 72–83 (2021), https://www.nature.com/articles/s41560-020-00695-4.

111 US Department of Energy, "Land-Based Wind Market Report: 2021 Edition," https://www.energy.gov/sites/default/files/2021-08/Land-Based%20Wind%20Market%20Report%202021%20Edition_Full%20Report_FINAL.pdf.

112 Huiming Zhang, Jiayun Yang, Xianqiang Ren, Qing Wu, Dequn Zhou, Ehsan Elahi, "How to accommodate curtailed wind power: A comparative analysis between the US, Germany, India and China," *Energy Strategy Reviews*, Volume 32, 2020, 100538, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2020.100538.

113 Eric O'Shaughnessy, Jesse R. Cruce and Kaifeng Xu, "Too much of a good thing? Global trends in the curtailment of solar PV," *Sol Energy*. September 15, 2020; 208: 1068–1077, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7470769/.

electricity being "abandoned." For private owners, such figures represent major losses of potential revenue. It is not hard to see how the prospect of using it to produce "green" hydrogen could seem appealing—provided they can find a buyer.

Although the detailed mechanics of curtailment vary for different jurisdictions, for those jurisdictions where electricity is managed in line with wholesale market pricing, an explanation from the California Independent System Operator (CAISO) helps to illustrate the critical points. According to CAISO,[114] curtailments can occur in three ways:

- economic curtailment
- self-scheduled cuts
- exceptional dispatch

In the first category, low or even negative wholesale prices lead the ISO to call for reductions in generation, and suppliers who respond are paid to do so. As explained in one commentary on the CAISO practices:

> These "decremental" bids can be worth as much as generation, though they can have other revenue implications for renewable generators. In economic terms, the decremental bid needs to be more than the opportunity cost of the producer to make it worth their while to turn down. Generators do get paid not to generate, but it is more economically efficient than the alternatives.[115]

The second category—self-scheduled cuts—are "for generators who have contracts directly with utilities and other power retailers." In the California case, "these generators place a quantity bid with CAISO, but not a price bid, meaning they take whatever the clearing price is for that hour."[116]

As the CAISO fact sheet explains, both economic curtailment and self-scheduled cuts are considered "market-based"; both result from considerations of cost minimization, and the ISO's market optimization software "automatically adjusts supply with demand."[117] If the automated first stage of economic curtailments does not remove sufficient supply to return the system to balance, the software will identify specific "self-scheduled"

114 California ISO, "Impacts of renewable energy on grid operations," https://www.caiso.com/documents/curtailmentfastfacts.pdf (accessed December 12, 2021).
115 Bentham Paulos, "Too Much of a Good Thing? An Illustrated Guide to Solar Curtailment on California's Grid," *Green Tech Media*, April 3, 2017, https://www.greentechmedia.com/articles/read/an-illustrated-guide-to-solar-curtailment-in-california.
116 Ibid.
117 California ISO, "Impacts of renewable energy on grid operations," https://www.caiso.com/documents/curtailmentfastfacts.pdf (accessed December 12, 2021).

generators to curtail. But this curtailment is based on location and other operational impacts, rather than a bid price.[118]

The third kind of curtailment, "exceptional dispatch," involves manual intervention by the system operator when "market-based solutions haven't cleared the surplus of electricity that could be generated," and which the system cannot at that moment absorb.[119] According to CAISO, this third option "is not preferred, because it does not ensure the lowest cost resources are called upon," and "in many cases, it reduces the output of renewable plants."[120]

This third kind of curtailment is currently rare for CAISO, and "has been declining even as solar, wind and hydropower output grow"—a fact that CAISO representatives see as showing that "the market" is working to solve the problems of curtailed electrical power.[121] Yet, it remains to be seen, of course, whether "the market" can handle the levels of oversupply that would accompany the kind of scaling up of variable renewable generation in the system that deep decarbonization would see. But the existence of a non-market mechanism for dealing with excess supply should serve as a reminder that curtailment need not take place as a purely "economic," market-based process; it can (and sometimes must) be carried out on a purely technical basis in order to ensure system stability.

Currently, however, much renewable power supply is provided on the basis of "power purchase agreements" (PPAs)—essentially a contract for the delivery of physical power that satisfies the required criterion for the relevant form of renewable energy credit or certificate of origin. PPAs for "green hydrogen" have grown significantly in recent years, up from just 14 in 2016 to 100 in 2020.[122] But according to an analysis from international law firm Baker Botts, the traditional PPA arrangement "is not likely to satisfy the run-time requirements of a green hydrogen project," which is not suited to accommodating the variability of sun and wind. As they write, "The specific operational requirements of a green hydrogen project will therefore likely require departures from traditional contractual structures."[123] Given this unsuitability of "traditional contractual

118 Bentham Paulos, "Too Much of a Good Thing? An Illustrated Guide to Solar Curtailment on California's Grid," *Green Tech Media*, April 3, 2017, https://www.greentechmedia.com/articles/read/an-illustrated-guide-to-solar-curtailment-in-california.
119 California ISO, "Impacts of renewable energy on grid operations."
120 Ibid.
121 https://www.greentechmedia.com/articles/read/an-illustrated-guide-to-solar-curtailment-in-california.
122 Pinsent Masons, "Green hydrogen PPAs could reshape market," September 2, 2021, https://www.pinsentmasons.com/out-law/news/green-hydrogen-ppas-could-reshape-market.
123 Baker Botts, "Integrating Renewable PPAs Into Green Hydrogen Projects," August 30, 2021, https://www.bakerbotts.com/thought-leadership/publications/2021/august/integrating-renewable-ppas-into-green-hydrogen-projects.

structures," various "innovative" approaches to contracting for hydrogen are being explored. These include the use of "virtual PPAs," which are essentially financial settlements for the exchange of renewable energy credits rather than physical power, and expanded trading in renewable energy credits to "back fill" requirements for power from renewable sources that cannot be directly procured through a standard PPA. Both of these approaches essentially kick responsibility for the scaling up of genuinely clean power generation for the production of hydrogen down the road (to other market players) and thus invite the further financialization and marketization of hydrogen provision. Baker Botts also notes that at least the second of these—greater reliance by hydrogen producers on renewable certificates—"may become problematic as governments increase their regulation of green hydrogen."[124]

Whatever the character of the power market for a given jurisdiction—whether wholesale markets or PPAs—as currently practiced the assignment of a share of curtailed grid generation potential is largely a function of needing to determine "whose" power is being curtailed, so that they can be compensated accordingly.

Outside of market considerations, it does not matter whether the electricity *drawn from the system* for hydrogen electrolysis is "assigned" to the electricity *coming into the system* that would otherwise be curtailed. At a technical level, the problem that needs to be solved is one of system balancing, not of identifying source energy in order to minimize losses to owners. In a hypothetical future system powered exclusively by wind and solar, any hydrogen produced through electrolysis could be considered "green"—or simply "hydrogen from renewable sources." But the designation is immaterial from the standpoint of system stability.

If an electrolyzer connected to a grid produces hydrogen when there is power available that would otherwise be curtailed, that does not mean the process is "powered by" that share of electricity. From a technical standpoint, its "carbon footprint" is still that of the entire system (as is that of every other user on the system). The additional load from the electrolyzer allows the excess power to be absorbed without destabilizing the system, but—again, from a technical standpoint—it is not being "powered by" that power, from a technical standpoint. It may be considered "green" (or "renewables based") for the purposes of compensation or planning, but that is a separate question.

Even within a marketized system, since there is no *direct* way to determine that any specific share of hydrogen produced by a grid-connected electrolyzer is "green," such determinations require a system of "guarantees of origin."

124 Ibid.

Guarantees (or certificates) of origin are documented verification that a given "share" of hydrogen "really counts" as "green" or whatever designation is defined or agreed by the relevant authorities.

As explained by Rob Butler of Baker Botts, such guarantee schemes are usually legal or regulatory in nature. Currently, however, there are no accepted international definitions or standards for what counts as any particular color or form of "low-carbon" or "clean" hydrogen. This is "primarily because there is currently no global trade in these products, and no industry or regulatory body has taken the step of providing an express standard or definition."[125] "In the absence of regulatory standards," he writes, "what constitutes blue, green or lower-carbon hydrogen will need to be contractually agreed between the relevant buyer and seller."

It is important to keep in mind that these regulatory and contractual complications arise because of the need to ensure that the conditions for private owners to be compensated are met. Without that requirement, other options could be relied upon to measure progress toward the use of hydrogen in support of decarbonization—options that could focus on the *aggregate* effects of the scaling of various decarbonizing technologies. Progress could be assessed at system level, and would not require elaborate systems of tracking and "certificates of origin."

Given the significant conversion losses associated with any use of hydrogen, as long as an electrical grid still relies on a mix of generation sources, it may generally make sense to operate any electrolyzers connected to that grid only when there is power available that would otherwise be curtailed. Of course, an integrated grid operating outside of a system of commodified pricing would still require sophisticated management and balancing. But in the absence of the imperatives to compensate private owners, this could be carried out on some other basis.

If an "all-renewables" (or even "mainly-renewables") approach to decarbonization is pursued, wind and solar generation sources can be scaled on the basis of the need for low-carbon generation, without worrying about "economic losses" from curtailed power. Under public ownership such losses matter less than whether there were other more pressing uses for the labor, raw materials, land and other resources put into play to deploy the generation assets in question. Electrolyzers could be built based on the anticipated need for hydrogen and run when it makes sense to do so, without excessive worry

125 Rob Butler, "Getting What You Paid For: Certification and Verification of Blue and Green Hydrogen," Baker Botts, July 8, 2021, https://www.mondaq.com/unitedstates/renewables/1088792/getting-what-you-paid-for-certification-and-verification-of-blue-and-green-hydrogen.

over "down time" and loss of revenues.

"Green Hydrogen for Grid Storage": Holy Grail or Unholy Distraction?

As noted in the introduction to this paper, green hydrogen has been called the "holy grail" for long-term storage of electricity. This is because—at least in principle—it can be produced using "surplus" wind or solar power, and stored for later use to generate electricity when supply falls short.

Technically, there are of course multiple steps involved in making this vision a reality. Electricity from wind, solar or some other acceptable source of "green" electricity must be used to generate "green" hydrogen. The resulting hydrogen must be stored (typically for some weeks or even months in order to serve the purpose often envisaged for it in addressing the challenge of seasonal storage). Eventually, that stored hydrogen must be used to generate electricity that can be fed back into the grid when needed. This overall cycle is sometimes called "Power-to-Hydrogen-to-Power" ("P2H2P")[126]; sometimes it is shortened to "Hydrogen Power to Power." We will look at each of these in order.

1. Power to Hydrogen...

Regarding the first of these—generating "green" hydrogen from "surplus" renewable power—it is important to distinguish two separate problems that are generally conflated.

First, because "renewable" sources of energy like wind and solar only generate electricity intermittently, a future that relies mainly or entirely on such sources must find a way to meet the need for electricity during periods when "the sun doesn't shine and the wind doesn't blow." This is a practical, technical problem of ensuring adequate electricity supply to meet the real needs of the system and those who depend on it.

Second, power generation assets like wind or solar occasionally (and somewhat unpredictably) generate electricity that is in excess of current market demand, and therefore not commercially viable. Faced with that situation, the owners of those assets understandably seek potentially profitable alternative uses for that electricity. This is a financial, commercial problem, and one that can be separated from the first practical, technical one. Much of the private sector

126 See for instance, Yuhong Xie, Yuzuru Ueda, Masakazu Sugiyama, "Greedy energy management strategy and sizing method for a stand-alone microgrid with hydrogen storage," *Journal of Energy Storage*, Volume 44, Part B, December 15, 2021, 103406, https://doi.org/10.1016/j.est.2021.103406.

interest in "green hydrogen," including for the power sector, has to do with the hope that it can solve this second problem for them—and if not through "normal" market forces, then by serving as another justification of subsidies and guarantees.

In principle, an electrolyzer could be run to generate hydrogen from dedicated wind or solar sources, and that hydrogen could be stored for later use to generate electricity that could qualify as sourced from "green" hydrogen. Indeed, plans for most "green hydrogen" production begin with an existing or planned large "renewable" power generation project—like a wind or solar farm. Under the current, for-profit policy paradigm, if the electrolyzer runs only intermittently, during periods when sale of the electricity being generated by the wind or solar capacity does not make sense on commercial terms, then its utilization rate will be low, making it more difficult to recoup the capital costs and start generating profits.

Leaving aside the question of losses associated with its subsequent storage and later reconversion to electricity, the use of electricity to produce hydrogen will always involve a conversion loss. According to IRENA, such losses currently amount to roughly one third, based on a reported average electrolyzer efficiency of 66%.[127] This is likely to improve over time, but only incrementally, with the theoretical maximum efficiency of "proton exchange membrane" (PEM) electrolyzers (currently the most likely technology to be widely scaled) of 94% unlikely to be approached in practice for many decades, if ever.[128] Given the inevitability of these losses for owners of wind or solar generation assets, there may often be an economic incentive to simply sell the electricity that might otherwise be used to produce green hydrogen. Producing green hydrogen for storage (and later reconversion and sale as electricity) will generally only make sense when there is a convergence of two variables: a relatively high availability of "surplus" power, and a relatively low available price for sale of that electricity. In IRENA's words, producing "green" hydrogen for grid backup only makes sense when there is "great availability of renewable power (especially at relatively low cost)." Only this convergence of factors can "ensure a good load factor at the electrolysis facility."[129] This matters because, when the "load factor"—the amount of "surplus" electricity available from the grid for powering electrolysis—is low, then the resulting cost of the hydrogen produced will be relatively high. Under such conditions, the capital costs for the electrolyzer—a major component of the cost of green hydrogen—have to be recovered from relatively low production volumes of

127 IRENA, *Green Hydrogen Supply: A Guide to Policy Making*.
128 Paul Breeze, "Power System Energy Storage Technologies," in *Power Generation Technologies*, 3rd Edition, Newnes Books, February 21, 2019, https://doi.org/10.1016/B978-0-08-102631-1.00010-9.
129 IRENA, *Innovation Landscape Brief*, 9.

saleable product.[130]

Given this reality, many project developers end up looking for ways to build a project that covers the entire "value chain"—in other words, where dedicated production of "clean" hydrogen (whether blue or green) can be linked to a dedicated buyer (often called an "offtaker"). This then creates the need to balance the project's location between a desirable and feasible site for wind or solar generation against the location of the buyer, potentially with additional costs for transport and storage (which are considerable). From the standpoint of private owners and investors, each of these additional considerations further undermines a project's commercial viability.

Another option is to connect the electrolyzer to the grid itself, so that during periods when it is not being operated on power from the dedicated wind or solar generation assets, it can still produce hydrogen from grid power. For grid-connected electrolyzers, the "carbon footprint" is ultimately determined by the overall carbon footprint of the grid; there is no way to ensure that it is powered only by those wind and solar resources that happen to feed power into the grid at some location or other. In the words of John Williams, an energy analyst with management consulting firm AFRY, "Just connecting an electrolyzer to the grid doesn't result in green hydrogen."[131] Where grid-provided power has a high carbon intensity (due to a significant share of unabated coal, for instance), the carbon footprint of grid-connected electrolysis may even be higher than that for "gray" hydrogen (let alone "blue").[132] Such hydrogen obviously cannot be commercially saleable as "clean" or "green" hydrogen.

Faced with price volatility and curtailment, commercial providers may consider adding electrolyzer capacity to allow alternative use of the electricity that might otherwise be "curtailed." A key question—at least under the current, profit-driven policy paradigm—is whether the hydrogen produced can be sold at high enough rates to allow the (private) owner to recoup the capital costs and make a profit—considerations that potentially fall away under a comprehensive program of public ownership and decommodification of energy systems.

Of course, when it comes to hydrogen as backup for grids, converting "surplus" electricity to "green" hydrogen is only part of the story. We still have to store that hydrogen, then convert it back to electrical power when it is needed.

130 Ibid.
131 AFRY, *Green hydrogen: what are the commercial issues?* April 2, 2020, https://youtu.be/eubqp-CqgWJA?t=408.
132 Ibid.

2. .... to Storage...

Once produced, hydrogen requires special conditions for storage and transport. In its pure form hydrogen can make metal brittle, can escape through tiny leaks and can be explosive—making both transport and many forms of storage especially challenging.[133]

There are a few established ways to store hydrogen, each presenting serious and specific technical challenges. It can be stored geologically, usually in underground salt caverns or disused mines. It can be stored under extremely high pressure, or under extreme refrigeration (or some combination of the two). Or it can be chemically converted into other compounds (such as ammonia) that can be transported and stored more easily. A detailed examination of each of these methods—and the complexities, risks and losses associated with them—is beyond the scope of this paper, but a few points are worth noting.

Geological storage of hydrogen in salt caverns is an established technology, already in use at industrial scale, but is highly constrained by local conditions, limiting its usefulness to support wholesale decarbonization at scale.

As an example of how this method is currently being developed, Japanese power company Mitsubishi Power has partnered with fuel storage company Magnum Development to build the "largest clean energy storage system in the world" in the US state of Utah. Scheduled to be operational by 2025, the Advanced Clean Energy Storage (ACES) project aims to build more than 1 gigawatt (GW) of electrolysis facilities capable of producing more than 450 metric tons of "green" hydrogen per day; the project's salt caverns "will be capable of holding more than 5,500 MT of hydrogen—equivalent to 150 gigawatt hours (GWh) of "carbon-free dispatchable energy and/or decarbonized fuel that can be used in other industries."[134] The project partners have been invited by the US Department of Energy to apply for up to $595 million in support under the Title 17 "Innovative Energy Loan Guarantee Program."[135] In other words, this "flagship" example of geological storage is also a striking example of public funds being used to underwrite private investment and ensure private profits. But the project does go some distance toward demonstrating the technical potential of the approach.

There is of course no straightforward way to project overall requirements for

133 Michael Liebreich, "Separating Hype from Hydrogen."
134 Mitsubishi Power, "Advanced Clean Energy Storage Project Invited to Submit Part II Application for up to $595 Million Financing from US Department of Energy for Proposed Hydrogen Hub and Long-duration Renewable Energy Storage Project," May 11, 2021, https://power.mhi.com/regions/amer/news/20210511.html.
135 Ibid.

hydrogen storage in decarbonized future energy systems without making a range of assumptions about how large a role hydrogen will play in future economies—assumptions that can vary widely. But the IEA's Net Zero scenario projects a need for roughly 50 Mt (million metric tons) of hydrogen storage by 2050, which would provide roughly 1,680 TWh of energy—roughly 60% of the total 2,780 TWh of electricity generated in the EU in 2019.[136]

The largest share of that by far is likely to be provided by salt cavern storage, which the IEA calls a "proven technology," even while acknowledging that existing sites in the US and UK "have not been tested to see if hydrogen can be rapidly injected and extracted as wind and sunshine vary."[137] Given the reported capacity of the Utah-based Advanced Clean Energy Storage facility, meeting the total requirements projected by the IEA would mean roughly 1,100 such sites being built globally (a bit over 11,000 total caverns, since the Utah site is planned eventually to have 100 separate caverns). That would mean the construction of roughly 400 such sites each year between now and 2050, or a bit more than one new cavern each day.

While building that storage capacity would clearly represent a massive undertaking, it is worth noting that there is seemingly considerable potential for the expansion of underground storage of hydrogen in many countries. In Europe, a detailed analysis published in the *International Journal of Hydrogen Energy* found that salt cavern storage of hydrogen offers at least 10 times the energy storage potential of pumped hydropower, and potentially many times more than that.[138] As the authors write, "Even in the most restricted scenario, a large difference of one order of magnitude is evident compared to the technical storage potential of pumped hydropower."[139]

Other methods for storage of hydrogen tend to be highly energy intensive, and/or to involve significant losses due to evaporation (often called "boil-off")—all characteristics that limit their commercial appeal. A review of 15 hydrogen energy storage projects published in the *International Journal of Hydrogen Energy* in September 2021 found that, while such storage systems "are technically feasible, they still require large cost reductions to become commercially attractive."[140] The authors note, however, that "there are currently

136 Eurostat, "Electricity production, consumption and market overview," Data extracted in August 2021, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview.

137 IEA, "Proving the viability of underground hydrogen storage," October 22, 2021, https://www.iea.org/articles/proving-the-viability-of-underground-hydrogen-storage.

138 Dilara, Gulcin, Caglayan et al, "Technical potential of salt caverns for hydrogen storage in Europe," *International Journal of Hydrogen Energy*, Volume 45, Issue 11, February 28, 2020, 6,793-805, https://doi.org/10.1016/j.ijhydene.2019.12.161.

139 Ibid.

140 Egeland-Eriksen, Hajizadeh, Sartoria, "Hydrogen-based systems for integration of renewable energy in power systems," 31,963-83.

very few alternatives for long-term storage of electricity in power systems" and, for this reason, "interest in hydrogen for this application remains high from both industry and academia."

3. … And Back Again

To complete the cycle of using hydrogen as backup for grid electricity, stored hydrogen must be used to generate electricity again. There are two main ways in which this is done: through electro-chemical processes in a fuel cell, and through combustion in a gas turbine. Again, a detailed analysis of each is beyond the scope of this paper, but there are important details that should be understood.

Hydrogen fuel cells produce electricity by combining hydrogen with oxygen in an electrochemical cell (similar to a battery); the process produces electricity, water and a small amount of heat.[141] There are many varieties and sizes of fuel cells, which can run small electronics, power passenger vehicles and even provide electricity to grids at utility power stations.[142]

The current use of hydrogen fuel cells for grid electricity is minimal. Expanding this would be a major task in achieving the role envisaged for hydrogen as backup and storage for grids, because fuel cells are currently the only truly "clean" technology for turning stored hydrogen back into electricity.

While hydrogen can be used in gas turbines to generate electrical power, this currently means blending with natural gas at levels that vary according to the model and age of the turbine.[143] Examples exist where hydrogen has been used at very high percentages to generate power, including at Italy's Fusina power station (operating on pure hydrogen), a South Korean petrochemical plant (operating on 95% hydrogen) and at a steel mill in Wuhan, China (60% hydrogen), with additional facilities planned to operate on 100% hydrogen in the Netherlands and the previously mentioned one in Utah.[144]

But "commercial viability" for such installations remains elusive. According to Joey Mashek, business development manager at engineering firm Burns & McDonnell, "All the major OEMs have advanced-class gas turbines that are

141 https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php.

142 As of October 2020, there were more than 160 fuel cells operating in the United States with a total of about 250 MW of power generation capacity. See: https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php.

143 Dr Neil D'Souza, "Hydrogen's role in power generation," *Argus*, April 20, 2021, https://www.argusmedia.com/en/blog/2021/april/20/hydrogens-role-in-power-generation.

144 Ben Emerson, Tim Lieuwen, Bobby Noble and Neva Espinoza, "Electric Power Research Institute Hydrogen substitution for natural gas in turbines: Opportunities, issues, and challenges," *Power Engineering*, June 18, 2021, https://www.power-eng.com/gas/hydrogen-substitution-for-natural-gas-in-turbines-opportunities-issues-and-challenges/.

available and can blend up to 30% hydrogen,"[145] but commercial production at scale of true "100% hydrogen capable" turbines "is still about 10 years" away. Italy's Fusina power station, for instance, produced power for just two years at a capacity of just 16 MW, and at five or six times the cost of conventional electricity.[146] It was decommissioned in 2018.[147]

P2H2P: Prospects and Implications

In order to assess the prospects of green hydrogen for grid storage, it is important to consider the implications of the overall P2H2P cycle.

As noted previously, each of the individual steps in that cycle—production of hydrogen from renewably sourced electricity, storage and conversion back to electricity—involves energy losses. Cumulatively these are very significant. According to the September 2021 review article cited previously, "roundtrip efficiency" for the P2H2P cycle ranges from 15% to 40%.[148] In other words, cumulative losses for the overall cycle are between 60% and 85%. As the authors of that article explain:

> The main challenge and frequent showstopper with hydrogen energy storage systems [note that the authors are referring to the entire P2H2P cycle, not simply the storage phase] is cost. All the reviewed projects that consider the economic side of the project conclude that significant cost reductions and efficiency improvements for both electrolyzers, hydrogen storage and fuel cells will be necessary before hydrogen energy storage systems can approach a point where they are commercially feasible, not to mention profitable. An added challenge here is that some of the system modifications that increase the overall efficiency for the energy system also increase the cost of the hydrogen system. An example of this could be a wind/hydrogen system where you want a large high-power hydrogen system to be able to store as much energy as possible when the wind is really strong and the power consumption is low. However, a hydrogen system of this size would be grossly oversized for most of the operating time and hence a very costly solution.[149]

145 Aaron Larson, "Hydrogen and the Energy Transition," *Power Magazine*, February 25, 2021, https://www.powermag.com/hydrogen-and-the-energy-transition/.
146 Svetlana Kovalyova, "Enel to start major plant conversion to coal 2011," July 12, 2010, Reuters Green Business News, https://www.reuters.com/article/us-enel-idUSTRE66B4KB20100712.
147 di Gianni Favarato, "Chiusa la centrale a idrogeno," *La Nuova di Venezia e Mestre*, January 21, 2018, https://nuovavenezia.gelocal.it/venezia/cronaca/2018/01/20/news/chiusa-la-centrale-a-idrogeno-1.16377980 [in Italian].
148 Egeland-Eriksen, Hajizadeh, Sartoria, "Hydrogen-based systems for integration of renewable energy in power systems," 31,963-83.
149 Ibid.

From the perspective of private investors, the economics and uncertainty involved in projects like this are hardly appealing, and thus projects like this seem highly unlikely to produce the levels of investment required to achieve any meaningful scaling up.

By contrast, for a pro-public approach to the future of energy, the kind of infrastructure required for decarbonized grids can and should be thought of in *strategic* rather than *commercial* terms. The "grossly oversized" hydrogen capacity required to maintain balance for the kind of major power grid in the example should be thought of along the lines of a "strategic reserve" rather than a commercial asset. Its "value" cannot easily (or even reasonably) be assessed in strictly commercial terms, since it plays a key function in maintaining the functionality of the system as a whole. No private company can generally afford to maintain such "unproductive" assets.

Some Inconvenient Truths About Hydrogen Pricing

Of course, on mainstream policy approaches, competitive forces and market prices are supposed (at least eventually) to drive the shift from "dirty" forms of hydrogen to "clean" ones. But in economic terms, "unabated" hydrogen from fossil fuels (whether "gray" from methane or "black" or "brown" from coal) is generally still far less costly to produce than either "blue" or "green" hydrogen (or any other "colors," not yet in use at scale). This is because production costs are determined mainly by the price of the natural gas or coal from which they are produced. In the words of analyst and commentator John Poljak, drawing on a detailed analysis by the IEA's Greenhouse Gas R&D Programme: "The reality is natural gas and coal as a feedstock are incredibly cheap. You would need to assume prices at some of their highest levels in the last 20 years and/or renewables at their lower prices before green becomes close to competitive."[150]

According to the IEA, average hydrogen production costs for 2019 by production method were as follows:

- Unabated natural gas ("gray") $0.7-1.6/kg
- Natural gas with CCS ("blue") $1.2-2.1/kg
- Electrolysis from dedicated renewables ("green") $3.2-7.7/kg[151]

150 John Poljak, "Hydrogen Economics—Which Colour is Cheapest?" Keynumber, January 30, 2021, https://www.linkedin.com/pulse/hydrogen-economics-which-colour-cheapest-john-poljak/.
151 IEA, "Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050," updated September 23, 2020, https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050. Note that the IEA does not use the common color terminology.

In its July 2020 Hydrogen Strategy, the European Commission (EC) cited regional data from the IEA for hydrogen in the EU that is broadly similar, concluding from the data that, currently, "neither renewable hydrogen [i.e., "green"] nor low-carbon hydrogen, notably fossil-based hydrogen with carbon capture [i.e., "blue"], are cost-competitive against fossil-based hydrogen [i.e., "gray"]."[152] Across the Atlantic, in the United States, the Department of Energy estimates the current cost of "green" hydrogen at $5 per kg—near the midpoint of the ranges noted by the IEA and the EC.[153]

Production costs for all colors of hydrogen vary considerably, based on a variety of factors. For "green" hydrogen, production costs are most affected by the cost of the electrical power available to generate it. For both "gray" and "blue" hydrogen, high gas prices have caused a recent, sharp rise in production costs, roughly tripling them over a period of months.[154] But the causes of that spike are complex, involving pandemic-related, geopolitical and weather-related factors, and it is not clear that they indicate any systemic shift vis-a-vis the longer-term "competitiveness" of gray or blue hydrogen against green. Nevertheless, on average, as the figures above indicate, final costs remain considerably higher for "green" than for "gray" or "blue" hydrogen. According to IRENA's 2020 *Green Hydrogen: A Guide to Policy Making*, green hydrogen from "an average VRE ["variable renewable energy"] plant in 2019 would be two to three times more expensive than gray hydrogen."[155]

The volatility of green hydrogen pricing raises special concerns. In liberalized markets, price uncertainty and volatility can and often do undermine the willingness of private investors to invest. A February 2020 analysis of the effects of electricity price uncertainty, by a team of researchers based at the Imperial College Business School's Centre for Climate Finance & Investment, found that: "a prototypical wind investor would require an additional 2.84% return under "merchant pricing" (i.e., competitive wholesale market) conditions compared to a 30-year "fixed price" contract as compensation for the additional electricity price risk; an investor in solar would expect an additional 2.53%.[156] For many years and in many countries, the authors explain,

152 European Commission, *A hydrogen strategy for a climate-neutral Europe*, July 8, 2020, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
153 US Department of Energy, "Secretary Granholm Launches Hydrogen Energy Earthshot to Accelerate Breakthroughs Toward a Net-Zero Economy," June 7, 2021, https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net.
154 Gerben Hieminga, Nadège Tillier, "High gas prices triple the cost of hydrogen production," ING Bank N.V., October 28, 2021, https://think.ing.com/articles/hold-1of4-high-gas-prices-triples-the-cost-of-hydrogen-production/.
155 IRENA, *Green Hydrogen: A Guide to Policy Making*.
156 Anastasiya Ostrovnaya, Iain Staffell, Charles Donovan, Robert Gross, "The High Cost of Electricity Price Uncertainty," Centre for Climate Finance & Investment, Imperial College Business School, February 9, 2020, https://www.imperial.ac.uk/business-school/faculty-research/research-centres/cen-

fixed price contracts have "provided guaranteed payments for renewable electricity generated."

Of course, such subsidies and guarantees were supposed to be temporary—a means to "jump start" progress in new technologies, allowing them to catch up to incumbent, fossil fuel-based systems, and creating a "level playing field." Given the advances to date, the Imperial College authors write, "many industry commentators have speculated on an era of 'subsidy-free' renewables." The problem, the authors explain, is that such contracts "have historically offered renewable power generators two benefits: a subsidy and a market hedge"; a shift to market price conditions for renewables "would see both [benefits] fall away." But exposure to such market pricing risk also "raises the cost of capital for merchant renewable generators." And, as the authors point out, the implications are not limited to making projects more expensive; such a shift can also lead to a drying up of investment, as investors look elsewhere for the rates of return they seek: "Unless new private or government actors provide hedging solutions, fewer developers will undertake new renewable energy projects, slowing the energy transition and increasing its cost to society."[157]

The kinds of risks to investment and deployment highlighted here should raise concern about the suitability of such mainstream policy approaches to drive the development of *any* "clean" technology. For decarbonized hydrogen, such concern can only be heightened by the serious energy losses associated with its production and use—losses that can only add to the requirement for investor subsidies and assurances.

IRENA further contends that the high production costs for green hydrogen remain a major impediment to its expansion at the speed and scale necessary, as the pricing disadvantage of green hydrogen is exacerbated by a "lack of value recognition." As they explain, "There is no green hydrogen market, no green steel, no green shipping fuel and basically no valuation of the lower GHG emissions that green hydrogen can deliver."[158] At the same time, the "lack of targets or incentives to promote the use of green products inhibits many of the possible downstream uses for green hydrogen" further limiting demand for green hydrogen.[159]

The Need for Policy Supports

tre-climate-finance-investment/research/the-high-cost-electricity-price-uncertainty/.

157 Anastasiya Ostrovnaya, Iain Staffell, Charles Donovan, Robert Gross, "The High Cost of Electricity Price Uncertainty," Centre for Climate Finance & Investment, Imperial College Business School, 9 February 2020, https://www.imperial.ac.uk/business-school/faculty-research/research-centres/centre-climate-finance-investment/research/the-high-cost-electricity-price-uncertainty/.

158 IRENA, *Green Hydrogen: A Guide to Policy Making*.

159 Ibid.

Given such realities and the potential impediments they pose to the investment and deployment goals of the major stated policies, it is not surprising that major policy voices are calling for a range of policy interventions. In the words of one analyst from management consulting firm AFRY, reflecting on the hydrogen production cost realities: "[D]isplacing gray hydrogen in existing applications and encouraging use in new sectors is going to be a real challenge, and is going to require policy mechanisms and support in order to enable the 'kickstarting' of the low-carbon hydrogen industry."[160] Similarly, the industry-based Hydrogen Council states:

> This deployment of clean hydrogen will not happen without the right regulatory framework—both governments and businesses need to act. Requirements include a set of suitable policies such as mandates and robust carbon pricing, the development of large-scale infrastructure, and targeted support and de-risking of large initial investments.[161]

Mainstream climate policy has grounded itself in the broader neoliberal vision, according to which governments are ill equipped, both technically and financially, to tackle major societal challenges and should instead focus on ensuring the conditions for private actors to fill the void. In terms of the challenge of decarbonization, this means that governments should focus on putting policies in place that create the right "sticks and carrots": "sticks" like a carbon tax or emissions trading scheme to discourage "dirty" fossil fuels, and "carrots" like financial subsidies or contractual guarantees to encourage the growth of low-carbon technologies.[162]

For hydrogen, such policies are seen as crucial to steer investment in the directions required. In the words of Steinar Eikaas, vice-president for low-carbon solutions at the Norwegian energy company Equinor:

> "It's all a matter of cost.... Either you have to have industries that expect the ETS [i.e., the carbon price within Europe's Emissions Trading System] to grow significantly in a few years, or you would need a framework of subsidies assistance—financial contributions from the state—to facilitate the transition."[163]

160 AFRY, *Green Hydrogen: What are the commercial issues?*
161 Hydrogen Council, "Hydrogen for Net Zero," November 3, 2021, https://hydrogencouncil.com/en/hydrogen-for-net-zero/.
162 UK Parliament (2007) "Select Committee on Treasury, 'Examination of Witnesses,' Tuesday, February 6," available at: https://publications.parliament.uk/pa/cm200708/cmselect/cmtreasy/231/7020605.htm.
163 Leigh Collins, "A wake-up call on green hydrogen."

The policy "carrots" typically take the form of various mechanisms to guarantee returns on investment—these come with assurances that governments will pick up the tab for those enabling features of the emerging infrastructure on which private profits will depend. As IRENA articulates this in their December 2020 report titled *Green Hydrogen Cost Reduction*, governments can and should establish regulations and design markets that support investments in innovation and help scale-up the production of green hydrogen. Crucially, this includes policies that "enabl[e] new business models that can guarantee predictable revenues for the private sector to invest at scale."[164]

As the current wave of interest in hydrogen is still in its relatively early stages, and because it emerged in the context of the disruptions of the Covid-19 pandemic and the responses to it, the policy landscape is rapidly changing. New commitments are announced regularly, often as part of Covid-related relief and recovery packages. According to the "Energy Policy Tracker" website (maintained by the International Institute for Sustainable Development), at least 14 countries have either made new policy commitments or revised existing commitments since the beginning of the pandemic specifically supporting hydrogen and totaling at least $23.63 billion.[165] A full examination of these is beyond the scope of this paper, but it is worth looking at a few key examples—the EU, Germany and the United States.

Prior to the pandemic, the EU adopted its *Hydrogen Strategy*,[166] which aimed to develop "renewable hydrogen, produced using mainly wind and solar energy," as "the most compatible option with the EU's climate neutrality and zero pollution goal in the long term and the most coherent with an integrated energy system." As the strategy explains:

> The choice for renewable hydrogen builds on European industrial strength in electrolyzer production, will create new jobs and economic growth within the EU and support a cost-effective integrated energy system. On the way to 2050, renewable hydrogen should progressively be deployed at large scale alongside the rollout of new renewable power generation, as technology matures and the costs of its production technologies decrease.

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164 IRENA, *Green Hydrogen Cost Reduction*, December 2020, https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction.

165 IISD, Energy Policy Tracker, https://www.energypolicytracker.org/search-results/?_sfm_energy_type=hydrogen (accessed December 10, 2021). Countries with documented commitments currently include Australia, Canada, China, Colombia, France, Germany, India, Italy, Norway, Poland, Russia, Spain and the UK, as well as the EU.

166 European Commission, *A hydrogen strategy for a climate-neutral Europe*, July 8, 2020, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.

> In the short and medium term, however, other forms of low-carbon hydrogen are needed, primarily to rapidly reduce emissions from existing hydrogen production and support the parallel and future uptake of renewable hydrogen.[167]

In the strategy's first phase (2020-2024), the objective is "to install at least 6 GW of renewable hydrogen electrolyzers in the EU and the production of up to 1 million tons of renewable hydrogen, to decarbonise existing hydrogen production, e.g. in the chemical sector and facilitating takeup of hydrogen consumption in new end-use applications such as other industrial processes and possibly in heavy-duty transport."[168]

In order to promote this investment, the EU hydrogen strategy would rely on a range of both existing and new mechanisms to promote and facilitate investment and cooperation "along the hydrogen value chain."[169] In order to deal with the cost disparities and encourage the growth of low-carbon hydrogen (especially from wind and solar), the EU hydrogen strategy invokes the need for "support schemes," which "are likely to be required for some time, subject to compliance with competition rules."

As explained by a commentary on the EU's hydrogen strategy by Konrad Adenauer Stiftung Australia, the European Commission (EC) has "introduced a 'carbon contracts for difference' pilot program, which will pay the cost spread between preset and actual permits in the EU-Emissions Trading System (ETS) through sales of carbon allowances to encourage investment in hydrogen."[170] The hope is that such a "green hydrogen" economy "could create 1 million new jobs for highly qualified personnel in the EU by 2030 and up to 5.4 million by 2050 across the entire value chain."[171] The EC is also supporting a new "Clean Hydrogen Alliance" to promote the production of 40 GW of green hydrogen in the EU as well as lending support to 40 GW in Ukraine (10 GW) and North Africa (30 GW), with grants and subsidies of €145bn, incentivizing total investments of some €430bn.[172]

In November 2021, EC President Ursula von der Leyen announced a new "Clean Hydrogen Partnership" as part of the strategy. The new public-private partnership aims to "produce clean hydrogen at ~€1.5-3/kg" and to reduce

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167 Ibid.
168 Ibid.
169 Ibid.
170 Dr Frank Umbach and Dr Joachim Pfeiffer, "Germany and the EU's Hydrogen Strategies in Perspective," Konrad Adenauer Stiftung Australia, August 2020, https://www.kas.de/documents/274425/8492225/German+%2B+EU+Hydrogen+Strategies.pdf/b069d44b-5af0-9ec8-da1c-e0c10335e08e?version=1.0&t=1597804839540.
171 Ibid.
172 Ibid.

the distribution "costs to less than €1/kg at scale." The partnership is to be supported by €1 billion from the EU's Horizon research program, and €1 billion from industry partners.[173] Changes in priority also signal a shift away from the previous focus on hydrogen fuel cell passenger vehicles (which have been outpaced by battery electric cars) and toward industrial applications, long-haul aviation, maritime shipping, backups for renewable energy and in large-scale heating grids.[174]

In Germany, the country's National Hydrogen Strategy, released in June 2020, provides roughly EUR 7 billion in support to industry for "speeding up the market rollout of hydrogen technology in Germany [through conversion of hydrogen production processes], and another 2 billion euros for fostering international partnerships."[175]

Overall, the German federal government "seeks to use green hydrogen, promote its rapid market rollout and establish the necessary value chains." The strategy aims to develop a "strong domestic market" for hydrogen, which it argues will "send an important signal, encouraging other countries to use hydrogen technology as well." Toward this end, the German government will "design the incentives for speeding up the rollout of hydrogen technology in Germany and particularly for the establishment and operation of electrolyzers in a way that is compatible with the energy transition." The strategy targets the installation of "up to 5 GW" of hydrogen production capacity by 2030, "including the offshore and onshore energy generation facilities needed for this," which it estimates will require 20 TWh of renewables-based electricity per year; an additional 5 GW of capacity will eventually be added, by 2035 if possible and no later than 2040.[176]

Because Germany's domestic generation potential for green hydrogen "will not be sufficient to cover all new demand," most of the hydrogen anticipated to be needed under the strategy will have to be imported, including from Morocco and Ukraine (both countries with large solar potential). For these "partner countries," the strategy provides EUR 2 billion for "setting up large-scale hydrogen production plants 'Made in Germany' … to cover Germany's import needs."[177]

173 Nikolaus J. Kurmayer, "€2 billion 'Clean Hydrogen Partnership' signals move away from hydrogen cars," EURACTIV.com, December 2, 2021 (updated December 7, 2021), https://www.euractiv.com/section/energy/news/e2-billion-clean-hydrogen-partnership-another-move-away-from-hydrogen-cars/.
174 Agora, "Sources, transport, applications—12 insights on hydrogen," November 18, 2021, https://www.agora-energiewende.de/en/events/12-insights-on-hydrogen/.
175 Federal Ministry for Economic Affairs and Climate Action, *The National Hydrogen Strategy*, October 6, 2020, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html. See also, https://www.cleanenergywire.org/news/germany-gives-energy-transition-some-extra-boost-economic-stimulus-programme.
176 Ibid., 5.
177 Ibid. See also, https://www.cleanenergywire.org/news/germany-gives-energy-transi-

In the United States, a major infrastructure bill passed in August 2021 included $9.5 billion in dedicated funding for "clean hydrogen," most of which ($8 billion) is earmarked to set up new "regional clean hydrogen hubs," with two planned in areas of the country that produce fracked gas. A third hub will be powered by nuclear energy and the fourth will use renewables. The remaining $1.5 billion is for clean hydrogen manufacturing and advancing recycling research, development and demonstration. Another $10 billion is invested toward "carbon capture, direct air capture and industrial emission reduction," although this is not specifically directed for hydrogen production alone.[178]

As TUED has argued elsewhere, the policies that have been pursued over the past two decades or so in an attempt to "incentivize" that wider energy transition have resoundingly failed to do so. This has not led to an energy *transition*, but rather an energy *expansion*, in which the use of essentially *all* forms of energy continues to rise. As stated in a recent publication with the Transnational Institute titled *Energy Transition or Energy Expansion*, "Despite the commitment of huge amounts of public money to incentivize private investment, there is growing concern that both renewable energy and decarbonization more broadly are facing a serious and growing investment deficit."[179] Quoting IEA's 2019 assessment, that report notes:

> There are few signs of the major shift of capital toward efficiency, renewables and innovative technologies that is needed to turn emissions around.... Investment and financing decisions are shaped by policies: today's frameworks are not yet equipped to avoid multiple risks for the future.[180]

Although it is too early for there to be any real data on the outcomes of the current wave of policy commitments to support hydrogen, the record for promoting renewables more broadly should be ample to advise caution. In the US, the "Build Back Better" bill—which would have seen an expansion of renewables—met sufficient political opposition that only its infrastructure provisions were passed, giving skeptics who see hydrogen as just a gift to the fossil fuel industry more fuel for their argument.

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tion-some-extra-boost-economic-stimulus-programme, 5.

178 US Department of Energy, "DOE Fact Sheet: The Bipartisan Infrastructure Deal Will Deliver For American Workers, Families and Usher in the Clean Energy Future," November 9, 2021, https://www.energy.gov/articles/doe-fact-sheet-bipartisan-infrastructure-deal-will-deliver-american-workers-families-and-0

179 Sean Sweeney, John Treat and Daniel Chavez, *Energy transition or energy expansion?*, TUED and TNI, October 22, 2021, https://www.tni.org/en/publication/energy-transition-or-energy-expansion

180 Ibid.

Who Will Build the Clean Hydrogen Infrastructure?

An additional major hurdle facing the scaling up of hydrogen is the lack of dedicated infrastructure. As the IRENA authors explain, historically hydrogen has been "produced close to where it is used, with limited dedicated transport infrastructure." To put the scale of dedicated hydrogen infrastructure in context, they note:

> There are only about 5,000 kilometers (km) of hydrogen transmission pipelines around the world, compared with more than 3 million km for natural gas. There are 470 hydrogen refueling stations around the world, compared with more than 200,000 gasoline and diesel refueling stations in the United States and the European Union. Natural gas infrastructure could be repurposed for hydrogen, but not all regions of the world have existing infrastructure.[181]

The lack of dedicated infrastructure for hydrogen is a major concern for energy professionals. A large majority (71%) of respondents to the DNV survey mentioned at the outset "believe current hydrogen ambitions underestimate the practical limitations and barriers to adoption." As the authors of the survey state:

> Without sufficient progress on infrastructure, hydrogen economy participants will face significant barriers; based on our research, this is a major concern. Respondents selected a lack of investment in hydrogen infrastructure (38%) as the joint highest risk their organizations face in relation to hydrogen.[182]

This infrastructure challenge for hydrogen recalls the better-known "chicken and egg" problem facing electric vehicles: The relative scarcity of charging stations diminishes the appeal of EVs for consumers, while the relatively small number of EVs on the roads makes investing in the charging infrastructure unappealing to investors. The existence of such a dilemma, which faces the adoption of many new technologies, is why governments typically play the decisive role in developing such infrastructure. Of course, such publicly funded and publicly developed infrastructure is yet another form of subsidy to

181 IRENA, *Green Hydrogen: A Guide to Policy Making*.
182 DNV, *Rising to the challenge of a hydrogen economy*, July 2021, https://www.dnv.com/focus-areas/hydrogen/rising-to-the-challenge-of-a-hydrogen-economy.html.

private interests—if hydrogen production is to remain in private hands.

Conclusion: Toward a Pro-Public Vision for Hydrogen in Decarbonization

As we have tried to make clear through a detailed consideration of the key technical and legal issues involved in "clean" hydrogen, we think there is ample reason to believe that hydrogen will play a role in future energy systems, and that only public ownership offers a realistic pathway to ensuring it can and does play the role we need it to play. Given the difficulty in decarbonizing crucial sectors and processes in other ways, it seems very likely that hydrogen will be used in transport, shipping, industry and the power sector.

Of course, many in the labor and environmental movements rightly recognize that reaching the levels of decarbonization necessary to protect the climate and prevent further ecological and social harms will require eliminating a great deal of wasteful energy consumption and economic activity. But it would be a mistake to assume that even after such waste is eliminated, our need for such technologies as decarbonized hydrogen will go away. Unions in all sectors should be mindful of the serious technical questions and difficult trade-offs regarding technology options and choices, and hydrogen is no exception.

As we have seen, deploying "clean" hydrogen (and its related fuels and technologies) at scale involves formidable challenges. Many of these challenges are *technical* in nature, and solving them seems crucial to decarbonizing energy systems in line with agreed, science-based targets. Major changes in how hydrogen is produced and used will be necessary, and making these changes will involve massive investment and construction across the full spectrum of hydrogen's production, storage and use.

Current practices and ownership arrangements—which are taken for granted and reinforced by mainstream climate and energy policy—add an additional layer of *commercial* challenges to those technical ones. Those practices and policies insist on profit- and market-driven approaches to deliver the changes required, adding not only a layer of complexity but also providing a basis and context for the continued use of public money to "incentivize" private investors.

The Dream of "Green Hydrogen" and the Case for Public Ownership

Of course, for reasons we have investigated in this paper, interest in hydrogen for decarbonization focuses mainly on prospects for "green" hydrogen. For that reason, understanding the case for public ownership as a condition for realizing the decarbonization potential of hydrogen seems most important in relation to green hydrogen.

As we have attempted to make clear in this paper, in important ways the idea of "green hydrogen" risks masking important technical realities. As noted above, from a technical standpoint, the "carbon footprint" of some share of hydrogen that has been produced by electrolyzers connected to a grid that is powered by a mix of generation sources *is simply the carbon footprint of the overall mix of sources*. There is no way to "force" or "allow" only those electrons put in motion by the renewable sources to power the electrolyzer.[183] That share of hydrogen is only "green" if it is *assigned* to some share of renewably sourced power that is available to the system during the period in which the electrolyzers are running.

But the need to assign some share of hydrogen the color status "green" is not the same as the technical requirement to establish mechanisms for determining when the electrolyzers should be run: the software that enables decisions to be made in real time whether to "curtail" some amount of incoming electrical power, or alternatively to start operating electrolyzers to soak up the excess supply and produce hydrogen. From a technical standpoint, what matters in terms of decarbonization is not that the hydrogen produced is assigned to some color-coded status, but that the electrolyzers are run during periods when "excess" power is available to the grid.

Within a mixed grid, such "excess" power is generally considered to be due to variable wind and solar sources, but this itself is an artificial determination. The "excess" power available to the system during periods of strong wind or intense sunlight could just as easily be attributed to (i.e., "blamed on") characteristics of other sources: It is no more "caused by" the surge in wind or sunlight than it is by the stubborn inability of other generation sources to be ramped down quickly enough to avoid destabilizing the grid, and thus avoiding the emissions they produce.

Fortunately, most of these questions and considerations really only matter if

183 This is not necessarily true for standalone hydrogen production facilities with dedicated generation, but such facilities do not help address the balancing and storage requirements for power systems with significant shares of variable renewable energy sources.

the various generation sources in question are owned by different, competing private interests (or at least subject to different systems of remuneration). Under comprehensive public ownership, the *economic* need to maintain some kind of "certificates of origin" falls away, and the purely *technical* challenges of determining when it makes most sense to send some share of electricity to the electrolyzers can be tackled as what they are: technical challenges, with only resource- and emissions-based considerations left in play.

Perhaps more clearly in the case of hydrogen than for many other parts of energy systems, public ownership opens up possibilities for treating needed resources and technologies as "strategic reserves," rather than as sources of profit. This difference in treatment could prove crucial in ensuring the investment and deployment required are carried out, and without simply channeling enormous quantities of public money to private owners to ensure profitability of assets that may need to be left idle much of the time, in the form of "capacity payments" or something similar.[184] Under public ownership, electrolyzers could be allowed to remain "idle" during periods when there is no "surplus" electrical power entering the grid from wind and solar sources, without requiring the use of public money to compensate private owners, and incurring the resulting *political* risk of doing so.

"Off-grid" solutions may be appropriate at specific points in the system, for specific industrial or other applications, but ensuring their compatibility with true "net decarbonization" goals cannot be assured if decisions about their deployment are to be made on the basis of commercial viability or profitability. These must be assessed on the basis of public need and net decarbonization impacts.

What is needed instead is a reconceptualization of the task, and the debates, that brings the technical requirements for decarbonizing specific sets of energy assets clearly into view and subjects them to public scrutiny. The question to be answered in any given case is not, "Is green hydrogen the solution to this challenge?" but questions like, "Does it make sense from an ecological and social perspective to add electrolyzer capacity to this system and in this context? How much? What about hydrogen storage? What kind and how much? Fuel cells? Of what capacity? What distribution and other infrastructure is needed to enable hydrogen to play the role we believe it needs to play in decarbonizing key sectors and processes? These are distinct technical choices, each with its own resource implications. The public debates over "green hydrogen," largely framed by private interests and mainstream

184 For a discussion of capacity payments, see for instance Sean Sweeney, John Treat and Irene HongPing Shen, *Working Paper 13: Transition in Trouble? The Rise and Fall of "Community Energy" in Europe, Trade Unions for Energy Democracy*, March 2020, 25-27.

policy voices, seem often to push these questions into the background, leaving them to be solved on the basis of commercial considerations once public opinion has been won.

Minimizing emissions associated with producing the hydrogen required to provide adequate backup would mean considerable "overbuild" of wind and solar capacity. In other words, it would imply a strategy to ensure that, over time, there is a considerable "excess" of power that would otherwise be "curtailed" but which could instead be used to generate hydrogen much of the time. Given what we know about variable power from wind and solar sources, about the technologies involved in deploying hydrogen at the scales necessary to solve the challenge of seasonal storage, and about the substantial idle productive capacity involved and the substantial public subsidies that would be necessary to make that compatible with private ownership, we think public ownership is clearly the best path forward to ensure that hydrogen can play whatever role we will need it to play in future decarbonized energy systems.

It must also be noted that concerns have been raised about the prospects of a new "scramble for resources." For instance, the European Green Deal aims to establish a supply of "green" hydrogen from Africa as part of its own decarbonization efforts—an initiative that has been criticized as an example of "green colonialism."[185] The massive expansion of the requirement for platinum for both electrolyzers and fuel cells[186] as well as other minerals also raises the specter of widespread ecological damage from a massive expansion of "green" hydrogen production and use.

Paying for the Hydrogen (and Everything Else) We Need

As responses to the Covid-19 pandemic have made clear, many national governments have considerably more "fiscal space" to respond to public crises than has been widely understood or acknowledged. However, many other governments face serious constraints in formulating such responses, based on issues of foreign debt, reliance on imports for necessary economic inputs (food, energy resources, technology), intellectual property restrictions and more. Recent years have seen the opening of active debates about the full meaning of these differing realities, and about ways forward that work to embrace, enhance and democratize public spending power in ways that

185 Hamza Hamouchene, "Green Hydrogen: The new scramble for North Africa," *Al Jazeera*, November 20, 2021, https://www.aljazeera.com/opinions/2021/11/20/green-hydrogen-the-new-scramble-for-north-africa

186 Baker McKenzie, "Seizing Hydrogen Investment Opportunities," March 10, 2021, https://www.bakermckenzie.com/en/insight/publications/2021/03/seizing-hydrogen-investment-opportunities

can serve truly developmental and pro-public aims and programs.[187] Given the anticipated costs of developing hydrogen and the need to address the investment deficit currently confronting the transition, it is important that unions continue to participate in debates on the "fiscal space" available to governments, and how to ensure it is sufficient to tackle the task at hand, or can be made sufficient if it is not.

Either way, it is crucial that the expansion of hydrogen—and energy systems more generally—is pursued in ways that are consistent with true "net decarbonization," and that are driven by climate considerations rather than commercial concerns. "Incentivizing" and "de-risking" investment for private actors has not produced the results that were hoped for and promised in relation to wind and solar power; we see no reason to believe the results will be different in relation to hydrogen. We need a different approach to solving the formidable challenges that must be faced in driving forward the transition to genuinely sustainable future energy systems.

Hydrogen technologies have to be assessed in light of specific circumstances and requirements, including existing infrastructure and available technological options for decarbonization. All potential means for decarbonizing the production of hydrogen should remain on the table, and should be assessed not on commercial-economic terms but in terms of their ability to produce the hydrogen that future energy systems will require, while minimizing ecological impacts. There are no "one size fits all" solutions.

Freed from the imperatives of profits for private owners and investors, decisions about technological options, scale and timing can prioritize instead consideration of resource use, ecological impacts, implications for jobs (and union density and strength) and more.

Hydrogen in the Context of the Energy Transition

It should be kept in mind, of course, that the role envisaged for "clean" hydrogen in decarbonization is just part of a wider required transition, and the scaling up of hydrogen envisaged under the IEA's net zero scenario (or essentially any other mainstream scenario) must, of course, be viewed in the context of a much wider transition. Because of its likely role in crucial areas that will be difficult to decarbonize in other ways, clean hydrogen seems likely to be necessary to the transition we need, but not wildly insufficient on its own.

187 See for instance, Fadhel Kaboub, "Africa's Path towards Resilience and Sovereignty: the Real Wakanda is within Reach," *Tax Justice Network*, March 30, 2021, https://taxjustice.net/2021/03/30/africas-path-towards-resilience-and-sovereignty-the-real-wakanda-is-within-reach/.

That wider transition involves, as noted above, electrification of many processes that currently rely on other forms of energy, and shifting electricity generation away from fossil fuels to "low-carbon" sources.

It should also be kept in mind that the role for hydrogen envisaged in the NZ50 (net zero by 2050) scenario (and other similar scenarios) depends on other net zero goals being achieved. Expanding the applications of hydrogen and decarbonizing its production will not on their own "solve" the climate emergency, and will mean little if other decarbonization efforts fall behind. Concrete plans and strategies for hydrogen need to be understood, analyzed and developed within a comprehensive strategy for the energy transition. A paper such as this can perhaps provide broad insight and guidance on possibilities, challenges and pitfalls, but working out concrete solutions for any given national or regional context will require detailed engagement with locally relevant conditions (technical, ecological, political, social, economic) that fall well beyond the scope of the present paper. Of course, the labor movement is uniquely positioned to provide leadership in such work.

We urgently need a different approach—one that breaks with the mainstream insistence on private investment to drive the transition. As a growing number of unions around the world recognize and affirm, meeting the challenge we face requires "a public, planned approach to energy transition"—one that is grounded in a series of detailed, concrete policy changes that can and must be fought for and won.[188]

188 "Trade Union Program for a Public, Low-Carbon Energy Future," Launched: November 4, 2021—Glasgow, Scotland, https://docs.google.com/document/d/1cNoOqfAsmFTYlt-dmVbsbiK0oi-WY5kk0WJk2cXA8J0Q/.