Renewable Hydrogen Policy Principles

(Active Document)

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1. Introduction

Hydrogen's perceived promise as a valuable decarbonized energy source, and its continued penetration in conversations surrounding decarbonization of electricity generation, transportation, and industrial applications prompted this examination into hydrogen's potential role in the Northwest. The resulting review and policy principles represent the culmination of stakeholder feedback, in-depth literature review and independent research on the role of hydrogen in the electricity sector. While the below represents our current understanding of, and recommendation for Renewable Northwest's engagement around hydrogen policy in the Northwest, it is important to note that infant nature of "renewable" or "clean" or "green" hydrogen production and use, make any analysis meaningful only in so much as it can evolve with changes in underlying technology, policies, and regulations. Accordingly, this document will continue to evolve to address developments impacting hydrogen production, use, and the involved ancillary processes. Importantly, we recognize that collaboration among interested stakeholders similar to the PNW Renewable Hydrogen Action Plan will be of central significance as policies impacting hydrogen's production and use are proposed, debated, and implemented. As such, we welcome member input as the mechanisms governing hydrogen's production and use, as well as the technology underlying renewable hydrogen's production, transportation, storage, and use, continue to develop. This document will continue to be updated as necessary to account for such developments.

Hydrogen is the smallest and most abundant element in our world and has long been the object of speculation surrounding its use as an energy source. Renewed interest in the development of a "hydrogen economy" among governments, investors, and industries has been spurred, at least in part, by the continual decline in the cost of renewable energy and the continued and growing support for economy-wide decarbonization. While technological barriers currently limit hydrogen's emission reduction potential, continued investment in research and development, use of regulatory and tax incentives, renewable portfolio standards (RPSs), and low carbon fuel standards (LCFS) could see emission-free hydrogen play a significant role in the decarbonization of our energy system.

Today, hydrogen is produced nearly exclusively through the carbon-intensive process of steam methane reforming (SMR). This carbon-intensive hydrogen production method is labeled "blue" if the process uses carbon capture and storage to minimize greenhouse gas (GHG) outputs, "grey" if produced using natural gas, and "black" or "brown" hydrogen when relying on power generated using coal gasification. The primary interest of this document however is "green" hydrogen which refers to hydrogen produced using clean & non-emitting energy resources to power emission-free hydrogen production processes. While numerous developmental stage technologies aim to produce hydrogen using alternative processes, the only technology in commercial use currently is the process of electrolysis. Electrolysis, the process of splitting water into its constituent elements and harvesting the resulting hydrogen, has existed for decades but has struggled to compete with the cheaper, but more carbon-intensive SMR process. Reliance on the previously mentioned colors, as well as others not mentioned here, should be understood as an oversimplification that probably has no place in nuanced policy or legislation, but is nonetheless potentially useful in explaining differences in hydrogen production sources to a non-technical audience. Looking at hydrogen from the lens of decarbonization, it is more effective to focus on the source of electricity used to produce the hydrogen molecules in light of the decarbonization mandates and goals in states across the US.

The emerging support for "renewable" or "green" or "clean" hydrogen economy internationally, as well as at the federal and state levels in the US, has led to a breadth of policy questions addressing the unique challenges and advantages of hydrogen production, storage, transportation, and markets of jurisdictions across the world. There is little doubt that hydrogen, when produced using clean and non-emitting electricity, has the twin benefit of decarbonizing hard-to-abate sectors as well as providing flexibility and other grid services in the electricity sector. In this discussion draft, we portray some of the inherent elements and principles that can be complemented with policy action to ensure that hydrogen production using clean, non-emitting resources plays an effective role in advancing decarbonization goals in the electricity sector.

2. Background on Hydrogen Production

Hydrogen has been produced for commercial applications for decades and has been primarily used in the production of fertilizers, treatment of metals, and petroleum refining. At present, nearly all the hydrogen used globally is produced using the carbon-intensive process of steam methane reforming (SMR). As efforts to decarbonize both global and domestic economies intensify, and as the cost of renewable energy sources continues to fall, hydrogen has increasingly become viewed as a central piece in a fully decarbonized economy. A recent study[1] conducted on net-zero pathways and scenarios concluded that "high-electrification scenarios rely on a drastic expansion of green hydrogen created via renewable-powered electrolysis to replace fossil fuels in hard-to-decarbonize sectors such as cement and steel production and aviation, shipping and long-haul transportation." While hydrogen markets are in a nascent stage right now in our region , renewable hydrogen could supplement a pathway to decarbonization by providing a zero-emission fuel source to sectors from transportation and aviation to long-term storage of otherwise curtailed renewable energy, to decarbonizing those industries already relying on hydrogen produced using carbon-intensive SMR. Still, the hydrogen industry faces challenges in widespread adoption, including in production, storage, transportation, and market development

[1]Net Zero America Study, Princeton University
https://www.princeton.edu/news/2020/12/15/big-affordable-effort-needed-america-reach-net-zero-emissions-2050-princeton-study

for green hydrogen. The Pacific Northwest Renewable Hydrogen Action Plan addresses these issues by synthesizing insights from experts and distills a set of actions that will put the Northwest on a shared path forward to build a robust RH2 sector.The Action Plan makes specific calls to action which includes "Lead with Projects" that produce RH2 and deliver it to customers, and the second is to "Create a 10-Year RH2 Roadmap" that lays out RH2's role in the optimized energy portfolio of the future, and the steps to get there.

Currently, the primary impediment to renewable or green hydrogen's adoption is the cost to produce the hydrogen molecules using electrical energy. In recent years the cost at the point of production for green hydrogen has been in the range of $2.50-$6.80/kg[2] while for hydrogen produced using natural gas, the range was $1.50-$3.50/kg[3] with hydrogen produced using coal at around $1.00-3.00/kg[4]. While significant progress is needed to further depress the cost of green hydrogen, the capital costs of electrolysis have fallen 60% since 2010[5] and are expected to continue to decline as pilot projects are deployed throughout the world and increased manufacturing volumes which allow electrolyzer manufacturers to develop further cost-saving measures. While sustained research and development together with economies of scale from the production of more and larger electrolyzer equipment will continue to reduce the capital costs of electrolytically produced green hydrogen, even with expected technological advances, to reach cost-parity with SMR, electricity input for electrolysis would need to be 1-2¢/kWh. For context, the average cost per kWh for industrial customers in the Northwest Power Pool (NWPP) was nearly 6-7¢/kWh in 2020[6].

Further challenges facing green hydrogen's wider adoption (in electric energy generation at least) are the efficiency losses associated with the process starting from production to end-use consumption. The electrolysis process is currently 65-70 percent efficient although the technology is improving with more investment into research & development of more efficient electrolyzers. Conversion of hydrogen to liquid hydrogen for transport or to common hydrogen carriers like ammonia is another area where further improvements may be needed.. Finally, conversion of hydrogen back to electricity using fuel cells can lead to an additional energy loss[7] which may be improved with technological advancements. The use of hydrogen electrolyzers as a flexible demand-side resource in the industrial sector and provision of ancillary services by ramping hydrogen production up or down (as a load-follower) makes it a potentially pivotal resource along with battery storage to integrate renewable energy resources and provides the opportunity for the benefits to outweigh the losses due to efficiency and curtailments in deep decarbonization scenarios. For example, Tacoma Power recently developed a pilot demand response project that will offer producers of electrofuels like green hydrogen a discounted

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[2] Bloomberg New Energy Finance, BNEF (2020). "Hydrogen Economy Outlook."
[3] Gaffney Cline. "Focus on Blue Hydrogen." (August 2020)
[4] IEA (2019), "The Future of Hydrogen" IEA, Paris.
[5] Hydrogen Council's Path to Hydrogen Competitiveness: A Cost Perspective, 2020
[6] EIA - Oregon Profile
[7] IRENA (2020), *Green Hydrogen: A guide to policy making*, International Renewable Energy Agency, Abu Dhabi.

electricity rate in exchange for the ability to curtail their electric service potentially up to 1,300 hours a year.[8] Interruptible loads like hydrogen electrolyzers can offer utilities increased flexibility to operate their power systems. For applications such as ammonia and fertilizer production, or production of aircraft fuels, or establishing fueling stations for trucks and other transportation it will be important to develop strategies that minimize efficiency losses including:

- Manufacturing hydrogen where it is to be used or dispensed;
- Delivering hydrogen in large quantities through pipelines;
- Using hydrogen to replace other inefficient processes involving fossil fuels such as gas turbines and internal combustion engines;
- Using hydrogen to generate electricity in high value, low volume applications such as back-up or peaking power.

Hydrogen in the Regulatory and Policy Context

Notably, schemes vary greatly both in reference and methodology for calculating green hydrogen standards, and in the end-uses they apply to. For example, the EU's CertifHy scheme applies across multiple production or end-use methods, whereas Low Carbon Fuel Standards (LCFS) and REII apply only to transportation fuels. Such a dynamic could see various agencies administering regulation around green hydrogen depending on its end-use. For example, with a state's utility regulator overseeing Green Hydrogen's use as a long-term storage resource, and the state's department of transportation overseeing LCFSs governing transportation fuels.

Similar divergence can be found in the definitions of Green Hydrogen put forth by various states. For example, Washington's **Clean Energy Transformation Act (CETA) (2019)** defines "Renewable hydrogen" as:

> [H]ydrogen produced using renewable resources both as the source for the hydrogen and the source for the energy input into the production process. And "Renewable resource" as "(a) Water; (b) wind; (c) solar energy; (d) geothermal energy; (e) renewable natural gas; (f) renewable hydrogen; (g) wave, ocean, or tidal power; (h) biodiesel fuel that is not derived from crops raised on land cleared from old growth or first growth forests; or (i) biomass energy.

In contrast, Montana's recently enacted HB 170 defines "Green hydrogen" as "hydrogen that is produced from non-fossil fuel feedstock sources and does not produce incremental greenhouse

[8] Tacoma Power proposes rate to support renewable electrofuel producers. https://www.publicpower.org/periodical/article/tacoma-power-proposes-rate-support-renewable-electrofuel-producers

gas emissions during its production. The term does not include hydrogen produced using steam reforming or any other conversion technology that produces hydrogen from fossil fuel feedstock." Washington's proposed HB 1569 (2021-2022) would define "Green electrolytic hydrogen [as] hydrogen produced through electrolysis, and does not include hydrogen manufactured using steam reforming or any other conversion technology that produces hydrogen from a fossil fuel feedstock." California's Low Carbon Fuel Standard (LCFS) sets parameters for Hydrogen for transportation based on a Carbon Intensity (CI) threshold based on variables such as the method of production. Such variation is to be expected as states move forward with decarbonization policies without significant federal guidance, but efforts to ensure compatible definitions and tracking mechanisms for Green Hydrogen among states could contribute to cost-savings, carbon reductions, and interstate markets for Green Hydrogen.

Figure 1: Emergence of varying tracking mechanisms employed by various jurisdictions. Image courtesy of: IRENA (2020), *Green Hydrogen: A guide to policy making*, International Renewable Energy Agency, Abu Dhabi.

BODY	REFERENCE	THRESHOLD	QUALIFIED PROCESSES
AFHYPAC	None	100% renewable	All renewable-based solutions
Low Carbon Fuel Standard	Well-to-wheel emissions from new gasoline vehicles	30% lower GHG, 50% lower NO_x	Green hydrogen, catalytic cracking of biomethane or thermochemical conversion of biomass, including waste
CertifHy	Grey hydrogen	60% lower GHG than reference (36.4 gCO_2/MJ)	Two labels: • "Green hydrogen" if the hydrogen is made from renewable energy • "Low carbon hydrogen" otherwise Hydrogen must meet the threshold with 99.5% purity
TÜV SÜD	Grey hydrogen	35-75% lower than reference depending on process	Renewable electrolysis; biomethane steam methane reforming; pyro-reforming of glycerine
Clean Energy Partnership	Grey hydrogen	100% renewable	Renewable electrolysis; biomass
REDII[12]	Transport fuels	70% reduction	Renewable transport fuels of non-biological origin
Technical Expert Group on Sustainable Finance	None	5.8 tCO_2/tH_2 or 100 gCO_2/kWh used as input	Water electrolysis

Notes: REDII = Renewable Energy – Recast to 2030; NO_x = nitrogen oxides; gCO_2/MJ = grams of carbon dioxide per megajoule; gCO_2/kWh = grams of carbon dioxide per kilowatt hour; tCO_2/tH_2 = tonnes of carbon dioxide per tonne of hydrogen.

Sources: Jensterle et al., 2019; Velazquez Abad and Dodds, 2020.

Yet another central consideration is the extent to which hydrogen produced through electrolysis actually reduces greenhouse gas (GHG) emissions. For example, electrolyzers can be deployed in three ways: *co-located with clean, non-emitting generation resources*, *connected to the grid, or a hybrid mechanism where the electrolyzer is both connected to a renewable resource and the* *grid*. In the latter two scenarios, the extent to which renewable energy is used in the electrolysis will depend on the grid's underlying power mix at the time of production and the extent to which a renewable energy power mix is contracted to improve on the grid's standard mix. Any new load on the grid, such as an electric car or bus, a data center or an electrolyzer, unless paired or coinciding with increased production of renewable energy, will most likely cause an increase in net electricity demand supplied by the grid's marginal production generators, mostly fossil fuels today. Hydrogen production through electrolysis followed by compression, transportation and electricity production may not result in net negative decarbonization when compared to alternative uses for the electricity, at least until the grid itself becomes more decarbonized and is dominated by clean, non-emitting generation resources. Some proponents of green hydrogen's adoption in the Northwest point to the region's aggressive grid decarbonization commitments as mitigating factors that justify viewing investments in hydrogen production from the lens of a continuing trend towards a cleaner grid which in turn leads to production of incrementally cleaner hydrogen.

Market purchases, especially the ones not tied to a specific resource, called "unspecified market purchases," can create a situation when a lack of detailed accounting for carbon intensity may lead to inadvertent consequences in production of green or low-carbon hydrogen. For example, the power Bonneville Power Administration (BPA) purchases on the wholesale market cannot be attributed to a specific resource. These unspecified market purchases, which are assigned a default emissions factor, make up about 3 to 12 percent of BPA's total annual power supply and may be used to generate hydrogen, if not, tracked effectively creating a risk of extending the economic life of coal and natural gas resources. Additionally, as the region moves toward more regional coordination of our energy markets, we must keep in mind the possibility that in states without clear mandates on fossil fuel generation, the potential exists for additional fossil generators or life-span extension of existing fossil generators to produce hydrogen, which will be sold into a regional market as a clean energy resource.

Oregon's recently passed SB 333 (2021) "directs State Department of Energy to conduct study of benefits of, and barriers to, renewable hydrogen production and use in Oregon." Similarly, HB 3375 (2021) establishes a goal "to plan for the development of up to three gigawatts of floating offshore wind energy projects within the federal waters off the Oregon coast by 2030," and directs the study's authors to examine the efficacy of producing hydrogen from the offshore installment. Another bill introduced in the most recent session, HB 2535 (2021), which sought to exempt from Ad Valorem taxes those properties engaged in the production of hydrogen through electrolysis, or from renewable natural gas, was met with some opposition both from Northwest environmental groups, and natural gas providers and ultimately never made it out of the House Committee of Energy and Environment.[9]

[9] See testimony submitted to the House Committee on Energy and Environment.

It will be key to ensuring the success of a new renewable hydrogen industry that the origin of the energy of the product be understood, and that its carbon intensity be calculated and made publicly available. Ensuring transparency in both the feedstocks and the carbon intensity will be critical to the marketability of the product and the environmental community's acceptance of it.

3. Definitions of Green Hydrogen

Green hydrogen is defined as hydrogen produced by splitting water into hydrogen and oxygen using clean and non-emitting energy resources like solar, wind, off-shore wind, and hydro-power. This process is called electrolysis, in which an electric current breaks water down into its constituent elements thereby transforming electricity into chemical energy. The electrolyzers involve two electrodes (an anode and a cathode), an electricity source, and an electrolyte that together form a closed electrical circuit. Electrolyzers cause water to be reduced at the cathode (adding electrons, generating hydrogen gas) and to be oxidized at the anode (removing electrons, generating oxygen gas). As stated previously, currently, the majority of hydrogen is produced either through the process of steam reforming of methane or gasification of coal. Both of these production processes emit significant quantities of carbon dioxide, but they can be partially decarbonized if combined with technologies such as carbon capture & utilization & storage (CCUS), leading to what is termed as 'blue hydrogen'. Recent scientific research[10] points out that "blue hydrogen has emissions as large as or larger than those of natural gas used for heat. The small reduction in carbon dioxide emissions for blue hydrogen compared with natural gas are more than made up for by the larger emissions of fugitive methane." This makes blue hydrogen unsuitable for meeting decarbonization goals unless the technology improves drastically.

To support the concept of generating hydrogen with electrolysis using renewable power (also known as power to hydrogen), a large amount of carbon-free power will be required. One of the key aspects in support of this is the concept of using *curtailed electricity*, above and beyond what is needed to meet demand, to generate hydrogen. Due to the significant growth in the use of renewable power sources in the US, there is potential to use excess renewable energy to support a hydrogen production ecosystem especially in states like Texas and California. However, the power required for electrolysis of water to supply hydrogen for generation in typical power turbines is currently larger than the curtailed renewable power. Thus, creating an ecosystem that generates large volumes of hydrogen for use in power generation will require much larger amounts of renewable capacity[11].

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[10] How green is blue hydrogen? Howarth and Jacobson, 2021. https://onlinelibrary.wiley.com/doi/full/10.1002/ese3.956

[11] Power to Gas: Hydrogen for Power Generation - Fuel Flexible Gas Turbines as Enablers for a Low or Reduced Carbon Energy Ecosystem. GE Power. *See* Table 3 and Table 5.
https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20Power%20to%20Gas%20-%20Hydrogen%20for%20Power%20Generation.pdf

Another related but separate definition looks at the net carbon impact of the hydrogen produced to create “decarbonized hydrogen” i.e., hydrogen produced with net-zero carbon emissions. For example, a hydrogen electrolyzer charging from the grid during limited renewable energy production and supplementing that amount of MWhs with an equivalent amount of unbundled RECs may be classified as “decarbonized hydrogen”. While decarbonized hydrogen may lead to net emission reductions based on specific use-cases, there is still an inherent risk that needs to be accounted for in future policies and programs incentivizing this interpretation of hydrogen until the electric grid is decarbonized. For example, the recently passed Infrastructure and Jobs Act defines clean hydrogen to mean “[h]ydrogen produced in compliance with the greenhouse gas emissions standard established under section 822(a), including production from any fuel source.”

There is also a simplistic way of defining hydrogen that goes beyond the color codes and strict definitions, by comparing the life-cycle carbon intensity reductions to the status quo i.e., hydrogen produced from steam methane reforming rather than relying on a strict definition based on the “colors” of hydrogen. This entails creating an emission-reduction threshold of “X%” over which hydrogen produced, stored, and transported would be considered “green” without needing to provide on-site connection or a separate and additional power purchase agreement to a clean energy resource. This is currently being followed in the European Union using CertifHy[12]. In this program, green hydrogen refers to hydrogen generated by renewable energy with carbon emissions 60 or 70% below the benchmark emissions intensity threshold (= GHG emissions of the hydrogen produced by steam reforming of natural gas). The Guarantee of Origin scheme (GO) essentially provides information on the GHG emissions of the hydrogen produced and enables the state or regional policy to decide how “low” the GHG emissions should be and set a price for it. This definition allows clean energy to be located separately from the hydrogen production facility thereby needing geographical and temporal safeguards to ensure that fossil fuels are not inadvertently being encouraged and used to generate hydrogen.

Under different policy contexts or certification programs, there may be cases when green hydrogen is produced in conjunction with grid-based hydrogen due to supply variability and economics, but according to the primary definition, grid-based hydrogen does not equate to strictly “green hydrogen” unless the electric grid is completely decarbonized with 100% electricity sourced from clean and non-emitting generation resources. A reasonable threshold could also be defined in a policy context based on stakeholder consensus by ensuring the overall environmental costs do not exceed the benefits of the hydrogen produced. This is because green hydrogen by itself has negligible emissions but electrolysis using other power sources including grid-charged energy may have a larger carbon footprint depending on the marginal generation, current grid fuel mix, and level of decarbonization in the region. Hydrogen production requires

[12] CertifHy Low-GHG hydrogen is hydrogen with emissions lower than the defined CertifHy Low GHG-emissions threshold, i.e. 36.4 gCO2eq/MJ, produced in a plant where the average emissions intensity of the non-CertifHy Low-GHG hydrogen production (based on an LCA approach), since sign-up or in the past 12 months, does not exceed the emissions intensity of the benchmark process (SMR of natural gas), i.e. 91.0 gCO2eq/MJ.

significant amounts of electrical energy and thus would create significant amounts of carbon-dioxide if produced from this carbon-intensive grid electricity. For example, in 2017, the US electricity grid had an average carbon intensity between that of natural gas– and coal-fired power. If average grid power had been used for electrolysis, the carbon emissions intensity would be more than twice that of SMR because of the inefficiency in the additional step of energy conversion.

With the retirement of coal-fired power plants and the increase in wind and solar power resources, the carbon intensity of the US power sector is surely decreasing. The use of curtailed electrical generation has also provided a pathway for hydrogen production from existing and new clean & non-emitting capacity resources. In the Pacific Northwest, the dominance of clean resources like hydro-power in the generation mix offers strategic advantages, particularly in locations with access to readily available and low price hydro-electricity. As stated previously, the main cost driver for green hydrogen is the price of electricity, with other key contributors being the capital cost of the electrolyzer plant and the utilization or "capacity factor", a measure of how often the electrolyser runs throughout the year. Driving down the cost of electricity by investing in clean and non-emitting energy and capacity resources in the region would bode well for both the economics as well as the environmental attributes of the hydrogen produced irrespective of varying definitions of hydrogen.

4. Member Inputs and Feedback

Member input varied greatly depending on the orientation of the source to the new technology. The notes presented hereafter are generalizations from relatively informal conversations with organizations at vastly different stages of developing policy positions on hydrogen. Not surprisingly, project developers generally opposed co-location requirements, requirement of additionality, or tracking mechanisms that would ensure carbon-free hydrogen produced from verified renewable generation as opposed to low-carbon hydrogen created through electrolysis with the energy mix inherent to the connected grid, or the hybrid approach. The justification for this position was largely based upon the growing percentage of Northwest energy demand being supplied by renewables as a result of falling costs, Renewable Portfolio Standards, and emission-reduction targets such as Washington's Clean Energy Transformation Act, and Oregon's recently passed HB 2021. Renewable developers also noted that other clean energy strategies, including support for electric vehicles, the RPS, the low carbon fuels standard, and CETA each involve pathways, not a jump from zero to perfect. Renewable developers also saw policies that increased the cost, or banned completely, the construction of new natural gas infrastructure as increasing hydrogen's competitive advantage.

Because it is widely agreed that RECs are inadequate for substantiation of Hydrogen's "Green" status, two methods for tracking have been proposed which attempt to ensure any given hydrogen's "green" status. First, many developers and trade organizations favor the use of the carbon intensity (or CI) method which would essentially attempt to quantify the amount of emissions factoring in variables such as grid mix or energy input, method of transportation, and achieved reductions from a baseline (typically the next best available technology) for any given hydrogen. The second method, and that generally favored by environmental NGOs, sees the lack of granular tracking in market settings where "unspecified purchases" are common as a central impediment to hydrogen's potential as a decarbonized energy source. Such granular tracking technologies are currently nascent[13] and are not being used currently across the Western states.

5. Policy Principles

Hydrogen has the potential to play a significant role in tackling climate change and poor air quality. It should be seen as a key to achieving a low carbon energy future and not a silver bullet to decarbonize the whole economy including the power system. Since there are several barriers to the realization of a hydrogen-based economy including: production at scale, infrastructure investments, bulk storage, distribution, and safety considerations, carefully deliberated regional-level policies should be tailored to create the maximum impact instead of a "one-size fits all" solution. A brief caveat to note here are these policy principles reflect Renewable Northwest's current understanding of hydrogen for use primarily in the electricity sector. These policy principles also reflect key issues which would be formative for any state or regional green hydrogen policy and are stated below:

1. ***Clean* -** Green or Clean or Renewable Hydrogen should strictly mean hydrogen produced by an electrolytic process using clean, renewable, and non-emitting generation resources such as solar, wind, geothermal, off-shore wind, tidal and hydroelectric energy. While this definition may be applied to different policy contexts, the definition itself must be kept separate. Since resources such as biomass, nuclear, natural gas with carbon capture and renewable natural gas are not emission-free, they should not be included among the sources of production of green hydrogen. The sourcing of hydrogen could occur through either direct connection (on-site clean, non-emitting energy production), use of off-site power purchase agreements, or through use of non-energy attributes such as RECs that are not used to meet another clean energy standard. It is important to note here that only the first option is actually producing "green hydrogen". There may be criteria placed for the other two options that may allow it to be considered "low carbon or partially decarbonized hydrogen" for ex. only allowing renewable energy projects (through a virtual PPA) in a specific geographical/electrical boundary to be eligible, perhaps also requiring temporal matching on an hourly basis or requiring both. Investing in

[13] Power Ledger's tech to be used in global REC market, following North American registry M-RETS and Clearway deal — Power Ledger

zero-carbon electricity generation resources would ensure that the grid is decarbonizing and essentially the electricity used to supply the hydrogen electrolyzer is cleaner and emission-free.

Alternatively, green hydrogen can also be defined based on the percentage reduction in lifecycle GHG intensity (or carbon intensity) of production relative to steam methane reforming, but it is important to note that the ensuing production might not be considered completely "clean" or "green" but may be considered "low-carbon or partially decarbonized" hydrogen. Using this framework for defining *low-carbon* or *partially decarbonized hydrogen* may be more effective for sectors other than the electricity sector (for example, use in LCFS). A methodology for establishing the appropriate threshold of carbon intensity (CI) of hydrogen must require that non-energy attribute certificates like renewable energy certificates (or RECs) be used (i.e., retired) to substantiate use of clean & non-emitting resources. This method is currently being used for California and Oregon's Low Carbon Fuel Standards (LCFS).

Action: Support increased level of decarbonization of power grids to ensure electricity used for hydrogen is clean and emission-free through enabling policies and financial incentives.

2. ***Additional* -** In the short term, for the electricity sector, green hydrogen production should follow the principle of additionality i.e., additional renewable electricity consumption should always be covered by additional renewable capacity. Green hydrogen producers could be obligated to execute power purchase agreements (PPAs) with new, unsupported generation assets. To ensure that this goal is measured and understood, transparent methods to track and report are going to be necessary. The need for additionality should fade as the region achieves a certain threshold of grid carbon intensity measured through the level of power delivered by clean generation resources. Specific use-cases wherein a high level of curtailment may be beneficial for hydrogen production or an existing clean, renewable and non-emitting generation power plant is repowered to serve green hydrogen production may also be exceptions to the principle of additionality. An important point to note here is that this principle applies only for hydrogen use in the electricity sector i.e. as a source for power generation or energy storage.

   Keeping this guardrail would ensure that renewable power already being supplied to the grid is not diverted to produce hydrogen thereby avoiding multi-stage efficiency losses and subsequent increases in fossil fuel dispatch. To ensure true additionality, calculation methods for renewable shares under clean energy standards or similar policies would need to be adapted. The overall renewables target could be corrected for clean electricity used for green hydrogen production, either by increasing the final energy target or by subtracting the electricity during target accounting.

It is important to point out here that schemes like Renewable Energy Credits (RECs) or Guarantee of Origin (GO) do not ensure additionality and also may not allow a sufficient level of temporal and geographical correlation between renewable energy and hydrogen production. In the context of additionality, power purchase agreements offer the best way forward since they provide price certainty for renewable energy developers. Using a PPA instead of RECs or GOs also simplifies the verification process of a clear link between the electricity and fuel production units.

Action: Scale-up investment into new or additional zero carbon generation capacity, as soon as possible. Finding new flexible loads to absorb excess electrical energy when demand is low will be critical to maintaining the value and effectiveness of clean, renewable and non-emitting resources. This will bring down the cost of electricity and help green hydrogen become cost-competitive compared to the carbon-intensive hydrogen production methods.

3. ***Trackable* -** There should be sufficient and accurate information about the source of the electricity used to produce hydrogen with relation to its geographical and temporal attributes. A "Guarantees of Origin (GoO)"[14] or a similar tool for clean electricity can be used to track the origin of the electricity generation, but their use alone does not trigger additional clean energy generation. If only relying on schemes like GoOs, hydrogen production may consume renewable electricity already being produced, thereby increasing the overall demand for electricity partly delivered by fossil-based generation.

    - In cases when the hydrogen electrolyzer is not directly connected or co-located with a renewable resource, there is currently no practical and legal way of aligning hydrogen production and energy production within a granular 5, 15, or 30-minute interval. Tracking schemes using blockchain technology like M-RETS and Power Ledger have the technical capability to provide 24/7 matching, but implementation is in the initial stages and currently tracking generation only in limited jurisdictions. Furthermore, the practicality of ramping up and down hydrogen production in tandem with a clean energy source at such intervals may also be challenging given operational limitations on hydrogen generation

[14] A Guarantee of Origin (GO) labels the origin of a product and provides information to customers on the source of their products. It operates as a tracking system ensuring the quality of a product such as hydrogen or electricity. https://www.certifhy.eu/project-description/certifhy-1.html

equipment which has yet to be practically implemented in this manner although it has been tested[15].

- Ideally, an hourly tracking system would eventually be required, but in the interim, a practical way to implement the policy would be to enable monthly matching with a phase-wise transition to daily and then hourly matching. In the short term, connecting electrolyzers to the grid may be financially beneficial because they would be able to produce hydrogen incessantly compared to the full onsite electricity generation option where hydrogen production is tied to times where the power plant is generating electricity. Greater utilization of the electrolyzers in a year would consequently decrease the investment component of the hydrogen cost. In that case, it is important to calculate the amount of carbon-free, renewable energy being indirectly used to produce hydrogen, through a Guarantee of Origin or a similar scheme.
- A clean and non-emitting energy resource or a virtual PPA "delivering" electricity to the hydrogen electrolyzer should be located within the same balancing authority area ("BAA") to ensure that emission transfers and other unintended consequences are avoided.

Action: Prioritize research and development of certification and tracking systems [KD20] [NH21] with the goal of appropriately crediting green hydrogen and derived products, sourced from clean electricity sources.

4. ***Targeted* -** The application and use of green hydrogen should be targeted towards hard-to-abate sectors initially until a sufficient level of scale is achieved thereby creating new markets for use of green hydrogen. In the electricity sector, although not widely used currently, hydrogen is one of the only technologies available to meet the seasonal storage needs of a fully decarbonized electric grid. There are also pilot projects and studies available that consider the role of hydrogen in absorbing excess electricity from renewable energy resources. One such study[16] states that low-cost, low-carbon electricity that would otherwise be curtailed may provide a substantial economic opportunity for entities that can flexibly adapt their electricity consumption like a hydrogen electrolyzer. As cited above, challenges relating to cost, efficiency, and substantial infrastructure requirements remain but flexible hydrogen production may find increasing use and cost-effectiveness in locations such as California, Texas, Germany and the UK. Thus,

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[15] Role of Electrolyzers in Grid Services. US Department of Energy. Fuel Cell Technology Office. 2017. https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_may_2017_h2_scale_wkshp_hovsapian.pdf

[16] https://www.sciencedirect.com/science/article/pii/S2666792421000433

policies promoting green hydrogen should be targeted towards sectors which provide the maximum carbon abatement per unit of hydrogen produced.

- Currently, over 50% of the current worldwide production of hydrogen is used in the synthesis of ammonia, which, in turn, is principally used to make fertilizers. Production of green hydrogen will significantly reduce the greenhouse gas emissions associated with fertilizer production.
- Four industries in particular – iron and steel, chemicals and petrochemicals, cement and lime, and aluminum – account for around 75% of total industrial emissions (IRENA, 2020). Green or Low-carbon hydrogen could provide a substantial level of emission-reduction in these industries.
- By focusing on energy-intensive or CO2 intensive industries such as aviation, maritime shipping, steel, cement and related industrial processes, green hydrogen can make a big impact in reducing their carbon intensity at a lower cost. Currently, steel is responsible for 8% of global carbon dioxide emissions while cement accounts for 7% of the share. Adding low-carbon hydrogen to this equation may provide a reasonable level of benefits.
- Transportation contributes 14% of worldwide carbon emissions[17]. While battery electric vehicles make sense in many applications, hydrogen fuel cell vehicles are the better choice in others, especially in heavy duty ground transportation, marine, rail, transit, aircraft, material handling, and drayage vehicles.

Action: Incentivize and encourage use of clean or low-carbon hydrogen in hard-to-abate or hard-to-electrify sectors like ammonia production, steel & cement manufacturing, maritime and aviation industries.

5. ***Aligned* -** Any adopted definition of green or low-carbon hydrogen should be in lockstep with the long-term decarbonization goals or energy policy of the state in terms of its eventual impact on the electric grid. This includes creating guardrails to ensure that the production of hydrogen does not inadvertently lead to an extension of the operational life of fossil fuel infrastructure assets whose primary purpose was not to generate hydrogen and is antithetical to clean energy policies or standards of the region. Production of green hydrogen should also not lead to additional fossil fuel dispatch to serve the incremental needs of hydrogen generation[KD28] .

[17] https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector

Action: Create policy and regulatory frameworks and guardrails that reward clean electricity supply consistent with state decarbonization policies. This would incentivize green hydrogen producers by creating financial certainty causing manufacturing scale-up and reduced costs.

Table 1. Summary of Policy Principles.

Policy Principle	**Objective**	**Implementation/Action**
Clean	To ensure differentiation between green and low carbon/decarbonized hydrogen.	Policies incentivizing use of clean and non-emitting generation resources directly to produce hydrogen or ensuring a specific threshold over which hydrogen can be considered “low-carbon” or “decarbonized”.
Additional	To avoid competition with the decarbonization of the power sector as deviating existing renewable capacity from the grid may create indirect emissions by bringing fossil generators ‘into the money’ in power markets.	Using power purchase agreements or other contractual mechanisms to ensure additionality and provide a link between renewable energy generation and hydrogen production.
Trackable	To ensure that the hydrogen electrolyzer is “using” renewable energy in cases when it is not co-located and is charging from the grid.	Creating specific criteria ensuring a sufficient level of temporal correlation using intra-day matching (hourly); and geographical correlation by only allowing electrolyzer and power plant to be situated in the same balancing authority area or other similar attributes.
Targeted	To provide the maximum decarbonization benefits based on economic and environmental costs of producing hydrogen.	Incentivizing use of green or low-carbon hydrogen in hard-to-abate sectors like maritime shipping, steel & cement manufacturing, etc. Given the criticality of green hydrogen to abate some sectors and achieve full decarbonization, an important policy would be to ease access to wholesale markets to take

		advantage of periods of low, zero, or even negative market prices.
Aligned	To ensure that hydrogen production does not extend the life of fossil-based infrastructure assets whose initial purpose was not to produce hydrogen.	Creating policy guardrails to ensure that hydrogen use is not incentivized for cases where fossil fuel dispatch increases to serve incremental hydrogen production.

Conclusions and Lessons Learned

It is important to understand that despite the promise of green hydrogen and its suitability to replace fossil fuels, at this point in time, it cannot be considered a 1:1 substitute for fossil fuels, neither technologically nor economically especially in the electricity sector. Instead, it is just one of several possible decarbonization alternatives that should be carefully weighed when setting policy programs & priorities and may be tweaked based on a state or a region's decarbonization pathway. Due to its current end-to-end efficiency challenges, it cannot compete with other electricity sector decarbonization technologies but it may not need to if it can be applied to niche sectors (hard to abate) in the beginning and eventually move along the learning curve . The cost of electricity delivered to the electrolyzer remains the most important limiting factor in hydrogen production followed by the capital cost of the electrolyzer.

As regions decarbonize their electric grids in the future, it would be increasingly techno-economically viable to produce hydrogen using low-cost wind and solar resources, but the question remains as to how we ensure that the renewable energy is not being diverted from meeting customer demand to serve hydrogen. Thus, the selection of the supporting policies and regulatory structures should weigh the relative costs and benefits of green hydrogen compared to other contemporary decarbonization solutions for specific end-uses, especially given continuing progress in competing technologies like battery storage, electric vehicles, and building electrification. In many cases, direct electrification using renewable energy, along with energy efficiency, may be a faster and more economically viable solution to decarbonizing the energy system than using green hydrogen. Hydrogen does provide off-grid decarbonization pathways in the transportation and heavy industry sectors which were not evaluated in this document.

The single greatest barrier to the production of green hydrogen is its cost – it is currently two to three times more expensive to produce than grey hydrogen. Policymakers should identify the highest-value applications for a given amount of green hydrogen, to guide their policy efforts where they could provide the most immediate advantages and enable economies of scale. One potential role for green hydrogen policy is to support and then accelerate a shift to green hydrogen in industrial applications where hydrogen is already used, such as refining and the production of ammonia and methanol. Notably, the demand from these facilities is large enough to enable economies of scale in production and infrastructure, making the shift to green hydrogen even more cost-effective in these applications compared to distributed applications[DB3] .

More importantly, it is not advisable to fall into the color-coded trap of different hydrogen production pathways but ensure that policies that stipulate emission reduction and procurement of clean & non-emitting energy resources, recognize the source, impacts, and eventual use of the hydrogen production. This would provide the maximum benefits relative to cost including economic and social costs of producing hydrogen. In a fully decarbonized society, the need for hydrogen produced from carbon free resources is going to be substantial. It is a critical intermediate step towards a final carbon-free fuel for specific energy services and an essential feedstock to critical manufacturing sectors.

As the production of hydrogen grows, measures must be put in place to ensure that the electricity used by electrolyzers is as low-carbon and cost-effective as possible and that enough renewable electricity is available for both the direct electrification of end-uses and the production of hydrogen since both these pathways would be required to achieve full decarbonization of our energy system. Policies supporting incentives and market rules that reduce capital costs and encourage electrolyzer operators to use renewable electricity that would otherwise be curtailed or locating electrolyzers in areas with recurrent grid congestion may be good options.

In the electricity sector, hydrogen has the potential to provide a significant benefit in the future by providing long-duration and seasonal storage as well as grid flexibility required to achieve deep decarbonization. Studies have shown that hydrogen can be stored "by compressing it into underground salt caverns or depleted fossil fuel sites, blended with fossil gas or used to produce other fuels." It can then be converted back into power when required or used for other purposes in the energy system, such as transport fuels. In the short term, though, battery storage technology tends to provide a much higher round-trip efficiency[18] compared to hydrogen for storage purposes although they are limited by their duration, a problem hydrogen storage can solve in the future. Hydrogen molecules can be used when energy needs to be stored for days or weeks as batteries suffer from self-discharge over longer periods.

With that said, with the current set of facts at our disposal, it is unlikely that the electricity sector would be the first priority for extensive use of hydrogen (although it may become incrementally important in the future), it is nonetheless crucial to decarbonize other parts of the economy which may be even more carbon-intensive than the electricity sector, thereby providing a unique value

[18] Potential and risks of hydrogen-based e-fuels in climate change mitigation. Ueckerdt et al., 2021. https://www.nature.com/articles/s41558-021-01032-7.epdf?sharing_token=WNMrraktjyxydmZ37t5XrtRgN0jAjWel9jnR3ZoTv0NvvcjgkZX46JlO7Nfw7zfyvoADBvTOq9WIfhdmgV2dg_Zm-ooRIvDUajySVOgslfK-wkOrhQeaskxdoHd9CQkDKrEyWaG7Nek-etV6-wjBn0LukVZpsV7ZIbuxiMdSO6Q%3D

to our energy economy. As technologies involved in hydrogen production evolve, this document will be updated to capture recent developments and their effects on the underlying policy principles.

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