

ENVIRONMENT AND NATURAL RESOURCES PROGRAM

# Geopolitical and Market Implications of Renewable Hydrogen

## New Dependencies in a Low- Carbon Energy World

Fridolin Pflugmann

Nicola De Blasio



HARVARD Kennedy School

**BELFER CENTER**

for Science and International Affairs

REPORT  
MARCH 2020



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## Glossary

<b>ARENA</b>	Australian Renewable Energy Agency
<b>BEV</b>	Battery electric vehicle
<b>CCS</b>	Carbon capture and storage
<b>CHP</b>	Combined heat and power
<b>FCEV</b>	Fuel-cell electric vehicles
<b>OPEC</b>	Organization of the Petroleum Exporting Countries
<b>RES</b>	Renewable energy sources
<b>SMR</b>	Steam Methane Reforming

### *Energy units*

<b>GW</b>	Gigawatt ( $10^9$ Watt)
<b>PWh</b>	Petawatt hours ( $10^{15}$ Watt hours)
<b>EJ</b>	Exajoule ( $10^{18}$ Joule)

## Approximate conversion factors

<b>One kilogram of</b>	<b>approximately equals</b>
Hydrogen	142 mega joules (upper heating value) 39.4 kilowatt hours 3.4 kilogram of crude oil 2.6 kilogram of natural gas
<b>One liter of</b>	<b>approximately equals</b>
Hydrogen, gas, 1 standard atmosphere @ 25°C (higher heating value)	0.33 liter of natural gas 0.00032 liter of crude oil
Hydrogen, liquified (higher heating value)	280 liter of natural gas 0.27 liter of crude oil

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**Electrolysis in action.**

Flickr user [ca\\_heckler](#) / CC by-nc-nd 2.0



# Executive Summary

To accelerate the global transition to a low-carbon economy, all energy systems and sectors must be actively decarbonized. While hydrogen has been a staple in the energy and chemical industries for decades, renewable hydrogen is drawing increased attention today as a versatile and sustainable energy carrier with the potential to play an important piece in the carbon-free energy puzzle. Countries around the world are piloting new projects and policies, yet adopting hydrogen at scale will require innovating along the value chains; scaling technologies while significantly reducing costs; deploying enabling infrastructure; and defining appropriate national and international policies and market structures.

What are the general principles of how renewable hydrogen may reshape the structure of global energy markets? What are the likely geopolitical consequences such changes would cause? A deeper understanding of these nascent dynamics will allow policy makers and corporate investors to better navigate the challenges and maximize the opportunities that decarbonization will bring, without falling into the inefficient behaviors of the past.

## ***Why renewable hydrogen?***

The successful deep decarbonization of energy intensive sectors—including power, mobility, buildings, and industry—will likely require the deployment of clean energy carriers at scale.

Hydrogen produced from renewable electricity has a variety of applications and the potential to tackle “hard-to-abate” sectors while mitigating the shortcomings of renewable energy sources such as intermittency.

Renewable hydrogen can be used in both mobility and stationary applications. As a sustainable mobility energy carrier, it can power

fuel-cell electric vehicles and/or be the base for synthetic fuels. In stationary applications it can be used to store renewable energy—both at utility scale and/or off-grid—hence providing backup to buffer renewable energy sources (RES) intermittency and/or serve as a carbon-free heating source. Furthermore hydrogen can be stored in large quantities for extended periods of time at lower costs than electricity.

Thanks to its unique versatility, renewable hydrogen is often described as the “missing link” in global decarbonization.

### ***What would renewable hydrogen systems look like?***

Though recent reports vary in estimating demand by 2050, renewable hydrogen could capture up to 14% of the future global energy markets. Two factors will determine hydrogen’s rate of global growth: competitiveness of production costs and deployment of enabling infrastructure at scale.

Currently, renewable hydrogen is around two to three times more costly to produce than fossil fuel-based hydrogen. However, countries and companies can consider a range of strategies to increase its competitiveness, including technological improvements, cost reductions along the value chain, and/or carbon pricing policies.

### ***What are the geopolitical and policy implications of adoption at scale?***

If renewable hydrogen is adopted at scale in the coming decades, future market dynamics will likely resemble today’s regional natural gas markets—with corresponding potential for geopolitical conflict. Whether renewable hydrogen will be as regionally concentrated as today’s oil markets or decentralized like renewables is dependent on technology, availability of enabling infrastructure, and future market structures.

Our analysis shows that countries will likely assume specific roles in global renewable hydrogen systems based on their levels of renewable energy resource and water endowment as well as their infrastructure potential. As a result, the geopolitical realities of resource-poor countries in Europe and South-East Asia might resemble the present, since these countries are expected to import renewable hydrogen from new energy export champions—including Australia and Morocco—that possess strong cost positions and access to large import markets.

These countries may implement policies to trigger technology innovation and infrastructure investments, paving the road toward dominant positions in future hydrogen markets. At the same time, sustaining high renewable deployment rates will also be key to achieve the necessary scale. Targeted federal policies could also reduce investment risk while addressing commercialization barriers.

On the other hand, importing countries must prepare and embrace strategic long-term supply diversification to increase national energy security.

It will also be essential for both importing and exporting countries to establish international standards for renewable hydrogen production, transportation, and use.

In summary, the many variables dictating renewable hydrogen's future include technology, infrastructure, environment, finance, global markets, and geopolitics. This paper provides a framework to address both the challenges and the opportunities they offer. Geopolitical competition, economic factors, technology, and safety concerns have thus far limited renewable hydrogen's reach; but new geopolitical forces, fuelled by the growing crises of climate change and global energy demand, may reshape the international conversation. Policy makers around the world have a decision to make: will they invest in such a transformative effort?



An experimental hydrogen fuel cell.

Adobe Stock

# 1. Introduction

Carbon-rich fuels—coal, petroleum, and natural gas—offer many advantages over other energy sources. They have a superior energy density relative to almost all other fuel sources, they have a wide range of use, and they are relatively easy to transport and to store. Often, they are also relatively inexpensive; particularly when existing infrastructure allows supply to meet demand. At the same time, carbon-rich fuels present significant downsides, particularly related to their impact on environment and climate. These issues, taken in combination with the persistent desire of countries around the world for more stable, more secure energy supplies, have sparked widespread interest in alternative energy sources.

While hydrogen has been a staple in energy and chemical industries for decades, it has recently attracted increasing attention from policy makers and practitioners worldwide as a versatile and sustainable energy carrier that could play a significant role in the transition to a low-carbon economy. Hydrogen had experienced a short-lived wave of enthusiasm in the early 2000s that ended in disillusionment, but the current trend might prove to be more robust, with a conceivable path toward impacting the long-term future of energy.

As governments become more serious about addressing climate change, it seems the time has finally come for hydrogen to become a major energy alternative to carbon-rich fuels. Thanks to the first universal and legally binding agreement reached at the 2015 United Nations Climate Change Conference in Paris, the traction to implementing environmental policies has increased. However, if the global community intends to stand by its commitment to limit global warming to less than 2°C, carbon emissions must be reduced far beyond what is currently agreed in the Intended Nationally Determined Contributions.<sup>1</sup> Thus governments must show actions that reach beyond replacing coal with renewable electricity, and all emitting sectors will need to contribute to emission reduction efforts. Renewable hydrogen could play a pivotal role in tackling “hard-to-abate” sectors and in mitigating the shortcomings of renewable energy sources (RES). Due to its versatility,

<sup>1</sup> United Nations Environment Programme (2018) *Emissions Gap Report 2018*. [http://wedocs.unep.org/bitstream/handle/20.500.11822/26895/EGR2018\\_FullReport\\_EN.pdf](http://wedocs.unep.org/bitstream/handle/20.500.11822/26895/EGR2018_FullReport_EN.pdf)

hydrogen is sometimes described as the “missing link” in global decarbonization. Renewable hydrogen can be used both in mobility and in stationary applications; as a mobility energy carrier, it can power fuel-cell electric vehicles (FCEV) and/or be a feedstock for synthetic fuels. In stationary applications it can be used as a means for storing renewable energy at utility scale but also off grid. Hence providing backup power to buffer RES intermittency and/or serve as a carbon-free heating source.

A prominent example highlighting the non-transient nature of this new hydrogen age is Japan’s 2017 pledge to become a “hydrogen society”. This endeavor is supported by considerable government investment in technology and infrastructure development for both stationary and mobility applications.<sup>2</sup> Japan’s largest company, Toyota, plays a pivotal role in this plan and in contrast to many other car manufacturers, it began to view hydrogen as a renewable fuel source not requiring customers to change their driving and fuel habits as early as 1992.<sup>3</sup>

In 2019, South Korea released a similar plan for renewable hydrogen integration.<sup>4</sup> In countries such as Australia, New Zealand, and Morocco, national hydrogen strategies are currently under development. In the same year, both the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) published papers on the future of hydrogen, further invigorating the global conversation.<sup>5</sup>

Most hydrogen is currently produced from fossil fuels, through natural gas cracking or coal gasification. Even if more expensive, various processes exist to produce hydrogen in a carbon-neutral way that contributes to emission reduction targets. In this paper we will focus on electrolysis (the splitting of water into hydrogen and oxygen) using renewable electricity. Hydrogen produced by electrolysis using renewable electricity is from now on referred to as *renewable hydrogen*.

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2 Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2017) Basic Hydrogen Strategy. [https://www.meti.go.jp/english/press/2017/pdf/1226\\_003b.pdf](https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf)

3 NPR (2019) ‘Japan Is Betting Big On The Future Of Hydrogen Cars’. NPR. 18 May. Available at: <https://www.npr.org/2019/03/18/700877189/japan-is-betting-big-on-the-future-of-hydrogen-cars> (accessed 30.10.2019)

4 Dae-sun and Ha-yan (2019) ‘South Korean government announces roadmap for hydrogen economy’. *Hankyoreh*. 20 January. Available at: [http://english.hani.co.kr/arti/english\\_edition/e\\_business/879097.html](http://english.hani.co.kr/arti/english_edition/e_business/879097.html) (accesses 16.01.2020)

5 IEA (2019a) *The Future of Hydrogen* and IRENA (2019a) *Hydrogen: A renewable energy perspective*.

For renewable hydrogen to reach its full potential as a clean energy solution, the international community must tackle several transitional challenges. Technological and economic questions need to be addressed in order to enable large-scale commercialization: industrial-scale production for renewable hydrogen still needs to prove its technological viability while achieving competitive cost levels. Currently renewable hydrogen production is around 2-3 times more expensive than hydrogen production from fossil fuels.<sup>6</sup> However, there are several strategies that could help increase its competitiveness, namely technology improvements, cost reductions along the entire value chain, and/or, carbon pricing. Other key obstacles include lack of enabling transportation and distribution infrastructure, established markets, and uniform regulations and/or policies. While hydrogen can be blended into existing natural gas grids, country-specific standards and regulation set a cap between 2-10% of the transmitted volume. Upgrades of pipelines and compressor stations would be required to enable the inclusion of higher shares of hydrogen. Similarly, significant investments in hydrogen-fueling infrastructure would be necessary for scaling up adoption in the transportation systems, which would also face competition with EVs. Besides these technological and economic challenges, the use of renewable hydrogen poses significant geopolitical implications.

The transition to low-carbon energy will likely shake up the geopolitical status quo that has governed global energy systems for nearly a century, hence policy makers need to consider the role their country could/should play in a new energy world. Renewables are widely perceived as an opportunity to break the hegemonies of fossil fuels-rich states and to “democratize” the energy landscape.<sup>7</sup> Virtually all countries have some access to renewable resources (e.g., solar and wind power) and could thus ideally substitute foreign supply with local resources. In the case of renewable hydrogen, whether resources will be as concentrated as today’s oil and gas supply or decentralized like renewables is strongly related to future market structures, technology and enabling infrastructure availability. Our analysis shows that the role countries are likely to assume in

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6 Current hydrogen production costs are around 1-2.5 USD/kgH<sub>2</sub> depending on local natural gas or coal prices. Renewable hydrogen production costs are in the range of 2.5 to 6.8 USD/kgH<sub>2</sub>. See IEA (2019a) and BNEF (2019) for detailed cost assumptions.

7 Casertano, S. (2012) *Risiken neuer Energie—Konflikte durch erneuerbare Energien und Klimaschutz* (Risks of New Energy—Risks Posed by Renewable Energy and Climate Protection). Brandenburg Institute for Society and Security (BIGS), No. 9.

future renewable hydrogen systems will be based on their resource endowment and infrastructure potential. As a result, the geopolitical realities of resource-poor countries in Europe and South-East Asia might look very similar to the present realities, as energy import dependencies may continue also for renewable hydrogen.

Furthermore, the potential impact of interruptions in hydrogen supply depends on how global the market will develop. If liquification and shipping across several thousands of kilometers became cost competitive, interruptions of supply in one part of the world could have impact on global prices. However, it seems plausible that hydrogen, similar to natural gas, will initially flourish in regional markets.

Our study explores the overarching question of whether a low carbon energy world would enable a more uniform access to energy, or if old dependencies perpetuate while new ones emerge. As hydrogen could play an important role in the carbon-free energy puzzle, it is key to understand how the geopolitics of hydrogen would look like if adopted at scale. Hence, these considerations raise the following question: what are the potential geopolitical and market implications of renewable hydrogen? In other words: how might renewable hydrogen influence energy-related international relationships? We believe a deeper understanding of these nascent dynamics is needed so that policy makers and investors can better navigate the challenges and opportunities of a low carbon economy without falling into the traps and inefficiencies of the past. Furthermore, our work aims to provide stakeholders the means to take informed decisions on policy instruments, technology innovation funding, and long-term investments in energy infrastructure.

The remainder of this paper is structured as follows: Section 2 introduces the envisioned renewable hydrogen scenario. Section 3 provides an overview of renewable hydrogen production, applications, and market potential. Section 4 reviews renewable hydrogen production and transportation costs. In Section 5 the map of renewable hydrogen is drawn. Section 6 analyzes the geopolitical implications of future renewable hydrogen markets. Section 7 addresses policy and commercial options. Section 8 outlines options for further analyses.



## 2. The scenario: A world powered by renewable energy

This paper explores the general principles of how hydrogen may reshape the structure of global energy markets and the geopolitical game between countries; to do so we propose an analytical framework, using renewable hydrogen as our case study. This framework can then be easily applied to other technologies, contexts, and/or transition pathways. In other words, our goal is to develop a useful tool to address “what if?” analyses on the opportunities and/or challenges facing the adoption of hydrogen at scale.

Renewable hydrogen could play a key part in decarbonizing our energy systems because it offers a pathway towards meeting climate and pollution goals while avoiding reliance on imported fuels and opening new avenues for developing clean technology manufactured goods. Technology innovation and policy are key transitional variables in accelerating the adoption of renewable hydrogen on a global scale.

Like the development and deployment of other low carbon technologies, a renewable hydrogen transition will be gradual. Initial R&D efforts are generally followed by first movers trying to leverage opportunities for site specific applications, followed by production and infrastructure deployment at scale. Various transition pathways and speeds can be envisioned and are likely to depend on the industrial sector being considered and might occur in parallel and/or sequence as a function of technology innovation. For instance, stationary applications in the power sector might adopt renewable hydrogen earlier than mobile applications in the transportation sector, but technological learning curves in the former could catalyze an accelerated deployment in the later. Regardless of the scenario and/or the transition pathway considered, a combination of a sharp decline in production costs—spurred by technology innovation—together with strong policy support (e.g., carbon pricing) for the deep decarbonization of the energy systems will be required to drive adoption at scale.

To showcase the proposed analytical framework, we envision a low carbon energy world powered by renewable energy sources. We assume that

renewable hydrogen will be widely adopted as a result of technology innovation and active national decarbonization policies and hence a relevant component of a low-carbon energy world. According to IRENA, more than 50 countries have already committed to some form of 100% renewable energy targets.<sup>8</sup> For instance, the European Commission published its long-term vision to achieve climate neutrality by 2050.<sup>9</sup>

For the sake of our analysis we establish three key premises:

- First, we envision future energy systems, in which renewable hydrogen will capture a considerable part of energy demand (around 10%). Hence, we assume that either not all applications can be directly electrified or that the use of renewable hydrogen for decarbonization is more cost-efficient, or both.
- Second, we assume that among all renewable energy sources, solar and wind power will become dominant sources due to their large-scale potential and favorable cost structures. Hence, these two energy sources will be primarily used for renewable hydrogen production in our scenario; even if also nuclear could play a role.
- Third, we assume that public acceptance for alternative, carbon-free hydrogen production processes is at present limited. While as mentioned, nuclear power could play a role, economic, public, and safety concerns are limiting its development and deployment. Furthermore, in a global low-carbon economy carbon capture and storage (CCS) will also need to play a role but this goes beyond the scope of our analysis.

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8 IRENA coalition for action (2019) *Towards 100% Renewable Energy. Status, Trends and Lessons learned*. [https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/IRENA\\_Coalition\\_100percentRE\\_2019.pdf](https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/IRENA_Coalition_100percentRE_2019.pdf)

9 European Commission (2019) *Leading the way to a climate-neutral EU by 2050* [Online]. Available at: [https://ec.europa.eu/environment/efe/news/leading-way-climate-neutral-eu-2050-2019-08-26\\_en](https://ec.europa.eu/environment/efe/news/leading-way-climate-neutral-eu-2050-2019-08-26_en)

### 3. The hydrogen molecule: production, applications and market potential

While hydrogen has been a staple in the energy and chemical industries for decades, it has recently attracted increasing attention from policy makers and practitioners worldwide as a versatile and sustainable energy carrier that could play a significant role in the transition to a low-carbon economy.

In this capacity, hydrogen is being pursued for both stationary and mobility applications as:

- A means to store renewable energy
- A fuel in stationary fuel cell systems for buildings, backup power, and/or distributed generation
- A sustainable mobility energy carrier, namely for fuel-cell electric vehicles (FCEVs)

Hydrogen is the most abundant element in the solar system, and stars such as our sun consist mostly of hydrogen. On earth, hydrogen naturally occurs only in compound form with other elements in gases, liquids, or solids, and hence it must be produced through one of several processes: thermo-chemical conversion, biochemical conversion, or electrolysis (water splitting).

Today, fossil fuels are the primary source for hydrogen production and Steam Methane Reforming (SMR) using natural gas is the dominant production process. Electrolysis, which is considerably more costly, currently accounts for less than 3% of global hydrogen production.<sup>10</sup> We assume that, in the future, hydrogen production from electrolysis will rise significantly if surplus electricity from renewables and/or nuclear will become increasingly available and production costs decrease.

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<sup>10</sup> IEA (2019a) *The Future of Hydrogen*.

## 3.1 Renewable hydrogen production by electrolysis

In this process, electricity is used to split water into hydrogen and oxygen. The required electricity can be provided by any energy source, but to be fully carbon-free, renewable energy such as solar or wind power is essential. In most countries, the current electricity mix is not purely renewable; therefore, electrolysis using grid electricity fails to fully eliminate carbon from the process.<sup>11</sup> The direct coupling of renewable generation assets and electrolysis facilities could circumvent this issue, but at the same time would limit electrolysis utilization times. In comparison to hydrogen production from natural gas (mainly SMR), existing water electrolysis plants operate at smaller scales (<5 Megawatt<sub>el</sub>). Besides electricity, freshwater is a key resource: to produce 1kg of hydrogen, nine times the amount of freshwater is necessary, i.e. nine liters.

Operating electrolysis with sea water is complicated by its high salinity, as salt leads to electrode corrosion. However, researchers from Stanford and other universities recently developed a coating that could make seawater electrolysis viable.<sup>12</sup> This emerging technology is particularly relevant for Middle Eastern countries, which possess rich renewable resources but are freshwater constrained.

A full overview of various hydrogen production processes based on renewable and conventional energy sources is provided in the appendix.

### **Synthetic hydrocarbons**

Hydrogen can be combined with carbon dioxide to form synthetic hydrocarbons (e.g., synthetic methane), or synthetic liquid fuels (e.g., synthetic gasoline or jet fuel). The needed carbon dioxide can be supplied from

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11 U.S. Department of Energy. *Hydrogen Production: Electrolysis* [Online]. Available at: <https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis> (accessed 21.11.2019)

12 Kuang et al. (2019) 'Solar-driven, highly sustained splitting of seawater into hydrogen and oxygen fuels'. *PNAS*. 116 (14). p 6624-6629.

carbon-emitting power plants or industrial facilities; alternatively, it can be captured directly from the atmosphere.

The main benefit of synthetic hydrocarbons is their integrational capacity in the existing energy infrastructure. For instance, synthetic methane can be stored and transported through existing natural gas systems. However, both alternatives have disadvantages. CO<sub>2</sub> capture from power plants and industrial facilities is not carbon neutral, as carbon emissions are regardless ultimately released into the atmosphere. Direct capture from the atmosphere is highly energy-intensive—and thus costly—due to carbon dioxide’s low atmospheric concentration. Furthermore, low overall efficiency increases production costs.

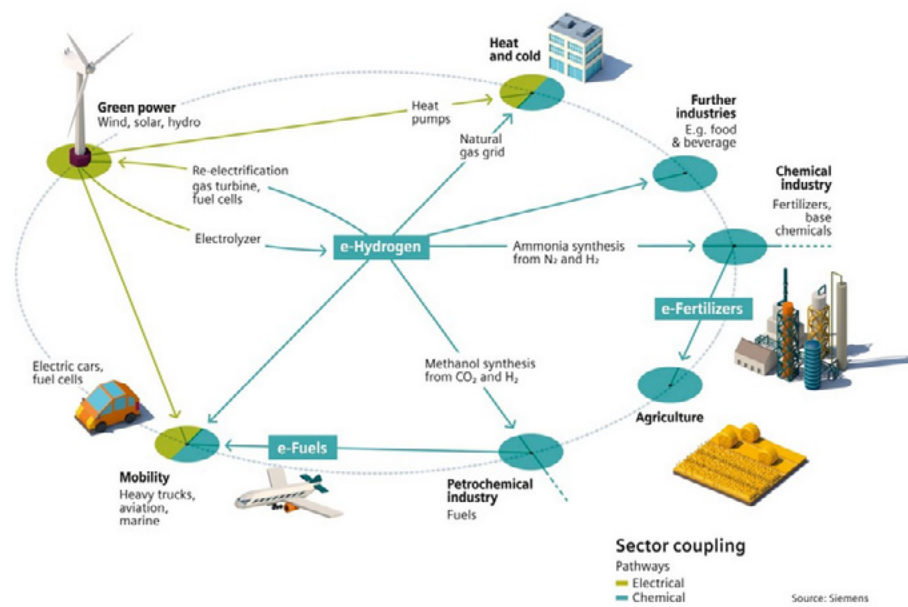
## 3.2 Areas of Application

It is clear that hydrogen could play an integral role in decarbonization as a versatile fuel and effective energy carrier. Yet the pathways to enacting these major global transitions have yet to be developed, leaving it unclear to experts whether direct electrification or low-carbon fuels such as hydrogen will dominate the markets of tomorrow.

While the energy transition has started in the power sector and its transition pathways are clearly visible, all other carbon-emitting sectors—mobility, buildings (heat and cooling), industry, and agriculture—must find further ways to substantially reduce emissions. Figure 1 provides a systematic overview of how renewable hydrogen (sometimes referred to as e-hydrogen<sup>13</sup>) could effectively couple the power sector with the other emitting sectors.

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13 Fuels produced from renewable power are called “Electrofuels” or “e-fuels”.



**Figure 1.** The role of hydrogen in sector coupling.  
Source: Siemens (2019)

The energy transition has started in the **power sector** and its transition paths are clearly visible. On a global level, the largest potential for renewable generation exists in solar and wind power. However, several countries also hold significant potential for hydro generation (e.g., Brazil and Norway). Since 2000, the installed renewable capacity has tripled worldwide,<sup>14</sup> and in 2015, global capacity additions of renewables overtook conventional power generation technologies for the first time.<sup>15</sup>

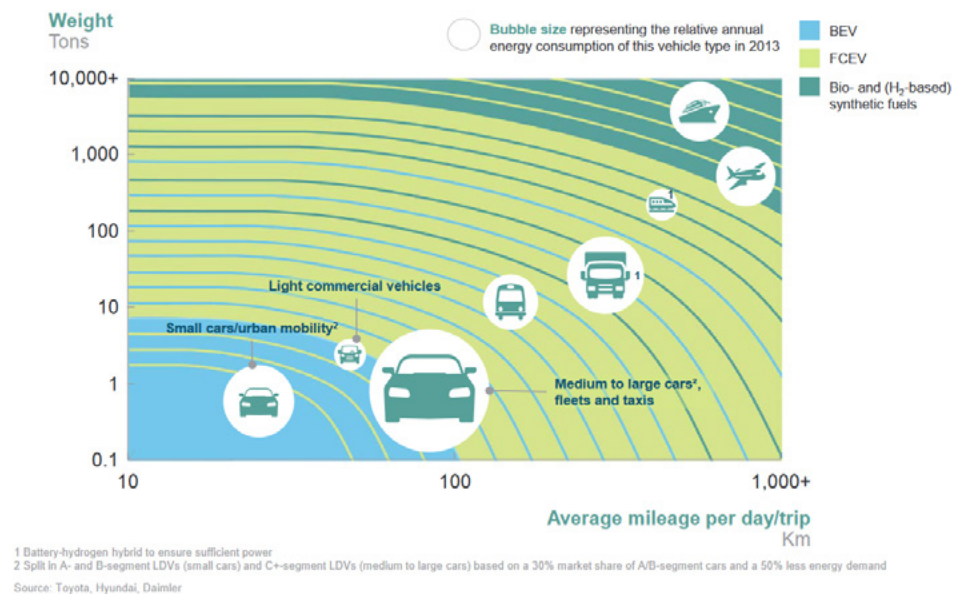
A key challenge in the transition to renewables is their intermittent nature. A high-renewable electricity system needs to be flexible enough to withstand situations in which a significantly higher amount of electricity is generated than required and, more importantly, situations in which renewables are unable to meet required demand. While several flexibility options exist, storage applications are the most straightforward. Hydrogen can be stored in large quantities for extended periods of time at a lower cost than electricity,<sup>16</sup> and hence well-suited to balance fluctuations in renewable generation.

14 IRENA (2019b) *Renewable Energy Statistics 2019*. International Renewable Energy Agency.

15 IEA (2016) *World Energy Outlook 2016 in Special Focus on Renewables*. p. 406-408.

16 See Jülich (2016) for cost comparison of various storage technologies and REN21 (2017) for an overview of storage system capacities.

Countries relying on natural gas could use existing infrastructure for large-scale hydrogen storage and/or partly replacing natural gas. Initially, hydrogen could be directly injected into gas grids between 2-10% of the transmitted volume depending on country-specific standards and regulation. Higher concentrations would require infrastructure upgrades. Alternatively, synthetic methane could be used as a drop-in alternative.



**Figure 2.** Hydrogen applications in the mobility sector.  
Source: Hydrogen Council (2017)

In the **mobility sector**, hydrogen has various application pathways. In the light-duty vehicles/passenger car market, two technologies currently compete: battery electric vehicles (BEVs) and fuel-cell electric (FCEVs) vehicles. BEVs rely on electric batteries for power, while FCEVs utilize hydrogen. To date, most car manufacturers have invested in BEVs, including Tesla, Volkswagen, and Renault. However, especially in Japan and South Korea, several car makers are developing FCEVs. BEVs are commonly projected to capture most of the carbon-free light vehicles market, primarily because ownership costs are lower in the foreseeable future. Charging infrastructure for hydrogen-powered vehicles is also lacking, while BEVs can be charged at various power grid access points.<sup>17</sup>

<sup>17</sup> Arthur D. Little (2017) *What's in the future for fuel cell vehicles?* Available at: [https://www.adlittle.com/sites/default/files/viewpoints/ADL\\_Future of Fuel cell vehicles.pdf](https://www.adlittle.com/sites/default/files/viewpoints/ADL_Future of Fuel cell vehicles.pdf) (Accessed 16.01.2020)

For heavy-duty vehicles, hydrogen is likely to play a larger role due to long-standing issues with battery systems in this sector. Large battery stacks are required to power heavy vehicles over long distances; in addition, recharging large stacks requires several hours,<sup>18</sup> while refueling with hydrogen could be performed within minutes. As utilization is a key performance driver, a short recharge time is a key purchasing criterion. Unless the entire stack of batteries could be easily and cost-effectively replaced instead of recharging (which on the other hand would raise liability and/or insurance issues), hydrogen may remain ahead of its competition.<sup>19</sup>

Nevertheless, both technologies are currently being developed for the truck segment, such as the electric Tesla's Semi and the Kenworth/Toyota fuel-cell electric truck. For similar reasons, decarbonization of air and marine transport will likely need to rely on hydrogen (or biofuels). Figure 2 illustrates for which mobility segments BEVs, FCEVs, and vehicles based on bio- and/or synthetic fuels are most applicable.

Within the **building (heating and cooling) sector**, hydrogen could be used in fuel cells to generate heat (and electricity). Japan and South Korea have programs for residential combined heat and power (CHP) fuel-cell; in the United States, larger fuel cells are present in the commercial heat market.<sup>20</sup> Furthermore, synthetic methane, based on renewable hydrogen, could replace natural gas in existing gas heating with the possibility of leveraging existing transmission and combustion infrastructure and thus avoid expensive replacements. Natural gas is a common heat source in regions with large seasonal temperature differences, such as northern Europe, Russia, and parts of the United States. For moderate-climate areas direct electrification alternatives, such as electric radiators or heat pumps, are more suitable.

In the **industrial sector** (including mining, manufacturing, and construction), hydrogen could play a dual role as a feedstock in chemical processes or high-temperature heat generation. The most straightforward use of

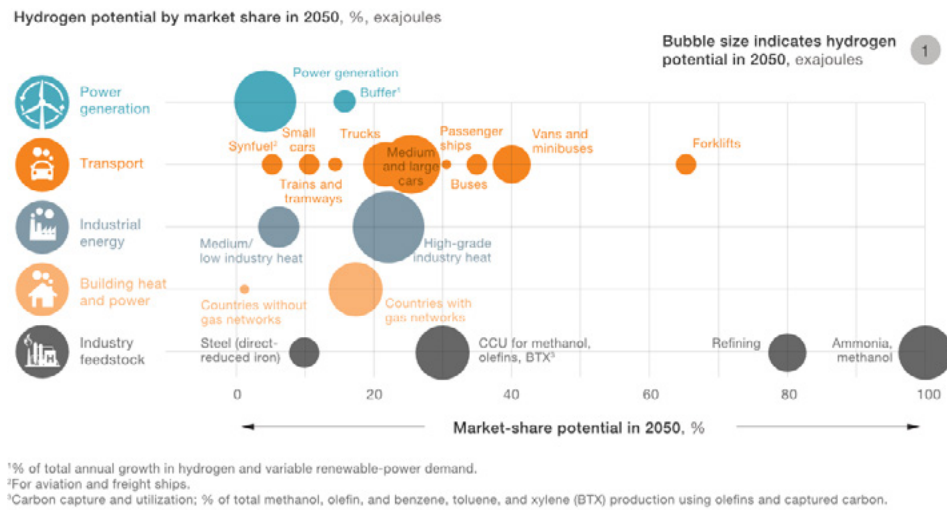
18 Recharging times of light-vehicles are also up to 10 hours on standard household 220-240 Volt outlets, however long recharging times in the light-duty vehicle segment are considered less critical due to customer driving patterns.

19 Another way for direct electrification of heavy-duty vehicles could be the construction of trolley wires along major highways (similar to the operations of electric buses in cities), however this requires significant infrastructure investments.

20 Dodds et al. (2015) 'Hydrogen and fuel cell technologies for heating: A review'. *International Journal of Hydrogen Energy*. 40 (5). Pages 2065-2083. doi.org/10.1016/j.ijhydene.2014.11.059



hydrogen as a chemical feedstock is in ammonia production. Hydrogen could also be utilized in new steel manufacturing techniques (i.e., direct-reduced iron).



**Figure 3.** Hydrogen potential by market share in 2050.  
 Source: McKinsey (2017)

For industrial heating, hydrogen-fueled furnaces could provide medium-to-high-temperature heat (>400°C), which is otherwise hard to decarbonize. Hydrogen could thus complement direct electrification such as heat pumps and electric heaters, which are more suitable for low-temperature heat up to 400°C. Hydrogen combustion is likely to fit better to the existing industrial process design and hence could be a more efficient route for decarbonization than electrification.<sup>21</sup>

21 Hydrogen Council (2017) *Hydrogen—Scaling up. A sustainable pathway for the global energy transition.*

### 3.3 Market potential

The role hydrogen will play in each sector is still uncertain. McKinsey (Figure 3) provides an overview of the market share hydrogen could capture by 2050 across sectors. It is highly probable that hydrogen will spike particularly as an industrial feedstock; as a high-temperature combustion fuel; and as an energy carrier in heavy transport applications.

Estimates on annual demand for hydrogen by 2050 vary widely among reports. The Hydrogen Council study estimates global demand at approximately 78 EJ, which would equate to around 14% of the world's total energy demand. Studies by BNEF (2019) and DNV GL (2018) are more conservative, with estimates hovering between 5 and 39 EJ annually. Shell (2018) predicts that the hydrogen market will not grow considerably before 2050. In 2100 the hydrogen market is expected to reach 69 EJ equating to about half of the current global demand for natural gas. Table 1 provides a comparison of the various estimates.

**Table 1.** Estimated annual demand for hydrogen in 2050

	Study	Est. annual demand (in EJ)	Remarks
<b>Hydrogen demand in 2050</b>	Hydrogen Council (2017)	78	Driven mainly by transportation (22 EJ) and industrial energy (16 EJ)
	BNEF (2019)	5-39	Estimates reflect conservative and optimistic scenarios
	DNV GL (2018)	15-39	Industrial feedstock accounts for more than 40% of demand in all scenarios
	Shell (2018)	9	Market only grows considerably after 2050 reaching 69 ET in 2100 (mainly driven by road transport, as well as heavy and light industry)
<i>For comparison: Current annual demand for</i>			
<b>Hydrogen</b>	IEA (2019a)	9-11	Global annual demand 2018 <sup>22</sup>
<b>Oil</b>	BP (2019)	195	Global primary consumption 2018
<b>Natural gas</b>	BP (2019)	139	Global primary consumption 2018

**Source:** Hydrogen Council (2017), BNEF (2019), DNV GL (2018), Shell (2018), IEA (2019a), BP (2019)

<sup>22</sup> Hydrogen used in pure form; a further 5-6 EJ is used in industry without prior separation from other gases.

## 4. Production cost of renewable hydrogen

Renewable hydrogen is not yet cost-competitive with fossil-fuel based production. Depending on local prices of natural gas and coal, current production costs range from 1 to 2.5 USD/kgH<sub>2</sub>. In comparison, renewable hydrogen costs range from 2.5 to 6.8 USD/kgH<sub>2</sub>.<sup>23</sup> However, significant renewable hydrogen production cost reductions and implementation of carbon pricing policies<sup>24</sup> could drive its competitiveness.

The production cost of renewable hydrogen is driven by three primary factors: electricity prices, capital expenditure for electrolysis units, and operating costs. If hydrogen is not immediately used at its production location, costs for storage, transportation, and distribution would also need to be taken into consideration.

Technology innovation and economies of mass production have resulted in a sharp decline in the costs for solar and wind generated electricity over the past decade. For example, solar module costs fell by about 90 percent between 2009 and end of 2018,<sup>25</sup> while cumulative installations soared from 22.8GW to 480.6GW. Similar dynamics are expected to drive down also electrolysis costs, due to the decline in CAPEX, improved lifetime and greater efficiency.

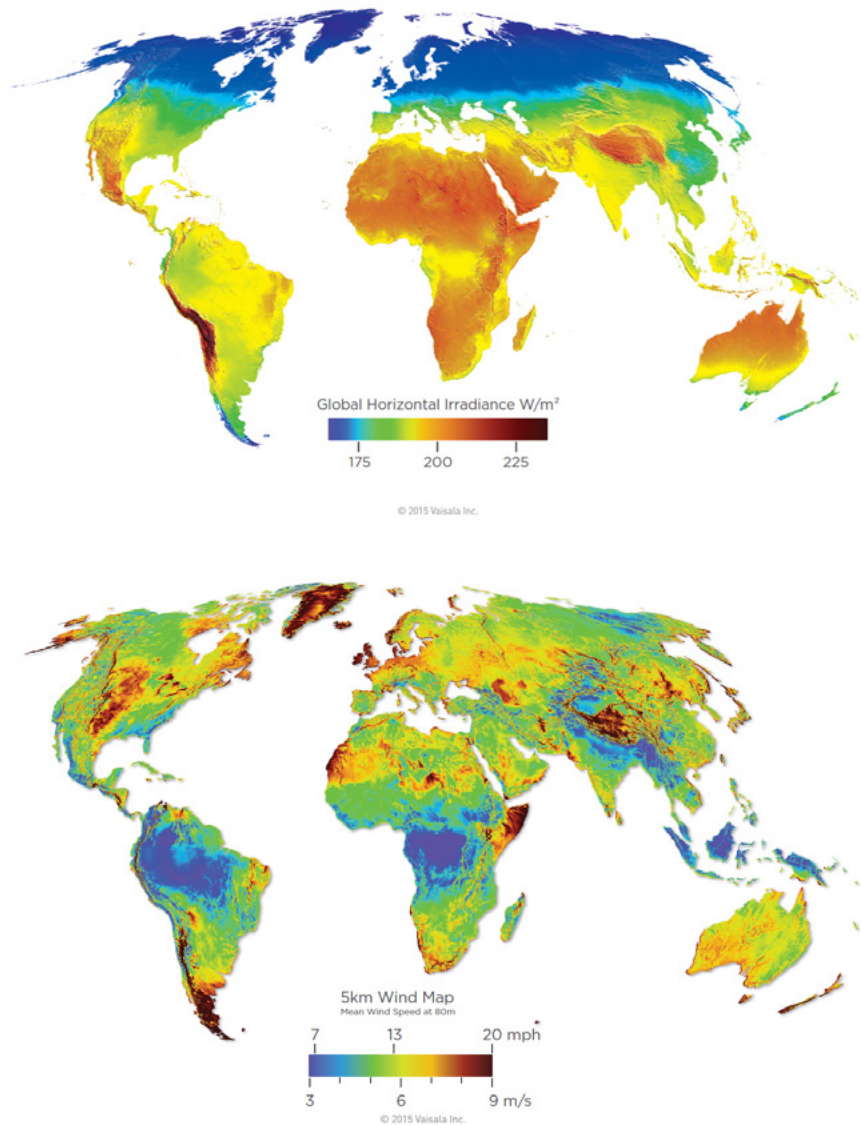
Even if renewable hydrogen production costs are expected to sharply decline, these costs will still significantly differ among countries. The main cost component of electrolysis is the electricity cost, which is a function of RES load factors, or in other words operating hours. As full load operating hours vary greatly geographically based on solar radiation and wind speeds, so does the resulting cost of electricity. Figures 4 and 5 depict the differences in solar irradiance and wind speed around the world. For example, while most solar plants in Germany operate between 800 and 1,050

23 See IEA (2019a) and BNEF (2019) for detailed cost assumptions.

24 A carbon price of 100 USD/ton approximately translates into a price increase of ~1 USD/kgH<sub>2</sub> for hydrogen produced with steam methane reforming using natural gas and ~2 USD/kgH<sub>2</sub> for hydrogen produced with coal gasification—in both cases without carbon capture (own calculation).

25 IRENA (2019c) *Renewable power generation cost in 2018*. International Renewable Energy Agency.

full load hours, Morocco's solar plants can generate between 1,400 and 1,750 full load hours with consequences for electricity costs.<sup>26</sup> Due to these geographical differences, it may be more cost-efficient for some countries to import renewable hydrogen rather than to produce it domestically, inducing transportation cost considerations, while also raising geopolitical issues.<sup>27</sup>



**Figures 4 & 5:** World solar potential (left) and world wind potential (right).  
Source: Vaisala (2019)

26 Pietzcker et al. (2014) 'Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power'. *Applied Energy*. Vol. 135. p. 704-720.

27 Besides the renewable potential, some countries might also lack space to produce sufficient amounts of renewable hydrogen and are thus inclined to import renewable hydrogen

Hydrogen can be transported by either pipelines or ships. Pipelines allow to transport hydrogen in its gaseous form, but capital costs are high since they are a linear function of the pipeline length, hence making shipping the more cost-competitive option for distances beyond 1,500 kilometers.<sup>28</sup>

When using ships hydrogen must be either liquified or converted into hydrogen-based fuels and/or feedstocks. With existing technology, liquefaction costs hover at around \$1 USD/kg. Shipping liquified hydrogen is additionally expensive due to the high capital cost of the ships themselves and associated hydrogen boil-off during transport.<sup>29</sup> As of today, there are no liquified hydrogen ships in operation.

Due to its higher hydrogen content, ease of transportation, existing infrastructure and established international trade routes ammonia could present a valid and economic alternative to liquified hydrogen. Ammonia production costs would need to be taken into consideration together with any reconversion costs to hydrogen, if ammonia could not directly be used as fuel in ammonia fuel cells and/or in ammonia-fired power plants. These complexities underline the stark need of a detailed comparison of shipping and production costs on a case-by-case basis.

The IEA analysis below shows that for Japan and the European Union (EU), importing renewable hydrogen could be a cost-competitive replacement for domestic production as early as 2030, assuming production cost reductions<sup>30</sup> and deployment of enabling infrastructure (see Figure 6). In practice, the cost advantage of importing hydrogen might shrink due to price markups by the exporter. Production costs in exporting countries could fall even further due to lower wages and cheaper building materials. Furthermore, manufacturers could potentially lessen transportation costs by upgrading existing gas infrastructure rather than designing new hydrogen-specific infrastructure.<sup>31</sup>

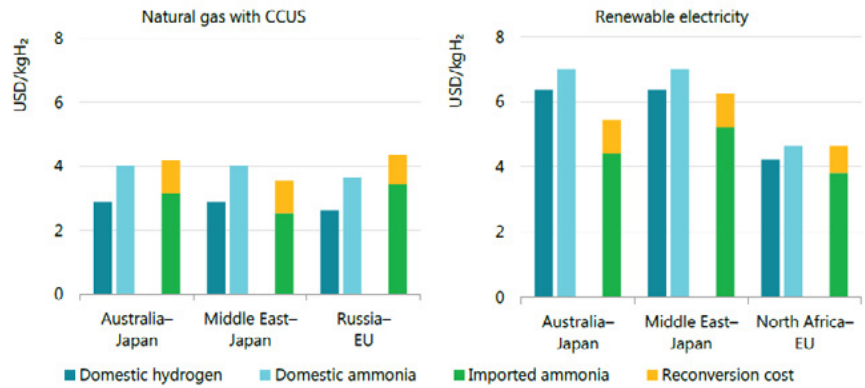
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28 IEA (2019a) *The future of Hydrogen*.

29 Capex amounts to around 400 million USD per ship with a capacity of 11,000 tons of H<sub>2</sub>. See IEA (2019a).

30 Capex for electrolysis unit is assumed to decrease from today's 900 USD/KW<sub>e</sub> to 700 USD/KW<sub>e</sub> by 2030, while electrolysis efficiency increases from 64% to 69% in the same time period.

31 However, due to the lower energy content of hydrogen significant less energy can be transported in the existing infrastructure.



Note: "Domestic" cost is the full cost of hydrogen production and distribution in the importing country (i.e. Japan or the European Union). All costs assume 50 km distribution to a large industrial facility. More information on the assumptions is available at [www.iea.org/hydrogen2030](http://www.iea.org/hydrogen2030).  
 Source: IEA 2019. All rights reserved.

**Figure 6.** Comparison of delivered hydrogen costs for domestically produced and imported hydrogen for selected trade routes in 2030. Source: IEA (2019a)

## 5. Drawing the geopolitical map for renewable hydrogen

The role a country could play in renewable hydrogen markets will depend on its ability to produce and distribute renewable hydrogen cost competitively and at scale. As discussed, the production of renewable hydrogen through electrolysis requires both renewable energy and freshwater resources.

Therefore, to analyze a country's renewable hydrogen potential we consider three parameters: (1) renewable energy resources (RES) endowment; (2) renewable freshwater resource endowment; and (3) infrastructure potential, defined as a nation's capacity to build and operate renewable hydrogen production, transportation, and distribution infrastructure.

### 5.1 Renewable energy resources (RES) endowment

RES endowment is defined as the combined generation potential of wind and solar power (Figure 7).<sup>32</sup> A country's RES endowment is also an indication for the attainable renewable electricity generation cost, as higher resource endowment often translates into higher capacity factors, which in turn influences generation costs.

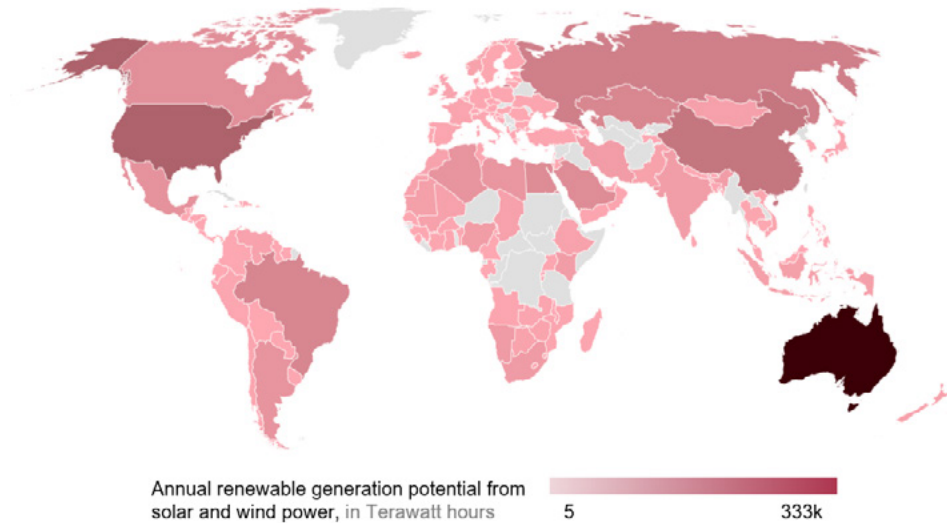
We consider a country's RES *poorly available* if its potential for renewable generation is less than 1.5 times its domestic primary energy consumption across all sectors.<sup>33</sup> Space constraints may also emerge for countries with high population density (above 150 inhabitants per square kilometer). In these denser nations, finding land for RES infrastructure forces competition with other industries such as agriculture and transportation.

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32 The combined renewable generation potential is calculated based on the wind power potential of a country derived from NREL (2014) and solar power potential derived from Pietzcker et al. (2014).

33 Primary energy consumption was derived for the year 2013 from EIA (2019).

We consider a country's RES *abundant* if renewable generation potential exceeds domestic primary energy consumption by at least 7.5 Petawatt hours, or about 5% of current global primary energy consumption. This excess renewable energy could be exported once internal energy demand is fulfilled.



**Figure 7.** Annual renewable generation potential from solar and wind power (in Terawatt hours)

## 5.2 Renewable freshwater resources endowment

A country's freshwater resources are considered *scarce* if its total annual internal renewable water resources are under 800 m<sup>3</sup> per inhabitant.<sup>34</sup> Countries in this category use their water resources predominantly for drinking, household consumption, industrial use, and/or irrigation. Our data for renewable freshwater resources is derived from AQUASTAT.<sup>35</sup>

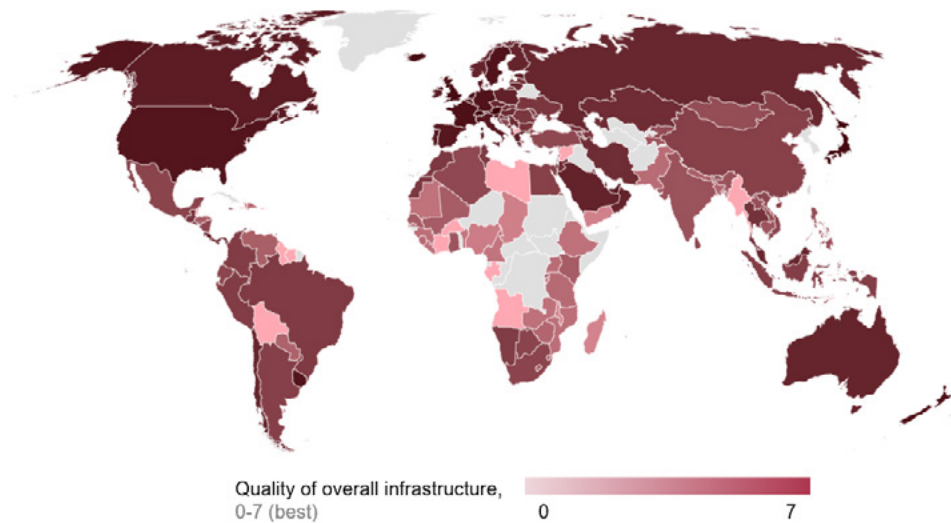
<sup>34</sup> For comparison: The United States withdraws 1,369 m<sup>3</sup> per inhabitant, India 602 m<sup>3</sup> per inhabitant and Germany 309 m<sup>3</sup> per inhabitant. Countries with limited freshwater resources tend to withdraw proportionately more in order to irrigate their fields.

<sup>35</sup> AQUASTAT is a global water information system developed by the Food and Agriculture Organization of the United Nations.



## 5.3 Infrastructure potential

As of today, no country has considerable renewable hydrogen production facilities or widespread transportation infrastructure. Therefore, we must rely on the status of a country's existing infrastructure to estimate its ability to build and operate hydrogen production, transportation and distribution. Thus, our proxy measurement is the overall infrastructure score in the World Economic Forum's 2019 Global Competitiveness Index (see Figure 8). Countries with scores below 4 (on a 1-7 scale) are considered *infrastructure constrained*.



**Figure 8.** Quality of overall infrastructure (scale 0-7, where 7 is the highest score)

The following table aggregates countries into five groups based on the discussed three analysis parameters: renewable energy resource endowment, renewable freshwater resource endowment, and infrastructure potential. For a detailed country classification see Figure 9.

#	Group	Resource endowment		Infrastructure potential	Example countries
		Renewable energy resources	Renewable freshwater resources		
1	Export champions with vast renewable energy and water resources, as well as high infrastructure potential	++	+	+	Australia, United States, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	++	--	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	-	+	+	Parts of the EU, Japan, Korea
4	Resource-rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Resource-rich countries with low infrastructure potential	+	+/-	-	Most parts of South America

**Legend:** Abundant/very high (++); Available/high (+); Poorly available/constrained (-); Scarce/highly constrained (--)

**Group 1:** Export champions with vast renewable energy and water resources, as well as high infrastructure potential

Nations labeled “export champions” are well-positioned to emerge as suppliers in future renewable hydrogen markets: they are rich in water and renewable energy resources and possess clear capacity to deploy the requisite infrastructure. Some countries in this group, such as Australia, have already recognized the global potential of renewable hydrogen and taken steps to invest in domestic production. Group 1 also contains countries that are strong in conventional energy exports, increasing the likelihood of substantial success in exporting renewable hydrogen.

Cross-country renewable hydrogen trade would create opportunities to strengthen diplomatic ties, specifically between North Africa and the EU. For example, Morocco is especially well-situated to act as a key supplier of renewable hydrogen to European nations. In a 2019 study for Morocco’s Energy Ministry, Fraunhofer ISI highlighted this potential:

*“Morocco’s strategic geographical proximity to Europe, along with its exceptional potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with very high added value.”<sup>36</sup>*

In the long term, Morocco aims to reach 100% domestic renewable energy production. Its renewable generation capacity has almost doubled in the last five years, progressing towards the national goal of generating 52% of its electricity consumption with renewable sources by 2030.

#### **Group 1 Case Study: Australia**

- The Australian Energy Council is working on a national strategy for its hydrogen industry and seeks to position Australia as a major global player by 2030.
- A study conducted for the Australian Renewable Energy Agency (ARENA) estimates that by 2040, Australia’s hydrogen exports could swell to over three million tons per year, a figure worth up to 9.1 billion USD per annum. In addition, the study states that over 7 million jobs could be associated with the hydrogen sector in Australia by the same year. Japan, South Korea and Singapore have been identified as the main trading partners.<sup>37</sup>
- To overcome development barriers, ARENA provides financial support/funding for R&D in renewable hydrogen production, storage and use. At the end of 2018, the Agency announced plans to provide about 15 million USD in funding for 16 research projects.<sup>38</sup>
- According to the IEA Hydrogen Project database, three electrolysis pilot plants started operations in 2019; three additional plants are expected to launch in 2020 and 2021.

36 Eichhammer et al. (2019) *Study on the Opportunities of “Power-to-X” in Morocco. 10 Hypothesis for discussion*. Fraunhofer ISI. [https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/GiZ\\_PtX-Morocco/GiZ\\_PtX\\_Marokko\\_Report\\_PtX\\_Morocco\\_final.pdf](https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/GiZ_PtX-Morocco/GiZ_PtX_Marokko_Report_PtX_Morocco_final.pdf)

37 Acil Allen Consulting (2018) *Opportunities for Australia from Hydrogen Exports*. ACIL Allen Consulting for ARENA. <https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf>

38 Australian Renewable Energy Agency (2019) *Hydrogen* [Online]. Available at: <https://arena.gov.au/renewable-energy/hydrogen/> (accessed 30.10.2019)

**Group 2:** Renewable-rich but water-constrained nations with high infrastructure potential

Group 2 countries have abundant renewable energy resources but limited freshwater resources, challenging their likelihood of becoming hydrogen export champions. These countries could use seawater as an alternative; however, this would require desalination before the electrolysis process, increasing costs. Scientific breakthroughs allowing direct seawater electrolysis could significantly improve the positions of Group 2 countries as potential renewable hydrogen suppliers.<sup>39</sup>

For instance, if Saudi Arabia, one country belonging to this Group, wished to compete in renewable hydrogen markets, it would need to build new desalination capacity and deploy considerably more RES. Producing enough hydrogen to equal around 15% of Saudi Arabia's annual oil production (or around 10% of a future global hydrogen market of 40 EJ), the country would need to produce around 26 million tons of renewable hydrogen yearly, a feat requiring around 230 million m<sup>3</sup> of freshwater. To produce the necessary freshwater, Saudi Arabia would have to add at least five new large-scale desalination plants to its existing fleet of 31, currently contributing a total of about 1.8 billion m<sup>3</sup> of freshwater per year.

Because water is scarce in Saudi Arabia, renewable hydrogen production would directly compete with other water-intensive industries, such as agriculture. Furthermore, even without major investment in renewable hydrogen production, the Saudi demand for freshwater is projected to rise steeply.<sup>40</sup>

To become a large-scale exporter of renewable hydrogen, Saudi Arabia would also need to dramatically increase its solar power capacity from currently below 1GW to approximately 213GW.<sup>41</sup> The country's current plan

39 Kuang et al. (2019) 'Solar-driven, highly sustained splitting of seawater into hydrogen and oxygen fuels'. *PNAS*. 116 (14). p 6624-6629.

40 Demand is expected to double until 2035 according to De Nicola et al. (2015). However, changes in the pricing structure (e.g., reduction of subsidies) and increased efficiency could slow down demand growth.

41 Assuming no conversion losses. With conversion losses for CSP (34% capacity factor) and electrolysis unit (74%) solar power capacity of 457 GW would be required.

is to install an additional 40GW of photovoltaic power and 2.7GW concentrated solar power by 2030.<sup>42</sup>

Looking at China, while as a whole the country is not water constrained, freshwater availability varies greatly among regions.<sup>43</sup> Furthermore, increasing industrialization poses growing threats to the nation's access to adequate freshwater resources. For this reason, China could be forced to import renewable hydrogen, rather than leading as a global export champion. Our analysis shows that, it will likely be more affordable for some Chinese regions to forgo extensive infrastructure development and import hydrogen from neighboring countries instead. These issues make us categorize China as partly *water-constrained*.

### **Group 3:** Renewable-constrained nations with high infrastructure potential

Countries in Group 3 will need to import renewable hydrogen due to their limited renewables potential and/or land availability. Most countries in this group—including Japan and parts of the EU—are already dependent on energy imports today. Hence, energy dependencies might perpetuate also in the future.

A global transition to low-carbon technologies may not change the geopolitical position of these countries, given that reliance on foreign fossil fuels would simply be replaced with reliance on foreign renewable energy supplies. Thus, for these nations, the energy sector may not yield the geopolitical gains suggested by some scholars.

Because several Group 3 nations are leading in global decarbonization efforts, new domestic regulations might give them a head-start on growing their renewable hydrogen systems and sectors. In turn, this market opportunity may spur significant renewable hydrogen investments in Group 1 countries (see the Japan-Australia trade arrangements in the Group 3 Case Study).

42 Helio SCSP (2019) 'Saudi Arabia targets 2.7 GW Concentrated Solar Power in 2030'. 1 November. <http://helioscsp.com/saudi-arabia-targets-2-7gw-concentrated-solar-power-in-2030/> (accessed 30.10.2019)

43 According to the Food and Agriculture Organization of the United Nations (FAO) the renewable water resources per capita vary from less than 500 m<sup>3</sup>/year in the Huai and Hai-Luan river basins in Northern China, to over 25,000 m<sup>3</sup>/year in river basins in South-West China. (FAO (2011) Country profile China. Water resources. [http://www.fao.org/nr/water/aquastat/countries\\_regions/CHN/index.stm](http://www.fao.org/nr/water/aquastat/countries_regions/CHN/index.stm))

### Group 3 Case Study: Japan

- In 2017, aiming to mitigate climate change and increase energy security, Japan announced its goal to develop into a “hydrogen-based society”.
- According to the government's plans, renewable hydrogen will make a significant contribution to reducing Japan's carbon emissions from power generation, transportation, heating, and industrial applications. Furthermore, the introduction of hydrogen is seen as a means of diversifying supply sources, which fundamentally increases energy security for the country.
- Japan intends to build a global supply chain that can produce and deliver large amounts of hydrogen produced inexpensively in foreign countries. Japan aims to lead hydrogen projects in producing countries, and it is developing long term supply agreements like existing LNG contracts.
- Japan is currently carrying out three pilot projects on hydrogen: one in the Fukushima Prefecture and two international ones in Brunei (based on natural gas) and one in Australia (based on coal with CCS).
- The Fukushima Prefecture plant, designed to produce up to 900 tons of hydrogen per year, will be one of the world's largest renewable hydrogen production plants and it will be powered by solar generated electricity.<sup>44</sup>
- By 2030, the Japanese Basic Hydrogen Strategy aims to increase the country's commercial hydrogen supply chain capacity to 300,000 tons per year and lower production costs to \$3 USD/kg. By the same year, the number of fuel-cell electric vehicles in Japan is planned to reach 800,000 from today's approximate 2,500.<sup>45</sup>
- The 2020 Summer Olympics will take place in Tokyo from July 24-August 9, granting Japan massive international exposure. The Japanese government plans to showcase the advantages of its hydrogen technologies throughout the games.

44 Japan Times (2018) 'Construction begins on large hydrogen plant in Fukushima'. *Japan Times*. 10 August. Available at: <https://www.japantimes.co.jp/news/2018/08/10/national/construction-begins-large-hydrogen-plant-fukushima/#.Xbn2rmZCeUk> (accessed 30.10.2019)

45 Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2017) *Basic Hydrogen Strategy*. [https://www.meti.go.jp/english/press/2017/pdf/1226\\_003b.pdf](https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf)

#### **Group 4:** Resource-rich nations with high infrastructure potential

Countries in Group 4 have the renewable and freshwater resources potential to satisfy their renewable hydrogen demand through domestic production. While these countries are potentially self-sufficient, they may still complement domestic production with imports due to cost considerations. Hence, nations in Group 4 are typically faced with a make-or-buy decision.

EU member states in Group 4, such as Spain and France, have the potential to develop their renewable hydrogen industries beyond domestic production needs and thus to export surpluses to neighboring countries. While these nations lack the renewable resources potential to become major global export champions, they could still thrive as regional exporters. Taking this scenario into consideration, as a whole the EU could have the potential to meet most of its hydrogen demand internally.

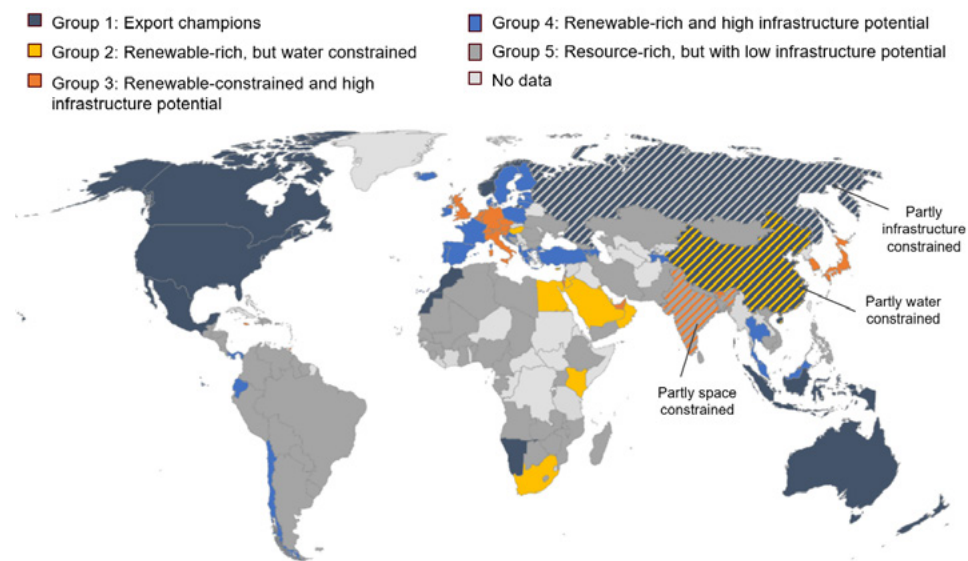
#### **Group 5:** Resource-rich countries with low infrastructure potential

Countries in Group 5 have vast access to renewable resources but are likely unable to build the required infrastructure for the production, transmission, and distribution of renewable energy. The larger the geographical extension of a country, the more complex and costly it is to deploy a cohesive national infrastructure. Therefore, a likely path forward for these countries is hydrogen production at smaller off-grid sites. While these off-grid solutions cannot benefit from large-scale economies, they might still be the most effective solution given the infrastructure constraints.

India exemplifies this: due to its infrastructure challenges throughout the vast subcontinent the country spans, India will likely employ a mix of off-grid and large-scale grid solutions to produce renewable hydrogen. To support the extremely dense populations in certain regions, India might also need to import large quantities of hydrogen. Therefore, our analysis considers India as partly resource-constrained with low infrastructure potential.

Another example in this Group, Russia, is considered partly infrastructure-constrained due to its Global Competitiveness Index score falling below the discussed threshold. However, one could argue that Russia's extensive energy infrastructure demonstrates its potential to build also the required hydrogen infrastructure. However, Russia's existing infrastructure was largely made possible by its exceptional low natural gas and oil production costs. It is unlikely that Russia could achieve such favorable conditions in renewable hydrogen markets: while the country's vast extension could support large-scale production of renewable energy, comparably low solar radiation and wind speeds limit Russia's chances of becoming cost-competitive.

Figure 9 depicts the country classification in Groups 1 to 5.



**Figure 9.** The global renewable hydrogen map.



## 6. Geopolitical implications of renewable hydrogen markets

In a low carbon future, geopolitical dynamics will depend not only on energy systems and markets dynamics, but also on which energy sources will dominate the energy mix. A separate analysis is therefore necessary for the geopolitical implications of renewable hydrogen, given its unique physical characteristics, value chain structure and applications.

Resource-specific geopolitical tensions are well-documented in conventional energy markets, frequently centering around oil (e.g. the OPEC oil embargo in 1973) and/or natural gas (e.g. the Russia-Ukraine gas dispute in 2006).

On the other hand, few examples have centered around coal as coal markets are either domestic or regional due its high transportation costs. Furthermore, high-energy-consuming countries like the United States usually produce enough coal to meet needs domestically, which limits the growth of international markets.<sup>46</sup> Coal is also mainly used for heat and/or electricity generation, and thus it can be easily substituted with other energy sources like natural gas. On top of these considerations, market choices of coal exporting countries are rarely driven by geopolitical concerns. One rare example was China's decision to establish de-facto ban on Australian coal imports in 2019, possibly to bolster domestic trade.<sup>47</sup>

In the same way conventional energy sources need to be evaluated individually, renewable hydrogen must be assessed separately from renewable electricity. The geopolitical implications of rising renewable electricity adoption will not translate accurately to the geopolitics of renewable hydrogen. From some angles, it is our opinion that the geopolitics of renewable hydrogen would compare more closely to the international dynamics of conventional energy carriers, like natural gas, than to renewable electricity.

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46 BP (2019) *BP Statistical review of World Energy*. 68th edition.

47 In February 2019 China set quotas for coal imports from Australia after several political disputes including disregarding Huawei as supplier for 5G broadband technology and denying visa to an important Chinese business traveler. See Reuters (2019).

## 6.1 Geopolitical realities of renewable hydrogen

As discussed, today's geopolitical tensions often link to energy: resource abundance creates geopolitical influence, while lack of resources reveals vulnerability. Consequently, unequal access to resources often serves as a catalyst for international conflict. Natural oil reserves are highly concentrated in specific parts of the world: five countries account for over 60% of total oil reserves.<sup>48</sup> Renewable resources, however, are found around the globe, presenting an opportunity to disrupt the hegemony of these resource-rich states and “democratize” the energy landscape.<sup>49</sup>

Virtually every country has some access to renewable resources (e.g., solar and/or wind power), and could thus increase its energy security by reducing energy imports in favor of domestic production. In fact, current investment strategies in renewables indicate that countries tend to prioritize domestic energy security and hence local renewable deployment even if international cooperation and efficient allocation of renewable resources could lower overall energy costs.<sup>50</sup> Even for countries within close-knit political alliances like the EU, renewable investments usually serve national agendas rather than optimizing collective outcomes.

For the renewable hydrogen industry, future levels of regional concentration will be determined by global market structures, technological advancements, and infrastructure development. As illustrated in section 5 of this paper, countries will assume specific roles based on their renewable and freshwater resource endowment and infrastructure potential.

Several countries identified as candidates to become renewable hydrogen “export champions,” such as the United States and Australia, are pivotal players in today's energy system. On the other hand, some of today's conventional energy exporters, like the oil-heavy yet water-constrained Saudi

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48 BP (2019) *BP Statistical review of World Energy*. 68th edition.

49 Casertano, S. (2012) *Risiken neuer Energie—Konflikte durch erneuerbare Energien und Klimaschutz* (Risks of New Energy—Risks Posed by Renewable Energy and Climate Protection). Brandenburg Institute for Society and Security (BIGS), No. 9.

50 Connecting electricity grids across national borders could help to smooth variations in renewable generation, as well as balance demand peaks due to differences in electricity use.

Arabia, might be prevented from replicating their influence due to limited resource endowment. In contrast from today's fragile authoritarian states dominating the oil trade, the countries we have identified as potential hydrogen export champions are largely secure market economies. Thus, the reshuffling of power could significantly boost stability throughout global energy markets.

It is almost certain that the Middle East would play a less prominent role in renewable hydrogen markets than it occupies in today's oil markets. As a result, international political interest in the region could deteriorate, shifting to regions like North Africa with rich renewable resources. One could argue that less global meddling in the Middle East would lessen conflict in the area. But considering that fossil fuels exports are a vital source of government revenue for Middle Eastern oil states, shrinking economic relevance could easily destabilize the region further.

For Group 3 countries that would need to import renewable hydrogen, geopolitical opportunities might see little change. Parts of the EU, Japan, and South Korea are RES-constrained, perpetuating dependency on foreign energy. On the contrary, some Group 4 European nations currently dependent on imports could meet renewable hydrogen demands internally and eventually develop into regional energy exporters. Such countries might grow increasingly influential in regional energy geopolitics. For example, due to their resource endowment and importance as transit hubs for imports from North Africa, Spain, and other European Group 4 member states could assume a greater role within EU's energy hierarchy.

## 6.2 New alliances

One of the main reasons why renewable electricity is expected to reduce geopolitical tensions is the reciprocity of trade. With increasing interconnection of transmission lines and the subsequent buildup of regional electric *super-grids*, countries are becoming increasingly interdependent<sup>51</sup> thus reducing

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51 Scholten, D., and R. Bosman (2016) 'The Geopolitics of Renewables; Exploring the Political Implications of Renewable Energy Systems'. *Technological Forecasting and Social Change*. Vol. 103. 273–283.

the risk of geopolitical tensions. Electricity interconnection is especially beneficial if generation profiles are complementary. For example, one country may have a suitable topology for wind generation, while another may have a vast landmass and high solar penetration.<sup>52</sup> Coupling such markets would be economically appealing for both sides, but such extensive cooperation would result in codependence. This trade reciprocity may ultimately reduce the risk of geopolitical power plays by any one participant.

These equitable dynamics could prove different for renewable hydrogen: if hydrogen is produced where resources are most abundant and costs the cheapest, the supply flow could become one-sided, designating countries as either importers or exporters. Under this circumstance, the geopolitics of energy may continue to revolve around access to resources, security of supply, supplier rents and transportation disputes.

However, new alliances and trade relationships could emerge between export champions in Group 1 and import states in Group 3. For instance, Australia might deepen its trade relationships with countries in Southeast Asia, particularly Japan and South Korea. European hydrogen demand might come to rely on exports from North Africa or North America. While increased cooperation with North Africa would fit into the European Neighborhood Policy<sup>53</sup> to foster stabilization, security and prosperity in the region, it would also increase EU relations with more fragile trade partners. Alternately, increasing energy trade with North America would strengthen the transatlantic partnership, but those diplomatic benefits would be accompanied by higher supply costs.

Especially in the case of Europe, these new trade relationships would result in a profound geopolitical shift. For decades, Russia has been by far EU's main supplier of natural gas and oil (accounting for 40.5% and 27.3% of extra-EU imports in 2018<sup>54</sup>). These trade dynamics exert considerable influence on EU's relations with Russia, and despite EU's efforts to reduce its

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52 Ochoa, C. and A.v. Ackere (2015) 'Winners and losers of market coupling'. *Energy*. Vol. 80. p. 522-534.

53 European Union External Action (2016) *European Neighbourhood Policy (ENP)* [Online]. Available at: [https://eeas.europa.eu/diplomatic-network/european-neighbourhood-policy-enp/330/european-neighbourhood-policy-enp\\_en](https://eeas.europa.eu/diplomatic-network/european-neighbourhood-policy-enp/330/european-neighbourhood-policy-enp_en) (accessed 16.01.2020)

54 Eurostat (2019) EU imports of energy products—recent developments. Statistics Explained. <https://ec.europa.eu/eurostat/statistics-explained/pdfscache/46126.pdf>

energy dependency, Russian imports have increased in recent years. While Russia could leverage its vast geography for large-scale renewable energy production, comparably low solar radiation and wind speeds limit its ability to be cost-competitive. Therefore a transition to a low carbon economy is likely to reduce EU's energy dependency on Russia, while, at the same time new dependencies on renewable hydrogen exporters might emerge.

## 6.3 New game—old rules?

Despite their dominant market power, energy exporters usually prefer not to simply cut off supplies, as they depend on the associated revenues to fund their extensive government programs. Nevertheless, many countries have used and use energy as a geopolitical weapon to serve their agendas, and this could perpetuate also with renewable hydrogen.

Pascual (2015) provided a comprehensive overview of possible market interventions to influence energy markets and serve national interests.<sup>55</sup> Several of these interventions—such as constraining production capacity, flooding markets, and/or starving markets—could be similarly exercised if hydrogen production becomes highly concentrated.

Similarly, geopolitical defensive strategies aimed at protecting a nation's energy security could work for renewable hydrogen: such as fuel-switching, forced load shedding for industrial customers, and building strategic reserves. As with natural gas, a strategic reserve of hydrogen could keep a country from running dry even during longer supply interruptions.<sup>56</sup> Strategic hydrogen storage would however present safety and environmental concerns. Finally, supply diversification would be needed to reduce the risk of politically driven supply disruptions and increase a country's energy security.

Furthermore, renewable hydrogen infrastructure would be prone to the same geopolitical threats as those faced by oil and gas. For example, in

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55 Pascual, C. (2015) *The new geopolitics of energy*. Center on Global Energy Policy. Columbia University. New York.

56 For instance, Spain obliges natural gas and liquified petroleum gas operators to maintain minimum stocks equivalent to 20 days of consumption in underground storages.

the case of oil markets, the Strait of Hormuz is of paramount importance, with over 20% of global oil trades passing through it. The Strait of Hormuz could remain highly relevant also in a low carbon economy, if renewable hydrogen produced in the Middle East were to be exported.

Transporting renewable hydrogen from North Africa to Europe using pipelines faces the same geopolitical uncertainties as the current system transporting natural gas. However, new supply routes (e.g., between Australia and/or Southeast Asia) could also pose geopolitical risks. In this case the main shipping routes would likely run through the East China Sea, which regularly draws international attention due to territorial disputes between China and Japan, yet with less media scrutiny than the multi-stakeholder dispute in the South China Sea.<sup>57</sup>

## 6.4 Impact of conflicts

The recent drone attack on Saudi Arabia's oil infrastructure illustrates the global impact of oil supply interruptions. After the attack, oil prices soared worldwide, amounting to the sharpest increase in 30 years.<sup>58</sup> On the other hand, natural gas disruptions due to the intrinsic regional nature of natural gas markets tend to be more geographically contained. Russia's gas cut-off to Ukraine in 2006 which mainly affected European supply, with little effect on prices and supply beyond the continent, exemplifies this.

The potential impact of hydrogen supply disruptions depends on how global hydrogen markets will become. If renewable hydrogen were to be adopted at scale, we believe that future market dynamics will resemble today's regional natural gas markets—with corresponding potential for similar geopolitical conflicts.

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57 Chandran, N. (2017) 'A second territorial dispute in Asia could be more dangerous than the South China Sea'. *CNBC*. 20 December. <https://www.cnbc.com/2017/12/20/east-china-sea-could-be-riskier-than-south-china-sea.html> (accessed 30.10.2019)

58 Wearden, G. (2019) 'Oil prices spike after Saudi drone attack causes biggest disruption ever—as it happened'. *The Guardian*. 16 September. Available at: <https://www.theguardian.com/business/live/2019/sep/16/oil-price-saudi-arabia-iran-drone-markets-ftse-pound-brexite-business-live> (accessed 30.10.2019)

At the same time, regional markets negatively affect a country's energy security by reducing options to diversify supply and find alternatives in the case of disruptions. This is particularly true if hydrogen were to be shipped mainly via pipeline and alternative infrastructure was not available.

Finally, we must also consider the extent to which critical infrastructure and key economic sectors are reliant on hydrogen. As stated in the technological analysis in Section 3, many industrial applications are likely to be directly electrified; a breakdown in the transmission grid could thus have a more devastating impact than interruptions to hydrogen supplies. However, if hydrogen were also to be used in power generation, supply disruptions would immediately impact the grid and affect all customers. In the case of hydrogen supply, disruptions would have a more delayed impact as shorter interruptions could be buffered with supplies from reserves and/or fuel switching.

## 7. Policy and commercial options

We believe only a deeper understanding of these nascent dynamics will allow policy makers and investors to better navigate the challenges and opportunities of a low carbon economy without falling into the traps and inefficiencies of the past. Based on the considerations outlined in the previous sections, it becomes clear that policymakers, investors, and other stakeholders need to assess the economic, environmental, and geopolitical implications of renewable hydrogen, develop strategies to address them and define implementation plans. In the following section, we outline some of the key policy and commercial options for each group of countries:

Export champions with vast renewable energy and water resources, as well as high infrastructure potential (Group 1):

“Export champion” nations may define policies to trigger renewable hydrogen infrastructure investments, thus paving the way for a dominating position in future markets. A key obstacle would be sustaining RES deployment rates high enough to achieve the needed scale. For instance, supplying 5% or 2 EJ of future global hydrogen markets in 2050, would require countries to deploy more than 100GW of dedicated renewable capacity, even under favorable generating conditions.

Furthermore, targeted federal policies could help to lower market risk and address commercialization barriers. Since the renewable hydrogen industry is still nascent, countries may start by focusing funding on innovation and/or pilot projects. Such policies could contribute to achieve the required economies scale, and eventually to reach the tipping point at which renewable hydrogen technologies become cost competitive. We believe policy efforts to reduce market risks as well as direct government support are key to secure the necessary private investments needed for commercialization at scale.

Because of their potential dominant positioning in renewable energy markets, Group 1 countries are more likely than their peers to become



international advocates for a hydrogen-fueled future. In addition, clear international regulations and standards on renewable hydrogen production, transportation and “green certification” would open the gates for trade at scale. This could be achieved by establishing international agencies responsible for developing these standards and working with national regulatory bodies to facilitate implementation.<sup>59</sup> Internally, countries may also revisit their own regulatory frameworks to ensure that oversight is streamlined for new hydrogen regulations.

Renewable-rich but water-constrained nations with high infrastructure potential (Group 2):

Renewable-rich countries scarce in water resources must address two questions: how many water resources to allocate for renewable hydrogen production, and whether it makes economic sense to try to compete with Group 1 countries. Strategic investments in desalination capacity would be key to address water scarcity issues.

If other forms of water consumption need to be prioritized over renewable hydrogen production, these countries will need to assess how to best meet their domestic renewable hydrogen needs. Like countries in Group 3, Group 2 countries may initiate trade partnerships and devise strategies to secure diversified hydrogen supplies.

Renewable-constrained nations with high infrastructure potential (Group 3):

Import countries in Group 3 may set policies to stimulate local renewable hydrogen markets focusing on their climate policy goals (e.g., by defining blend-in quotas for gas grids). Transparent regulations and long-term investments in hydrogen infrastructure would send strong signals to investors in countries in Group 1, thus spurring their investments in renewable hydrogen production capacity. Long-term contracts and direct investment by Group 3 countries would further help to reduce market risk for producers.

<sup>59</sup> IRENA (2019a) *Hydrogen: A renewable energy perspective*.

Furthermore, countries within this group may cooperate with exporting champions to establish international standards for renewable hydrogen production, transportation, and use.

In order to mitigate dependencies, and increase national energy security, governments in importing countries need to define clear long-term hydrogen development and deployment strategies including options to diversify supply. Specific policies should then be implemented to catalyze investment in partner countries to build a diversified supply base. These analyses should also entail a strategic decision if hydrogen is to be transported via pipelines or by shipping. While pipelines present economic advantages for imports from countries in proximity, pipelines are highly inflexible and the option to shift to different suppliers very limited.

#### Resource-rich nations with high infrastructure potential (Group 4):

Countries in Group 4 face similar policy options as those in Group 1. The primary goal may be to establish a domestic renewable hydrogen industry able to supply internal demand. Beyond minimizing energy imports, policies that support RES deployment; establish enabling market conditions for renewable hydrogen; provide funding for research and commercialization; and remove regulatory hurdles are the key goals for Group 4.

Insufficient investment in the domestic renewable hydrogen industry could lead to a scenario in which Group 4 countries cannot produce renewable hydrogen at competitive prices due to lack of technology, infrastructure and/or talent; and therefore depend on imports to meet demand.

On the other hand, if the national hydrogen industry thrives, Group 4 countries could decide to invest in becoming a regional supplier. Regional trade could be an important pillar for the future EU energy security strategy: import-dependent EU countries could cooperate directly with potential suppliers within the EU rather than relying on export champions beyond the EU.

Resource-rich countries with low infrastructure potential (Group 5):

Countries in group 5 lack the capability to build and maintain large-scale hydrogen infrastructures: a serious roadblock for development. Policymakers therefore need to address this fundamental challenge. Two general options should be considered: 1) investing in cohesive nation-wide energy and water infrastructure and/or 2) developing distributed off-grid solutions.

Taking into consideration local energy needs, natural resource endowments, access to capital, and existing infrastructure a combination of both options will likely prove the most efficient and cost-effective solution for Group 5 countries.

Policies could focus on catalyzing foreign investments in infrastructure projects. Nations should reduce investment risk through well-designed laws and regulations, efficient federal administrations, effective law enforcement, and strong institutions. Furthermore, governments should focus on bringing foreign investors, project developers, and local communities together to develop off-grid hydrogen production capacity.

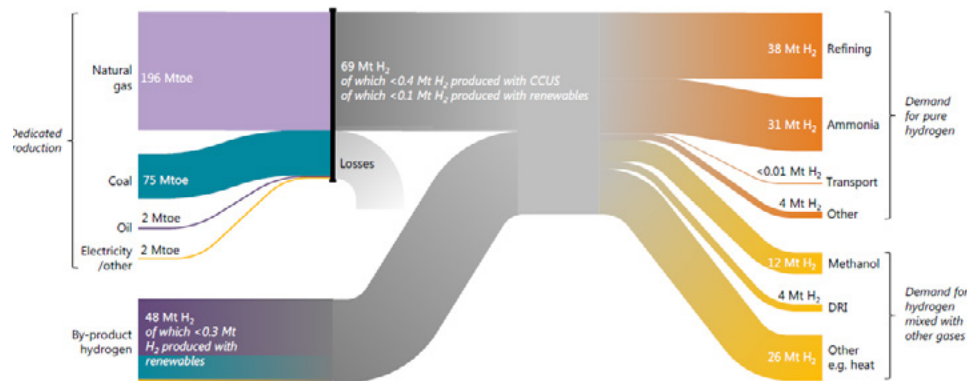
## 8. Options for further analysis

Beyond the direct scope of our analysis, we have identified several adjacent research topics in need of further academic analysis. Potential areas include, but are not limited to:

1. Applying our analytical framework to other production technologies and/or renewable energy sources. In particular, the analysis of hybrid global energy systems, which utilize a mix of renewable and conventional energy sources, could yield interesting insights (e.g., with respect to blending renewable hydrogen into the natural gas infrastructure).
2. Examining the transition to low-carbon energy systems and assess implications for various nations. This analysis could also identify important decision points and possible barriers to large-scale adoption of renewable hydrogen. Further research could address questions such as: How would the geopolitical landscape change during this transition? What factors would be key to which phases of the transition process (e.g., if renewable hydrogen is at 30% of its market potential compared to 85%)?
3. Carrying out a geographically focused review of the implications of renewable hydrogen adoption at scale; for example, by focusing on selected countries and/or regions. Such an analysis could focus on heterogeneous or geopolitically complex regions, for instance Europe, North Africa, or Southeast Asia.

# Appendix: Production of hydrogen

Hydrogen can be produced through either thermo-chemical conversion, biochemical conversion or electrolysis. Most of today's global hydrogen production is based on fossil fuels through steam reforming; less than 3% is currently produced by electrolysis due to the high costs involved. Figure 10 depicts today's hydrogen value chains.



**Figure 10.** Today's hydrogen value chains. Source: IEA (2019a)

**Steam Methane Reforming (SMR)** is the most frequently used process for hydrogen production, and accounts for approx. half of global production. In the steam reforming process, methane reacts with water vapor and forms a synthesis gas, consisting of hydrogen, carbon monoxide and small amounts of carbon dioxide, water vapor and residual methane. The chemical process takes place at high temperatures (between 700 and 1,100°C) and the conversion is assisted by a (nickel) catalyst. The efficiency of the process can be increased if steam reforming is coupled with partial oxidation.

**Partial oxidation** can be used to generate hydrogen from heavy fuel oil or coal with the aid of oxygen. In the process thermal partial oxidation takes place at high temperatures and under pressure, resulting in a hydrogen-rich syngas. The syngas is then converted to hydrogen by means of the so-called water gas shift reaction and gas treatment. An alternative process is **gasification** where the carbon carrier is first dried and thermally cracked

to carbon and hydrogen through an anaerobic reaction; this is then followed by a partial combustion by oxidation. The heated carbon and water vapor produce a syngas consisting of carbon monoxide and hydrogen. By the subsequent water gas shift reaction carbon monoxide is converted to form carbon dioxide and hydrogen.

Due the carbon footprint of these production methods, the resulting hydrogen is often referred to as “grey” or “black”. By contrast, “blue” hydrogen is produced if the carbon emissions are either **captured and stored (CCS)** and/or used. CSS technology is already available, and its viability has been demonstrated in large-scale hydrogen plants, such as the Repsol plant in Spain since 2002.<sup>60</sup> Even though more than 90% of carbon emissions could be captured with existing technologies, “blue hydrogen” is not carbon neutral. Thus, it remains unclear whether blue hydrogen would be socially acceptable and whether its usage would be authorized by regulators with further decarbonization.

Besides carbon capture, new methods have been explored to either reduce or completely avoid carbon emissions. **Thermal methane pyrolysis** is one alternative. In the thermal treatment of methane in the absence of oxygen, solid carbon and gaseous hydrogen are produced. As methane pyrolysis is a highly endothermic process, heat is required to crack the methane molecules. For reaching a carbon-neutral end product, the heat source needs to be “green”. Thus, a fraction of the produced hydrogen must be used to heat the reactor itself. This poses two challenges. First, it needs to be demonstrated whether methane pyrolysis could be performed at industrial scale at competitive costs. Process designs for industrial production could be like current iron ore blast furnaces. Second, the significant amounts of solid carbon by-products need to be disposed. This could be done by producing carbon monoxide as a feedstock for fuels and/or the chemical industry, or by using the solid carbon as a fertilizer. Solid carbon is not toxic to plants; it improves nutrient availability and does not decompose to carbon dioxide over time.<sup>61</sup>

60 Santos (2015) Understanding the Potential of CCS in Hydrogen Production. *Process Industry CCS Workshop*. IEA GHG. March 2015.

61 Ozin, G. (2018) 'Decarbonizing Natural Gas: Methane Fuel without Carbon Dioxide'. *Advanced Science News*. 20 March. Available at: <https://www.advancedsciencenews.com/decarbonizing-natural-gas-methane-fuel-without-carbon-dioxide/> (accessed: 21.11.2019)

In an explorative study, scientists at the University of Calgary developed a method to extract hydrogen from an oil sand reservoir while leaving the carbon in the ground. Oxygen is injected into the reservoir, which reacts with the oil to form hydrogen. Special **hydrogen filters** prevent other gases from reaching the surface; this prevents carbon emissions and allows to obtain hydrogen as a sole end product. If the technology reaches commercialization, several advantages would arise: oil and oil sand reserves could be used to produce hydrogen directly, and existing infrastructure could be partly re-used for extraction and transportation.<sup>62</sup>

Hydrogen is called “green” when produced by water electrolysis using renewable electricity. In the electrolysis process, electricity is used to split water into hydrogen and oxygen. The required electricity could be generated by any energy source. In order to be carbon free, it is necessary to use solely renewable generation, such as solar power, wind power, or nuclear. As the current electricity mix in most countries is not purely renewable, electrolysis with grid electricity is not carbon free.<sup>63</sup> The direct coupling of renewable generation assets and electrolysis facilities could circumvent this problem, but this can potentially limit electrolysis utilization times. In comparison to hydrogen production based on natural gas (mainly Steam Methane Reforming), existing water electrolysis plants are operating at smaller scales (<5 MW<sub>el</sub>). Besides electricity, freshwater is the other key resource. For the production of 1kg of hydrogen, nine times the amount of freshwater is necessary, i.e. nine liters.

Another alternative is **biomass gasification**. A carbon carrier (in this case biomass) reacts with oxygen to form a synthesis gas, or syngas. Biomass is first dried and broken down thermally in the absence of air to form carbon and hydrogen compounds, followed with partial combustion by oxidation. The heated carbon and water vapor produce a syngas consisting of carbon monoxide and hydrogen. By the subsequent water gas shift reaction, carbon monoxide is converted to form carbon dioxide and further water

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62 Goldschmidt Geochemistry Conference (2019). *Scientists extract H<sub>2</sub>gas directly from oil and bitumen, giving potential pollution-free energy source* [Press Release]. 20 August. Available at: [https://whiteiron.org/uploads/conferences/29/press\\_releases/file6Ggd5L.pdf](https://whiteiron.org/uploads/conferences/29/press_releases/file6Ggd5L.pdf) (accessed: 21.11.2019)

63 U.S. Department of Energy. *Hydrogen Production: Electrolysis* [Online]. Available at: <https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis> (accessed 21.11.2019)

vapor to hydrogen.<sup>64</sup> Even though biomass gasification releases carbon emissions, the full-cycle emission balance is considered neutral if as much CO<sub>2</sub> is absorbed during plant growth as emitted during combustion.<sup>65</sup>

**Table 2.** Hydrogen production processes

	<b>Production process</b>	<b>Energy source</b>	<b>Maturity / commercialization</b>	<b>Environmental sustainability</b>
<b>Grey/black hydrogen</b>	Steam Methane Reforming	Natural gas	Well-established, large-scale operations	High carbon intensity
	Partial oxidation	Mainly coal and heavy oil	Well-established, mid-scale operations	Very high carbon intensity
	Gasification	Mainly coal	Well-established, mid-scale operations	Very high carbon intensity
<b>Blue hydrogen</b>	SMR with CCS	Natural gas	Established, large demonstration plants	Low carbon intensity
	Thermal methane pyrolysis	Natural gas	Explorative stage	Potentially carbon neutral
	Hydrogen extraction with specialist filter	Oil sand, oil	Explorative stage	Potentially carbon-neutral
<b>Green hydrogen</b>	Electrolysis	Renewable electricity or nuclear	Well-established, and mainly small-scale operations	Carbon neutral
	Gasification	Biomass	Established	Carbon neutral

64 For further details on hydrogen production processes, see Shell (2017) *Hydrogen Study. Energy of the future?*

65 Bracmort, K. (2016) *Is Biopower Carbon Neutral?* Congressional Research Service. <https://fas.org/sgp/crs/misc/R41603.pdf>



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