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Will Hydrogen Be a New Natural Gas? Hydrogen Integration in Natural Gas Grids

Gerald Linke

Department of Energy, Deutscher Verein des Gas- und Wasserfaches e.V., Bonn, Germany; email: gerald.linke@dvgw.de

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Abstract

Hydrogen is similar to natural gas in terms of its physical and chemical properties but does not release carbon dioxide when burnt. This makes hydrogen an energy carrier of great importance in climate policy, especially as an enabler of increasing integration of volatile renewable energy, progressive electrification, and effective emission reductions in the hard-to-decarbonize sectors. Leaving aside the problems of transporting hydrogen as a liquid, technological challenges along the entire supply chain can be considered as solved in principle, as shown in the experimental findings of the Hydrogen Innovation Program of the German Technical and Scientific Association for Gas and Water. By scaling up production and end-use capacities and, most importantly, producing hydrogen in regions with abundant renewable energy, hydrogen and its applications can displace natural gas at affordable prices in the medium term. However, this substitution will take place at different rates in different regions and with different levels of added value, all of which must be understood for hydrogen uptake to be successful.

1. INTRODUCTION

Hydrogen is the hope for achieving ambitious climate protection goals in energy. Together with highly efficient cold combustion of fuel cell technology, hydrogen was a game changer for energy systems decades ago, without, however, the surge of change that is being seen these days. Undoubtedly, hydrogen as an energy carrier has properties that are important for a reliable energy system, such as its easy transport and storage capability. But does that justify giving it equal importance with natural gas, a reliable energy supply, albeit a fossil gas, that accounts for approximately 25% of primary energy worldwide (1)?

To answer this question reliably, we must identify technical challenges and market entry hurdles or regulatory restrictions, as well as assess innovative approaches to solutions and their degree of maturity and chances of realization. We must also classify a hydrogen-based energy supply relative to the process of increasing electrification and direct use of wind and solar energy to assess the relative growth, relevance, and size of the hydrogen market. Finally, pricing, which is strongly influenced by regulatory requirements and climate policy incentives, plays an essential role when it comes to the competitiveness of hydrogen versus natural gas, and thus its relative share in a gas-based energy supply.

This article deals with these aspects and perspectives for hydrogen, first by following the classic value chain and second by looking at cross-cutting issues. It describes the properties of the energy carrier itself, answers what quantities can be produced and how hydrogen can be transported and distributed on a large scale, and identifies applications that are predestined or offer growth potential. Typical cross-cutting issues include the systemic relevance of hydrogen in general, taking into account different degrees of climate policy ambition with target regions for hydrogen and market conditions that will lead to accelerated growth.

Hydrogen can become the new natural gas, but realization or turnaround times differ regionally and depend heavily on the extent to which a regional natural gas market can be considered saturated today and on the share of renewable energies in primary energy demand. The scientific findings and sources on which these statements are based are primarily those of the current Hydrogen Innovation Program (2), a professionally broad-based, multiyear program of the German Technical and Scientific Association for Gas and Water (DVGW), the state-legitimized regulator for natural gas and hydrogen via the Energy Industry Act of the Federal Republic of Germany, which also manages an association of research institutions. Results from the program therefore reflect the state of the art.

2. ASPECTS OF A TRANSITION FROM NATURAL GAS TO HYDROGEN

2.1. Properties of Hydrogen and Comparison with Natural Gas

Natural gas—essentially consisting of methane—is the cleanest fossil fuel: Compared to other higher hydrocarbons, the ratio of hydrogen atoms to carbon atoms in the CH_4 molecule is at a maximum and ensures minimal CO_2 emissions during combustion. Hydrogen, being the smallest atom on the planet, has no carbon atoms at all and burns or oxidizes to water. Both substances are gaseous under normal conditions but differ in density and calorific value. This means that hydrogen is the energy carrier with the highest calorific value in terms of mass; however, in terms of volume, it has only approximately one-third of the energy content of natural gas.

This fact is often used in discussions outside expert circles as an argument against replacing natural gas with hydrogen, stipulating wrongly that today's supply infrastructure could deliver only one-third of the energy to end customers under otherwise identical boundary conditions. This blanket assumption is wrong because the power output of energy in end appliances such as gas condensing boilers and the transport capacity of a pipeline in which the gas flows depend on the

Table 1 Comparison of characteristic values of natural gas, hydrogen, and mixtures according to Reference 3 and author calculations

Parameter	Symbol	Unit	Methane CH_4	NG (Russia) + 20% H_2	Hydrogen H_2	Biomethane
Calorific value	H_S	MJ/m^3	11.06	9.65	3.54	10.64
Relative density	d	-	0.555	0.473	0.070	0.587
Wobbe index	W_S	kWh/m^3	14.85	14.03	13.43	13.88
Combustion oxygen	$O_{2,\,min}$	m^3/m^3	9.57	8.21	2.39	9.19
Ignition temperature	T_{ign}	°C	645	618	530	530
Lower explosion limit	$C_{i,l}$	vol-%	5	4	4	4
Upper explosion limit	$C_{i,u}$	vol-%	14	27	73	15
Max. flame speed	u_{max}	m/sec	43	44	346	43
Ad. combustion temperature	T_{ad}	°C	1,922	1,951	2,086	1,930
Methane number	MN	-	100	73	0	100

Wobbe index (see Section 2.4). This, in turn, is the ratio of the calorific value and square root of the relative density of the gas and is approximately the same for methane and hydrogen (**Table 1**). But because the relevant equations for calculating pipeline capacity—the Darcy–Weißbach equation given in Section 2.4 (Equation 1)—and the well-known Bernoulli equation for the power of a boiler depend on only the Wobbe index and no other gas parameter, natural gas can be substituted by hydrogen in its range of quantities. Questions of the safety and integrity of the infrastructure—leak tightness and service life—are covered in Section 2.4.

2.2. Types of Hydrogen Production and Links to the Natural Gas Industry

Although hydrogen is the most common element in the universe, it rarely occurs naturally in its pure form or two hydrogen atoms, white hydrogen or H_2. Therefore, hydrogen is not harvested like coal, oil, or natural gas but can be produced through the treatment of hydrocarbons or—more sustainably—can be generated by splitting water in electrolyzers using renewable power as the primary energy source. For this reason, hydrogen should be regarded as an energy carrier and not a source.

The energy industry has developed a set of color labels for hydrogen, with the aim of elucidating production type. However, these labels suggest a greenhouse gas footprint that is misleading.

For example, hydrogen is labeled green if it has been produced using renewable energy, notably renewable electricity to power the electrolytic process (typically wind or solar energy), or if hydrogen is produced from biogas via steam reformation. If electricity produced from nuclear energy is used to power the electrolytic process, the produced hydrogen is labeled red or pink.

Hydrogen is labeled blue if natural gas is the feedstock and/or if it has been produced using nonrenewable energy sources, typically using grid power, for the hydrogen extraction process of steam reforming. The CO_2 by-product is not released into the atmosphere but injected underground and stored via carbon capture and storage. Alternatively, a new use for the CO_2 has to be found that keeps it in the energy mass cycle of the economy via carbon capture and utilization.

If the process omits the second essential step of CO_2 reuse or storage, but instead releases CO_2 into the atmosphere, then in principle nothing other than burned natural gas with an intermediate step of endogenous hydrogen production has occurred. Therefore, this production process is by no means clean, which is why hydrogen produced in this way is also labeled gray. Hydrogen produced electrolytically using coal-fired electricity also would be declared gray.

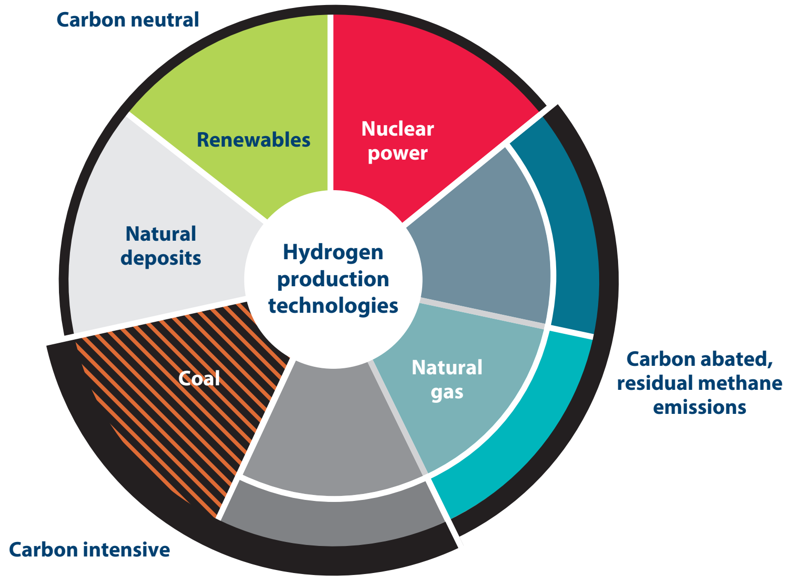

Figure 1

Color labels for hydrogen produced in different technological ways in accordance with Reference 4.

Another common hydrogen color is turquoise, which occurs when natural gas has been broken down into pure (black) carbon and hydrogen in a pyrolytic process without the formation of climate-harming CO_2. **Figure 1** provides an overview of these color designations.

More color labels can be made for other, more insignificant process variants; however, clearly that would be unscientific, because it is not the selected process itself that determines the value of the hydrogen but exclusively the carbon footprint attached to the product. All steps of the respective process play a decisive role; for example, green hydrogen produced with electricity from photovoltaic panels made in China using coal-fired electricity can have a carbon footprint that is higher that blue hydrogen produced from natural gas using a cleaner process (5). Particularly noteworthy is the fact that pyrolytic processes, which use not only natural gas but biogas feedstocks, can achieve negative emissions (see **Figure 2**).

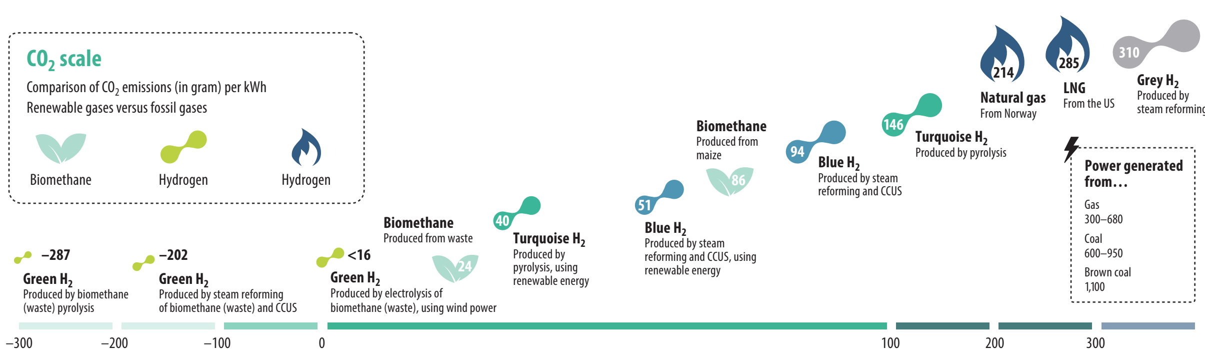

Figure 2

Carbon footprint of various gases (6). Abbreviation: CCUS, carbon capture utilization and storage.

2.3. Market Size, Market Potential, and Market Developments of Hydrogen Compared to Natural Gas

Natural gas makes up approximately 25% of the global primary energy market, at 37,000 TWh, and is one of the most important energy sources worldwide. Annual global hydrogen production is ∼47 Mt, corresponding to slightly less than 1,900 TWh. Current hydrogen production is mainly from fossil sources, namely, natural gas (47%), coal (27%), and oil (22%), and from renewables (4%) (7).

If, on the one hand, carbon capture and storage or utilization technology is not expanded rapidly, hydrogen will not be able to contribute to improving climate protection in the mid-term, before possibly being overtaken by green hydrogen in the long term. On the other hand, a phase-out of fossil fuels means that hydrogen can grow at a faster pace, and indeed must do so if emissions reduction targets are to be met. Various countries see this as an essential cornerstone of their feasible future hydrogen strategies: sun- and wind-rich countries in the increase of production—meaning the establishment of electrolysis services—and importing countries such as Germany in the expansion of global hydrogen sourcing, such as intensification of import efforts (see **Figure 3**).

A change in awareness of the importance of hydrogen has begun, as the drastic addition of wind and solar farms has created overcapacities in power generation. Given the intermittent nature of renewables, they carry the inherent disadvantage of not being reliable for baseload. They cannot represent energy on demand and therefore must be supplemented by electricity storage facilities. Such large electricity storage, on a scale that guarantees a national energy supply, can be realized only with the aid of a large-scale (chemical) storage system.

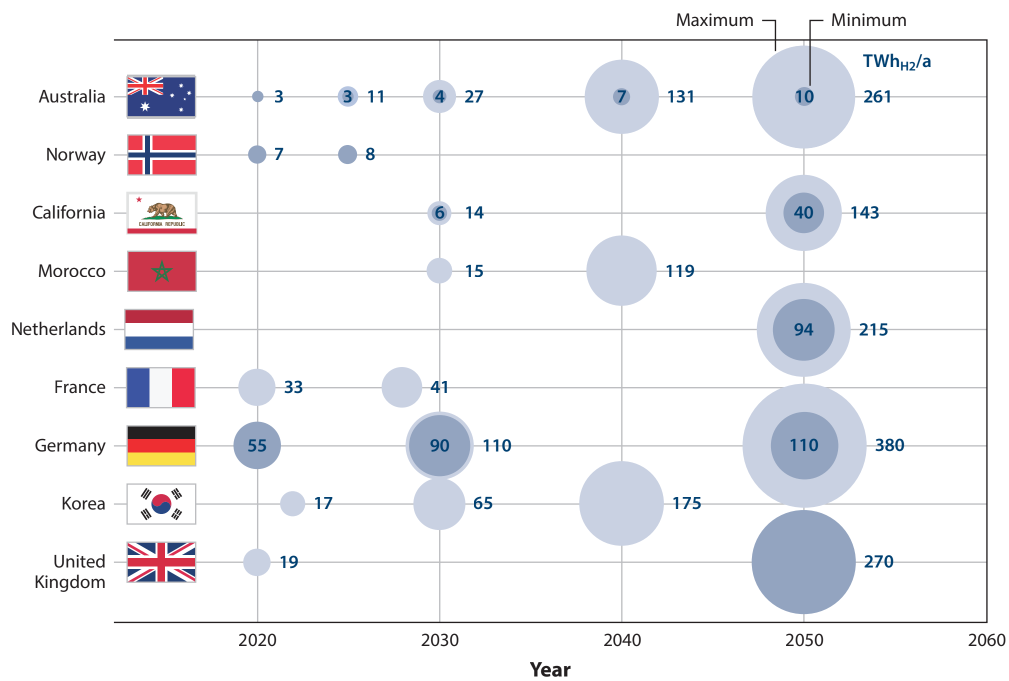

Figure 3

Expected annual hydrogen consumption in TWh_{H2} per year (8). The countries and states selected were among the first to publish a national hydrogen strategy.

In Germany, where the installed wind and solar capacities over the last 20 years already exceed the average reserve capacity in the electricity grid, it quickly became obvious that the electricity grid alone is overburdened with a steady expansion of renewables. This is because in addition to the lack of storage options, bottlenecks also occur in the transmission delivery systems. By diverting electricity energy flows into the gas grid, through hydrogen production and sector coupling, such handicaps can be circumvented, as compressible gases, and generally every chemical energy carrier, has a high energy density and thus represents an almost unlimited sink for surplus electricity. Therefore, global growth of renewable energy and the size of the potential hydrogen market are directly correlated, and the potential global market development of natural gas and hydrogen is driven predominantly by climate policy objectives (see Section 2.8).

Burning natural gas instead of coal and oil leads to massive emission reductions, especially in the power sector: Gas CCGT (combined cycle gas turbine) emits 350 kg CO_2 per MWh; oil emits 759 kg CO_2 per MWh; and coal emits 1,020 kg CO_2 per MWh (9). Because hydrogen can feasibly replace gas from a technical viewpoint, electricity decarbonization strategies can be adapted to meet hydrogen availability and cost through cleverly chosen strategies, such as increasing national natural gas consumption to displace coal- or oil-fired power plants and in synchrony increasing the share of hydrogen to displace natural gas over time.

This strategy is complemented by direct use of available renewable energy. However, such direct use must not be understood as competition to hydrogen production by electrolysis, because hydrogen, as described above, helps to store electricity and circumvent grid bottlenecks and can also make use of other sources besides local electricity sources due to its easy transportability. In other words, hydrogen is predestined for global trade and acts as a balancing mechanism between markets of different indigenous renewable energies. This opens up specific options for emerging sun- and wind-rich regions to enter into energy trade relations with highly industrialized energy-importing countries, relations that traditionally were reserved for classic oligarchs in fossil-dominated regions. Therefore, it is plausible and feasible that green hydrogen will be as important in the 2050s as natural gas is today (see **Figure 4**).

2.4. Transport Options for Hydrogen

Pipelines are the dominant means of delivering natural gas from the production site to consumers and customers. Of the total global natural gas volume, approximately one-third is transported

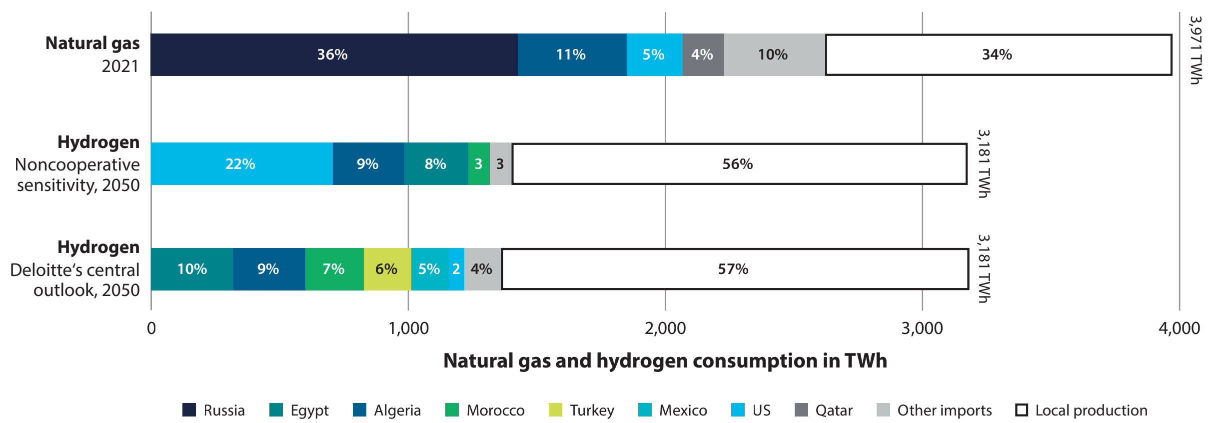

Figure 4

Supplier mix in Europe for natural gas (2021) and hydrogen (2050) (4).

across borders. Until recently, two-thirds of this cross-border volume was by pipeline, with the rest mostly being shipped as liquified natural gas (LNG). After Russia's invasion of Ukraine, LNG shipping has been increasing and fighting for parity with cross-border pipeline gas. But domestically, especially in the area of energy distribution, pipelines are unbeaten: They are orders-of-magnitude superior to all other transport options, such as energy transport by rail, ship, or truck, due to their continuous and energy-efficient operation with minimal losses and vast established infrastructure.

With regard to repurposing the natural gas infrastructure, DVGW has carried out groundbreaking research work (10). In response to concerns about hydrogen-accelerated growth of micro cracks in pipelines, they carried out 3 years of extensive tests on 300 different pipeline steels used in Europe. They provided scientific evidence that natural gas pipelines are also suitable for long-term operation with mixes of natural gas and hydrogen as well as pure hydrogen. Residual lifetimes of 100 to well over 1,000 years were determined. The reason for these impressive results is clearly that pressure-load fluctuations in gas systems happen with low amplitudes and rarely more often than once a day. Both facts make the fatigue process of the material abnormally slow. Governments and industry alike anticipate that production and international trade of hydrogen will ramp up from 2035, with one-third traded across borders, half by ship, mostly shipped as liquid ammonia, and half by pipeline (11).

Individual components of natural gas infrastructure systems may require replacement to meet revised safety specifications. This is the case, for example, with meters calibrated for natural gas, as well as components optimized for natural gas combustion that could lead to malfunction due to higher flow velocities expected with hydrogen transport. What these are, and which substitutes are H_2 ready, has been largely clarified and is available in the DVGW database, VerifHy (**https://www.verifhy.de/**).

Gas transport in pipelines is based on differences between system inlet and outlet pressure. The higher inlet pressure, the lower outlet pressure, and fixed geometry parameters such as pipe diameter and length, as well as the integral pipe roughness, determine system capacity. This law is known as the Darcy–Weißbach equation (12); see Equation 1:

$$\dot{Q} = W_S \times D^{2.5} \times \sqrt{\frac{\left(p_i^2 - p_o^2\right)}{\hat{\lambda} \times L \times K_m}}, \qquad 1.$$

where the friction parameter $\hat{\lambda}$ combines parameters of pipe roughness and other quantities to be assumed as almost constant, namely,

$$\hat{\lambda} = \lambda \cdot \frac{16}{\pi^2} \cdot \rho_{air} \cdot \frac{T_m}{T_n} \cdot p_n, \qquad 2.$$

and the Wobbe index,

$$W_S = \frac{H_S}{\sqrt{\frac{\rho_{gas}}{\rho_{air}}}} =: \frac{H_S}{\sqrt{d}}, \qquad 3.$$

is the quotient of the calorific value and the square root of the relative substance density.

Thereby $\dot{Q}$ is the energetic line capacity in kWh/s, and D and L are the diameter and length of the pipeline section with an inlet pressure p_i and an outlet pressure p_o. T_m is the average temperature of the medium; T_n is the normal temperature (273 K); p_n is the normal pressure [1.013 mbar]; and the two variables ρ_{gas} and ρ_{air} denote medium and air densities, respectively. The two remaining parameters, λ and K_m, are integral pipe roughness and medium compressibility.

In the representation chosen here, pipeline system capacity is therefore given in energy per unit of time and not in cubic meters per unit of time. Clearly, when one transport gas is replaced by another—which has approximately the same Wobbe index and the same compressibility in the operating pressure range of the pipeline—the energy capacity is maintained. In layman's terms, although the calorific value of hydrogen is three times lower than that of natural gas, approximately the same energy per unit of time flows through the cross-section of the pipe due to its three-times-higher flow velocity.

It therefore makes sense, in transforming the supply economy toward climate neutrality, to recycle natural gas infrastructure and systems for use in transporting hydrogen. This is a feature of the plans to build a hydrogen infrastructure, be it the draft of the European Hydrogen Backbone published by Gas4Climate (13) or the latest publications on the German Hydrogen High Pressure Core Network (14) with a total length of over 11,000 km. Proposed hydrogen networks include 40% to 60% existing natural gas pipelines, whereas the rest is expected to be new construction. The percentages could be even higher, but in the initial phase the remaining natural gas network must remain largely fully operational and ensure continued basic supply. According to estimates by various institutions (see in particular References 13 and 15), the reuse of natural gas infrastructure is far superior to the construction of new hydrogen pipelines, in terms of approval and implementation times but also in regard to required investment, at approximately 20% of new construction costs.

Non-pipeline-based hydrogen transport is technically difficult, in particular the cryogenic low temperatures needed to cool hydrogen to a liquid, which will complicate international trade for years. At 20 K, the condensation point of hydrogen is still approximately 90 K below that of natural gas. This means that LNG carriers and LNG tank farms cannot be easily converted to handle cryogenic hydrogen. Worldwide, the first ship trials—the Suiso Frontier of Kawasaki Heavy Industries Ltd. (16)—are being conducted currently to transport liquid hydrogen from Australia to Japan. With a capacity of 1,250 m^3, it is approximately 200 times smaller than comparable LNG ships of the Q-Max class.

For this reason, alternative options are favored until liquid hydrogen transport is ready for large-scale commercial use, leading to simpler manageability. These include the transport of hydrogen

- as liquid ammonia (NH_3),
- as methanol (CH_3-OH),
- dissolved in oil (liquid oil hydrogen carrier), and
- as LNG or synthetic gas.

Currently, several projects that focus on the respective advantages of these options are underway in Germany. In the case of ammonia, it is the possibility of direct utilization for the production of artificial fertilizer—without detours or bound hydrogen recovery. In the case of liquid oil hydrogen carrier, where the hydrogen is entrained in oil, the handling makes transportation relatively easy. With synthetic gas, there are immediate opportunities to enter the international energy trading business and use existing LNG carriers. However, the CO_2 required in the reaction (Equation 4) must always remain in a closed commodity cycle and not be released into the atmosphere, or green CO_2 must be used from the start (CO_2 from biogenic processes or from air capture), which increases the initial cost:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O. \qquad 4.$$

If there is certainly room for all three options in a growing hydrogen trade at the beginning and ammonia initially appears to be ahead, rankings will change over time as the technologies mature (17). The relatively small international ammonia trade, with a total volume of approximately 20 Mt, is also a factor inhibiting hydrogen trade.

In conclusion, the technological challenges of non-pipeline hydrogen transport are a limiting factor in the ramp-up of a hydrogen global market, dependent on international trade. In contrast, the reuse of natural gas pipelines for hydrogen transport is an enabler and has only low barriers to entry. For countries with well-developed pipeline networks and direct connections to producers, as is inherent in European countries such as the Netherlands or Germany via offshore pipelines to Norway or Spain and Italy via pipeline routes toward North Africa, it is a strategic advantage in the race for hydrogen.

2.5. Hydrogen Storability

The previous section discusses hydrogen storage in the course of transport. Also systemically relevant, however, is large-scale storage—comparable to seasonal natural gas storage or the stockpiling of the national oil reserve. For this, the underground natural gas storage facilities themselves come into question. To date, tests on hydrogen storage in cavern storage facilities have been promising; the German company EWE aims to examine process engineering procedures in more detail in a cavern that has been specially constructed for research purposes (18). Among other things, this involves drying the hydrogen that is brought back to the surface, a common process in natural gas production, in which the initially moist gas is dried via glycol circuits.

Pore reservoirs are more demanding in terms of hydrogen storage because the embedding of H_2 in the sediment structure with a much higher exchange surface to the rock can lead to reactions with microorganisms, for example, "archaea," as cultivated in the Sun Conversion storage project (19). In this project, hydrogen was successfully converted into methane. In a unique new project, Underground Sun Storage 2030 (20), the Austrian storage operator RAG is investigating how pore-storage facilities can be prepared for pure hydrogen.

What is not a problem with pipelines, namely, the lower energetic density of hydrogen, and what could be compensated for by higher flow speed (as found in the DVGW studies), poses challenges for system designers of complete hydrogen infrastructure systems: Natural gas storage facilities can store three times as much as stored gaseous hydrogen. Even if hydrogen storage facilities are employed differently in the future, for example, operated with higher annual turnovers, more storage facilities must be built if hydrogen is to fully replace natural gas with the same total annual energy.

In conclusion, hydrogen storage in underground facilities is feasible, but such facilities take years to build. Therefore, their expansion must begin quickly to be able to fulfill seasonal gas demand fluctuations and allow the large-scale hydrogen storage infrastructure required with sector coupling.

2.6. Hydrogen-Based Applications

Hydrogen application possibilities are almost unlimited (see **Figure 5**). The practical conversion of natural gas systems to hydrogen still faces challenges. For example, glass firing processes can lead to different glass colors when hydrogen is used instead of natural gas (24), requiring process modifications.

Similar technological adaptation in converting processes from natural gas to hydrogen is being investigated by the DVGW with industry partners Green Platforms (25). In parallel, the need for associated standardization is being determined in a large-scale project funded by the federal government, the Hydrogen Standardisation Roadmap (26).

In the field of industrial applications, the production of green steel using hydrogen is one better-known and challenging example; it is currently being investigated within the European Union in several specially funded projects (27). Decarbonization of industry processes using green or low-carbon hydrogen is faster wherever gray hydrogen is being used already, such as in the chemical industry to crack hydrocarbons or produce nitrogen fertilizer (28). For the cluster of

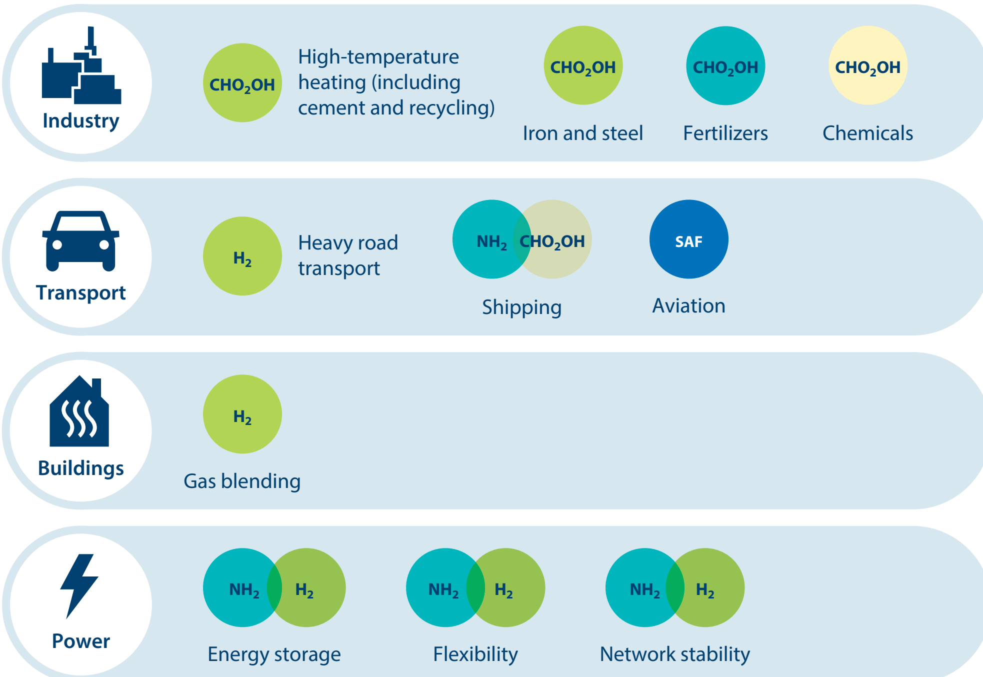

Figure 5

Main use of clean hydrogen and its derivatives in a climate-neutral energy system according to the International Energy Agency (21), the International Renewable Energy Agency (22), Hydrogen4EU (23), and Deloitte (4). Abbreviation: SAF, sustainable aviation fuel.

industrial hydrogen applications (first line in **Figure 5**), there is therefore still a need for a large number of individual projects to grasp the specific features of natural gas substitution.

In the transport sector, natural gas or LNG has conquered places where heavy loads and large mobile units must be moved. Although natural gas also plays an important role in individual transport in some countries, such as Italy, China, or Iran, there is growing superior competition from electromobility, which can also outcompete hydrogen cars where the hydrogen refueling structure is underdeveloped. In Europe, for example, there are approximately 138,000 petrol-diesel filling stations but only approximately 140 hydrogen filling stations (29). This handicap does not occur when hydrogen is used for railways or when hydrogen-based ship propulsion systems are considered, because generally fewer refueling points are required and can be planned well in advance. Because larger loads requiring larger quantities of hydrogen in high-pressure tanks play no role in rail or marine systems, it is only a matter of time, or further tightening of emission guidelines, until hydrogen displaces LNG or natural gas in heavy-duty transport. There are no technological hurdles to switch to hydrogen, because hydrogen-powered engines and e-drives that source electricity from fuel cells are already the state of the art.

The conquest of air traffic, in contrast, is unlikely to succeed as quickly with the direct use of hydrogen, due to the more cost-effective and efficient path of using synthetic fuels in conventional turbines—which, however, can be obtained from hydrogen. This breakthrough of sustainable aviation fuel is keenly awaited.

The fourth line in **Figure 5** deals with hydrogen-based electricity generation. It plays a key role in a highly sector-coupled system, because it allows hydrogen produced from wind and solar energy to be converted back into electricity in times of need. Hydrogen-ready turbines are available already from some suppliers, but the International Technical Association of Energy Plant Operators (VGEB) attests that the development of the broad range of manufacturers requires a few more years. This also applies to experience and projects for upgrading existing turbines (30). For countries like Germany that must replace a fleet of coal-fired power plants, the use of hydrogen power plants is feasible and, depending on the year of commissioning, may require an intermediate step in the form of the addition of gas-fired power plants retrofitted to burn 100% hydrogen efficiently. In addition to central power plants, there will also be an increase in the number of local fuel cell power plants, because these can be easily integrated into a local heating strategy and used to feed locally produced hydrogen back into the electricity system, thus stabilizing the system without waste heat remaining unused.

Direct hydrogen use is more difficult in the building sector (third line of **Figure 5**). It depends, among other things, on building standards and the existing penetration rate of natural gas heating systems. In countries where the vast majority of private households and businesses operate gas burners, such as the Netherlands and Germany, the use of hydrogen for heating makes sense. On the one hand, hydrogen can be mixed with natural gas in a ramp-up phase without having to replace the existing appliances. This is borne out by basic physical considerations based on the almost unchanged maintenance of the Wobbe index, the variable that defines burner performance given by Equation 5:

$$P = A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_{air}}} \cdot \frac{H_S}{\sqrt{d}} = A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_{air}}} \cdot W_S. \qquad 5.$$

Here, P is the power output of the burner, A is the cross-section of the nozzle, Δp is the gas pressure (above atmospheric pressure) in the supply pipe, ρ_{air} is the air density, and W_S is the Wobbe index. Clearly, because all parameters in Equation 5 in front of the Wobbe index are defined by burner geometry or operational setup or are fixed quantities like air density, no significant change of the dominating Wobbe index leads to the same power output of the burner. The flame speed of hydrogen–natural gas mixtures is also almost identical to that of natural gas at admixtures below 50% and guarantees a stable flame without pulsations in the combustion chamber of a burner (see **Figure 6**).

Large-scale field tests—for example, in the community of Schopsdorf in Germany (32) or in Winlaton in England (33)—show empirical evidence that old or existing appliances can operate with mixed gases without any problems. However, if the hydrogen concentration is increased and the aim is to supply pure hydrogen, the combustion chambers must be replaced, or the units must be completely renewed. Currently, 100% H_2-ready burners have been tested, and there are already various suppliers of 20% H_2-ready appliances (34).

Even for municipal heating planning, it is not far-fetched to build hydrogen heating on large scales because, simply put, the power grid is not capable of doing so, and its expansion would entail considerably major new construction costs—usually at all grid levels. The lengthy approval procedures, which lead to the deplorable fact that the European electricity grid lags far behind expansion plans, also raise doubts as to whether the heat market can be decarbonized quickly enough via electrification. Because electricity transport (alternating current) is associated with high losses—which is why energy is better transported over long distances in chemical form, such as natural gas or hydrogen—only locally generated electricity can actually be considered for an economic and ecological downstream heat supply. But this is still in short supply, especially on the European continent. In contrast, it is more promising to transport large quantities of renewable electricity from sunny and wind-rich regions of the world via hydrogen to Europe and Germany as an aspiring hydrogen country.

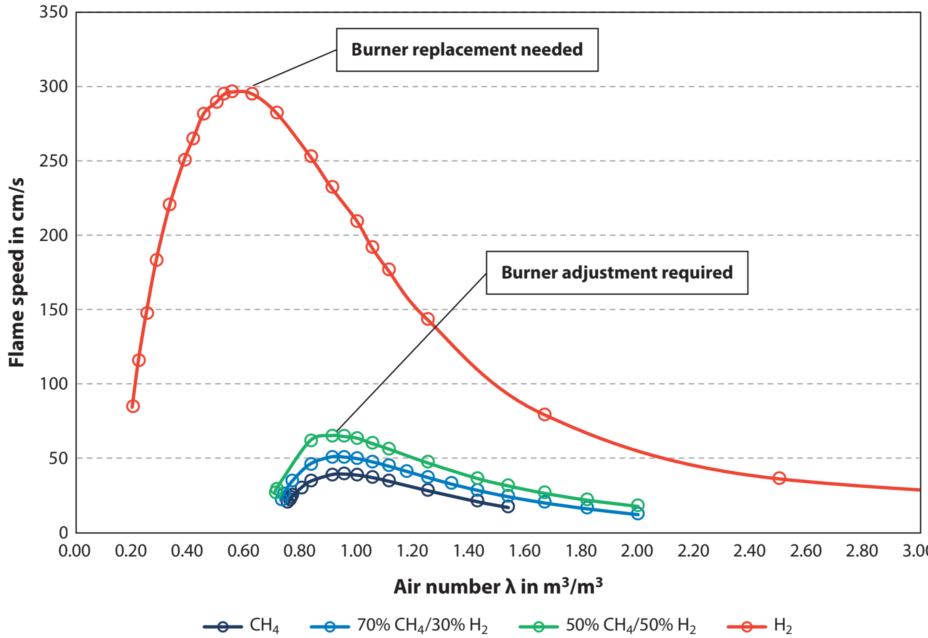

Figure 6

Change in flame speed according to hydrogen admixture (31).

The compelling argument for pursuing hydrogen-fueled heat is that here the demand for residential heat far exceeds that for electricity, in some cases by a factor of ten. The heat market is also characterized by high power peaks. On cold winter days, peak power demand from the gas grid in Germany can reach values of more than 300 GW—equivalent to the output of more than 300 coal-fired power plants (35). In comparison, the electricity grid supplies an average of 70–80 GW. Even multiples of installed capacity bring no relief. For example, in Germany, there are currently 59 GW of onshore wind, 8 GW of offshore wind, and 60 GW PV installed (36), together more than the average demand if the peak power could be provided continuously. But the higher the share of power that cannot be called up in a plannable manner becomes, the more hydrogen-based reserve power and storage are needed to avoid houses turning cold in cases of doubt due to a dark lull.

The interim conclusion on hydrogen applications is therefore positive overall. There are not only areas of application in which hydrogen will be the new natural gas as an energy carrier for thermal purposes and as a feedstock but also many examples in which hydrogen will experience a high market share as a resilient technology to stabilize the overall electricity–gas–heat system and optimize the transformation costs to a net-zero energy supply.

2.7. Systemic Relevance of Hydrogen

According to KPMG & Kearny (37), the global primary energy demand in 2022 was 604.6 EJ (167.9 PWh). Of this, 45.18 EJ (12.5 PWh) were of renewable origin. This is approximately 7.5%.

Oil has been on a relatively downward trend for years, which, similar to that for coal, saw a turnaround at the start of the Russia–Ukraine conflict. Natural gas has so far held a steady market share of just under 25%. Considering that the Russian natural gas that has been lost to the world market is well on its way to being replaced by new LNG production in the United States and

Australia through the rapid expansion of LNG fleets, and considering the drastic emission-reduction effects that can be generated with natural gas compared to coal or oil in power generation, a global upward trend in natural gas demand is predicted in the coming years and even decades. However, as the share of natural gas in primary energy demand grows, the question of its decline in the face of decarbonization arises: This is the gap that hydrogen can fill.

At the same time, it can be assumed that the growth of renewables will continue. Here, too, there is a task for hydrogen in smoothing fluctuations due to the intermittent nature of renewables—in other words, storing small and large quantities of energy. Only with hydrogen can more solar or wind energy grow beyond the actual local system limits, which become noticeable, for example, at the regional level in electricity grid bottlenecks or in non-time-synchronous demand. Only with hydrogen can sun- or wind-rich countries enter into a global energy market and trade their natural resource energy.

According to estimates, technically feasible hydrogen production in 2050 is 2,400 Mt, almost 100 PWh (4). However, due to high capital requirements and techno-political hurdles, the authors assume that 600 Mt will be available on the world market. This is still six times the current European demand for natural gas. Cumulative CO_2 reductions are estimated at 85 Gt, twice as much as global CO_2 emissions in 2021. Consequently, hydrogen can make its decarbonization contribution in a convincing way.

Already, certain support mechanisms linked to sustainability criteria, such as the US Inflation Reduction Act; the European Important Project of Common European Interest; or the German H2Global initiative (**https://www.h2global-stiftung.org/**), which is currently undergoing its expansion to a European context, ensure that positive impulses are set for growth in generation capacities. Clearly, and as proven in many system studies (38), even if the expansion of renewable energy or investment in large-scale electrolyzers is associated with massive capital investment, an energy system that combines the best of both worlds—highly efficient and emission-free electricity generation on the one hand and the storage and transport capability of gases, above all hydrogen on the other—operates in a cost-optimized manner.

Conversely, in an energy system dominated by renewable energy, hydrogen is the system-relevant energy store and, due to its storage capacity, the energy transmission medium for all areas that are difficult or impossible to electrify. Without hydrogen, there is no resilient energy system.

2.8. Target Regions for Hydrogen

Favorable conditions for hydrogen to become a significant energy carrier in a market and replace natural gas vary greatly from region to region. Accelerators and retarding moments are discussed below. The risk affinity of governments and companies is also considered. In this sense, the portfolio of opportunities and risks of rapid entry or development of a hydrogen economy varies from region to region.

Large expansion of the natural gas pipeline infrastructure is certainly conducive to a shift from natural gas to hydrogen. This includes high connection rates of end users, such as those found in the Netherlands, Germany, or Japan. As a rule, one also finds developed energy routes there with parallel laying of pipelines, which allows natural gas and hydrogen infrastructures to coexist and thus favors the transformation. Emerging countries that are in the process of building these structures—usually focused on connecting singular locations such as new gas-fired power plants—certainly will not participate in the first wave of the hydrogen revolution, unless they belong to the ranks of hydrogen-exporting countries. But even then, for the foreseeable future, higher returns are likely to be realized with exports than with local use. This makes it clear that industrial nations will become the drivers and pioneers of the hydrogen economy.

A further catalyst for positive consideration of the conversion of a natural gas–based supply to hydrogen is likely to be high demand from hard-to-decarbonize sectors, notably heavy haulage and transport like aviation and shipping and some industrial processes like steel and glass making, where no alternative decarbonized fuels exist. This is true for industrialized countries and highly export-dependent nations, like Germany, where, as a rule, the current saturation level of the share of low-carbon electricity in primary energy is low. In Europe, the share of electricity in primary energy is on average below 20%, and less than half of this has a renewable origin. However, if more than 80% of the primary energy is molecule based, then arguably the hydrogen produced electrolytically has little leverage to contribute significantly to decarbonization, but the need to replace the fossil molecule energy pillar with green imports is greater. This therefore favors the willingness to contract as much hydrogen as possible via the development of new international partnerships, such as H2Global (**https://www.h2global-stiftung.org/**).

Considering retarding factors that hinder a rapid market growth for hydrogen, current high production and supply costs—including transport to the consumer—are certainly among them. The natural gas trading price at the target market or hub is the reference value that must be undercut. Approaches that propose levelling initially high but later competitive hydrogen prices, such as contracts for difference (39), represent adequate solutions. Incidentally, comparable approaches are also being pursued to finance the development of hydrogen infrastructure, for example, in the debate about the 11,000-km-long hydrogen core network that Germany is planning, realization of which is to be anchored in a binding manner in the Energy Industry Act. Here, the focus is on private-sector capital procurement on financial markets (risk participation by the long-distance gas grid operators), whereas the state acts as a guarantor that ensures overall economic viability over the depreciation period.

Nevertheless, transformation from natural gas to hydrogen is highly complex. This applies both technically and logistically: technically, where end-use applications still must be adapted to the new energy yields, for example, in steel production or glass making (see Section 2.6), and logistically, where network-level grid conversion plans must be implemented along with logistic plans with regard to the conversion or connection of consumers building by building, as is familiar from the conversion processes from L-gas (low calorific gas) to H-gas (high calorific gas).

At the same time, the gas business is fragmenting in the transition from natural gas to hydrogen, for example, into areas to be served with locally produced hydrogen and regions further away to be supplied via the hydrogen backbone. Other sources are being added, such as hydrogen from waste recycling or biogas and hydrogen supplied via an intermediate carrier such as ammonia.

On this path, traditional natural gas supply industries must develop into energy/chemical industries, requiring new skills. Despite the opportunities, this is a challenge and a time-consuming element of transformation.

The simultaneous ramp-up of sector coupling elements requires financial resources and time, such as the construction of H_2-ready power plants. The hydrogen economy is thus caught permanently between time pressure dictated by ambitious climate protection goals and the knowledge that there is no alternative; it is ultimately only a specific manifestation of the expansion of renewable energy and a circular economy.

Despite the lack of alternatives, the degree of ambition with which various countries replace natural gas with hydrogen remains subject to the dictates of national climate policy and political willingness. In strongly meshed, cross-border networks and markets with high interoperability, a common, transnational strategy is therefore needed. Even more, a joint project plan is requested for when parts of the European Hydrogen Backbone will be armed and ready for hydrogen. The absence of joint plans ultimately slows national conversion plans. In this respect, transnational initiatives such as the European Hydrogen Backbone (13), the German–Norwegian Working Group on Hydrogen (40), or the German–Australian Hydrogen Alliance (41), to name but a few, are keys to success.

Such common approaches include the joint and uniform clarification of unanswered open questions such as the clear climate assessment, certification, and tradability of hydrogen. At least within coherent market areas, such as in Europe, there must be clear regulations on certificates of origin and carbon footprints of new energy sources that are not made absurd by arbitrary criteria (such as additionality). This has not yet been achieved sufficiently with the European Renewable Energy Directive, RED II (42).

Accepting and dealing with the complexity of the new hydrogen economy are key for success, not only the setting of overambitious targets or ramping up of electrolyzer manufacturing. In Germany, for example, convictions in political circles that Germany can sell electrolyzers and technical plants in return for hydrogen imports from emerging countries can be encountered. However, these hopes are thwarted precisely by other governments' instruments, such as the US Inflation Reduction Act, which favors national production with corresponding subsidy policy. Moreover, pyrolysis technology, the handling and use of ammonia and other derivatives, and questions of overall system integration are paramount. Be they global players or highly specialized suppliers of today's niche products, companies that know how to deal with complex (energy) systems are likely to be among the champions and winners of a hydrogen transformation.

These considerations lead to the conclusion that natural gas will be quickly replaced by hydrogen where stable promoting market conditions exist. But ambitious national emission reduction plans and go-it-alone approaches can be counterproductive if they jeopardize or sacrifice energy security and affordability. Observation of other markets—especially Asia and future energy giants such as India and North Africa—provides correctives in this respect. Distortions play a role, arising from different carbon-reduction targets and target dates; when in the western world the goals of the Paris Climate Agreement are to be achieved by 2050, elsewhere longer transition periods are granted, and climate neutrality is demanded only later. This causes distortions in the cost of energy and thus in market penetration of hydrogen. A level playing field is needed. Expensive but climate-neutral production costs, for example, for green steel, must therefore be rewarded. Toleration of different decarbonization rates in different regions, for which there may be many good reasons besides the right to welfare and to catch up on historically caused disadvantages, must be paired with compensation mechanisms when trading identical products and goods but with different carbon footprints (Carbon Border Adjustment Mechanisms). This, too, is a condition sine quo non for rapid hydrogen ramp-up.

3. CONCLUSIONS

Hydrogen has the potential to be a new natural gas and should be given the importance that natural gas enjoys today. This conversion will be put into practice more quickly in highly industrialized countries than in still-emerging regions. A responsible climate policy must attach great importance to this new molecule right from the start. In addition to the usual instruments, such as increasing electrification and expanding renewable energy, there must be the objective of replacing the current lion's share of molecular, fossil energy and, in the process, building up a resilience element—in other words, a system storage in a sector-coupled interplay of electrons and molecules. This is the role of hydrogen as an energy carrier. However, hydrogen can fully replace natural gas in an international energy system only if it can fulfill all requirements of the classic energy triangle. In addition to the sustainability that naturally comes with suitable production, it also guarantees security of supply and represents affordable energy provision. It is not primarily technical hurdles but global commercial and regulatory aspects that must be clarified for hydrogen to succeed.

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