Making Sense of Hydrogen's Role in Reducing Greenhouse Gas Emissions

White Paper 513

Version 1

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Executive summary

When it comes to addressing global warming, clean hydrogen is being forecasted to play a critical role in electricity generation, industrial processes, transportation, and buildings. Clean hydrogen makes sense in certain applications like ammonia production, but not in others like passenger vehicle fuel. This paper explains the facts about hydrogen and then examines the major sources of greenhouse gas emissions. Hydrogen's potential to reduce those emissions is assessed. Finally, the paper summarizes the sectors in which hydrogen makes sense, does not make sense, and which are debatable.

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Introduction

When it comes to addressing global warming, the use of hydrogen is being forecasted to play a key role, even being called the "hydrogen economy". Funding for hydrogen projects has been significantly lagging[1] and must increase to trillions per year in order to reach Paris Agreement goals by 2050. Hydrogen is the most abundant element in the universe which piques the interest of various stakeholders because of its "green" zero-carbon footprint potential. However, a balanced assessment requires that the reader understand that similar, but seemingly contradictory, facts about molecular hydrogen (H_2) can be used by advocates and detractors. For example, the following facts are very positive:

- When pure H_2 burns, its only emissions are pure water.
- It has the *highest* energy density (**per unit weight**) of "all known substances" (~3 times that of gasoline[2])
- It can be derived anywhere there is water.

Reading these highlights, one gets the sense that this simple element holds the answers to many global warming questions. Yet, similar-sounding facts listed below seem to contradict this view:

- When H_2 burns in typical combustion applications like turbines or internal combustion (ICE) engines, it produces nitrogen oxide (NOx). While this doesn't produce carbon, NOx does lead to GHG emissions.
- It has the *lowest* energy density (**per unit volume**) of any fuel (~4 times less than gasoline)
- It requires 18 to 24 kg[3] (5-6 gallons) of water per kg of H_2, and currently requires fresh or desalinated water at scale.

Putting aside these biases, if the goal is to reduce man-made greenhouse gas (GHG) emissions, then the best solutions are those that can most effectively reduce the *largest* emissions by weight. It is with this framework that we investigate hydrogen's potential impact. **Table 1** provides a summary of the findings. This paper explains the practical facts about hydrogen and then examines the major sources of emissions. This is followed by an assessment of hydrogen's potential to reduce those emissions. Finally, we summarize in which sectors H_2 makes sense, does not make sense, and is debatable.

Table 1
Summary of where clean hydrogen makes sense, does not make sense, or is debatable.

Makes sense	Doesn't make sense	Debatable
• Electricity generation via fuel cell • Petrochemical refining • Ammonia production • H_2-based liquid fuels for marine & aviation	• Combustion fuel for electricity generation • Passenger vehicle fuel • Fuel for short-distance trucking • Combustion fuel for heating buildings	• Data center diesel generator replacement • Fuel for long-haul trucks • Combustion fuel for cement and steel industry

[1] Bloomberg NEF, *BNEF Signposts, 1Q 2021, Coming in from the cold*, p 4

[2] U.S. Energy Information Administration, *Hydrogen explained*

[3] IRENA, *Green Hydrogen Cost Reduction - Scaling Up Electrolysers to Meet the 1.5°C Climate Goal*, 2020, p 40

Facts about hydrogen

Despite being the most abundant element in the universe, hydrogen is rarely found on earth in its pure form. Therefore, it must be produced (i.e. derived) from water or organic compounds through various methods. Energy is required to break the hydrogen atoms from these molecules, which is why H_2 is considered a carrier of energy and a means of energy storage (like electricity in a battery). In fact, any form of energy produced through human manipulation, is an energy carrier (e.g. electricity). H_2 is also a common industrial feedstock, a "raw material supplied to a machine or processing plant", for example, ammonia production.

Today, roughly 70Mt (Megatonnes) of hydrogen (annual) are produced globally, with 76% derived from natural gas via SMR (steam methane reforming), 22% through coal gasification, and 2% via electrolysis.[4] So-called "Grey" H_2 is derived from fossil fuels (typically through SMR), while "Green" H_2 is derived through water electrolysis with zero CO_2 footprint (assuming renewable electricity generation). In 2018, grey H_2 production accounted for 1.5% of total GHG (11kg CO_2/kg H_2 or an emissions factor of 0.341kg CO_2/kWh H_2).[5] However, if SMR is used with carbon capture and storage (CCS), 80-90% of CO_2 emissions are captured. This is then called "Blue" H_2. Note that if all H_2 in 2018 were produced with electrolysis using the 2018 global energy mix, the CO_2 emissions would be over three times greater than with grey H_2.[6] **This means that electrolysis only bests SMR if the power generation emissions factor is less than 0.171kg CO_2e/kWh.** To get a sense for the magnitude of this drop, coal use (38% of mix in 2018) would need to drop to 0% (projected by 2040[7]).

Hydrogen production costs

Today, water electrolysis is 3-4 times the cost of fossil fuel-based processes.[8] **Figure 1** provides another estimate of the global levelized cost of hydrogen at varying renewable energy prices.[9] Similarly, green H_2 is projected to reach cost parity with grey H_2 (€0.82/kg) by 2050.[10] Costs are significantly driven by efficiency. Fossil fuel steam reforming efficiency is 65-75% compared to electrolysis system efficiency of 51-67%. Note that today, some types of electrolyzer efficiencies degrade 1.5%–2.5% per year (respectively).

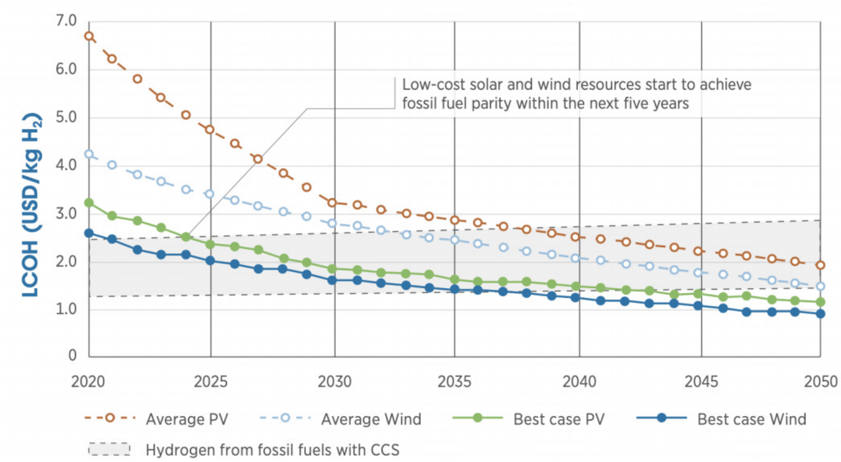


Figure 1
Forecasted global levelized cost of hydrogen (LCOH)

Source: Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe, June 2020, p.58

[4] U.S. DOE, *Hydrogen Strategy Enabling A Low-Carbon Economy*, 2020, p.5

[5] 2018 GHG values from p 4 *Trends in Global CO2 report*, H_2 values from IEA *The Future of Hydrogen*

[6] Using global 2018 CO_2 emissions factor of 0.543kg CO_2e/kWh and comparing it to the grey H_2 factor (note that the 0.543 value excludes T&D losses since that's accounted for in the electrolysis process)

[7] IEA, *Net Zero by 2050, A Roadmap for the Global Energy Sector, 2021*, p 19

[8] Jean-Jacques Marchais, Vincent Minier, Vincent Petit, *Hydrogen*, November 2019

[9] Note that H_2 cost from fossil fuels assumes a carbon price of €41/tonne in 2030, €82/t in 2040, and €164/t in 2050. LOCH is similar to LOCE Note 1 Euro = 1.22 US Dollars throughout this paper.

[10] Bloomberg, *Hydrogen Economy Outlook*, figure 6, p 5

Hydrogen energy requirement

Electrolysis consumes roughly 45-53 kWh[11] to produce 1kg of H_2. **Using a global forecasted demand of** 700Mt H2/year by 2050[12] **(10X** today's **demand) would require 32-37,000TWh of electricity, or 1.6 times the 2019 global electricity consumption.** Substituting **today's current global H_2 production** with green H_2 corresponds to 3,150-3,710TWh of additional power demand globally (or the electricity demand of Europe in 2019).

Hydrogen water requirement

In addition to electricity, it takes 18 to 24 kg[13] (5-6 gallons) of water to produce 1 kg of H_2. In a scenario with a production of 700 Mt H_2/year, that would translate into about 15 billion m^3 of water, or around 0.4% of global water demand. This amount of water use is obviously more challenging for water-scarce countries. However, water scarcity becomes a non-issue if ocean water were the main source for H_2. Desalination would require about 10-13 kWh[14] per 3,785 liters (1,000 gallons) which amounts to an additional 0.056-0.072 kWh/kg H_2 of energy, small in comparison to electrolysis.

Hydrogen storage

Once produced, H_2 must be stored and transported, but the optimal method of doing so is dependent on the application. The common method of storage is through compressing H_2 gas into steel cylinders and, for large applications, steel spheres, all of which incur losses. It's also possible to compress into rock or salt caverns. Compression is acceptable for onsite production, but companies are looking for alternative storage methods to reduce the cost of transportation, especially overseas. Other methods include:

- Hydrogen liquefaction – cooling H_2 to 20.3 Kelvin (-252.87°C / -423.17°F) changes it from a gas to a liquid, saving space but consuming about 4-5 times more energy compared to typical compression pressures.
- Ammonia – H_2 is used to produce ammonia. Since ammonia is easier to liquify, it's easier to ship. Though the roundtrip efficiency is about the same as liquification, the existing ammonia transportation infrastructure provides a lower overall cost.[15]
- Metal hydrides – like ammonia, hydrogen can be stored chemically in metals. This method provides a solid-state form of hydrogen storage.

Table 2 provides a summary of pros and cons for hydrogen.

Table 2
Hydrogen pros and cons

H_2 Pros	H_2 Cons
• Light weight • Can be zero carbon • Non-toxic and abundant • Burns cleaner and more efficiently than fossil fuels • "Highest gravimetric energy density of all known substances" (J/kg)	• Currently more expensive than fossil fuels • Energy-intensive to produce & compress • Electrolyzer efficiency degrades over time • Not a "drop-in" replacement for natural gas • Inefficient transportation in gaseous state • Low volumetric energy density (J/m^3)

[11] Energy Transitions Commission, *Making the Hydrogen Economy Possible – Accelerating Clean Hydrogen in an Electrified Economy*, 2021, p. 51

[12] SailingStone Capital Partners, *The Energy Transition, Outlook and Implications for Upstream Commodities*, 2020, p 35

[13] IRENA, *Green Hydrogen Cost Reduction - Scaling Up Electrolysers to Meet the 1.5°C Climate Goal*, 2020, p 40

[14] Desalination and Energy Consumption

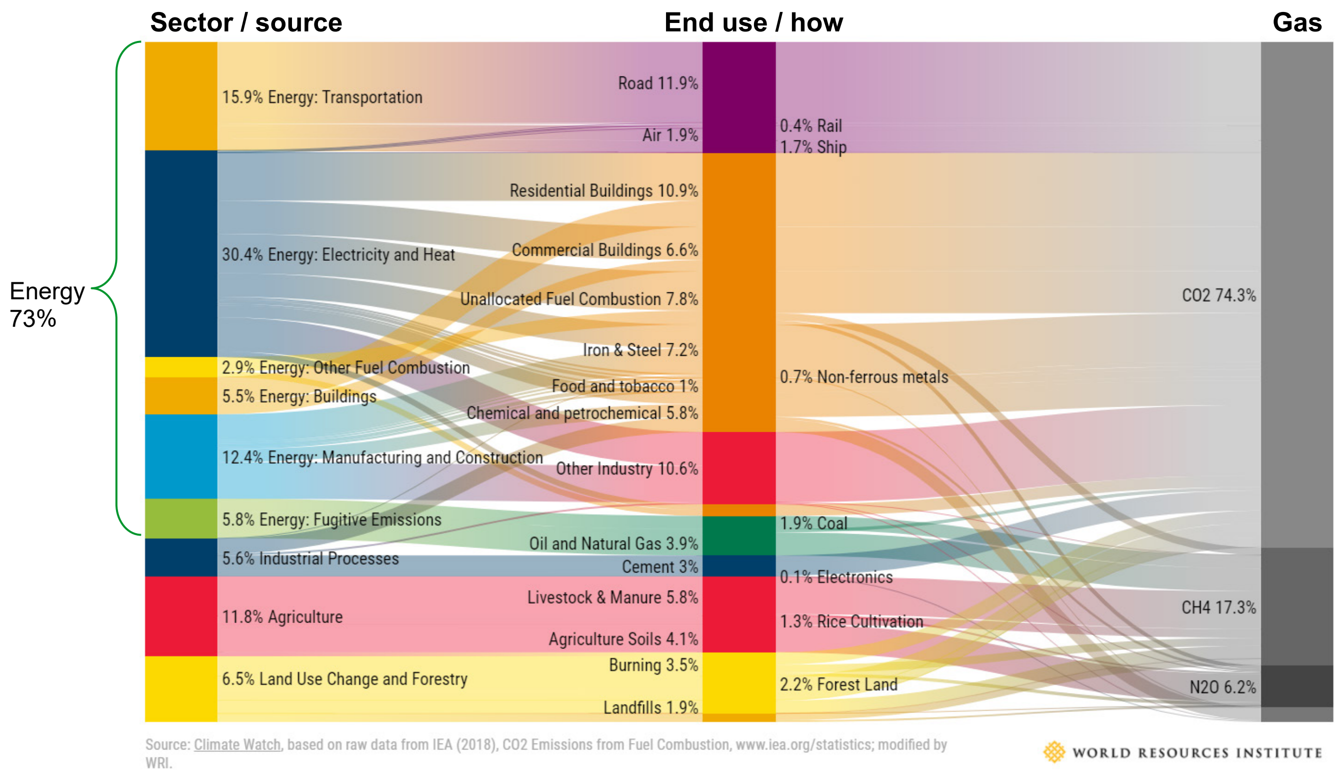
[15] Ammonia - a renewable fuel made from sun, air, and water - could power the globe without carbon

Sources of GHG emissions

To assess hydrogen's potential for reducing emissions, we must know the largest **sources** of GHG, as well as **how** those emissions are produced. For example, hydrogen won't help reduce landfill emissions because they're produced by the breakdown of waste. Furthermore, we need to understand which greenhouse *gas* hydrogen can address. **Figure 2**[16] shows all three in a single Sankey diagram[17].

From **Figure 2**, it's clear that the "Energy" sector (values on the left) is the largest emitter that hydrogen has an opportunity to address (73%). The diagram conveniently breaks down the values by **source** (first column) and **end use / how** (middle column). For example, commercial buildings (end use 6.6%) uses both electricity (4.9%) and natural gas (1.7%), which informs us that for commercial buildings, electricity emissions are a far larger source of global emissions than natural gas.

Figure 2
*2016 Global GHG emissions by sector, end use, & gas (**Total 49.4Gt CO_2e**)* Source: Our World in Data



Thus, from **Figure 2** we identify the largest decarbonization opportunities for H_2.

- **Electricity generation & heat** (**30.4%**) – emissions from the combustion of primary fuels (i.e. coal, oil, natural gas) to generate electricity (vast majority) and heat (e.g. district heating) as a delivered utility. These are described as indirect emissions because no emissions are generated at the point of use.
- **Manufacturing, construction, & industrial processes** (**18.1%**) – these industrial sectors are responsible for electricity emissions (indirect), direct combustion emissions (fossil fuels burned onsite), and emissions through chemical processes. Note that this total excludes 11.6% indirect emissions from electricity consumed. Industrial processes are chemical processes used to produce products like cement, ammonia, and petrochemical refining. The portion of

[16] This figure is available as an interactive Sankey diagram

[17] This diagram is unavailable for 2021 but is still valuable in presenting a clear visualization of this data. A comparison to 2018 values indicates nearly identical percentages across all sectors.

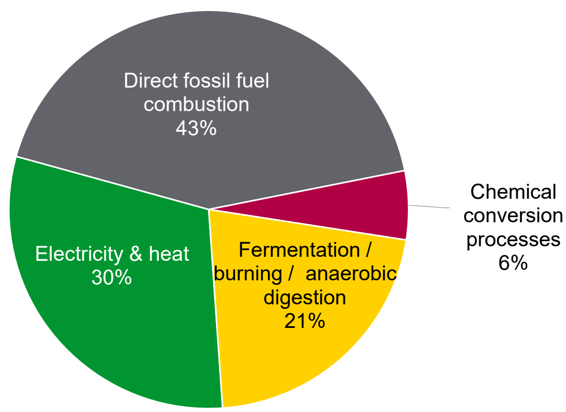
hydrogen production emissions from chemical processes is included in industrial processes.

- **Transportation** (**15.9%**) – mainly direct emissions from fuel combustion used in road transport, aviation, marine/ships, rail, and pipelines. Note that this excludes 0.4% from electricity used in rail and electric vehicles (EV).
- **Buildings (5.5%**) – commercial and residential buildings responsible for direct combustion emissions such as natural gas for heating (and to a much lesser extent cooking). Residential buildings make up 69% of direct emissions. Note that this total excludes 11.9% indirect emissions from electricity consumed.

Note that we didn't include "energy: fugitive emissions" (5.8%) even though it's slightly higher than buildings. Fugitive emissions are a consequence of extracting oil and natural gas and coal mining. These processes release gases like methane and in some cases this gas is deliberately burned (i.e. flaring). Hydrogen could indirectly reduce these emissions if hydrogen were to displace fossil fuels in the future.

If we recategorize the values in **Figure 2** according to whether they're produced by electricity generation (indirect), fossil fuel combustion (direct), organic processes[18] (direct) and chemical processes (direct), we arrive at **Figure 3**. From this figure we can see that direct fossil fuel combustion is a major opportunity to reduce emissions. However, unlike the centralized power plants, it becomes much more challenging to reduce direct combustion emissions because they're distributed over many end uses. This is why it's important to assess each end use.

Figure 3
2016 Global GHG emissions broken down by how they are produced



The following sections assess hydrogen's potential role in reducing emissions in each of these sectors. In addition, we also address data centers, a specific type of building which represents approximately 0.24%[19] of global emissions. However, data centers represent roughly 2% of total global energy consumption and is projected to increase as demand for compute and storage increase.

Electricity generation (30.4%)

Roughly a third of global emissions are from electricity and heat (**Figure 4**), and roughly 70%[20] of these emissions are from electricity generation. Therefore, if H_2 is to make a meaningful contribution to reducing GHGs in this sector, it must be through electricity generation.

[18] This includes the loss of grasslands/forests, crop burning, anaerobic digestion, fertilization, livestock manure, and decomposition of organic matter.

[19] Based on 2018 global energy consumption estimate of 205 TWh, using a global average emissions factor of 576 kg CO_2e/MWh (includes T&D losses), as a % of the total global emissions in **Figure 2**.

[20] Kevin A. Baumert, et. al., *Navigating the Numbers Greenhouse Gas Data and International Climate Policy*, 2005, p 60

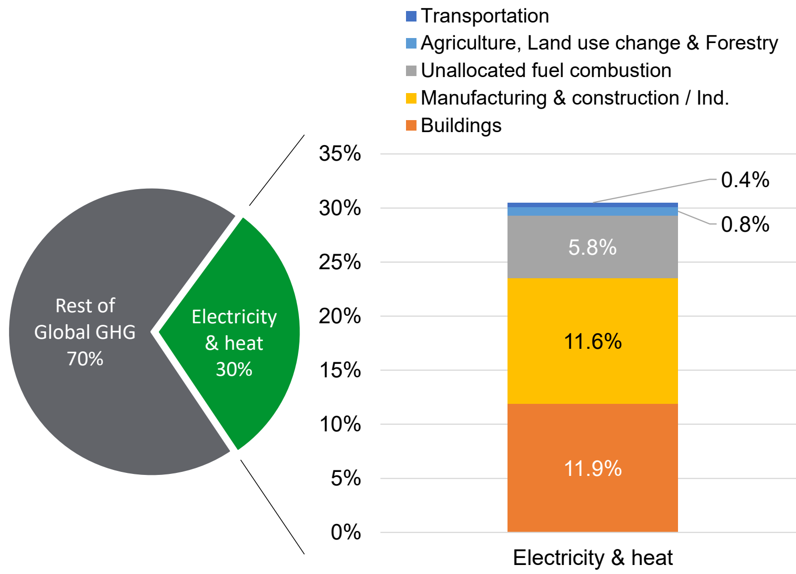


Figure 4
Breakdown of GHGs from electricity & heat

As of 2018, the global average generation mix was 38% coal, 23% natural gas, 10% nuclear, 3% oil, and 26% renewables. The 23% natural gas is the "easiest" fossil fuel hydrogen could begin to replace, but at a much higher cost of electricity **€0.115/kWh**, assuming a €2.47/kg price of H_2.[21] This is much higher compared to a November 2019 levelized cost of energy (LCOE) between **€0.036-0.056/kWh**[22] for natural gas combined cycle generation. And even higher if you consider current LCOE projections for solar **€0.02-0.03/kWh**.[8] As a reference, the world average electricity price for businesses is €0.10/kWh.

Given the high cost and low efficiency of producing green H_2 (70% in the future[23]), using it to produce electricity through combustion (i.e. as a direct natural gas replacement) is wasteful. Taking the global average efficiency ~30%[23] for natural gas-fired electricity generation, this amounts to an overall 21% efficiency (70% x 30%), not to mention the NOx emissions produced. Furthermore, as mentioned in the "Facts about hydrogen" section, as long as the electricity emissions factor is greater than 0.171kg CO_2e/kWh, it makes more sense to replace natural gas with grey H_2 because it has a *lower* carbon footprint than electrolyzed H_2. In the short-term blending H_2 into natural gas pipelines is an easy way of reducing emissions, albeit a minimal amount, because there are no major retrofits required for this.

A significant investment should go toward expanding solar and wind power generation capacity, with costs now below **€0.041/kWh** for both[24], and continuing to fall. One problem with this is that as more capacity is added, curtailment is likely to increase. Therefore, instead of curtailing renewable energy in times of oversupply, this overabundance of clean energy could be used to produce H_2 using electrolyzers. The closer the electrolyzers are to renewable energy generators, the less likely transmission network constraints will limit their utilization, allowing H_2 generation facilities to absorb 100% of all excess energy. **Figure 5** provides examples of curtailment percentages for different countries. This article also provides solar energy curtailment data. Upon generating and storing H_2, fuel cells could then be used to supply zero-carbon electricity to the grid when there's no sun or wind.

[21] Sonal Patel, *How Much Will Hydrogen-Based Power Cost?*, 2020

[22] 1 Euro = 1.22 US Dollars throughout this paper

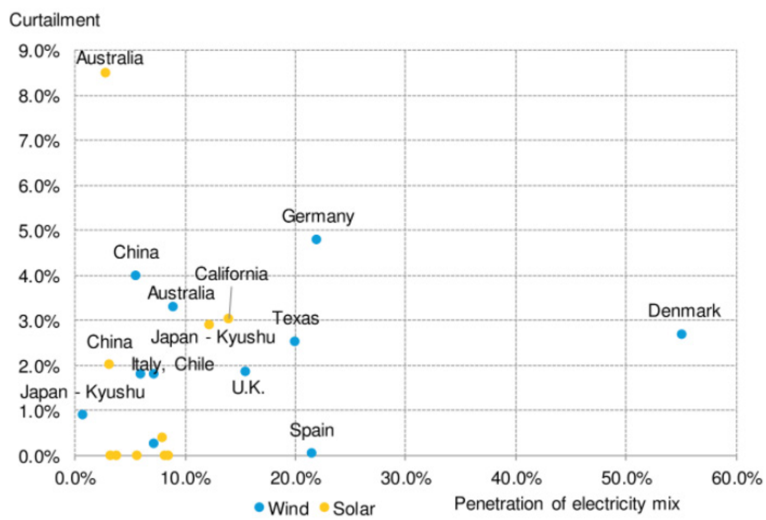
[23] From **Table 3**, future efficiency not including fuel cell and electric motor efficiency (95% x 90% x 82%)

[24] Douglas Broom, *5 charts show the rapid fall in costs of renewable energy*, 2020

In terms of land use, fuel cell plants consume much less than solar or wind. For example, the Hanwha Energy fuel cell power plant, currently the largest in the world at 50 MW, occupies 400 m^2/MW. When combined with the roughly 100 m^2/MW for the electrolyzer plant, a self-sustaining hydrogen fuel cell plant occupies roughly 40 times less space than a solar farm and roughly 270 times less than an offshore wind farm.[25] In terms of efficiency, a fuel cell / electrolyzer plant efficiency is ~30% today (includes electrical distribution losses). This 30% efficiency is roughly equivalent to the global average natural gas plant (including pre-combustion losses and distribution losses).[26] Fuel cell and electrolyzer efficiencies are further discussed in the transportation section.

Figure 5
Wind and solar curtailment for various countries

Source: Solar and Wind Curtailment: A Waste of Energy?



Alternatively, the H_2 produced through curtailment could play a complementary role in power generation - blending in green H_2 with natural gas lowers carbon output. However, power producers could also sell their H_2 supply to industry players depending on the pricing of their fossil fuel (e.g. natural gas) vs. H_2. A more challenging solution is to build out more nuclear plant capacity as a means of producing green H_2. **Ultimately, we believe the optimal use of hydrogen in this sector is to use it as energy storage to balance out intermittent renewable power.**

Manufacturing, construction, & industrial processes (18.1%)

Manufacturing & construction (12.4% - fossil fuel combustion) and industrial processes (5.6%) were combined in this section, representing total global emissions of 18.1%. To show a complete picture of emissions, we also broke out the "Electricity and heat" portion of these sectors (11.6%), shown in **Figure 6**. However, it's important to emphasize that hydrogen's role in reducing electricity generation emissions occurs at the generation plants NOT at manufacturing and industrial plants.

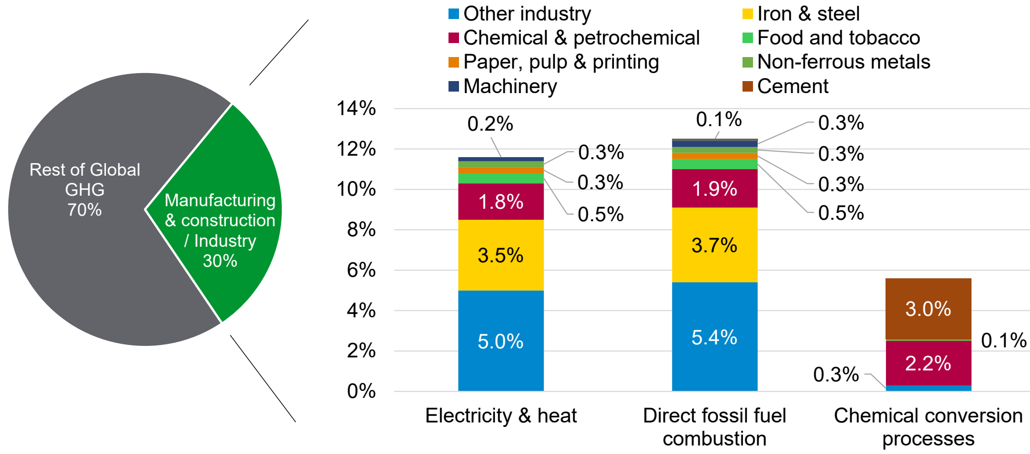
The two single largest contributors, chemical & petrochemical and iron & steel, represent 7.8% of global emissions (5.6% direct combustion & 2.2% chemical process), *nearly half* of the 18% total combustion and chemical process emissions from these sectors. H_2 is already used as a feedstock to Ammonia production (which is then used as feedstock to nitrogen-based fertilizers & nylon, etc.), food production, drug production, oil refining, steel production, and others. This makes feedstock substitution with green H_2 easy and simply dependent on price. Oil refining is another area

[25] Based on wind and solar farms and electrolyzer plant estimates from Green Hydrogen Cost Reduction

[26] This assumes a split of 65% natural gas (NG) combined cycle and 35% NG steam turbine plants. Pre-combustion eff. 89% and distribution eff 94%. Combined plant efficiencies are based on heat rates from page 18 of Environment Baseline, Vol 1: Greenhouse Gas Emissions from the U.S. Power Sector.

where easy substitution is possible for over 60% of global H_2 used, which is currently derived from natural gas.[27]

Figure 6
Manufacturing and industrial process emissions broken out by electricity, fossil fuel combustion, and chemical processes



Hard-to-abate industries like steel, cement, chemicals, and metals represent a large opportunity for hydrogen substitution of natural gas or coal for heating. The IEA states that the steel sector alone is the largest consumer of coal.[28] Steel is made from iron ore, but coke (distilled from coal) is used for both the chemical reaction and heat to produce steel.[29] Hydrogen can serve the purpose of both and significantly reduce emissions in the process.[30] Unfortunately, to take advantage of green hydrogen combustion in high-temperature (700-1,600°C) industrial applications (e.g. cement, steel, ethylene), new furnace designs are required and will likely require changes to the current production process[31]. Substitution in these cases will take significant time. In lower temperature applications, like food & beverage and pulp & paper, heat pumps could be used (using renewable electricity).

Transportation (15.9%)

As broken down in **Figure 7**, road transport represents 11.6% of global emissions (60% passenger / 40% heavy transport) followed by aviation (1.9%) and marine (1.7%). If H_2 is to have a material impact on this sector, it should be through road transport, mainly passenger and heavy road (i.e. trucking).

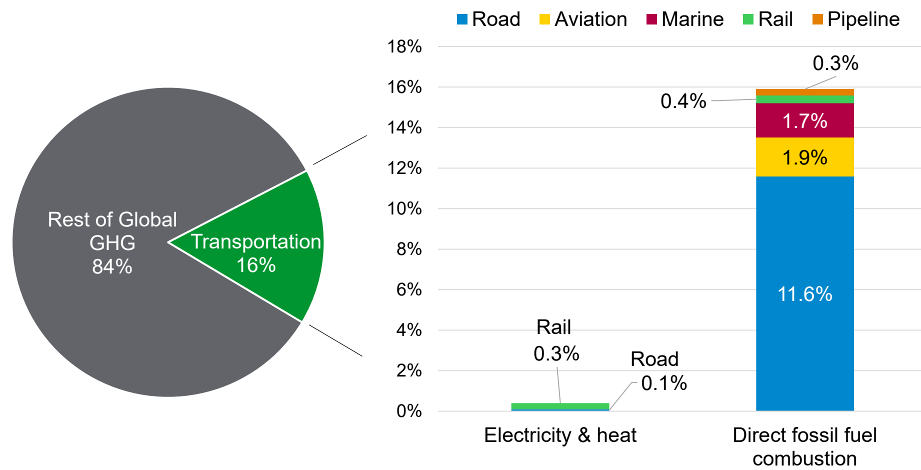
Passenger vehicles

There are two competing technologies – battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). New FCEVs available today use the proton-exchange membrane (PEM) fuel cell technology that uses hydrogen fuel. Most BEVs available today use li-ion batteries. These two technologies have key advantages and disadvantages. We provide a high-level assessment of each across four key criteria:

- Carbon emissions / efficiency
- End user lifecycle cost (capex and opex)
- Charging times and range
- Infrastructure cost

[27] IEA, *The Future of Hydrogen: Seizing today's opportunities*, 2019, p 89
[28] Iron and Steel Technology Roadmap
[29] Hydrogen Could Replace Coke In Steelmaking & Lower Carbon Emissions Dramatically
[30] How hydrogen could change the face of steel production as we know it
[31] Arnout de Pee, et al (McKinsey), *Decarbonization of industrial sectors: the next frontier*, 2018, p 7

Figure 7
Transportation emissions broken out by electricity and fossil fuel combustion



Carbon emissions / efficiency
There has been a significant increase in renewable electricity over the last 20 years. For example it represented 27% of all electricity in 2019. As regions and countries progress toward 100% renewable electricity, BEVs and FCEVs emissions will approach zero. Therefore, we assess the carbon emissions of FCEV and BEV using efficiencies (**Table 3**) and emissions factors (**Table 4**) based on current and future values. These system efficiencies are similar to a Frontier Economics study. Note that the PEM FC EV columns in **Table 4** assume the vehicle refuels in a station that produces H_2 on site which incurs the grid's transmission and distribution losses. A loss would have also been incurred had the H_2 been transported to the station.

Table 3
Efficiency comparison fuel cell EV vs. Li-ion EV

Step	Equipment	PEM FC EV (today)	PEM FC EV (future)	Li-ion bat. EV (today)	Li-ion bat. EV (future)
Electricity transmission	T&D	95%	95%	95%	95%
Use electricity to convert to H2	Electrolyzer	61%	90%		
Battery charge and discharge	Li-ion battery			86%[32]	88%[33]
H2 Compression and distribution	Compressor (700 Bar)	82%	82%		
Generate electricity on vehicle	Fuel cell in vehicle	60%	70%		
EV drivetrain	Electric motors	80%	90%	80%	90%
Grid to wheel efficiency		**23%**	**44%**	**65%**	**75%**

Table 4 shows the emissions factors for a BEV, FCEV Green, and FCEV Grey. The terms "FCEV Grey" and "FCEV Green" mean that the fuel cell uses grey and green H_2 to generate the electricity. These emissions factors represent the carbon emissions generated per kWh of electric motor output. The table assumes a 2018 global electricity generation mix resulting in an emissions factor of 0.543 kg CO_2/kWh of electricity generated and a 2050 fuel mix resulting in 0.135 kg CO_2/kWh. These factors largely determine the carbon footprint of battery charging and green H_2 production that power the respective EVs. Based on **Table 4** we conclude that **with a 2018 emission factor, it doesn't make sense to drive a FCEV using green H_2. The FCEV with electrolyzed H_2 has almost three times the emissions of the BEV.**

[32] K Mongird, et al, *Energy Storage Technology and Cost Characterization Report*, 2019, p 4.4

[33] IRENA, *Electricity Storage and Renewables: Cost and Markets to 2030*, 2017, p 77

But the emissions from the BEV and FCEV Grey are comparable. **With a 2050 emission factor, an FCEV Grey produces three times the emissions of a BEV and almost twice the emissions of an FCEV Green.** Finally, the last row provides electricity emissions factors needed to reach emissions parity with an FCEV Grey.

Table 4
Emissions factors (carbon generated) per kWh of electric motor output for BEV and FCEV

Factor	2018			2050		
	BEV	FCEV Green	FCEV Grey	BEV	FCEV Green	FCEV Grey
CO_2 emissions produced per kWh of EV motor output (kg CO_2 / kWh elec)	0.831	2.38	0.711	0.179	0.306	0.541
Global electricity generation emissions factor needed for parity with grey H_2 (kg CO_2 / kWh elec)	0.464	0.162		0.407	0.239	

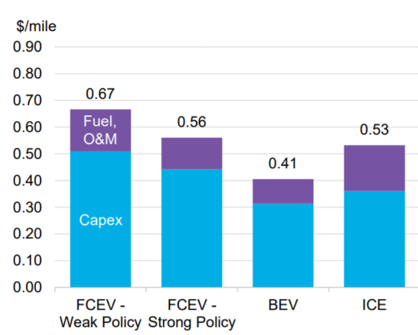
Of course, these emissions factors are based on global electricity generation mix and the results will change based on the proportion of renewable electricity a region or country has. The point is to show that it's not so simple to suggest that BEV or FCEV is the solution for lower emissions *TODAY*, however, in the *FUTURE*, BEVs will still be significantly more efficient than FCEVs (as shown in **Table 3**) and it is certain that there will be more renewable electricity available which favors BEVs from both a carbon emissions and efficiency perspective.

End user lifecycle cost (capex and opex)
The average capex for a 2021 BEV in the US is €32k vs FCEV €49k[34] (excluding luxury models). Though this represents a 51% premium over BEV, this price difference is expected to moderate as more models make it onto the market. To put this in perspective, Kelley Blue Book announced in September 2020 that the average transaction price for a light vehicle was €31,830.

Opex includes maintenance and fuel costs. Fuel costs are €2/100 km for BEV vs. €12/100 km ($14.4/62 miles) for H_2 (current prices).[9] Furthermore, green H_2 FCEVs are more sensitive to electricity prices than BEVs, due to the inherent round-trip inefficiency of hydrogen production and hydrogen conversion to power (via fuel cell). BEVs are nearly three times more efficient than FCEVs. Another way of measuring fuel costs is by the kilogram, which is typically how it's purchased. Current costs are roughly €9.86/kg which equates to about $6 per gallon of gasoline. By 2030 this H_2 cost is projected to be competitive with gasoline according to University of California, Irvine researchers.[35] In terms of TCO, **Figure 8** shows the TCO for FCEV and BEV in 2030 with FCEVs having a 37% TCO premium over BEVs, under the "Strong Policy" scenario and 63% under "Weak Policy". ICEs are also predicted to have a 29% TCO premium over BEVs.

Figure 8
TCO in 2030 between FCEV, BEV, and internal combustion engines (ICE)

Source: Bloomberg NEF, Hydrogen Economy Outlook - Key Messages, 2020



[34] Includes 5 models Honda Clarity, Toyota Mirai XLE & Limited, Hyundai NEXO Blue & Limited

[35] Susan Carpenter, *Meet the Other Kind of Electric Car: Hydrogen Fuel Cell EVs, 2020*

Charging times and range

Charging times are a key requirement for owners which makes FCEVs attractive in this regard. It currently takes 3-5 minutes to refuel a FCEV but recharge times for BEVs can range from 30 minutes to 30 hours, depending on the BEV model and battery charger capacity.[36] BEV makers realize this is a barrier and we can expect to see significant reductions in charging times. For example, Volkswagen aims to reduce recharge times to about 12 minutes at 70% of charge.[37] In terms of range, the average range of five FCEVs currently in production from Honda, Hyundai, and Toyota is 596 km (371 mi) compared to an average of 461 km (287 mi) for 44 BEVs currently in production. The average FCEV has about 20% higher range. In terms of maximum ranges, the Tesla Model S Plaid+ currently has the highest range 837 km (520 mi) vs. 647 km (402 mi) for the Toyota Mirai XLE FCEV.

Infrastructure cost

BEV charging station costs depend on the charger capacity and the number of chargers. A single 1.3 kW charger can cost €3,288 installed while a 350 kW charger is €164,400.[38] The cost declines with multiple chargers installed per site. For example, six chargers can range from €16,440 (1.3kW) to €817,000 (350kW).

FCEV refueling stations are significantly more expensive. For example, stations that depend on delivery of gaseous H_2 can cost about €1.64 million, with liquid H_2 can cost about €2.3 million, and can get even more expensive for those stations that generate their own H_2 (€2.63 million).[39] While this higher cost will make it more challenging to scale the sales of FCHV, they don't need as many given their longer range.

Heavy-road transport

The primary issues in this category are range and recharging capability, however public transportation is less susceptible to these issues given the high percentage of urban buses in certain European cities.[40] Though the medium and heavy-duty sector only represent 4% of the vehicle fleet, it represents 25% of vehicle fuel use annually.[41] The main issue put forth by Hydrogen proponents is the lack of battery suitable for heavy transport. However, there is progress on battery technologies. The Rocky Mountain Institute issued a detailed 2019 study[42] on new technology developments. This study demonstrates that:

1. Li-ion energy density is likely to double in the coming decade (from 200 Wh/kg to 400 Wh/kg), halving the weight (and the cost) for a similar range or doubling the range for the same weight.
2. Alternative technologies such as solid-state batteries could quadruple density (up to 800 Wh/kg).

Apart from battery technology advances, fuel cells may struggle to account for a large portion of the heavy road transport sector according to Auke Hoekstra, senior advisor smart mobility at the Eindhoven University of Technology. His main points:[43]

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[36] InsideEVs, *Let's Look At Charging Times For Some Of Today's Popular Electric Cars*, 2019

[37] James Frith, *VW's 'Power Day': The Impacts, 2021*

[38] Michael Nicholas, *Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas*, 2019

[39] California Fuel Cell Partnership

[40] Sustainable Bus, *In Denmark, Luxembourg and Netherlands over 2/3 of bus registrations are ZE*, 2021

[41] U.S. DOE, *Department of Energy Hydrogen Program Plan, 2020*

[42] Rocky Mountain Institute, *Breakthrough Batteries: Powering the Era of Clean Electrification*, 2019

[43] Clean Energy Wire, *Battery-electric trucks will win race against fuel cells and e-fuels*, Nov. 2020

- Most trucking distances are within battery-powered capabilities. Regulations limit the amount of miles truck drivers can drive in a single day. For example, in the Netherlands, 80% of trucks travel a maximum of 750 km (466 miles) per day at the very most. This tends to be higher in the U.S. at 1,046 km (650 miles). Companies could easily increase this distance by adding a second driver but this is generally cost-prohibitive. Other countries have similar limits, but his point is that the majority of miles driven by heavy road transport are within reach of battery technology. The remaining 20% longer-distance routes represent a “niche” opportunity for fuel cells.
- Long-haul trucks would need to carry 100% of the required hydrogen fuel. The requirement to switch trailers means that the truck must carry all its fuel, a challenge given the large gaseous H_2 footprint compared to diesel. At 690 bar and 25C, H_2 requires over 8 times the volume compared to diesel. Alternatively, trailers could be designed to carrying extra hydrogen fuel.
- Most trucks return to base. Unlike long-haul routes, Hoekstra contends that the majority of trucks return to their base where they can charge their batteries overnight.

Marine and aviation

There’s a very low probability of hydrogen directly fueling long-distance ships due to the low storage density given the high premium of cargo space. Work is currently underway in marine applications like cargo ships and tankers to either retrofit existing engines or develop new internal combustion engines that can run off of ammonia fuel made with green hydrogen.[44] In addition to the engine, stakeholders must ensure the entire supply chain can meet the safety, economic, and regulatory requirements in order to make ammonia fuel a reality. Until this happens biofuel may be the best choice to lower marine carbon emissions in the short-term.[45]

Aviation poses an even bigger challenge in terms of optimizing passenger / cargo space around a carbon-free fuel source. For example, the cost of a Boeing 777-300 freighter is over 1,500 times that of an ultra large container ship, per cubic meter of cargo capacity. Therefore, it’s even less likely to see this mode of long-haul transportation reduce its cargo space in exchange for a lower-carbon power plant and drivetrain. It’s more likely that large planes use biojet kerosene and synthetic jet kerosene, of which hydrogen is a feedstock. By 2050, the IEA forecasts that 45% of total aviation fuel consumed will be biojet kerosene and 30% synthetic hydrogen-based fuels.[46] These sustainable aviation fuels (SAF) are drop-in replacements to current jet engines.

Buildings (5.5%)

Buildings emissions come largely from electricity consumption (indirect) and fossil fuel combustion (direct). To show a complete picture of emissions, **Figure 9** breaks out the direct emissions (5.5%) and indirect emissions (11.9%). Note that the 17% value in **Figure 9** is a percentage of **all** sectors and **all** GHGs which appears lower than other publications which quote values of 28%. This is mainly because these higher percentages are based off only **energy-related** sectors and only CO_2. Adjusting for these two factors, **buildings represented 27% of global energy-related CO_2 emissions in 2016**. Furthermore, some buildings values also include about 10% energy-related emissions from the buildings construction industry for a total of

[44] Jonathan Lewis, *Zero-carbon fuels and marine shipping: Both a will and a way?*, 2021

[45] Eric C. D. Tan et. al., *Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses*, 2021

[46] IEA, *Net Zero by 2050, A Roadmap for the Global Energy Sector, 2021*, p 136

37% of energy-related emissions in 2016. **Figure 10** provides more granularity of this breakdown by showing the split between electricity and district heating. As with previous sectors, hydrogen's role in reducing electricity generation emissions occurs at the generation plants NOT in buildings. This leaves H_2 with the opportunity to eliminate 5.5% of GHG emissions from direct fossil fuel combustion in buildings, most of which are a result of heating buildings.

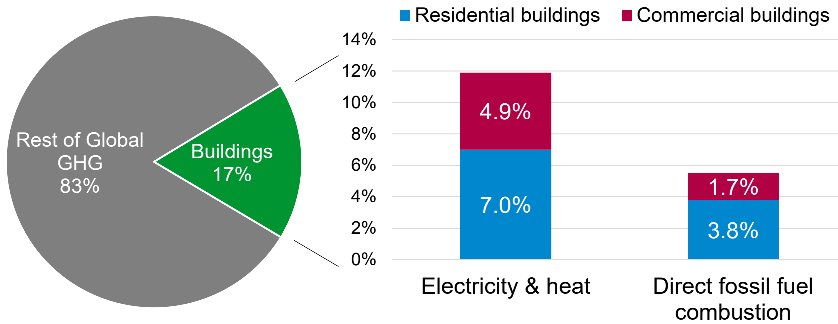

Figure 9
Building emissions broken out by electricity and fossil fuel combustion

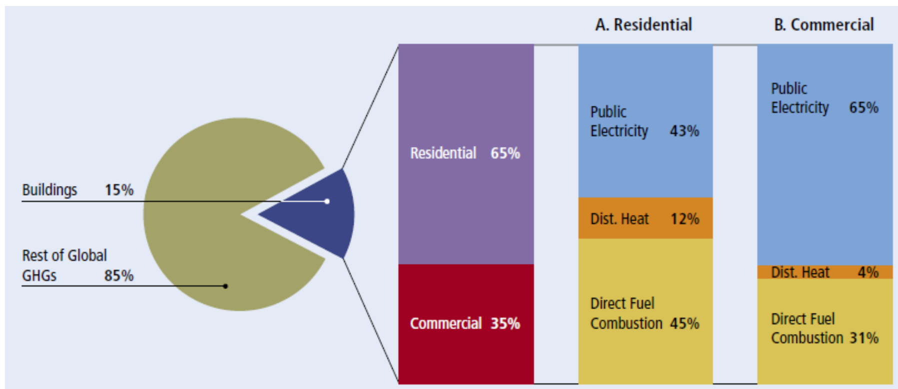

Figure 10
Further breakdown of building use emissions by electricity, district heat, and direct fuel combustion (year 2000)

Source: *Navigating the Numbers Greenhouse Gas Data and International Climate Policy*

Two proposed methods of reducing GHG emissions for building heat include:

- Replace natural gas with hydrogen
- Use heat pumps

Replace natural gas with hydrogen

This seems like the easiest solution because most people believe that hydrogen can simply use the same piping distribution as natural gas (NG). Unfortunately, this is not the case. While blending up to 15% hydrogen in existing NG pipelines happens today, 100% hydrogen requires special piping to prevent piping degradation and minimize leakage.[47] In addition, hydrogen cannot be used in existing furnaces and boilers. Blending is perhaps the best solution because it doesn't require retrofits and **does** lower the carbon footprint. Finally, burning H_2 does not produce CO_2, but it does produce NOx, as discussed earlier in this paper. Furthermore, because natural gas has three times the energy of hydrogen at sea level, one would need three times the volume of hydrogen to heat the same space as natural gas. This doesn't even account for the electrolysis energy required to produce the H_2. Couple this with the significantly higher cost of hydrogen, and it's fair to say that converting natural gas utility grids to 100% hydrogen and using it to heat buildings doesn't make sense.[48]

[47] U.S. DOE, *Hydrogen Pipelines*

[48] Recharge, *Why using clean hydrogen for heating will be too difficult, expensive and inefficient*, 2021

While burning hydrogen is less than ideal, there is also the option of using fuel cells for power and hot water. There has been some movement in using residential fuel cells in some countries. For example, Japan has over 300,000 fuel cells operating in residential buildings.[49]

Use heat pumps

A heat pump is basically an air conditioner operating in reverse. It uses electricity and a refrigerant compressor to transfer heat. If you imagine the inside of your refrigerator is the outdoors, that will come close to a heat pump because it transfers the heat from the outdoors to the indoors. Heat pumps are also very efficient because they don't have to generate heat by combusting a fuel. Moving heat energy is much less energy intensive than converting chemical energy into thermal energy. The metric used to measure the effectiveness of this heat transfer is known as coefficient of performance (COP), heat transferred divided by input energy. These values range depending on the outdoor temperature and indoor temperature, but on average the COP is above 2, meaning that heat pumps transfer more than 2 watts of heat for every 1 watt of electricity it consumes. On average, heat pumps are over 3 times more efficient than natural gas boilers (3 times more energy consumed).[50] **Figure 11** provides a building heating system efficiency comparison. Some heat pumps can also operate in cooling mode in the summer, which means the same system can heat and cool a building as opposed to requiring two separate systems. For more information on heat pumps and other heating systems, see White Paper 504, "*Factoring Carbon Pricing into Business Decisions: A Building Heating Case Study*".

In those applications (<10%) where direct electrification presents challenges, district heating or a biogas furnace may suffice.[51] In addition to these hydrogen headwinds, increased costs for H_2 safety infrastructure and safety regulations are likely, in order to overcome public resistance.[8] For information on cost competitiveness of heat pumps vs. oil and gas heating systems, see White Paper, *Building Heat Decarbonization: Practical pathways for decarbonizing the heating of buildings by 2050*.

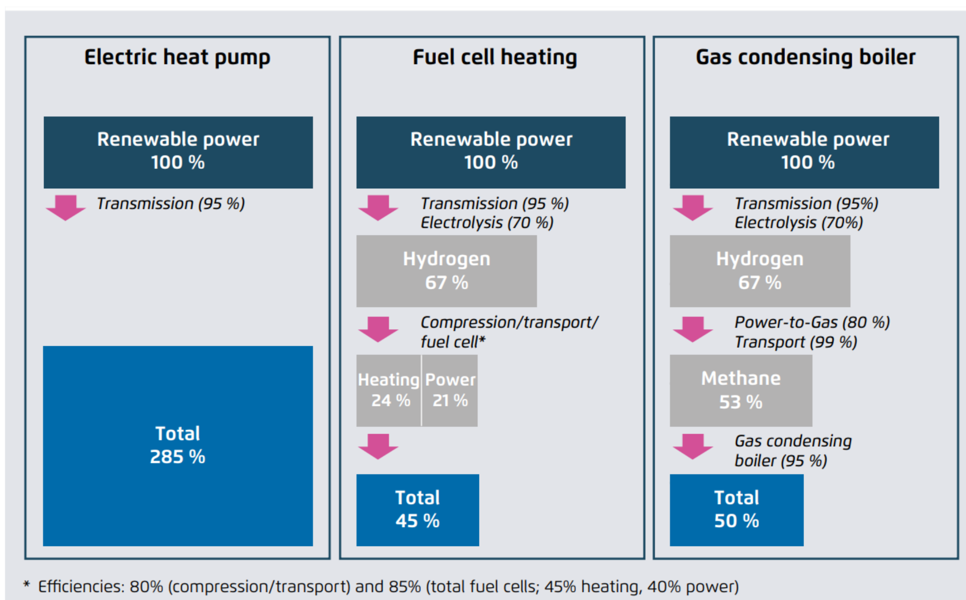

Figure 11
Heating system comparison

Source: The Future Cost of Electricity-Based Synthetic Fuels, p 13

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[49] U.S. DOE, *Department of Energy Hydrogen Program Plan*, 2020, p 30

[50] Based on water-source heat pump across 8 climate zones using Building Heating Method Calculator

[51] Bertrand Deprez, Thierry Djahel, et. al., *Hydrogen – Europe case*, October 2020

Data center (0.24%)

By some estimates, current data center energy consumption represents 1-2% of total global energy consumption.[52] Despite this, data centers represented only 0.24% of 2018 global GHG emissions. Since data centers consume nearly all of their energy as electricity, GHG emissions will tend to improve over time as more renewable electricity comes online. However, data center operators of large cloud and service providers continue to decarbonize because of regulations, brand reputation, and in some cases to lower operational costs. Onsite standby generators are one area that represent a risk for data centers, most significantly in terms of regulatory restrictions (unable to secure permitting to run diesel generators), but also with regards to public perception. Alternatives to diesel generators include:

- Genset elimination – No genset – rely on reliable 2N HV substations
- Genset replacement – with zero carbon alternatives like fuel cells and green H_2
- Genset use minimization – Using li-ion as a bridge for the "first few" hours during grid outage

Genset elimination appears to be a good strategy for developed electrical grids where there's a very low statistical probability that power from both HV stations will fail simultaneously. Genset replacement with H_2 fuel cells is a potentially beneficial option which has led some companies like Google and Microsoft to investigate this solution. A preliminary analysis from the National Renewable Energy Laboratory (NREL) estimates that for runtimes above 12 hours, a hydrogen fuel cell has a lower levelized cost of energy (€/kWh) than li-ion batteries.[53] While the capital cost of batteries may not make it feasible to purchase days of runtime, they do allow the potential to carry a data center through nearly all outages. Statistically most outages are less than 24 hours and for longer outages, natural gas generators could still be used. **Table 5** provides pros and cons of a battery energy storage system (BESS) compared to a hydrogen fuel cell solution.

Table 5
Li-ion and hydrogen pros and cons

Source: The Pros and Cons of Hydrogen Fuel Cells as Backup Generators

	Li-ion BESS for generator replacement	H_2 fuel cell for generator replacement
Pros	• High system efficiency >85% • Lower operating cost • No moving parts like generators • Financially feasible for 4-12 hour runtimes • Zero carbon footprint means no runtime restrictions • Quiet and no moving parts like generators	• Lower capital cost at longer runtimes than li-ion batteries – extra runtime requires only more H_2 • Capable of long runtimes • Zero carbon footprint means no runtime restrictions • Standby operation allows time to generate H_2 • Quiet and no moving parts like generators • On-site production wouldn't require H_2 delivery
Cons	• More expensive for long runtimes (e.g. 1 day) • Higher capital cost – more runtime = more batteries • Cobalt becoming more difficult to obtain	• Higher operating cost • Efficiency degrades over times • Requires onsite H_2 generation plant for higher availability • Fuel cells don't handle step loads • Low system efficiency ~40%

[52] Masanet, Shehabi, Lei, Smith, Koomey, *Recalibrating global data center energy-use estimates*, 2020

[53] Michael Penev, Et al, NREL, *Energy Storage: Days of Service*, 2019, p 10

Where H_2 makes sense

Based on the research provided in this paper, we believe hydrogen makes sense in the following areas from environmental standpoint, and in the long-term could become financially competitive with traditional solutions.

- As a means of absorbing curtailed renewable grid energy to produce hydrogen and electricity via H_2 fuel cells during periods of high electricity demand and low solar and wind supply.
- As a feedstock substitution for industrial processes, notably for chemical & petrochemical and iron & steel.
- As a substitute for the grey H_2 used in ammonia production. Ammonia is produced by combining H_2 and nitrogen at high temperature and pressure.
- As a feedstock for hydrogen-based liquid fuels used in cargo ships (ammonia-based fuel) and in aviation (synthetic jet kerosene).

Where H_2 does not make sense

Based on the research, we believe the following alternative solutions to H_2 are better for the environment and cost effective compared to hydrogen solutions.

- As a fuel for traditional power generation plants. Given the inefficiencies of producing hydrogen, it doesn't make sense to combust it in order to generate electricity. Excess hydrogen is better off being stored and used to feed fuel cells for electricity generation during periods of low renewable generation.
- As a fuel for passenger (light duty) vehicle transportation (cars). BEVs have a significant head start on commercialization and consumer acceptance. Battery technology research is putting downward pressure on price and energy density, making it difficult for fuel cells to overcome price and efficiency headwinds posed by the physics of producing H_2.
- As a fuel for short distance heavy vehicle transportation (i.e. trucks that return to base).
- As a fuel for heating buildings. Heating buildings by combusting H_2 has similar limitations to those mentioned in the first bullet (power generation). Heat pumps are significantly more efficient and can both heat and cool a building vs. using an air conditioner and combustion heating system.

Where H_2 is debatable

The research available for hydrogen use in the certain areas is not definitive enough. Therefore, we believe the following uses for hydrogen are debatable.

- As a means of data center diesel generator replacement if fuel cell costs decrease.
- As compressed gaseous fuel for busses and long-haul trucks.
- As a substitute for natural gas or coal for heating in hard-to-abate industries like steel and cement. Other measures may make more sense like process improvements and the use of electric furnaces. Given the high heat requirements for producing clinker (1,450°C), the key ingredient to of cement, biofuel or electric furnaces may be a better choice.

Conclusion

When it comes to addressing global warming, perhaps the most agreed-upon conclusion is that there is no single solution to the problem. Instead, we believe that the best solutions are those that can most effectively reduce the largest contributors to greenhouse gas emissions (CO_2eq). Green hydrogen has a significant role to play in global decarbonization. In the zero-carbon economy of 2050, clean electricity is projected to become the dominant vector to decarbonization, supplying 68% of global energy complemented by 17% hydrogen and hydrogen-derived fuels.[54]

Today, hydrogen is mainly used as an ingredient or catalyst in chemical processes and refining. In the future when significant clean power capacity comes on-line (wind, solar, nuclear, hydro), hydrogen will likely be used in industrial applications that need a very high temperature heat source like the iron and steel industry. Another likely future application will be long duration transportation including marine vessels and aviation. Ongoing debate will continue for applications including urban transportation, trucking, a back-up power source for data centers, and primary and back-up grid power. Where hydrogen is unlikely is in light duty vehicles like automobiles and building heat where it cannot compete with electric solutions on cost and efficiency.

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[54] Energy Transitions Commission, *Making the Hydrogen Economy Possible – Accelerating Clean Hydrogen in an Electrified Economy*, 2021, p. 13

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