CleanEnergyGroup

The Colors of Hydrogen Production: Emissions, Costs, and Concerns

Currently, hydrogen production is dominated by fossil fuels and used mostly in chemical manufacturing and petroleum refining. Newer hydrogen production technologies have been receiving increased interest, and proposals for new end uses are growing. It is important to consider the emissions, costs, and environmental impacts of these different types of production, especially when discussing hydrogen's role in decarbonization.

Hydrogen is a colorless gas that can be produced through a wide range of methods that use a variety of raw materials or "feedstocks," such as coal, natural gas, and water. Different production processes for hydrogen gas result in distinct byproducts like carbon dioxide, solid carbon, and oxygen. These differing processes are often assigned a color, which aids in quick identification but can obscure details about the emissions and impacts of each process. Understanding the full environmental, economic, and social implications of each type of hydrogen production is crucial in determining its role in the energy landscape.

Grey Hydrogen

- **How it's made:** Grey hydrogen is the most widely produced type of hydrogen, making up over 75 percent of hydrogen production globally (source). Grey hydrogen is produced mainly through methane reforming, a process in which methane reacts with steam in a high-temperature and high-pressure environment to produce carbon dioxide and hydrogen. Two common forms of methane reforming are steam methane reforming and autothermal reforming. The methane reforming process typically relies on natural gas as a feedstock (source). Methane reforming commonly boasts an energy efficiency rate (i.e., energy in versus usable energy out) of 60 to 85 percent, however this number can decrease to just 38 percent when looking at the entire supply chain (source 1, source 2).
- **Carbon intensity:** Grey hydrogen is extremely carbon intensive, producing up to 13 kilograms of carbon dioxide equivalent emissions (kg CO_2e) per kilogram of hydrogen (source). The carbon intensity of grey hydrogen production increases if the full supply chain is considered, as fugitive methane emissions from the extraction and transportation of natural gas could add more than 5.2 kilograms of CO_2e emissions per kilogram of hydrogen produced. Current global grey hydrogen production results in 830 metric tons CO_2e emissions per year (source).
- **Cost:** The cost of grey hydrogen production varies depending on fluctuating natural gas prices, generally ranging between \$0.67 to \$1.31 per kilogram of hydrogen produced, making it the least expensive production method (source).
- **Other environmental concerns:** Grey hydrogen production doesn't just emit greenhouse gases. Air pollutants like fine particulate matter, nitrogen oxides, and volatile organic compounds are also released into the surrounding environment during grey hydrogen production, increasing risk of respiratory illness, cancer, and premature death for nearby neighborhoods (source).

Black/Brown Hydrogen

- **How it's made:** Black/brown hydrogen, often a subcategory of grey hydrogen, is produced through coal gasification of lignite (brown hydrogen) or bituminous (black hydrogen) coal. In 2023, 23 percent of global hydrogen production was through coal gasification (source). Coal gasification is a series of three chemical processes whereby coal reacts with air and steam in the presence of heat to produce hydrogen and carbon dioxide.

— continue on page 3 —

The Hydrogen Production Color Chart

		Raw material (feedstock) and process	Direct global warming impacts	Additional global warming impacts[2]	Other environmental concerns	% of global production in 2023	Cost[3]	Role in decarbonization
HIGH PRODUCTION	Black Hydrogen	**Coal** gasification	19 kg of CO_2 equivalent emissions per kg of hydrogen	Coal mining results in significant methane emissions	Groundwater and air pollution	23.1%	Low	Should be phased out of current end uses that include petroleum refining and ammonia production
HIGH PRODUCTION	Grey Hydrogen	**Methane**[1] reforming	13 kg of CO_2 equivalent emissions per kg of hydrogen	Significant methane leaks throughout the natural gas supply chain	Groundwater and air pollution	75.5%	Low	Should be phased out of current end uses that include petroleum refining and ammonia production
LIMITED PRODUCTION	Blue Hydrogen	**Methane**[1] reforming + Carbon capture and storage (CCS)	Carbon capture rates are low, only reducing CO_2 emissions by ~10% compared to grey hydrogen	In addition to natural gas supply chain leaks, CO_2 pipelines and storage facilities will leak	CCS equipment can increase local air pollution from methane reforming	1.2%	Medium	Should be phased out of current limited production due to carbon intensityas CCS is innefective at scale
LIMITED PRODUCTION	Green Hydrogen	**Water** electrolysis using renewable electricity	No direct emissions from production	Would result in high indirect emissions if renewable energy is diverted away from the grid	Very energy and water intensive	0.1%	High	May have limited relevance in difficult to decarbonize industries, however many current end-use proposals (including energy production) are not feasible
DEMONSTRATION ONLY	Turquoise Hydrogen	**Methane**[1] pyrolysis	No direct emissions from production	Significant methane leaks throughout the natural gas supply chain	3x the amount (by weight) of solid carbon is produced compared to hydrogen	0	Medium	No feasible future uses due to significant natural gas use and carbon intensity
DEMONSTRATION ONLY	Pink Hydrogen	**Water** electrolysis using nuclear electricity	No direct emissions from production	Would result in high indirect emissions if nuclear energy is diverted away from the grid	Very energy and water intensive	0	High	No feasible future uses due to high cost and limited technological maturity

1 Hydrogen itself is an indirect greenhouse gas whose purposeful or accidental release into the atmosphere can lead to significant global warming. See Clean Energy Group's fact sheet on hydrogen's global warming impacts.
2 Typically natural gas
3 Cost is compared to other types of hydrogen production. Cost of hydrogen production of any kind is high compared to other forms of energy and fuel.

CleanEnergyGroup
MAY 2025

- **Carbon intensity:** Producing hydrogen through coal gasification is even more carbon intensive than using natural gas, producing 19 kg CO_2e per kg of hydrogen produced (source).
- **Other environmental concerns:** Mining coal for hydrogen production adds to the harms of this process through groundwater and air pollution, land degradation, and additional greenhouse gas emissions (source).

Blue Hydrogen

- **How it's made:** Blue hydrogen follows the same production process as grey hydrogen: methane reforming. But in this case, the reforming process is paired with carbon capture and storage (CCS) technologies. The energy needed to run CCS reduces the efficiency of the process to around 70 percent, though when considering the full supply chain from extraction to end use, the efficiency drops to 37.5 percent (source 1, source 2).
- **Carbon intensity:** Although the industry has made claims that CCS can capture 95 percent of the CO_2 emissions at the point of production, existing projects have consistently failed to achieve capture rates of more than 80 percent, with many of them falling far short of achieving even that number (source). Upstream methane emissions rates for blue hydrogen exceed that of grey hydrogen due to additional natural gas required to power the CCS, contributing to a mere 9 to 12 percent reduction in total emissions when compared to grey hydrogen production (source).
- **Cost:** Blue hydrogen production costs also fluctuate as a result of natural gas prices, but the addition of CCS raises the price to $1.69 to $2.55 per kilogram of hydrogen produced (source).
- **Other environmental concerns:** Transportation and long-term storage of the captured carbon dioxide introduces additional challenges and safety concerns. Multiple CO_2 pipelines and storage facilities have seen leakages and ruptures in the past, bringing into question the feasibility of perpetual CO_2 storage (source 1, source 2, source 3).

Turquoise Hydrogen

- **How it's made:** Turquoise hydrogen is made through methane pyrolysis, a process that exposes methane to high temperatures and splits it into hydrogen and solid carbon (source).
- **Carbon intensity:** While turquoise hydrogen does not produce CO_2 as an end product, methane pyrolysis uses 79 percent more methane compared to steam methane reforming, greatly increasing the amount of fugitive methane emissions released during gas extraction and transportation and leading to a higher overall greenhouse gas emissions rate compared to grey and blue hydrogen production (source).
- **Other environmental concerns:** Producing turquoise hydrogen results in three times the amount of solid carbon by weight than hydrogen produced (source 1, source 2). The economic viability of turquoise hydrogen production partially relies on the solid carbon market and the ability to sell this by-product to industries marked by air and water pollution, like rubber manufacturing (source).

Green Hydrogen

- **How it's made:** Green hydrogen is produced through the electrolysis of water, a process that uses renewable energy to split water molecules into hydrogen and oxygen (source). Alkaline and protein exchange membrane (PEM) electrolysis are the two most common methods to produce green hydrogen.
- **Carbon intensity:** Green hydrogen production diverts renewable energy sources, like wind and solar power, away from more beneficial direct decarbonization uses—such as replacing fossil fuel power plants with clean electricity generation. Deploying renewable electricity directly onto the grid results in two to five times more emissions reductions per kilowatt-hour compared to the benefits of replacing grey hydrogen production with green hydrogen (source). If green hydrogen is produced without the addition of new renewable energy sources to power it, its CO_2e emissions could be up to three times higher than grey hydrogen production (source). Even when green hydrogen is produced through newly built renewable energy sources, its climate beneficial applications are sparse (source 1, source 2).
- **Cost:** Green hydrogen can be expensive, costing up to $7.39 per kilogram of hydrogen produced (source).
- **Other environmental concerns:** While green hydrogen may claim to have a lower carbon intensity than many other production methods, it is extremely water and energy intensive. One kilogram of green hydrogen requires 2.6 gallons of purified water and 53 kilowatt-hours of energy (source 1, source 2).

Pink Hydrogen

- **How it's made:** Pink hydrogen is produced through water electrolysis by using nuclear power to split water molecules into oxygen and hydrogen. Pink hydrogen only differs from green hydrogen in that the process is powered by nuclear energy instead of renewables like solar and wind (source). There are very few operational pink hydrogen plants globally, but interest in the production pathway and plans for demonstration projects are on the rise (source).
- **Cost:** Nuclear energy is more expensive than solar and wind, so pink hydrogen can be more costly than green hydrogen. Heat is a waste product of nuclear power production, and producing hydrogen through high-temperature electrolysis or thermolysis (sometimes referred to as purple or red hydrogen) could bring down the price significantly (source).
- **Other environmental concerns:** Pink hydrogen production results in similar water and energy use concerns apparent in green hydrogen production and similarly diverts nuclear energy away from decarbonizing the grid, potentially increasing fossil fuel powered energy generation. Any project involving nuclear power increases the risks associated with nuclear waste disposal, radioactive contamination, and nuclear proliferation (source).

Other Colors

- **White hydrogen** is geologic hydrogen, naturally occurring through oxidization processes in iron-rich rock formations below the earth's surface. The prevalence and availability of natural hydrogen is uncertain, though it is the subject of continued research (source).
- **Gold hydrogen** can also refer to geologic hydrogen (source). It sometimes refers to the production of hydrogen through injecting water and microbes into depleted oil and gas wells, employing fermentation to produce hydrogen. This production method is still in its early stages of development (source).
- **Orange hydrogen** refers to the acceleration of natural hydrogen production through the injection of water into iron-rich rock formations (source). It also occasionally refers to hydrogen produced from plastic waste or biomethane (source 1, source 2).
- **Yellow hydrogen** either refers to hydrogen created through electrolysis powered by energy from the grid or to electrolysis powered by solar energy (source 1, source 2).

As more research arises on the viability of hydrogen for decarbonization, and with billions of dollars in federal funding available to support its development, it is important to remember one crucial fact: **hydrogen is an indirect greenhouse gas, whose accidental leakage or purposeful venting into the atmosphere could have grave consequences for global warming**. (See this Clean Energy Group fact sheet for more information.) An accurate lifecycle analysis of any type of hydrogen production must consider the global warming potential of hydrogen itself, although few do. Whether grey, blue, green, turquoise, or pink, hydrogen production has the potential to thwart true climate solutions like electrification and to perpetuate the continued harms of the fossil fuel industry at the expense of the climate and human health.

CleanEnergyGroup

To learn more about other harms associated with hydrogen's production and use, visit www.cleanegroup.org/initiatives/hydrogen.