Climate Impacts of Fugitive Hydrogen Emissions

Hydrogen has the potential to serve as a zero-carbon energy carrier that facilitates a transition towards deeply decarbonized energy systems. However, fugitive hydrogen emitted to the atmosphere has the potential to cause indirect global warming effects. While hydrogen is not a direct greenhouse gas, it can lead to indirect radiative forcing by increasing the amount of ozone and water vapor in the atmosphere as well as extending the lifetime of atmospheric methane. For energy systems that are increasingly reliant on hydrogen as an energy carrier, the magnitude of fugitive hydrogen emissions could increase considerably relative to today.

This paper summarizes the research conducted so far on the climate impacts of fugitive hydrogen emissions. Research questions cover emission rates of hydrogen, including supply chain leakage and uncertainties. Climate impacts include direct and indirect radiative forcing, global warming potential (GWP) of hydrogen, as well as a comparison with fossil fuels.

Emission Rates

Hydrogen concentrations vary across the world: the larger landmass present in the northern hemisphere absorbs more hydrogen.[1] Magnitudes of hydrogen sources and sinks are uncertain. Emission rates of hydrogen have not been investigated in detail until recently, unlike emission rates of other gases like carbon dioxide and methane.

Hydrogen is not directly emitted when used, but it can leak.[1] The small size of the hydrogen molecule means it can more readily leak than other larger molecules such as methane. Hydrogen releases can happen anywhere in the value chain. The physical characteristics of hydrogen make it difficult to detect but new designs and operational changes can be implemented to measure and mitigate leakage. Existing sensing technologies were designed to detect large leaks that could compromise safety; they cannot detect small leaks that would impact climate but not safety.[2]

Loss rates today are highly uncertain and estimates vary. Assuming a loss rate of 10%, around 8 million metric tons (MMT) of hydrogen is globally emitted by the existing hydrogen industry every year.[1] Researchers are uncertain about future hydrogen production and emissions because the infrastructure for a future net-zero hydrogen economy has not been built yet.[2] Empirical evidence shows that hydrogen and methane leak at the same rates from existing low-pressure natural gas infrastructure.[3] Hydrogen may not preferentially leak in a natural gas mixture in faulty pipes.[3]

A UK study estimated hydrogen emissions throughout the value chain by interviewing industry players.[4] Total hydrogen emissions were centrally estimated to be 114 kt per year (1.0% of 12,000 kt) with a maximum value of 174 kt per year (1.5% of 12,000 kt). Leakage rates from electrolysis were centrally estimated at 3.3% (maximum of 9.2%) due to venting and purging. Transport, distribution, and storage were expected to have the highest leakage rates with a maximum of 6.5% for gaseous tanker storage and a maximum of 13.2% for boil-offs during liquid hydrogen distribution.

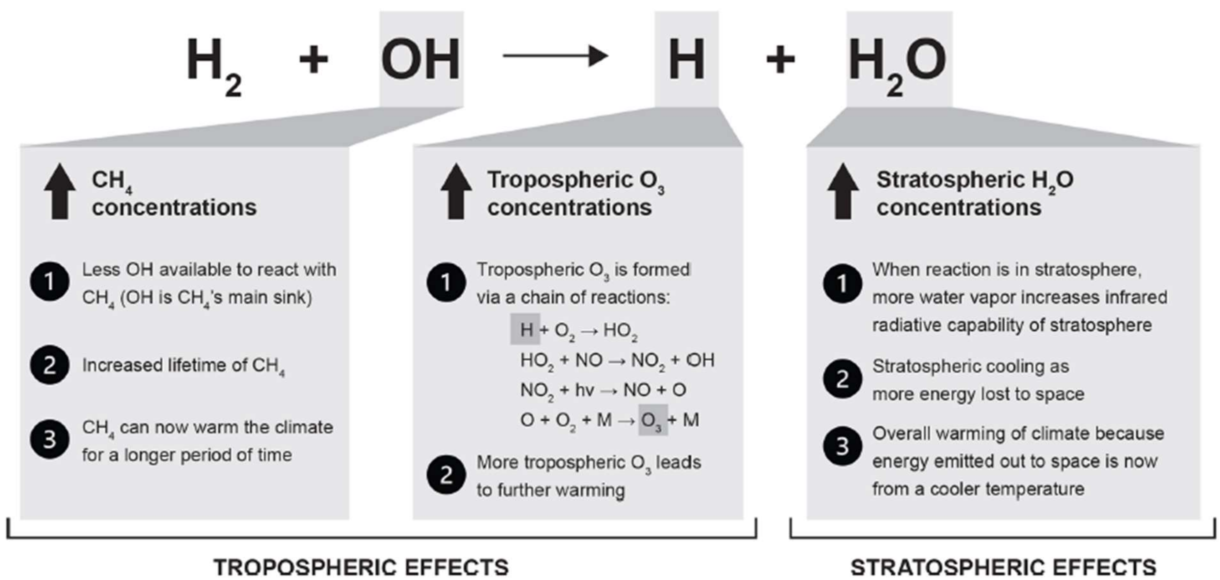
A U.S. study also estimated hydrogen leakage throughout the value chain, but by reviewing existing literature because there is little data on hydrogen leakage in the existing value chain.[5] The little existing data is based on theoretical or simulated calculations or extrapolated from comparisons with similar technologies. There is almost no empirical data on hydrogen leakage in the entire value chain today. A major uncertainty identified in this study is that leakage rates could increase or decrease in the future.

Climate Impacts

The climate impacts of hydrogen are not widely known or understood. Multiple research groups have attempted to study the direct and indirect radiative forcing of hydrogen and to calculate the GWP of hydrogen. Given the recent discussions around hydrogen as a substitute for fossil fuels in difficult-to-decarbonize sectors like industry, some papers have attempted to quantify the climate benefits of a hydrogen economy relative to fossil fuels.

Hydrogen is not a greenhouse gas (GHG), but it affects atmospheric chemistry and can indirectly influence radiative forcing through its interactions with other gases in the atmosphere.[1] Hydrogen lengthens the lifetimes of other GHGs like methane (CH_4), ozone (O_3) and water vapor (H_2O). Hydrogen reacts with the hydroxyl radical (OH) and oxygen (O_2) to produce H_2O and HO_2. This reduces the amount of OH left to act as a sink for CH_4, indirectly increasing the lifetime of the potent GHG methane. A paper reported that 70-80% of hydrogen is removed by soils but 20-30% reacts with the OH radical in the atmosphere.[2]

Figure: Atmospheric Interactions of Hydrogen



Hydrogen indirectly causes radiative forcing by interacting with other atoms in the atmosphere. It increases tropospheric concentrations of methane (CH_4) and ozone (O_3) and stratospheric concentrations of water vapor (H_2O). Note: hv denotes sunlight, h = Plank's constant, v = frequency of light.[2]

Several research groups have computed various climate metrics (with different units) for hydrogen based on its direct and indirect climate impacts. Researchers have noted that the short-lived warming effects of hydrogen are not characterized well by standard methods that focus on long-term effects (e.g., GWP100 of CO_2).[2] The short lifetime of hydrogen–2.5 years in the atmosphere and 2.1 years in the troposphere–compared to other molecules makes it harder to calculate the climate impacts of hydrogen relative to other gases.[6] So, one study assumed constant hydrogen emissions instead of a one-time pulse. They found that the GWP of hydrogen varies over time: it increases for seven years after the initial pulse, reaching a maximum of 60 then decreasing to 25; the central estimate is 40. The GWP_{20} of 33 is thrice the GWP_{100} of

11 (similar ratios are seen in GWPs of methane). Warming effects of hydrogen and methane are short-lived and not cumulative, unlike CO_2. A second study estimated hydrogen's GWP100 to vary from 5 to 11 kg_{CO2e}/kg_{H2} and GWP20 to vary from 12 to 33 kg_{CO2e}/kg_{H2}.[1] Another paper calculated hydrogen's indirect radiative forcing to be 0.84 $mW/m^2/Tg_{H2}/yr$ or 0.13 mW/m^2.ppbv.[7] A third study computed a GWP_{100} of 12.8 ± 5.2 and GWP_{20} of 40.1 ± 24.1 for hydrogen.[6]

Hydrogen, when substituted for fossil fuels, can have a net beneficial effect on the climate in the long run. According to one study, using gas-reformed hydrogen as a transition fuel may lead to increased warming in the short term due to CH_4 leakage, but if all hydrogen was produced from renewable sources with no losses, CH_4 emissions could be reduced by 18 MMT per year in a 2050 hydrogen economy.[1] Another study calculated the net climate impacts of electrolytic and gas-reformed (with and without CCS) hydrogen for varying leakage rates of 1% to 10%.[6] Electrolytic hydrogen with 0% leakage for 200 years would avoid 331 $GtCO_2$; gas-reformed hydrogen would avoid less CO_2 due to upstream emissions.[6] Another study also assumed leakage rates of 1% to 10% but incorporated marginal benefits of 5, 10, and 15 kg_{CO2} avoided per kg_{H2} consumed.[2] They found that using electrolytic hydrogen is 65% to 95% better for the climate than using fossil fuels. The climate impacts of gas-reformed hydrogen vary from being 60% worse than fossil fuels to 65% better than fossil fuels because upstream methane emissions cause global warming. The climate benefits of using hydrogen over CO_2-producing fossil fuels grow over time.

Conclusions

The scientific community is still in the early stages of understanding the climate impacts of fugitive hydrogen emissions: additional work is needed in this field. Technologies to detect and measure hydrogen leakage need to be developed and deployed to obtain a more accurate and precise estimate of fugitive emissions throughout the value chain. International organizations like the Intergovernmental Panel on Climate Change (IPCC) need to identify the 'correct' value for the GWP of hydrogen to help regulators enact sound policies around hydrogen emissions.

References

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