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An Assessment of Current Understanding of the Greenhouse Gas Impacts from H_2 Emissions

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ABSTRACT

With the anticipated growth in hydrogen generation and use as part of a broad shift in energy use away from fossil fuels, concerns have been raised regarding the impact of increased H_2 emissions on global warming. Atmospheric scientists have long recognized that H_2 emissions into the atmosphere do have an indirect impact on global warming, largely because a portion of emitted H_2 is consumed by the hydroxyl radical (OH), which is the primary reactant that removes the potent greenhouse gas methane from the atmosphere. Therefore, increases in H_2 emissions will result in decreases in the average OH concentrations in the atmosphere and an increase in the atmospheric lifetime of methane. Various assessments of the impact of H_2 emissions on global warming have been performed over the past couple of decades. These assessments have yielded significant variability and recognized uncertainty in the magnitude of the warming effect of a given quantity of emitted H_2, and an even greater uncertainty in the magnitude of H_2 leakage and releases that can be anticipated with an expanded H_2 infrastructure. Consequently, definitive estimates of the magnitude of the warming effect of additional emitted H_2 are lacking. However, given the current understanding of the warming potential of emitted H_2 and given reasonable expectations of the emission rate of an expanded H_2 infrastructure, it is anticipated that warming effects from emitted H_2 will offset no more than 5% of the reduction in warming associated with avoided CO_2 emissions from using clean H_2. Further, it is highly unlikely that the warming effects from emitted H_2 will offset more than 10% of the benefit from avoided CO_2 emissions, at least as considered over a typical 100-year accounting period. Because of the short atmospheric lifetimes of H_2 and methane, however, the warming effect of emitted H_2 is enhanced over the first few years following increases in H_2 emission.

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EXECUTIVE SUMMARY

Over the past two decades there have been several assessments of the impact of H_2 emissions on atmospheric chemistry and overall global warming. There is consensus that H_2 emissions do have an overall warming effect, primarily because they enhance the lifetime of methane in the atmosphere through reactive competition for the hydroxyl radical. The magnitude of the warming effect is directly dependent on the quantity of H_2 emissions and on estimates of the global warming potential of H_2, which vary by about a factor of three. When comparing the warming effect from H_2 emissions to the warming avoided by using clean H_2 instead of fossil fuels, both straightforward computations and complex system analysis arrive at the conclusion that the warming effect from H_2 emissions is unlikely to be more than 5% of the warming effect if the equivalent energy use were provided by fossil fuels. However, in the near-term, the warming effect of H_2 emissions will be somewhat larger because of the short atmospheric lifetimes of H_2 and methane.

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1. BACKGROUND

Several recent analyses have suggested that global H_2 demand could increase by about an order of magnitude and exceed 500 Mt by 2050, to help meet net-zero CO_2 emission goals in energy sectors that are difficult to electrify.[1-3] Coincident with these predictions of expanded H_2 use, concerns have been raised regarding the impacts of hydrogen released from leaks or releases on global warming and whether such effects could offset the positive impacts of CO_2 emission reduction from switching from use of fossil fuel energy sources to clean (i.e. green or blue) H_2 sources. In fact, assessments of the climate consequences of H_2 emissions have been undertaken with various levels of scientific fidelity for many years, beginning in the early 2000's,[4-8] when serious consideration was first given to the use of H_2 energy systems as an alternative to fossil fuels, particular for transportation applications. In contrast to direct greenhouse gases that participate in radiative exchange in the earth's atmosphere, hydrogen is considered an 'indirect' greenhouse gas, because while it does not directly participate in radiative exchange, its presence in the atmosphere is known to influence the concentrations of direct greenhouse gases through photochemical reactions, such that there is a net warming effect.

Current assessments of the inventory of H_2 in the earth's atmosphere place its concentration at approximately 530 ppb, on average, with a nominally balanced flux into and out of the atmosphere of 80 Tg/yr (i.e. 80 billion kg per year).[6,7,9] The largest contributing source of H_2 in the atmosphere is through the atmospheric oxidation of methane and other volatile organic compounds (VOCs). Biomass combustion (e.g. wildfires) and fossil fuel combustion systems (primarily spark ignition engines during cold-start or without a catalytic converter) are assessed to be the next largest sources of atmospheric H_2. Bacterial nitrogen-fixing reactions also contribute some H_2 to the atmosphere. H_2 removal from the atmosphere is primarily accomplished through two pathways. The largest sink of H_2 is by bacterial respiration (i.e. biological oxidation) in the soil. The second largest sink is through oxidation of H_2 by reaction with the hydroxyl radical (OH) in the atmosphere. This latter route of H_2 consumption results in global warming impacts, primarily through three different effects, as suggested by the chemical mechanism in Fig. 1.

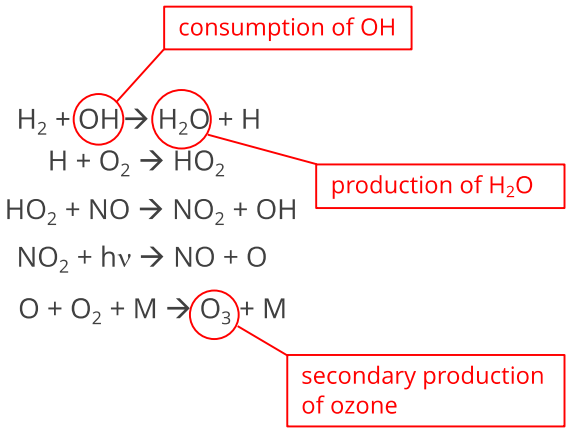

Figure 1. Primary consumption chemistry of H_2 in the earth's atmosphere, highlighting the most important reactants and products that influence the earth's energy balance.

The largest impact of H_2 oxidation on global warming is through its consumption of OH, which is the primary oxidant of methane in the atmosphere. As methane is a potent greenhouse gas (in total, methane currently contributes approximately 2/3rds as much as CO_2 to earth's warming),[10] any

factor that tends to reduce OH concentrations in the atmosphere, leading to a longer methane lifetime, thereby contributes to global warming. The other two warming effects of H_2 consumption that have been identified are smaller: additional production of tropospheric ozone, which is itself a greenhouse gas, and additional generation and transport of water vapor (generated from H_2 oxidation) into the stratosphere. Water vapor in the stratosphere tends to warm the earth due to radiative trapping (i.e. absorption and re-emission) of long wavelength (IR) radiation emitted from the earth's surface. Currently, H_2 in the atmosphere has a lifetime of approximately 1.5-3 years.[5,9,11-13]

2. ASSESSMENTS OF H_2 EMISSION IMPACTS

There have been several studies that have attempted to quantify the expected impact of hydrogen infrastructure leakage and releases on global warming.[4-9,13-17] Of course, such impacts need to be weighed against any reduction in global warming that will result from reduced CO_2 emissions associated with use of a hydrogen energy source that avoids the use of fossil fuels. There are substantial uncertainties in these estimates of H_2 emission effects on global warming associated with (a) the magnitude of H_2 leakage and releases that can be expected from H_2 infrastructure, (b) the extent to which the current rate of bacterial respiration of H_2 will scale with a higher concentration of H_2 in the atmosphere due to the additional emission of H_2, (c) the effect of increased H_2 use on emissions of CH_4, VOCs, and NOx into the atmosphere, all of which influence the concentration of the potent greenhouse gases CH_4 and O_3, and (d) the extent of increased water vapor transport into the stratosphere due to H_2 oxidation in the upper troposphere (which is difficult to predict). There are also significant variations in the predictions of how H_2 oxidation in the atmosphere affects OH concentrations and ozone production in the troposphere, due to differences in the transport-chemistry models that are employed, as well as differences in the various assumed tropospheric source and sink fluxes. As a result, there is substantial variation in the magnitude of warming effects predicted to result from H_2 leakage and releases.

A common metric used to measure the warming impact of gases introduced into the atmosphere is the Global Warming Potential (GWP), which is calculated as the change in the earth's temperature upon introducing a small pulse of the gas species in question, relative to the warming effect of an equal mass of CO_2 added to the atmosphere. By definition, CO_2 has a GWP of precisely 1.0, whereas the GWP of methane is approximately 30, underscoring its strong absorptivity of infrared radiation emitted by the surface of the earth. The GWP is typically quantified over the course of a 100-year timeframe, because the lifetime of CO_2 in the atmosphere is on the order of 100 years. Derwent et al.[1-2] first calculated a GWP for H_2 as 6, and subsequently calculated values of 3.3 +/- 1.4 [16] and 5 +/- 1.[15] However, these calculations were all based on a tropospheric 'box' model that ignored stratospheric impacts of increased H_2 in the atmosphere and also made rough extrapolations from shorter time period calculations to arrive at GWP_{100} values. Recently, Ocko and Hamburg[18] asserted that the results from the detailed full atmosphere study of Paulot et al.[9] implied a H_2 GWP of 10, and the full atmosphere study of Warwick et al.[13] reported a value of 11 +/- 5. While these larger GWP values reported for H_2 seem ominous, recall that GWP is defined on a *mass* basis. Consequently, a H_2 GWP of 11 implies that a H_2 molecule introduced into the atmosphere will have exactly one-half times the warming impact of a CO_2 molecule introduced into the atmosphere: $11 * (MW_{H2}/MW_{CO2}) = 0.5$. Noting that H_2 PEM fuel cells are approximately 60% energy efficient and heavy-duty diesel engines are approximately 40% energy efficient, it can be shown that for every 100 molecules of clean H_2 that are used in a fuel cell engine that replaces a heavy-duty diesel engine, there will be 60 fewer CO_2 molecules released into the atmosphere. (This simple analysis yields a result that is actually very similar to the detailed analysis for system-wide avoided CO_2 emission that was reported in the Hydrogen Council 2017 study,[1] wherein the avoided CO_2 emission/H_2 was estimated to be 0.5, on a molar basis.) Consequently, for each leak or release of 1% of the H_2 intended to be used in a fuel cell engine, the warming effect from that H_2 emission will offset 0.5/60 = 0.8% of the benefit of using H_2 to reduce global warming from avoided CO_2 emissions.

There is substantial uncertainty regarding the extent of H_2 leakage and releases that can be anticipated in an expanded H_2 infrastructure, which naturally influences the magnitude of the expected warming effect from such emissions. Cooper et al.[17] have estimated that overall H_2 emissions are unlikely to be more than 4% of the H_2 that is ultimately used. Air Liquide has analyzed H_2 losses and have determined that the largest losses are associated with purging during compressed H_2 vehicle refueling and with boil-off and related losses when liquefying and transferring liquefied H_2.[19] Total system losses for compressed H_2 used in vehicles is estimated to be around 4%, while pipeline H_2 use is estimated to have about a 1% loss rate, and liquefied H_2 used in vehicles currently is estimated to have a loss rate between 10-20%. This analysis suggests that from a global warming perspective, losses associated with liquefied H_2 need to be significantly reduced. Petitpas[20] has shown that with implementation of existing boil-off recovery strategies the loss associated with larger LH_2 dispensing stations could be reduced below 1%.

Based on the existing studies, an assumed 5% emission rate of H_2 in an expanded H_2 economy would appear to be a reasonable upper limit. Using the result of the analysis described previously for the CO_2 emission offset of using H_2 in a fuel cell engine, a 5% emission rate of H_2 corresponds to a 4% warming offset relative to avoided CO_2 emissions. This result is very similar to those that have been reported in the existing literature on the warming effects from H_2 emissions associated with a large global H_2 energy economy.[5-7,9,13-15] All of these studies have found that the expected warming effect is less than 5% of the warming that is avoided by converting a fossil fuel energy system to a clean H_2 energy system. Given the uncertainties in the true GWP of hydrogen as well as uncertainties in the expected emission rate of H_2, a very conservative upper bound of the warming effect from emitted H_2 would be at the level of 10% of the warming that is avoided by converting a fossil fuel energy system to a clean H_2 energy system.

Ocko and Hamburg,[18] and to a lesser extent Warwick et al.,[13] have emphasized that the warming effect from H_2 emissions occurs much quicker than that from emitted CO_2, on account of the shorter lifetimes of H_2 and CH_4 in the atmosphere. Essentially one pays for the heating effect from leaked H_2 right away (over the course of several years), while you need to wait many years to fully experience the benefit of reduced CO_2 emissions associated with using H_2. In fact, as shown by Ocko and Hamburg,[18] for very high H_2 leak rates (order of 10%) one can experience net warming over the first few years of switching from a fossil fuel system to a H_2 system. Over time, however, the benefits outweigh the short-term penalty and the avoided CO_2 emissions dominate the overall warming response.

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