Evolving Insights into Fugitive Greenhouse Gas Emissions in a Global Hydrogen Economy

A recent report commissioned by the Department for Business, Energy & Industrial Strategy in the UK considers the possible implications of fugitive hydrogen (H_2) emissions from an illustrative future scenario where widespread use of H_2 has been adopted globally. In this scenario, they assumed that set percentages of the final energy consumption in specified energy sectors, currently supplied by fossil fuel, switch to H_2.

The scenarios modelled for different amounts of fugitive H_2 leakage indicate that H_2 will affect the concentration of methane, ozone, and water vapor in the atmosphere. The changes in methane and ozone are driven by changes in the hydroxyl radical, OH, which is the major atmospheric oxidant and a key player in the chemistry of the atmosphere. Modelled changes in radiative forcing, like the modelled changes in atmospheric composition, indicate that, to maximize the climate and air quality benefit of a transition to a hydrogen-powered economy, minimization of both fugitive hydrogen leakage and a reduction of the ancillary emissions of, for example, CO, NOx, and VOCs is required.

Our commitment at PGS as such climate modeling developments arise is steadfast to reduce relative CO_2 emissions (t CO_2 per CMP km) from fleet activities by 50% compared to 2011 within 2030. Findings such as those discussed here potentially add an additional dimension to the already complex regulatory landscape within which CO_2 emissions reduction targets are being established, but also reinforce the value of digitalizing fleet operations and being able to transparently measure and report emissions.

Introduction

In the previous newsletter I discussed digitalization initiatives being developed by PGS to measure, report, and systematically reduce CO_2 emissions from its vessels. The specifications regarding bunker fuels used by the maritime industry are described in ISO 8217:2017, Annex VI of the MARPOL Agreement, and proposals such as the FuelEU Maritime regulation by the European Commission. Collectively, such regulations seek to reduce carbon intensity and incentivize the maritime industry to transition to alternative fuels such as hydrogen (H_2) or ammonia (NH_3).

Although hydrogen is known to be naturally produced by various processes in the subsurface (variously referred to as "native, geologic, white or golden hydrogen", most public dialogue regarding a possible global transition to a 'hydrogen economy' focuses upon the comparative merits and logistics of producing hydrogen fuels using either renewable energy sources ("green hydrogen") or by using readily-available natural gas as a "transition fuel" ("blue or grey hydrogen", depending upon whether CCS is involved or not, respectively).

What might happen to the greenhouse effect if the Earth transitions to a hydrogen economy? Climate modeling is complex and challenging, but a recent study, commissioned by BEIS and conducted by the University of Cambridge and the National Centre for Atmospheric Sciences with the University of Reading, explored the atmospheric impacts of a global hydrogen economy. "Atmospheric implications of increased hydrogen use" (referred to hereafter as the

BEIS report) used a chemistry-climate model, UKESM1, to calculate changes in atmospheric composition, which might follow fugitive hydrogen leakage into the atmosphere. After briefly revisiting the principles of how various greenhouse gases contribute to the greenhouse effect, some findings of the BEIS report are summarized below. Most notably, an increase in atmospheric hydrogen might increase the concentrations of both water vapor (H_2O) and methane (CH_4), as well as potentially decrease the concentrations of ozone (O_3). Such outcomes in no way decrease our obligation or ambition within the marine seismic industry to pursue measurable emissions targets for reduced CO_2 emissions, but they may lead to regulations affecting how H_2 is produced, transported, stored, and utilized.

Greenhouse Gases

The lowest portion of the atmosphere is the troposphere (**Figure 1**), a layer where temperature generally decreases with height. This layer contains most of Earth's clouds and is the location where weather primarily occurs. The lower levels of the troposphere are usually strongly influenced by Earth's surface. This sublayer, known as the planetary boundary layer, is that region of the atmosphere in which the surface influences temperature, moisture, and wind velocity through the turbulent transfer of mass. Generally confined within the troposphere, a "greenhouse gas" is a gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect. Without greenhouse gases, Earth's surface temperature would be about 33°C colder.

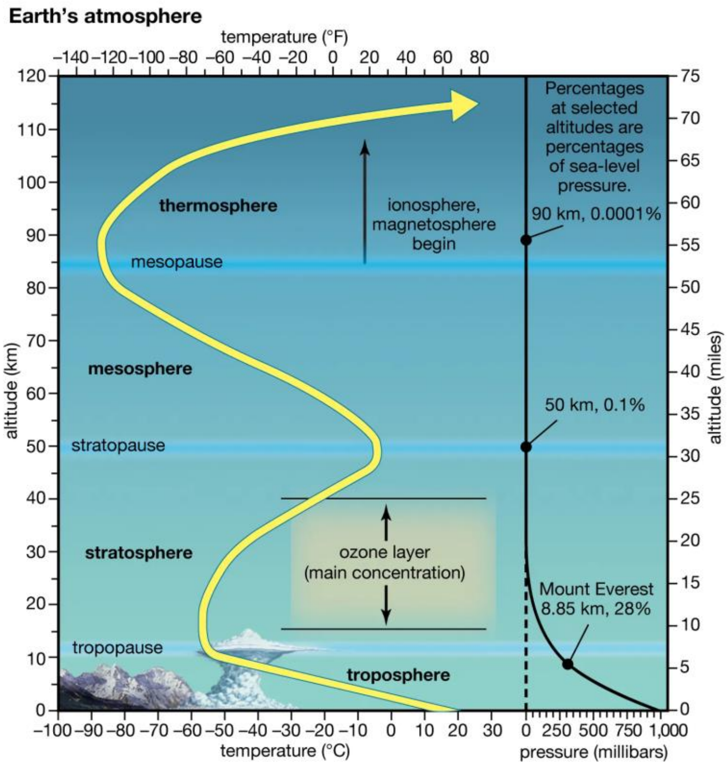

Figure 1: The layers of Earth's atmosphere, with a yellow line showing the air temperature at various heights. Encyclopædia Britannica.

The principal greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and fluorinated gases (hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; sulfur hexafluoride, SF_6; nitrogen trifluoride, NF_3). Excluding water vapor, the other greenhouse gases constitute about 0.05% of Earth's total atmosphere. Each gas is also non-condensable, so as atmospheric temperatures change, they cannot be converted to liquid form, and their concentration remains stable. Furthermore, CH_4 and CO_2 are not particularly chemically reactive or easily broken down by light in the troposphere.

Two concepts used frequently in discussions of the greenhouse effect are "Radiative forcing" (or climate forcing) and the "Global warming potential" (GWP) of a greenhouse gas. Radiative forcing is the change in energy flux in the atmosphere caused by natural or anthropogenic factors of climate change. Positive radiative forcing means Earth receives more incoming energy from sunlight than it radiates to space. This net gain of energy will cause warming. Conversely, negative radiative forcing means that Earth loses more energy to space than it receives from the sun, which produces cooling. The GWP is defined as the cumulative radiative forcing over a specified time horizon resulting from the emission of a unit mass of gas relative to a reference gas (CO_2). GWP is 1 for CO_2. For other gases it depends on the gas and the time frame. Over a 100-year timeframe, the GWC for methane is 25, for N_2O it is 298, and although it is negligible for water vapor other factors mentioned below are relevant. [https://en.wikipedia.org/wiki/Global_warming_potential]

Water vapor is Earth's most abundant greenhouse gas, and because it is condensable, its concentration depends upon the temperature of the atmosphere. Most public attention in recent years has understandably been on the greenhouse gases of anthropogenic origin, but little attention is given to the role of water vapor. Increased atmospheric temperature, generally attributed to increased anthropogenic emissions of greenhouse gases, leads to increased concentration of water vapor and a supercharging of the warming caused by the other greenhouse gases. At the start of the cycle, increased temperatures lead to increased evaporation from both water and land areas. Because warmer air holds more moisture, the concentration of water vapor increases. Specifically, this happens because water vapor does not condense and precipitate out of the atmosphere as easily as at high temperatures. The water vapor then absorbs the heat radiated from the Earth, thereby contributing to a positive feedback loop, and significantly increasing the warming that would occur from increasing carbon dioxide alone.

After introducing the framework of assumptions made within the BEIS report, I discuss how anthropogenic H_2 emissions may interact with the greenhouse gases and modify greenhouse effects.

Report Assumptions and Scenarios

The amounts of fugitive H_2 emissions resulting from a hydrogen economy will depend on the level of H_2 usage in different energy sectors and the percentage of H_2 that leaks to the atmosphere during its production, transport, and storage. The BEIS report estimated fugitive H_2 emissions from an illustrative future scenario where widespread use of H_2 has been adopted globally. In this scenario, they assumed that set percentages of the final energy consumption in specified energy sectors, currently supplied by fossil fuel, switch to H_2. In their illustrative scenario, 100% of the final energy consumption of fossil fuels in the buildings sector switches to H_2, along with 50% of the final energy consumption of fossil fuels in the transport sector, and 10% of the final energy consumption of fossil fuels in the power generation sector (refer to **Table 1**). The lower percentages for transport and power generation reflect the smaller role H_2 is assumed to play in these energy sectors due to the existence of low carbon alternatives such as electric vehicles and wind and solar power together with alternative storage options such as pumped hydro, batteries, and compressed air. In total, this represents a scenario in which approximately 23% of global energy consumption is supplied by H_2.

H_2 is currently present in the atmosphere with a mixing ratio of about 0.55 parts per million (ppm). Present day sources of H_2 include fossil fuel combustion and biomass burning which are estimated to represent approximately 50% of the total global H_2 source (about 20-25% from fossil fuel combustion), with the remainder arising from the oxidation of CH_4 and volatile organic compounds (VOCs) in the atmosphere (note: no consideration given for natural hydrogen emissions). Any decreases in H_2 emissions resulting from a reduction in fossil fuel combustion may therefore partially offset any increases in H_2 emissions resulting from fugitive H_2 leakage in a hydrogen economy. Furthermore, they assumed that H_2 will be generated using a production method with no associated upstream CH_4 emissions, and CO_2 is fixed in their model simulations (so changes to CO_2 emissions are also not considered). Today, the majority of H_2 is generated from steam methane reformation (SMR) which is associated with emissions of both CH_4 and CO_2 (unless CO_2 capture, and storage is utilized). Atmospheric H_2 is removed primarily by uptake to soils, but also through reaction with hydroxy radicals (OH) in the atmosphere (discussed also below).

Fugitive H_2 leakage rates are likely to be higher than for natural gas owing to the small molecule size of H_2. The BEIS report notes a recent study looking at the US natural gas supply chain indicated natural gas leaks of around 2.3% of gross gas production. The BEIS report considered a range of possible hydrogen future global scenarios, with surface mixing ratio increases ranging from 0.25 parts per million (50% increase) by volume (ppm or millimoles/mole) to 1.5 ppm (300% increase) above the current background mixing ratio of about 0.5 ppm. They believe these scenarios span much of the uncertainty in potential changes to the atmospheric mixing ratios of H_2 associated with the ultimate size of the hydrogen economy, the H_2 soil sink and H_2 leakage rates. For example, taking a hydrogen economy of the size required to supply 23% of present-day global energy consumption, and assuming the magnitude of the soil sink increases in line with the increase in H_2 mixing ratios (i.e., a constant deposition velocity), simulations indicate H_2 boundary conditions of 0.75, 1, 1.5 and 2 ppm represent H_2 leakage rates of about 3, 7, 13% and 20% respectively. Their 2 ppm H_2 scenario should be considered as an extreme end member designed to assess the linearity of the atmospheric response to increasing atmospheric H_2, rather than a prediction of potential future atmospheric H_2 levels in an H_2 economy. When combined with the proposed global widespread H_2-use, their upper leakage rate of 10% represents a likely upper limit on the increase in atmospheric H_2 associated with a hydrogen economy. A leakage rate of 10% would be likely to be both unsafe and expensive, leading to pressure for development of better containment.

They also considered the impact of changes in emissions of gases other than CO_2 which could follow increased adoption of H_2 as an energy source; these gases, emitted alongside CO_2 and called hereafter ‘co-emitted species’, include carbon monoxide (CO), CH_4, VOCs and the oxides of nitrogen (NOx).

	Final fossil fuel energy consumption (Million toe)	Percentage switch of final fossil fuel energy consumption to H_2 (%)	H_2 required to supply required energy consumption (Tg)	H_2 leakage at 1% (Tg yr^{-1})	H_2 leakage at 10% (Tg yr^{-1})
Buildings	1298	100	453	4.6	50.4
Transport	2768	50	284	2.9	31.5
Power	3500	10	122	1.2	13.6
Total	7566	40	859	8.7	95.5

Table 1: Estimates of potential fugitive H_2 leakage in a global hydrogen economy. 1 Tg = 1 million tonnes. From "Atmospheric implications of increased hydrogen use", Table 1.

Report Findings and Implications

Fugitive hydrogen leakage will affect the concentration of CH_4, ozone, and water vapor in the atmosphere. The changes in methane and ozone are driven by changes in the hydroxyl radical, OH, which is the major atmospheric oxidant and a key player in the chemistry of the atmosphere. H_2 acts as a chemical sink for OH, and so increases in hydrogen concentrations lead to a reduction in tropospheric OH:

$H_2 + OH = H_2O + H$ (1)

Another important consequence of any increase in atmospheric H_2, and the subsequent decrease in OH, would be to increase the lifetime of CH_4, which is largely controlled by the reaction with OH

$CH_4 + OH = CH_3 + H_2O$ (2)

Methane is second only to CO_2 in its impact as an anthropogenic greenhouse gas; lengthening the lifetime of CH_4 increases its radiative forcing (for a given CH_4 emission) and global warming potential (GWP). So, emissions of H_2 into the atmosphere would contribute indirectly to radiative forcing; H_2 is an indirect greenhouse gas.

The BEIS report concludes that if methane emissions remain constant, increased hydrogen emissions would result in a longer methane lifetime and a higher methane abundance. When reductions in emissions of carbon monoxide, oxides of nitrogen and volatile organic compounds are also considered alongside increases to atmospheric hydrogen, the decrease in hydroxyl radical, and hence increase in methane, is smaller. The response of methane to a shift to a hydrogen economy is therefore complex and strongly scenario dependent. Under the maximum increase of 1.5 ppm of hydrogen considered, to offset the potential increase in methane would require further decreases in not just emissions of methane, but also the co-emitted species of carbon monoxide, oxides of nitrogen and volatile organic compounds.

As observed in (2), changes in H_2 will also affect atmospheric water vapor. The H_2O abundance in the troposphere is dominated by the hydrological cycle (evaporation from the oceans, precipitation, etc.) but increases in atmospheric H_2 will likely lead to an increase in stratospheric water vapor and the associated radiative impacts. As an example of the modelling performed, **Figure 2** shows the zonal mean water vapor response to increases in atmospheric H_2. The impact from chemical reactions on tropospheric water vapor is ignored. It is observed in **Figure 2** that stratospheric water vapor mixing ratios increase with increasing H_2, with increases of up to 25% in the (upper) scenario of 1.5 ppm H_2 increase above the current background mixing ratio of about 0.5 ppm

The response of tropospheric ozone is complex and depends not simply on the changes in hydrogen abundance but also on changes in the emissions of other species. Stratospheric ozone is controlled by different chemical processes to those in the troposphere, but for the range of calculations performed, no discernible negative impacts on global stratospheric ozone recovery were modelled.

The BEIS report estimates the H_2 GWP over a 100-year timeframe to be 11 ± 5; a value more than 100% larger than previously published calculations. About a third of this arises from the changes in stratospheric water vapor that follow from an increase in atmospheric H_2. Most of the uncertainty in the GWP arises from uncertainty about the natural budget of atmospheric H_2, where the magnitude of the soil sink for H_2 is the most uncertain factor. Example modelled equilibrium global-mean temperature changes are shown in **Table 2** for different emissions scenarios.

The net top-of-atmosphere radiative forcing varies strongly regionally. It depends in a complex fashion on the changes in gas phase composition, the subsequent impact on aerosol production and on cloud and aerosol interactions. The changes in radiative forcing, like the changes in atmospheric composition, indicate that, to maximize the climate and air quality benefit of a transition to a hydrogen-powered economy, minimization of both H_2 leakage and a reduction of the ancillary emissions of, for example, CO, NOx, and VOCs is required.

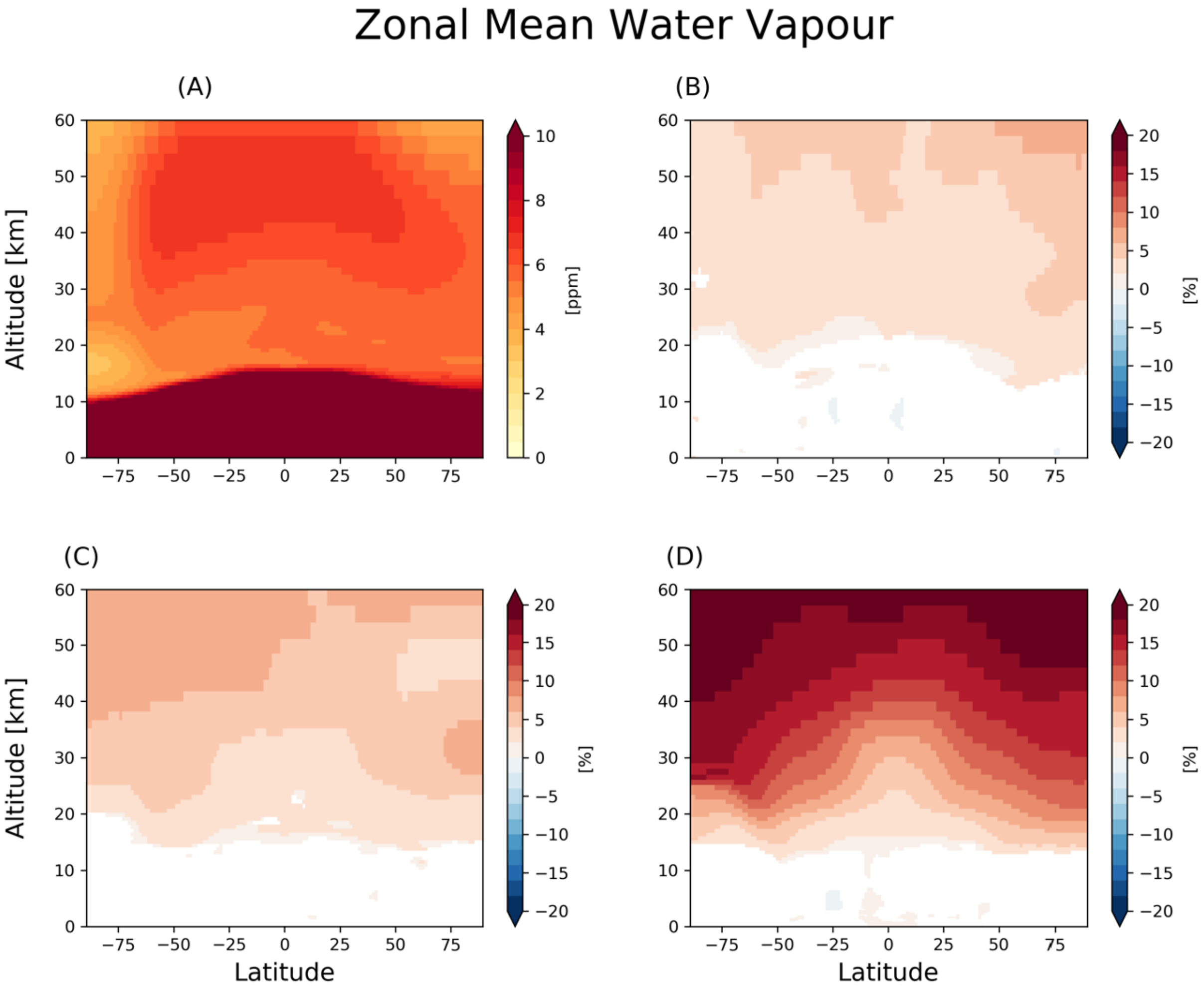

Figure 2: Global zonal mean H_2O mixing ratios for the background simulation of H_2 concentration (A), and percentage differences with respect to the background simulation for 0.75 ppm H_2 (B), 1 ppm H_2 simulation (C), and 2 ppm H_2 simulation (D). Results shown are averages from the final 25 years of the model simulations; only differences that are statistically significant at the 95% confidence level are presented. Vertical axis is altitude above MSL (refer also to Figure 1) and horizontal axis is latitude (0 = equator). From "Atmospheric implications of increased hydrogen use", Figure 3.

Emissions Scenario	Equilibrium Global-Mean Temperature Changes
An increase in H_2 of 1.5 ppm	0.12 °C
An increase in H_2 of 1.5 ppm and the CH_4 lower boundary is increased in a manner consistent with the H_2 -induced decrease in OH radicals	0.43 °C
No leakage of H_2 into the atmosphere, and CH_4 and other co-emissions are reduced	-0.26 °C

Table 2: Modelled equilibrium global-mean temperature changes for different H_2 emissions scenarios. From "Atmospheric implications of increased hydrogen use".

Summary

Climate modelling based upon fugitive emissions is clearly complex and must make many assumptions. No opinion or endorsement is made here regarding the veracity of the published results, but the implications for how fugitive H_2 might interact with greenhouse gases in the troposphere and stratosphere is interesting. Until H_2 bunker fuel is commercially practical on a global scale the fuel cannot be considered by the maritime industry anyway. Although regulations such as Annex VI of the MARPOL Agreement stipulate that H_2 has a CO_2 'emissions factor' of 0 (1 ton of combusted H_2 will produce 0 tonnes of CO_2 emissions), incentives to transition to such fuels in a hydrogen economy are likely to be governed by additional regulations regarding how H_2 is produced, transported, stored, and utilized. In the meantime, efforts to digitalize all energy consumption and report all associated greenhouse gas emissions are a critical path to building sustainable businesses (refer to the previous Industry Insights newsletter).

Further Reading

Atmospheric implications of increased hydrogen use. Research into the atmospheric impacts of fugitive hydrogen emissions in a future UK hydrogen economy. Department for Business, Energy & Industrial Strategy. 2022. Nicola Warwick, Paul Griffiths, James Keeble, Alexander Archibald, John Pyle, University of Cambridge and NCAS and Keith Shine, University of Reading. 75 p. https://www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use

A path to the reduction of marine seismic CO_2 emissions. 2022. Industry Insights, PGS. 8 p. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/industry_insights2022_01_reducing_emissions_final.pdf