Atmospheric Impacts of Hydrogen as an Energy Carrier
A 2020 literature review
Atmospheric Impacts of Hydrogen as an Energy Carrier
A 2020 literature review

8. oktober 2020

Maria Sand
Gunnar Myhre
Marit Sandstad
Ragnhild Bieltvedt Skeie
Title: Atmospheric Impacts of Hydrogen as an Energy Carrier

Authors: Maria Sand, Gunnar Myhre, Marit Sandstad and Ragnhild Bieltvedt Skeie

Financed by: Equinor

Project: Climate effects of hydrogen

Project Manager: Maria Sand

Quality Manager: Øivind Hodnebrog

Keywords: Hydrogen energy, hydrogen emissions, global warming, ozone layer, local air pollution, atmospheric impacts

Abstract: Hydrogen gas emissions to the atmosphere can very likely cause global warming through indirect effects. It can also possibly cause depletion of the ozone layer, and impact air pollution. These adverse effects are likely smaller than those of the fossil fuel usage hydrogen fuel would replace, however, it underlines the importance of keeping hydrogen leakage as low as possible. Current research on all these effects are uncertain, and the quality of estimates would benefit greatly from further research.

Language of Report: English
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Executive Summary</td>
<td>4</td>
</tr>
<tr>
<td>2 Scientific report</td>
<td>6</td>
</tr>
<tr>
<td>2.1 The Hydrogen Fuel Reaction and Hydrogen Leakage</td>
<td>6</td>
</tr>
<tr>
<td>2.2 The Hydrogen Cycle</td>
<td>6</td>
</tr>
<tr>
<td>2.3 Effects on Global Warming</td>
<td>8</td>
</tr>
<tr>
<td>2.4 Effects on the Ozone Layer</td>
<td>10</td>
</tr>
<tr>
<td>2.5 Air Pollution</td>
<td>11</td>
</tr>
<tr>
<td>2.6 Key Uncertainties</td>
<td>11</td>
</tr>
<tr>
<td>2.7 Summary and Outlook</td>
<td>11</td>
</tr>
<tr>
<td>3 Appendix</td>
<td>13</td>
</tr>
<tr>
<td>3.1 Appendix 1 – Hydrogen Sources and Sinks</td>
<td>13</td>
</tr>
<tr>
<td>3.2 Appendix 2 – GWP Values of H₂ on Different Time Scales</td>
<td>13</td>
</tr>
<tr>
<td>3.3 Appendix 3 – Atmospheric Climate and Environmental Effects under Different Background Emission Changes</td>
<td>14</td>
</tr>
</tbody>
</table>
1 Executive Summary

Hydrogen is an interesting energy carrier, effective for transport of energy derived from green sources (renewable energy), blue sources (fossil fuel usage with CCS) or traditional fossil fuels. When used at scale, its effects on the atmosphere and environment must be considered. This report aims to summarize the state of the scientific literature on these effects, particularly to the atmosphere.

When hydrogen is used for energy, the hydrogen is burnt to yield only water vapor emissions. When such emissions are released in the lowest part of the atmosphere, the water from this reaction becomes part of the natural water cycle. These emissions are much lower than the natural evaporation process from oceans and waterways and have negligible effect on the environment and climate.

When hydrogen is transported or stored for usage, some fraction of the hydrogen is likely to leak out. The magnitude depends on the mode of transportation and storage, but likely estimates are that 10% of the generated hydrogen being leaked is a high leakage rate, while 1% is a low leakage rate. These emissions of hydrogen gas from leakage can have effects on global warming, the state of the ozone layer and local air pollution.

Hydrogen is not a greenhouse gas, and as such does not cause global warming directly, but it does have indirect global warming effects through four main processes. First, hydrogen affects chemical reactions in the atmosphere, which may increase the atmospheric lifetime of methane so that methane warms the climate system more than it would have otherwise. Second, hydrogen decay in the lowest 15 kilometers of the atmosphere leads to production of ozone, a greenhouse gas. This extra ozone also has a global warming effect. Third, hydrogen that decays above 15 kilometers in the atmosphere, produces water vapor. This part of the atmosphere is extremely dry, and the lifetime of water vapor is much longer than in the lower atmosphere, so this extra water vapor has a global warming effect. Finally, hydrogen above 15 kilometers changes the ozone concentration at these heights, most likely decreasing them, although this is somewhat unclear and might vary with height and latitude. Ozone at this level is also a greenhouse gas.
Based on available literature, the global warming potential of hydrogen from these sources, i.e. methane lifetime and tropospheric ozone, gives a GWP\textsubscript{100} of 0-10, with the most likely value around 5. This means that over a 100-year period, the emission of 1 kg of hydrogen, leads to as much global warming as 5 kg of CO\textsubscript{2}. However, if hydrogen is replacing fossil fuel that emits CO\textsubscript{2}, the warming from hydrogen leakage based on current scientific literature likely amounts to less than 10% of the warming from CO\textsubscript{2} for the same amount of energy, even with the highest leakage rate. Thus, hydrogen from non-CO\textsubscript{2}-emitting sources is probably better for limiting global warming but minimizing leakage should be a priority.

In addition to hydrogen’s effects on global warming, emissions of hydrogen can also lead to depletion of the ozone layer. The ozone layer traps UV radiation from the sun, which could otherwise lead to adverse health effects such as skin cancer. This effect is quite uncertain but seems to lay in the range below 1% depletion even at quite high extra hydrogen emissions.

The effects of hydrogen emissions on local air pollution have not been very thoroughly studied, but the effects seem to be small based on current published literature. It is important to note that the effects of hydrogen leakage are highly uncertain. Studies performed so far are difficult to compare and have not always used tools with the necessary complexity. Also, some results lack better validation using different models. In addition, the effects of hydrogen depend on complex chains of chemical reactions. Hence, if hydrogen is not simply leaked into a constant background of emissions, but instead is emitted in place of other emissions (say fossil fuel burning emission are taken out), the effects are changed significantly. Therefore, more detailed modelling of the effects of hydrogen in different scenarios of future emissions and compared to different background emissions are needed to fully understand the effects. Regardless of uncertainties, however, hydrogen emissions can have adverse effects, and any usage should seek to minimize leakage. The main report below will go into details on the processes and effects.
2 Scientific report

Molecular hydrogen is an interesting energy carrier, as it can carry and release energy by reacting with oxygen to form water. This reaction is extremely energetic, yielding around 33 kWh of usable energy per kg of hydrogen gas [1]. Because of the energy density, hydrogen can be used for efficient storage and transportation of energy from other sources. Hydrogen used in this way is commonly divided into three categories; green, where hydrogen is produced with electrolysis using energy from renewable sources, grey or brown, where hydrogen is produced using fossil fuels, for instance by extracting it from the natural gas methane or coal, and blue, where carbon capture and storage (CCS) is combined with the hydrogen production from fossil fuels to remove the CO₂ produced in the hydrogen forming reactions. In this report we will look closer at the climate and environmental impacts particularly on the atmosphere from the usage of hydrogen as an energy carrier.

2.1 The Hydrogen Fuel Reaction and Hydrogen Leakage

Let us examine first the climate effects of the hydrogen burning reaction. From this reaction only water is released. Water vapor in the lower atmosphere, the troposphere, is a greenhouse gas, but it is already quite abundant, constantly evaporating from the world’s oceans at 3.8*10⁸ Tg (teragram) per year. If the entire World’s energy consumption in 2017 of 1.3*10¹⁸ Wh were to come from hydrogen fuel, this would yield an extra water vapor emission of 7.1*10⁶ Tg. Since this extremely high estimate is less than one part in fifty of the current natural evaporation, the climate effects of these emissions can safely be neglected.

Since the emissions from the fuel reaction are unimportant, we will focus this report on the effects of hydrogen leaked between production and its usage as fuel. The amount of leakage depends highly on the mode of transportation, and the distance between production and usage [2]. The literature estimates this leakage to lie somewhere between 0.3 % and 20 % [2-4], with values above 10% considered relatively unlikely. However, these numbers are highly uncertain, as even its leakage rates compared to natural gas in natural gas pipes are not fully known, for a more thorough discussion of this, see [5] and references therein. In addition to leakage emissions, it is important to note that hydrogen is highly combustible, and safe transportation, storage and other related aspects are therefore important to consider. However, these issues can be quite manageable [6, 7] and we will not consider the effects of that further here.

2.2 The Hydrogen Cycle

Molecular hydrogen is also a naturally occurring, but reactive gas, in the atmosphere. To understand its effects, it is necessary to have a basic understanding of its current cycle, sources, and sinks. The hydrogen concentration is currently around 550 parts per billion (ppb), and studies of South Pole Ice cores show an increase from 350 ppb over the last century[8]. Ground observations [9] and Greenland Ice cores[10] reveal that this trend has been more varied, or at least weaker, in recent decades. Fossil fuel emissions have contributed to the increase, but it is unclear whether other sources or sinks have changed during the industrial era.
In figure 1, we see these sources and sinks with approximate estimates for their strengths. The numbers have varying uncertainty, and a table providing estimates with uncertainties found in the literature can be found in Appendix 1.

The largest source is photooxidation in the atmosphere. Here, formaldehyde (CH$_2$O), which is the decay product of methane and various other organic substances, or emitted directly, takes up energy from solar photons to form hydrogen molecules. The second largest source is various forms of incomplete combustion processes. When fossil fuels or biomass burn (for instance forest fires), some fraction of the combustion is incomplete and produces carbon monoxide (CO). The carbon monoxide reacts with water molecules in the air to form hydrogen and carbon dioxide gas (CO$_2$). Hydrogen gas is also emitted from various geological sources, such as volcanoes. Finally, the biological process in which bacteria in oceans or on land fixate nitrogen from the air also produces hydrogen.

The hydrogen from various sources is removed from the atmosphere by mainly two sinks. The largest and most uncertain sink is the biological uptake [11]. This process depends on season and temperature, and seems to have increased with the recent rise in global temperatures [12]. The hydrogen that is not taken up by soil is destroyed in reaction (1) with OH

$$H_2 + OH \rightarrow H_2O + H$$  

(1)

The hydroxyl radical, OH, is an extremely important and powerful oxidant in the atmosphere. It is extremely reactive and able to oxidise many compounds in the atmosphere. Oxidation by OH leads to a decay not only of hydrogen, but also of methane and other substances. Hence, the efficiency of
reaction (1) depends on the levels of many other gases in the atmosphere, most notably methane, nitrogen oxides (NOx), CO and volatile organic compounds (VOCs). Currently, the atmospheric lifetime of H2 is roughly 2 years [12].

The processes are interconnected and subject to feedbacks. The destruction of methane is also a source of hydrogen through production of formaldehyde, while hydrogen decay competes for the OH with the methane decay. Figure 2 summarises the most important atmospheric reactions for hydrogen, and how they affect other important gases and atmospheric properties.

![Figure 2: The reaction of hydrogen with hydroxyl radicals, and important reaction chains affected by it.](image)

2.3 Effects on Global Warming

Molecular hydrogen itself is not a greenhouse gas, just as nitrogen and oxygen. However, unlike these gases, hydrogen is unstable, and decays in the atmosphere through reaction (1). Hence the effects that an increase in hydrogen has on the products of reaction (1) affects the climate system in various ways.

In the troposphere, the lowest layer of the atmosphere (see Figure 3), there are two main climate effects from increased hydrogen abundance: 1) longer lifetime of methane and 2) production of ozone.

The first reaction in the atmospheric decay chain for methane is:

\[ \text{CH}_4 + \text{OH} \rightarrow \text{CH}_3 + \text{H}_2\text{O} \quad (2) \]

Hence, when more hydrogen reacts with OH, less OH is available in the atmosphere, and methane has a longer lifetime and therefore a stronger global warming effect in the atmosphere.
Second, the hydrogen atoms (H) produced in reaction with O₂, rapidly go through a reaction chain that produces ozone (O₃). Ozone is also a greenhouse gas.

Derwent [13] made a review of the global warming from methane and ozone from hydrogen and found GWP₁₀₀ value of 0-9.8 with a central value of 4.3 with 95% confidence, after considering the many sources of uncertainty. Furthermore, this value was confirmed by a more recent study [14].

GWP-values defined over different time frames can be found in Appendix 2.

![Figure 3: The lowest levels of the atmosphere; the troposphere, the stratosphere, and the mesosphere on top. In the troposphere, the temperature decreases with height, whereas in the stratosphere the temperature increases with height. In the stratosphere, the ozone layer is located.](image)

In the troposphere the evaporation of water from ocean and inland water sources makes the air quite humid, and hence additional water vapor from either H₂ decay or H₂ burning has no impact on the overall water saturation. Although a greenhouse gas, H₂O-production in the troposphere from hydrogen leakage does not contribute to global warming. However, as hydrogen has a lifetime of roughly two years, some portion of the hydrogen will rise to reach the stratosphere, the upper level of the atmosphere, before reacting with OH (see figure 2). The stratosphere is very dry, as water vapor in the troposphere condenses and precipitate out before reaching the stratosphere. Hence, H₂O-production in the stratosphere can influence the climate. This might also have implications on the climate effects of H₂ fuel used in airplanes as these operate up to the low stratosphere. Figure 3 shows these atmospheric levels schematically. The effect of stratospheric water vapor from hydrogen has not been calculated in a consistent way in literature. We estimate a GWP₁₀₀ from this effect in the range 0-10 with a more likely value at the lower end. This value is based on water vapor increases in the stratosphere [3, 15], similar to the effects of methane on stratospheric water vapor [16], and should be considered highly uncertain.

For comparison, 1 kg of hydrogen yields 33.33kWh of usable energy, whereas fossil fuel usage produces 2.5-5 kWh/kg CO₂ emitted [17]. Thus, even with a 10% leakage rate, a high estimate for the hydrogen GWP, the climate effects of swapping energy sources from fossil fuel to blue or green
hydrogen is cut to roughly a tenth. Similarly, [14], finds that substituting fossil fuels with blue or green hydrogen with a 10% leakage rate, leads to a climate effect from the energy production that is 5-7% of the original fossil fuel usage. However, other emissions or energy use in the hydrogen production is not accounted for in these calculations. If one can attain a 1% leakage rate, they estimate that the climate impacts from the hydrogen leakage to be 0.7-0.5% of the climate impacts of the original fossil fuel.

It is important to note that the GWP value stated above was estimated by adding hydrogen without changing the concentrations of other gases. In practice, substantial adoption of hydrogen will likely come with, or alongside independent changes in the use and emissions of other gases that affect the impacts of hydrogen. Appendix 3 summaries results of hydrogen emissions simulations with simultaneous variations of different other substances as found in the literature. Most notable is NOX levels. If NOX levels decrease, less ozone is produced, and the lifetime of methane is prolonged [3, 18]. [13, 14] call for more studies using other 3D chemical transport models to reduce the uncertainties. Studies investigating more realistic scenarios in a realistically changing background would also be useful in assessing hydrogen adaption schemes. There are several potential climate effects of hydrogen emissions that is missing in the literature. The GWP estimates due to increased stratospheric water vapor have not been studied in detail. Furthermore, there are other short-lived climate forcers such as hydrochlorofluorocarbons (HCFCs) which decays depending on the OH concentration. This means that they might also have increased lifetimes and GWPs when hydrogen is emitted to the atmosphere.

### 2.4 Effects on the Ozone Layer

The ozone layer is located 15-35 km above the surface and protects the Earth from harmful UV radiation from the sun. Stratospheric ozone and ozone in the ozone layer are affected by a complex array of chemical reactions, which in turn are affected by temperature, concentration and transport processes in the stratosphere [19, 20]. In the mid-1970s it was discovered that chemicals from industry are destroying the ozone layer, especially over Antarctica during spring. These chemicals are chlorine-containing source gases (mainly chlorofluorocarbons (CFCs) and halons). Polar stratospheric clouds are important for this ozone destruction by these gases. These clouds form under extreme cold conditions and in the presence of UV-light, one single chlorine atom can continuously destroy ozone. The discoveries led to a ban on these chemicals in the Montreal Protocol that entered into force in 1989. Today the ozone layer is starting to recover, and it is projected that ozone levels will reach pre-1980s values around 2060 [21].

Hydrogen emissions may lead to increased water vapor in the stratosphere, at altitudes where the ozone layer is located. The water vapor leads to a cooling of the stratosphere [22], and colder temperatures makes the ozone destruction with CFCs more effective [23], as illustrated in Figure 2. However, cooling of the stratosphere can also drive ozone increase and lead to temperature feedback [19, 20]. Ozone responses vary in different heights and latitudes, and is also affected by future climate change [20, 24-26]. Therefore, the effects of hydrogen emissions on the ozone layer are not obvious. Various sources in the literature estimate a 0-11% decrease in ozone levels from hydrogen emissions [2, 3, 15, 18, 27, 28], where the upper limit is an extreme adaption and leakage scenario, and applying particularly to the Arctic in cold winters [15]. It must be emphasized that these studies have large uncertainties.

Ozone in the stratosphere is also a greenhouse gas. Changes in ozone in the stratosphere will influence the energy balance, either warming or cooling depending on where ozone changes. No studies have quantified this effect.
2.5 Air Pollution

The decay of hydrogen can lead to increased ozone at the surface and impact the air quality experienced by humans, animals, and plants. Local air pollution has adverse effects on health, and on nature and crop yields. When hydrogen is substituted for fossil fuel, local air pollutants are reduced leading to improved air quality. Consequences of hydrogen to local air pollution was considered in [29]. They assumed increased leakage of hydrogen from 0.1% to 4% in a scenario where all fossil fuel cars were converted to hydrogen driven cars and found local air pollution effects of below 1% decrease for OH and below 2% increase for NOx. Compared to the beneficial effects of removing the fossil fuel driven cars, this is very negligible. Studies have found both decreases [18, 30] and increases [3, 29] in ozone, depending on the hydrogen fuel substitute. [29] found that the increases were strongest when ground level ozone was low, but highly dependent on NOx emissions reduction. Overall, they concluded that the leakage of hydrogen, when kept below 4%, had only small effects on local air pollution.

2.6 Key Uncertainties

As we have seen, hydrogen emissions can impact global warming and the recovery of the ozone layer, meaning that minimizing leakage should be an important priority. On the other hand, it seems clear that the overall impact from hydrogen is smaller than that of fossil fuel usage. However, the effects of hydrogen are associated with large uncertainties. These uncertainties are exacerbated by the fact that the effects depend on the concentrations of other gases, particularly NOx, CO, CH4 and VOCs.

The hydrogen cycle (budget) is interconnected and deserve further exploration. The main sink, soil uptake, is highly uncertain and varies with season and humidity. As soil uptake seems to have increased with recent global warming [12], it might continue to change as temperatures continue to rise. Since this is a biological process in competition with other processes, the hydrogen concentration itself might affect the effectiveness of the process. A recent paper [31], pointed out that geological sources of hydrogen have been largely ignored in the literature. According to [31], this source is substantial, but further study is required to constrain both its size and variability.

The effects of hydrogen emissions on atmospheric processes is highly dependent on emissions and concentrations of other gases. Particularly, the evolution of emissions in methane, CO and NOx play crucial parts. In the context of stratospheric ozone depletion, future concentrations of halogens in the stratosphere are also important. So far, the investigations into this have not been standardized and results from different sources are not directly comparable [14]. Also, studies have either focused on stratospheric ozone depletion or methane lifetime or concentrations, rather than overall increase or decrease in global warming. Many studies have been conducted using 2D-models.

The need for robust and comparable 3D-modelling to look at several outcomes with a detailed hydrogen cycle and different conditions and concentrations of other gases, is clear.

2.7 Summary and Outlook

Since hydrogen is not a greenhouse gas, hydrogen gas emissions do not lead to global warming directly. However, hydrogen is involved in many chemical reactions in the atmosphere and will therefore affect the lifetime and concentrations of various other gases. Hydrogen can increase the lifetime of methane, making it a more potent greenhouse gas. Hydrogen can also change ozone concentrations. Ozone is both a greenhouse gas, a toxic air pollutant near the surface, and forms the ozone layer in the higher layers of the atmosphere. Hydrogen emissions may affect ozone concentrations in all layers of the atmosphere in different ways, increasing it both as an air pollutant and greenhouse gas, while simultaneously depleting the ozone layer. These adverse effects are likely
smaller than those of the fossil fuel usage hydrogen fuel would replace, however, it underlines the importance of keeping hydrogen leakage as low as possible.

The indirect effects of hydrogen emissions are strongly interconnected with the concentrations of other gases in the atmosphere. To quantify the climate effect of a transition to a hydrogen economy, we recommend detailed chemical multi-modelling of hydrogen leakages using different emission scenarios for key compounds.
3 Appendix

3.1 Appendix 1 – Hydrogen Sources and Sinks

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>11 ± 4</td>
<td>11 ± 4</td>
<td>15 ± 10</td>
<td>15 ± 6</td>
<td>18.3</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>15 ± 6</td>
<td>20 ± 10</td>
<td>16 ± 5</td>
<td>16 ± 3</td>
<td>10.1</td>
</tr>
<tr>
<td>N2 fixation ocean</td>
<td>6 ± 3</td>
<td>4 ± 2</td>
<td>3 ± 2</td>
<td>6 ± 5</td>
<td>6.0</td>
</tr>
<tr>
<td>N2 fixation land</td>
<td>3 ± 2</td>
<td>2.4 ± 4.9</td>
<td>3 ± 1</td>
<td>6 ± 5</td>
<td>0</td>
</tr>
<tr>
<td>Photochemical production</td>
<td>41 ± 11</td>
<td>41 ± 11</td>
<td>40 ± 16</td>
<td>64 ± 12</td>
<td>34.3</td>
</tr>
<tr>
<td>Geological sources</td>
<td>Not considered</td>
<td>23 ± 8</td>
<td>Not considered</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>Sources total</td>
<td>76 ± 14</td>
<td>100 ± 16</td>
<td>77 ± 16</td>
<td>107 ± 15</td>
<td>73d</td>
</tr>
</tbody>
</table>

**Sinks:**

<table>
<thead>
<tr>
<th>Sinks</th>
<th>Oxidation by OH</th>
<th>Soil uptake</th>
<th>Sinks total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19 ± 5</td>
<td>60 ± 20</td>
<td>79 ± 20</td>
</tr>
<tr>
<td></td>
<td>8 ± 3</td>
<td>90 ± 20</td>
<td>102 ± 25b</td>
</tr>
<tr>
<td></td>
<td>19 ± 5</td>
<td>56 ± 41</td>
<td>75 ± 41</td>
</tr>
<tr>
<td></td>
<td>19 ± 3</td>
<td>88 ± 11</td>
<td>107 ± 11</td>
</tr>
</tbody>
</table>

Table 1: Estimated output and uptake of molecular hydrogen in Tg/year from various sources and sinks as found in the literature. The estimates of the budget have been compared to observations, including budgets going back to ca 100 years ago [35]. a Except for the geological source, most estimates from Zgonnik [31] are taken from the literature, in particular, the results listed here are from [12, 18, 36, 37], though results from other sources are also stated. Ehhalt and Rohrer [12] also lists results of simulations done by [38-40] these are all relatively comparable to the results of [12, 32]. Price, Jaeglé [34] similarly includes the results of [37, 39-42].b The sink total found in Zgonnik [31] include escape to space [43] and uncertainties from possible ocean uptake. For the latter no estimates, or concrete references are given. c Price, Jaeglé [34] does not include uncertainty estimates. d Price, Jaeglé [34]’s source budget includes an estimated 4.4 Tg H\textsubscript{2}/year from burning of biofuels, which is not otherwise pulled out as a separate component. It might be attributed to biomass burning or fossil fuel/anthropogenic emissions elsewhere.

3.2 Appendix 2 – GWP Values of H\textsubscript{2} on Different Time Scales

<table>
<thead>
<tr>
<th>GWP-type</th>
<th>Methane lifetime</th>
<th>Tropospheric ozone</th>
<th>Stratospheric water vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP\textsubscript{100}</td>
<td>2.3±1.5 \textsuperscript{a}</td>
<td>2.1±1.1 \textsuperscript{a}</td>
<td>0-10\textsuperscript{a}</td>
</tr>
<tr>
<td>GWP\textsubscript{30}</td>
<td>7.7±11\textsuperscript{a}</td>
<td>7.5\textsuperscript{a}</td>
<td>0-30\textsuperscript{a}</td>
</tr>
</tbody>
</table>

Table 2: The global warming potential is defined as the time integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO\textsubscript{2}. The subscript 100 or 20, refers to the number of years over which the forcing is integrated. Hence short-lived forcers such as hydrogen through methane or ozone have much higher GWP\textsubscript{30} than GWP\textsubscript{100}, as their forcing effects comes mainly in the years right after the emission, whereas CO\textsubscript{2} provides near constant forcing over much longer time spans. Due to the different physical properties of climate drivers, there are no single perfect metric to be used to compare different drivers, and alternative metrics has been suggested [44-46], but GWP\textsubscript{100} is the one that are used in UNFCCC. a The GWP from stratospheric water vapor is own estimates based on available information in the literature. This estimate is highly uncertain as GWP estimates are not available in the literature. There might also be effects from other components that have not been considered in the literature. These include effects on stratospheric ozone and increases in lifetime of other short-lived forcers that decay through oxidation by OH. While the latter might increase the GWP further, the effects on stratospheric ozone might both lead to increase and decreased GWP.
3.3 Appendix 3 – Atmospheric Climate and Environmental Effects under Different Background Emission Changes

<table>
<thead>
<tr>
<th>Type of model simulation:</th>
<th>Pure hydrogen emissions</th>
<th>Fossil fuel emissions substituted with hydrogen</th>
<th>Fossil fuel emissions substituted with hydrogen, but NOx kept as originally</th>
<th>Fossil fuel emissions substituted with hydrogen, additional methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources that performed simulation:</td>
<td>[13-15, 18, 27, 28, 47]</td>
<td>[2, 3, 18, 30, 48]</td>
<td>[3, 18, 48]</td>
<td>[2, 3, 18]</td>
</tr>
<tr>
<td>Tropospheric ozone</td>
<td>0-0.50* 10^3 Wm^-2 per year per 1 Tg hydrogen point emission integrated over 100 years*</td>
<td>Decrease of 2-6% in ozone concentration</td>
<td>1-4% decrease to tropospheric ozone concentration</td>
<td>3% decrease to 2% increase found in the literature.</td>
</tr>
<tr>
<td>Methane</td>
<td>23-35% increased lifetime for 18Tg hydrogen emission pulse, in a setup which found GWP of 2.3 from this.</td>
<td>-3% til +15% increase in lifetime, depending on how much is being substituted, and leakage rate.</td>
<td>0-2% increase in lifetime (slight decrease in lifetime even possible, depending on how much methane is removed among the fossil fuel emissions)</td>
<td>10% increase in methane has much higher impact on methane lifetime.</td>
</tr>
<tr>
<td>Stratospheric water vapor</td>
<td>RF of 0.016 Wm^-2 for an increase in H_2 from 0.56 ppm to 1.10 ppm (for a 3.6% increase in Arctic Strat. H_2O, range 0.6-11% for H_2 in the range 0.65 ppm to 2.30 ppm)</td>
<td>Impacts are lowered compared to the pure hydrogen emission. In [18] the increase was only a third of the pure hydrogen emission, though still within the same range.</td>
<td>Higher/unremoved NOx emissions also lower the impacts on stratospheric water vapor.</td>
<td>Increased methane increases the impacts to stratospheric water vapor.</td>
</tr>
<tr>
<td>Stratospheric ozone*</td>
<td>0-9% loss (maximum for extreme hydrogen emission scenario with quadrupling of H_2),</td>
<td>&lt; 2% loss</td>
<td>&lt; 1% loss</td>
<td>No estimates in the literature</td>
</tr>
</tbody>
</table>

Table 3: Effects of hydrogen emissions found in the literature in different setups [2, 3, 13-15, 18, 27, 28, 30, 47, 48]. The first column describes emissions of hydrogen simply added to a fixed background. These results are the ones referred to in discussion in the main text. The other setups describe a more holistic hydrogen energy implementation, in which other emissions are eliminated as hydrogen fuel is being used in their place. These setups differ, but we have sorted them into three main categories. The first is a typical green hydrogen setup, where a fossil fuel emission sources is substituted with a hydrogen energy from a renewable source such as wind or solar power. Here all the emissions from the original fossil fuel sources that are being substituted are eliminated and hydrogen is added. This includes decreases in CO, OH, methane, NOx, and other trace gases. The second setup assumes co-emissions of NOx as certain hydrogen fuel burning co-emits NOx [48]. NOx is a key substance in the reactions affected by the hydrogen cycle. The third setup looks at substituting fossil fuel, while methane emissions are simultaneously increased. The amount of hydrogen being substituted and leaked (ranging from 5-6 Tg to 110 Tg), and the change in emissions of other gases differ significantly across the literature. Further information and list of experiments is given in [15, 18]. * All estimates here depend on height and latitude, with the highest losses in Northern high latitudes, and above the lower stratosphere, so locally the losses can be larger, and some locations may even see increased ozone concentrations.
References

17. Quaschning, V. 2015 [cited 2020; Available from: https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php#:~:text=If%20fuels%20are%20used%20for%20one%20kilowatt%20hour%20of%20electricity.
CICERO is Norway’s foremost institute for interdisciplinary climate research. We help to solve the climate problem and strengthen international climate cooperation by predicting and responding to society’s climate challenges through research and dissemination of a high international standard.

CICERO has garnered attention for its research on the effects of manmade emissions on the climate, society’s response to climate change, and the formulation of international agreements. We have played an active role in the IPCC since 1995 and eleven of our scientists contributed the IPCC’s Fifth Assessment Report.

- We deliver important contributions to the design of international agreements, most notably under the UNFCCC, on topics such as burden sharing, and on how different climate gases affect the climate and emissions trading.
- We help design effective climate policies and study how different measures should be designed to reach climate goals.
- We house some of the world’s foremost researchers in atmospheric chemistry and we are at the forefront in understanding how greenhouse gas emissions alter Earth’s temperature.
- We help local communities and municipalities in Norway and abroad adapt to climate change and in making the green transition to a low carbon society.
- We help key stakeholders understand how they can reduce the climate footprint of food production and food waste, and the socioeconomic benefits of reducing deforestation and forest degradation.
- We have long experience in studying effective measures and strategies for sustainable energy production, feasible renewable policies and the power sector in Europe, and how a changing climate affects global energy production.
- We are the world’s largest provider of second opinions on green bonds, and help international development banks, municipalities, export organisations and private companies throughout the world make green investments.
- We are an internationally recognised driving force for innovative climate communication, and are in constant dialogue about the responses to climate change with governments, civil society and private companies.

CICERO was founded by Prime Minister Syse in 1990 after initiative from his predecessor, Gro Harlem Brundtland. CICERO’s Director is Kristin Halvorsen, former Finance Minister (2005-2009) and Education Minister (2009-2013). Jens Ulltveit-Moe, CEO of the industrial investment company UMOE is the chair of CICERO’s Board of Directors. We are located in the Oslo Science Park, adjacent to the campus of the University of Oslo.