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Comment on acp-2022-91

Ilissa B. Ocko and Steven P. Hamburg

Author comment on "Climate consequences of hydrogen emissions" by Ilissa B. Ocko and Steven P. Hamburg, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2022-91-AC2, 2022

Dear Steven Kloos,

Thank you for taking the time to comment on our manuscript and helping to ensure its robustness. Below, we clarify our methods and assumptions for hydrogen emissions and impact metrics in support of our analysis. In particular, we address several specific misunderstandings, inconsistencies, errors, and assertions unsupported by data in your comments. Indeed the concerns you raise are among the very reasons that we undertook our analysis to begin with.

For example:

- Comment #1 states that we don't take volume into account and thus our analysis is not an "honest assessment of the impact of leakage of hydrogen vs methane or carbon dioxide, for example from a gas pipeline." However, volume is accounted for in estimates of hydrogen emissions used in our study, and we are *not* comparing hydrogen leaks to methane leaks and CO2 leaks from a pipeline. Rather, we are comparing the climate impacts from fossil fuel technologies (such as CO2 emissions from using diesel in a truck) to the climate impacts from hydrogen lost along the value chain (for example before it is used in a fuel cell to replace the diesel truck).
- Comment #2 states that "the authors must use GWP-100 as the standard because it is the standard" but then at the same time also argue in Comment #1 that GWP is problematic because it is based on mass and not volume. Comment #2 also states that "the GWP of hydrogen in the first years is higher than that in the out years – but that's the same with virtually every climate pollutant" which is not true – it is *not* the same with virtually every climate pollutant; it depends strongly on the lifetime of the climate impacts from a particular forcer, which vary tremendously for different forcers. So for some climate forcers, like hydrogen and methane, time horizon matters a lot more than for others, such as nitrous oxide.
- Comment #3 claims that hydrogen is a valuable product intentionally created, and therefore there is strong economic and practical motivations to prevent leaks. However, without data to confirm that emissions are minimal, we cannot assume that it is. This is precisely why we are writing this paper, to call attention to the need to develops methods to measure emissions.
- Comment #4 states that we "argue against using green hydrogen as a climate solution, in stark contrast to the well accepted role that green hydrogen must play in achieving decarbonization of hard to abate sectors." Nowhere do we make that assertion. To the

contrary, we say it is essential to address the concerns raised in the paper for the express purpose of ensuring that large scale hydrogen deployment – whether green, blue or otherwise – actually benefits the climate. To that end, we call for additional research, suggest use cases most likely to yield a positive result, and offer suggestions to maximize its benefits when it is used.

Below we respond point-by-point to the individual comments (comments in bold italics and responses in regular text).

Comment #1:

Hydrogen is a gas, as is methane and carbon dioxide. The paper concerns hydrogen 'escape' and 'leaks' into the atmosphere. When those escapes happen, a volume of hydrogen will be released, and the mass of the hydrogen released will depend on the volume, and pressure, of the release. If a similar leak of methane were to happen, for example, the volume of methane released would be similar but the mass of methane would be about 8X higher (because a mol of methane is about 8X heavier than a mol of molecular hydrogen). The problem with using comparative leaks using Global Warming Potential (GWP) values is that GWP is based on the mass of the climate pollutant, not the volume. So, while hydrogen has a higher GWP on a mass basis, the same volumetric leak of hydrogen relative to a leak of methane or carbon dioxide will have ~8 or ~22 times less mass (respectively), and the volume-adjusted GWP of the hydrogen from a leak is actually lower than that of both methane and carbon dioxide from the same volume of leak. An honest assessment of the impact of leakage of hydrogen vs methane or carbon dioxide, for example from a gas pipeline, should take this volume adjustment into account.

First, we think there is a misunderstanding here of our analysis. We never compare the warming potency of leaks between hydrogen, methane, and CO2. Rather, we assess (1) hydrogen's warming potency as a gas using the standard GWP climate metric, and (2) the net climate impacts of replacing a range of fossil fuel technologies (in transport, industry, and power) with hydrogen alternatives based on the avoided CO2 emissions from deploying a unit of hydrogen (for varying emissions rates).

We use the traditional GWP metric in its standard form to evaluate the potency of a non-CO2 gas relative to CO2, and in our revised paper we include new GWP equations derived specifically for hydrogen's indirect effects (Warwick et al., 2022). We agree there are many reasons why GWP can be problematic and misleading when comparing different climate forcers. However, for the same argument used in your Comment #2 – that it is the "standard" metric used for decades, and the most familiar to stakeholders – GWP is nevertheless a useful and important indicator of the potency of a gas, which is why we use it in its standard form based on mass. To argue in one comment that GWP is not appropriate without an adjustment, and then in another that it must be used in its traditional way, is perplexing.

We think that presenting the information using the standard GWP metric (via mass) is meaningful because it is easily understood and familiar. However, we agree that in order to truly understand the climate implications for hydrogen emissions in a hydrogen economy, one needs to consider the magnitudes of emissions of hydrogen relative to carbon dioxide, and that this will indeed depend on volume and pressure for hydrogen.

That is precisely the reason why, in the next component of our analysis – where we examine the net climate impacts over time for a generic case of replacing fossil fuel technologies with clean hydrogen alternatives for a range of future hydrogen emission rates – we carefully compare emissions magnitudes associated with hydrogen and fossil fuel technologies based on already published data for emissions rates which account for factors like volume (for example, see: the supplemental material for Cooper et al. Science of the Total Environment 2022; Frazer-Nash Consultancy, 2022). However, we note that all published studies we are aware of ultimately report the resulting emissions magnitudes in terms of mass, including:

Bond, S. W., Gül, T., Reimann, S., Buchmann, B., and Wokaun, A.: Emissions of anthropogenic hydrogen to the atmosphere during the potential transition to an increasingly H2-intensive economy, Int. J. Hydrogen, Energ., 36, 1122–1135, https://doi.org/10.1016/j.ijhydene.2010.10.016, 2011.

Colella, W. G., Jacobson, M. Z., and Golden, D. M.: Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases, J. Power Sources, 150, 150–181, https://doi.org/10.1016/J.JPOWSOUR.2005.05.092, 2005.

Cooper, J., Dubey, L., Bakkaloglu, S., Hawkes, A.: Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming, Sci. Total Environ., 830, http://dx.doi.org/10.1016/j.scitotenv.2022.154624, 2022.

Derwent, R. G., Collins, W. J., Johnson, C. E., and Stevenson, D. S.: Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects, Climatic Change, 49, 463-487, https://doi.org/10.1023/A:1010648913655, 2001.

Derwent, R. G., Stevenson, D. S., Utembe, S. R., Jenkin, M. E., Khan, A. H., and Shallcross, D. E.: Global modelling studies of hydrogen and its isotopomers using STOCHEM-CRI: Likely radiative forcing consequences of a future hydrogen economy, Int. J. Hydrogen Energ., 45, 9211–9221, https://doi.org/10.1016/j.ijhydene.2020.01.125, 2020.

Frazer-Nash Consultancy: Fugitive Hydrogen Emissions in a Future Hydrogen Economy, Department for Business, Energy & Industrial Strategy, https://www.gov.uk/government/publications/fugitive-hydrogen-emissions-in-a-future-hydrogen-economy, 2022.

Paulot, F., Paynter, D., Naik, V., Malyshev, S., Menzel, R., and Horowitz, L. W.: Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing, Int. J. Hydrogen Energ., 46, 13446–13460, https://doi.org/10.1016/j.ijhydene.2021.01.088, 2021.

Prather, M. J.: An Environmental Experiment with H2?, Science, 302, https://doi.org/10.1126/science.1091060, 24 October 2003.

Schultz, M. G., Diehl, T., Brasseur, G. P., and Zittel, W.: Air Pollution and Climate-Forcing Impacts of a Global Hydrogen Economy, 302, 622–624, https://doi.org/10.1126/science.1089527, 2003.

Tromp, T. K., Shia, R.-L., Allen, M., Eiler, J. M., and Yung, Y. L.: Potential Environmental Impact of a Hydrogen Economy on the Stratosphere, Science, 300, 1740-1742, https://doi.org/10.1126/science.1085169, 2003.

van Ruijven, B., Lamarque, J. F., van Vuuren, D. P., Kram, T., and Eerens, H.: Emission scenarios for a global hydrogen economy and the consequences for global air pollution, Glo. Env. Change, 21, 983–994, https://doi.org/10.1016/j.gloenvcha.2011.03.013, 2011.

Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J., Shine, K.: Atmospheric implications of increased Hydrogen use, Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/atmospheric-implications-of-

increased-hydrogen-use, 2022.

Wuebbles, D. J., Dubey, M. K., Edmonds, J., Layzell, D., Olsen, S., Rahn, T., Rocket, A., Wang, D., and Jia, W.: Evaluation of the Potential Environmental Impacts from Large-Scale Use and Production of Hydrogen in Energy and Transportation Applications, University of Illinois at Urbana-Champaign, United States, https://doi.org/https://doi.org/10.2172/1044180, 2010.

Comment #2:

The GWP of climate pollutants is measured in terms of the GWP over 100 years, i.e. GWP-100, which was established as the standard in 1990. The authors write: "reporting hydrogen's potency in GWP-100 has limited value." Yes, hydrogen has a short atmospheric half-life (~5 years) and the authors correctly point out that the GWP of hydrogen in the first years is higher than that in the out years – but that's the same with virtually every climate pollutant. The authors must use GWP-100 as the standard because it is the standard. If they choose to use GWP-10 as a comparative, that's fine and can help bring out more near-term effects, but GWP-100 is the broadly accepted standard and to say it has "limited value" is wrong.

We agree that some of our language initially used regarding issues with GWP-100 was overly strong. In our revised version, we have removed language like "misleading" and "limited value." However, we want to clarify that the context for our statement "reporting hydrogen's potency in GWP-100 has limited value" was regarding its short-term impacts, and how GWP-100 does not convey its atmospheric physics appropriately (which has been pointed out in numerous studies for over a decade, e.g. Shine et al., 2007; Alvarez et al., 2012; Allen et al., 2016; Cherubini and Tanaka, 2016; Ocko et al., 2017; Fesenfeld et al., 2018; Balcombe et al., 2018; Ocko and Hamburg, 2019; Cain et al., 2019; Collins et al., 2020; Severinsky and Sessoms, 2021; Lynch et al., 2021).

This is because either (1) its potency during the years it is influencing the atmosphere is masked, or conversely, (2), it is accounting for decades when a pulse of hydrogen is no longer influencing the atmosphere. Further, GWP-100 incorrectly suggests that a pulse of hydrogen would still impact the climate in 100 years after it is emitted. Therefore, our statement about "limited value" was meant in terms of representing atmospheric physics.

Nevertheless, we agree there is value in GWP and even GWP-100 (even if only because of its familiarity and widespread use). Therefore, we have removed this sentence and included a more objective discussion of GWP pros and cons.

We also note that our analysis does use GWP, because we see its value. We incorporate a constant emissions rate to be more realistic, and calculate results as a function of time horizon, such that we consider impacts for time horizons of 10 to 100 years. Therefore, our analysis is not at all inconsistent with the standard metric used in climate policy in which you argue should be used.

Finally, we note that the strong dependency of GWP on time horizon does *not* apply to "virtually every climate pollutant" as you assert. The shorter-lived the impacts of a climate pollutant, the more the GWP will depend on time horizon, and the larger it will be in the near-term relative to the long-term. For long-lived climate pollutants (such as N2O), there can be very little change in its relative potency over time compared to CO2. It is therefore very important to convey climate impacts over time for short-lived climate pollutants. Otherwise, if just the integrated 100-year impact is assessed, it will overlook much larger impacts in the near-term. (Please see Ocko et al. Science 2017 for more information.)

Comment #3:

Clean hydrogen, including green hydrogen, will be a purpose-manufactured, with a real continuous (i.e., variable) expense of producing the product, meaning that the green hydrogen will be produced for economic value. This is very different from fugitive Scope 1 emissions of methane or the release of carbon dioxide from combustion, cement manufacturing, or from industrial processes (e.g., steel production), where there is no economic incentive in recovering those released gasses. But with clean hydrogen there are strong economic and practical motivations to limit hydrogen leakage. The authors instead seem to wrongly equate the potential of hydrogen leakage with the leakages from uneconomical and unwanted methane and carbon dioxide and ignore this important nuance.

We agree that it is expensive to produce hydrogen, and that this should be an incentive to minimize leakage. One would expect a similar motivation to be true for methane (because natural gas is a valuable product), yet study after study has documented large scale methane leakage across the oil and gas industry value chain (see Alvarez et al. Science 2018 for a synthesis of U.S. studies).

In the absence of sensors able to monitor hydrogen emissions at the ppb level (of which we have confirmed through numerous discussions with dozens of companies, universities, and government agencies that no such technology currently exists), there is no way to know for sure that a substantial amount isn't leaked, vented, and purged during production, transport and end-use. Several recent studies confirm the lack of data and uncertainty in emissions (Meija et al. 2020; Cooper et al. 2022; Frazer-Nash Consultancy, 2022). Further, while most of the hydrogen infrastructure needed to achieve decarbonization goals has yet to be built there are plans underway to develop more pipelines and even pump hydrogen into individual homes – possibly through an existing natural gas distribution system which has already been shown to leak prodigious amounts of methane.

Note also that our assumptions of hydrogen emissions are taken directly from existing peer-reviewed literature, and are not of our own creation (Derwent et al., 2001, 2020; Prather, 2003; Schultz et al., 2003; Tromp et al., 2003; Colella et al., 2005; Wuebbles et al., 2010; van Ruijven et al., 2011; Bond et al., 2011; Paulot et al., 2021; Cooper et al., 2022; Frazer-Nash Consultancy, 2022; Warwick et al., 2022). To call into question our assumptions is to call into question the entire body of published research on this topic – with no empirical data to support such a challenge.

If it is eventually shown through credible measurements that current hydrogen emissions are indeed minor and that we shouldn't be concerned about this when scaling up infrastructure, it would be welcome news for the effectiveness of hydrogen as a decarbonization strategy. As of now, however, that data does not exist. Therefore, quantifying the climate risks from high leakage is an important part of getting stakeholders to take action now to build systems to monitor and minimize emissions.

It is much more difficult to retrofit an existing system than to build an efficient one from the get-go. Further, it should be in industry's best interest that they lose as little product as possible, as stated in your comment. Our paper is bringing attention to a potential future issue to ensure that it is addressed before it becomes an issue.

Comment # 4:

Because of these flaws, the conclusions greatly exaggerate the impact of hydrogen as a GHG and argue against using green hydrogen as a climate solution, in stark contrast to the well accepted role that green hydrogen must

play in achieving decarbonization of hard to abate sectors. The problem is hydrogen leaks, but as stated in point #1 above that a leak of hydrogen will have a lower GWP than a similar leak of methane or CO2 (based on the same volume of a leak) and as stated in point #3 that there is a strong economic incentive to limit such leaks.

We hope we have made it clear in our responses that your comments in no way support (or even suggest) a conclusion that our study "flawed." The volume of hydrogen *is* taken into account; we *do* use GWP and GWP-100 standard metrics; and there is no data to back up the claim that hydrogen shouldn't leak much because it is valuable.

Likewise, nowhere do we argue against using green hydrogen as a climate solution. To the contrary, we stated: "These impacts should be explicitly and quantitatively accounted for in order to maximize the climate benefits of replacing fossil fuel systems with hydrogen. Taking a proactive and scientific approach to understand the implications of and address hydrogen leakage can help ensure that the global rush to hydrogen delivers on its promise to benefit the climate over all timescales."

Sincerely,

Ilissa Ocko and Steven Hamburg