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Peer Review File

Effect of Hydrogen Leakage on the Life Cycle Climate Impacts of Hydrogen Supply Chains

Corresponding Author: Ms Esther Goita

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Ms Goita,

Your manuscript titled "Effect of Hydrogen Leakage on the Life Cycle Climate Impacts of Hydrogen Supply Chains" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

I-Yun Lisa Hsieh, PhD
Editorial Board Member
Communications Earth & Environment

orcid.org/0000-0002-1668-4094

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper thoroughly examines the Life Cycle Assessment, with a particular focus on the impact of hydrogen leakage throughout the entire supply chain. The findings are highly intriguing and will likely be valuable to both researchers and policymakers. I have a few minor suggestions for improving readability:

1. In line 50, the “530 Mt650MT” should be clearly separated or clarified.

2. In line 128, it would be better to remove the (1850 kg).
3. In line 130, the phrase “renewable energy based electrified heating” would be more precise.
4. In line 213, the term “t steel” should be replaced with tsteel.

Reviewer #2 (Remarks to the Author):

The authors present the manuscript titled ‘Effect of Hydrogen Leakage on the Life Cycle Climate Impacts of Hydrogen Supply Chains’ which presents the results of LCA modelling which factors in hydrogen emissions. The result show that when hydrogen emissions in hydrogen production, and hydrogen used in heavy good vehicles and in steel making, are taken in account, the impact on the GWP (100 and 20) is minimal. The work conducted is of high interest and value given the likely role hydrogen will play in decarbonising hard to abate sectors and that the environmental impacts of hydrogen is still an area with a paucity in the literature. Despite this, the manuscript is not suitable for publication in Communications Earth & Environment. The manuscript lacks key information crucial for LCA journal paper and fails to make comparisons to other similar studies. I elaborate this concern and others in more detail below:
• the information provided in the methodology is missing key pieces of information and it is not clear if the methodology used is ISO 14040/44 compliant
o which versions of ecoinvent data were used and which version of OpenLCA was used?
o Why has the IPCC 2021 (AR6) LCIA methodology been used instead of other LCIA methodologies?
o It is unclear if USA/Texas specific data was used to model all processes and activities in the LCA, or if proxy data was used
o The year the modelling is valid/representative of is not stated
o The electricity demand by the electrolyser (40 kWh in Table 4) is quite low. Typically ~50 kWh electricity is needed to produce 1 kg hydrogen. The value of 40 is very low and approaching the value for a system with no inefficiencies
o In general much more information is needed on the LCI data used in the LCA modelling as it would be very difficult for someone to try to replicate your modelling
• Why has a 2% leakage rate been assumed in the LCA modelling (Figures 1 and 2) when this leakage rate is only applicable to green hydrogen?
• A UK group have conducted research on hydrogen emissions and while they don’t carry out a LCA, some of their results would be useful for comparisons: https://www.sciencedirect.com/science/article/pii/S004896972201717X
• The discussion is very weak and it is not clear what the authors believe are the wide implications of hydrogen emissions on the environmental impacts of systems which use hydrogen
o Outside of GWP, hydrogen poses other environmental and safety concerns

Reviewer #3 (Remarks to the Author):

- In the manuscript, hydrogen is referred to as a low-carbon energy carrier (e.g., the first line of the introduction: 'Hydrogen is a promising low-carbon and scalable option...'). However, hydrogen's environmental impact depends on the production method and the source of energy used in production, as it may or may not be clean. To improve clarity, it would be better to specify 'clean hydrogen' or 'low-carbon hydrogen.' Alternatively, using hydrogen color codes could further clarify the text.

- While the importance of hydrogen and hydrogen leakage is mentioned in the introduction, there is less focus on the importance of the application of hydrogen in hard-to-abate sectors and the reasons for selecting these case studies to investigate.

- While the manuscript mentions a knowledge gap, specifically regarding leakage rates and global warming potential to quantify the life cycle climate effects from (1) different hydrogen production pathways, and (2) using hydrogen as an alternative to traditional energy sources in previously overlooked end uses, it lacks a robust literature review to support this claim. Only two studies (references [20] and [21]) are cited as related literature (Life cycle of hydrogen), which is insufficient to clearly establish the gap or differentiate this research from prior works in the field.

- Could the authors please clarify why electrolysis (wind) and electrolysis (grid mix) were not included in the sensitivity analysis shown in Figure 3?

- In the Methods - Production section, which explains the system boundaries, it would enhance the readability of the text to provide a separate description for each figure. Rather than stating that Figures 5, 6, and 7 display the system boundaries and then offering a combined description, addressing each figure individually will make the explanation clearer and more organised.

- I think the authors didn’t give enough credit to the recent literature on green hydrogen supply chains for the hard-to-abate sector. A straightforward search on search engines like Google Scholar shows this. I searched for “green hydrogen supply chains for the hard-to-abate sector” and I think the authors should use more recent papers (2023-2024) in their manuscript.

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Version 1:

Decision Letter:

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Dear Ms Goita,

Your manuscript titled "Effect of Hydrogen Leakage on the Life Cycle Climate Impacts of Hydrogen Supply Chains" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

All comments have been addressed very well.

Reviewer #2 (Remarks to the Author):

The manuscript has been revised and I am overall happy with the revisions and the replies to my comments. However, there are some minor issues with the manuscript which need addressing before it can be considered for publication:
• There are types throughout the paper e.g. lines 203 and 204 (in clean version)
• The 43% quoted in line 96 is not an emission rate, but a loss rate (hydrogen consumed within a process). The upper limit in emissions found in the Cooper et al paper is 4% for a hydrogen supply chain stage
• The discussion is still fairly weak as the importance of hydrogen emissions is still not evident. Perhaps if the CO2eq was calculated for the whole of the US's steel sector and HGV fleet (per annum) rather than per kg H2, the impact of hydrogen emission can be seen more clearly. The GWP impact of H2 is not being accounted for in any GHG emissions reporting, so it would be interesting to see how much CO2eq could be unaccounted for in a switch to hydrogen

Reviewer #3 (Remarks to the Author):

- The authors tried to address my comments. However, some of the comments still stand. In addition, the authors need to mention where they made the changes in the manuscript (Page and line). For the majority of the comments, the authors in the rebuttal letter mentioned we made the changes. For example, the author mentioned, "Some additional clarifications about clean hydrogen have been added, as appropriate, within the manuscript". Can I ask where? This happened for most of the comments. That is not the way to answer comments!

- -I still believe the authors didn't give enough credit to the current literature in the area of green hydrogen supply chain. For example:

Azadnia, A. H., McDaid, C., Andwari, A. M., & Hosseini, S. E. (2023). Green hydrogen supply chain risk analysis: A European hard-to-abate sectors perspective. Renewable and Sustainable Energy Reviews, 182, 113371.

Superchi, F., Mati, A., Carcasci, C., & Bianchini, A. (2023). Techno-economic analysis of wind-powered green hydrogen production to facilitate the decarbonization of hard-to-abate sectors: A case study on steelmaking. Applied Energy, 342, 121198.

Monteiro, E., & Brito, P. S. (2023). Hydrogen supply chain: Current status and prospects. Energy Storage, 5(7), e466.

Reviewer #1 (Remarks to the Author):

This paper thoroughly examines the Life Cycle Assessment, with a particular focus on the impact of hydrogen leakage throughout the entire supply chain. The findings are highly intriguing and will likely be valuable to both researchers and policymakers. I have a few minor suggestions for improving readability:

The authors thank the reviewer for their comments and have made the requested changes in the manuscript as indicated below.

1) In line 50, the "530 Mt650MT" should be clearly separated or clarified.
   - Edited typo on line 50. The statement was made to indicate a range from 530Mt to 650Mt
2) In line 128, it would be better to remove the (1850 kg).
   - (1850 kg) was removed
3) In line 130, the phrase "renewable energy based electrified heating" would be more precise.
   - The statement was corrected in line 130
4) In line 213, the term "t steel" should be replaced with tsteel.
   - Typo was corrected in line 213 with tseel instead of "t steel"

Reviewer #2 (Remarks to the Author):

The authors present the manuscript titled 'Effect of Hydrogen Leakage on the Life Cycle Climate Impacts of Hydrogen Supply Chains' which presents the results of LCA modelling which factors in hydrogen emissions. The result show that when hydrogen emissions in hydrogen production, and hydrogen used in heavy good vehicles and in steel making, are taken in account, the impact on the GWP (100 and 20) is minimal. The work conducted is of high interest and value given the likely role hydrogen will play in decarbonising hard to abate sectors and that the environmental impacts of hydrogen is still an area with a paucity in the literature. Despite this, the manuscript is not suitable for publication in Communications Earth & Environment. The manuscript lacks key information crucial for LCA journal paper and fails to make comparisons to other similar studies. I elaborate this concern and others in more detail below:

1) The information provided in the methodology is missing key pieces of information and it is not clear if the methodology used is ISO 14040/44 compliant

The authors thank the reviewer for the thoughtful comments and have addressed them as detailed below and with the necessary changes to the manuscript.

a. which versions of ecoinvent data were used and which version of OpenLCA was used?

- The authors used Open LCA v.2.10 and Econinvent v.3.10 - These additional details have been clarified in the manuscript.

b. Why has the IPCC 2021 (AR6) LCIA methodology been used instead of other LCIA methodologies?

- Within the ecoinvent database used the LCIA methods include CML. Crutal Scarcity Indicator, Cumulative Energy Demand (CED), Cumulative Exergy Demand (CExD), Ecological Footprint, Ecosystem Scarcity, Environmental Footprint (EF), EF allocation cut-off EN15804, Environmental Priority Strategies (EPS), IPCC, ReCipe, TRACI, Legacy Methods, Environmental Development of Industrial Products (EDIP), IMPACT 2002+, Selected LCI Results, and USEtox. Based on the options available the IPCC 2021 (AR6) methodology was most suited for our scope of work as it contained emissions metrics for Global Warming Potential (GWP) and Global Temperature Change Potential (GTP), which were the primary metrics of interest for the scope of this study.

c. It is unclear if USA/Texas specific data was used to model all processes and activities in the LCA, or if proxy data was used

- The authors thank the reviewer for this comment. These details are specified in the methods sections through the following statements:
    - The natural gas is sourced from markets in the US United States (U.S.), and the remaining inputs are sourced from the global market. The system boundary for the electrolysis pathways begins with deionized water, the designated electricity supplier (grid, solar, wind, or renewable mix) and their capital expenditure (CAPEX) emissions. The electricity for electrolysis is sourced from the Texas Regional Entity (TRE) for grid mix and wind electrolysis and from the Western Electricity Coordinating Council (WECC) for solar (photovoltaic) electrolysis.
    - The steel and heavy-duty transport pathways selected are based in Texas to mimic future scenarios as one of the DOE hydrogen hubs, Gulf

Coast Hydrogen Hub (HyVelocity), is expected to be constructed in Houston. A hydrogen pipeline transportation distance of 400km is assumed with the scenario that the hydrogen would be produced in Houston and used at some location within or on the outskirts of the Texas Triangle.

d. The year the modelling is valid/representative of is not stated

- The Ecoinvent database is updated and revised yearly. The validity year of the model is based on the release date of the used version of the database. The version of Ecoinvent used for this study (v.3.10) was released in November 2023.

e. The electricity demand by the electrolyser (40 kWh in Table 4) is quite low. Typically ~50 kWh electricity is needed to produce 1 kg hydrogen. The value of 40 is very low and approaching the value for a system with no inefficiencies

- The number initially used here for the electricity input (40 kWh/kg H_2) for electrolyser was based on an ideal scenario from NREL. However, the authors recognize the validity of the reviewer's statement and have updated the electricity input to 50kwh/kg H_2 in the model, as suggested. Subsequently, related results in the manuscript (text and graphs) were also updated in the manuscript. This adjustment did not materially affect the broader results, implications, and insights of the study.

2) In general, much more information is needed on the LCI data used in the LCA modelling as it would be very difficult for someone to try to replicate your modelling

- The authors have added additional details and descriptions to the methodology. The additional specifications about the Ecoinvent database version and process selections that clarify the specifics needed for the work to be replicated.

3) Why has a 2% leakage rate been assumed in the LCA modelling (Figures 1 and 2) when this leakage rate is only applicable to green hydrogen?

- The aim of the results shown in Figures 1 and 2 was to present a case where emission rates were a controlled variable and therefore assumed to be the same for all production pathways. The authors recognize that the 2% leakage rate assumed is not valid for all pathways or across the full supply chain, and so also included the results shown in Figure 3, which includes pathway specific

leakage rates and a sensitivity analysis to capture the uncertainty in actual leakage and fugitive emission rates.

4) A UK group have conducted research on hydrogen emissions and while they don't carry out a LCA, some of their results would be useful for comparisons: https://www.sciencedirect.com/science/article/pii/S004896972201717X
    - The authors have added a reference to this work for comparison in the literature review.

• The discussion is very weak and it is not clear what the authors believe are the wide implications of hydrogen emissions on the environmental impacts of systems which use hydrogen

- The authors have added language to the discussion to better describe the implications of hydrogen emissions and the environmental impacts of hydrogen systems.

o Outside of GWP, hydrogen poses other environmental and safety concerns

- The authors have added statements in the Methods section that acknowledge the other environmental and safety concerns of hydrogen and to clarify that the scope of this work is only considering the indirect climate effects and global warming potential impacts.

Reviewer #3 (Remarks to the Author):

1) In the manuscript, hydrogen is referred to as a low-carbon energy carrier (e.g., the first line of the introduction: 'Hydrogen is a promising low-carbon and scalable option...'). However, hydrogen's environmental impact depends on the production method and the source of energy used in production, as it may or may not be clean. To improve clarity, it would be better to specify 'clean hydrogen' or 'low-carbon hydrogen.' Alternatively, using hydrogen color codes could further clarify the text.
    - The authors thank the reviewer for their comments. Some additional clarifications about clean hydrogen have been added, as appropriate, within the manuscript. The authors do not wish to universally refer to only

clean hydrogen throughout because some non-clean pathways, such as grid connected electrolysis and unabated SMR, are also assessed using the LCA methodology.

2) While the importance of hydrogen and hydrogen leakage is mentioned in the introduction, there is less focus on the importance of the application of hydrogen in hard-to-abate sectors and the reasons for selecting these case studies to investigate.
   - The intent of the study was to provide an overview the climate impact of hydrogen production and a select number of hard to abate sectors. The end use applications considered are in no way comprehensive and as such were not made to be the emphasis of the study. The authors highlight the emissions reduction potential hydrogen has when used in steel production and heavy-duty transport which is discussed in the results and discussion sections. The following statement was added to the effect of this comment in the methods section of manuscript: "It must be noted that the pathways explored in this study do not encompass all the potential production, distribution, and end use components in future hydrogen scenarios. But rather represent a selection deemed by the authors as most eminent based on literature and policies".
3) While the manuscript mentions a knowledge gap, specifically regarding leakage rates and global warming potential to quantify the life cycle climate effects from (1) different hydrogen production pathways, and (2) using hydrogen as an alternative to traditional energy sources in previously overlooked end uses, it lacks a robust literature review to support this claim. Only two studies (references [20] and [21]) are cited as related literature (Life cycle of hydrogen), which is insufficient to clearly establish the gap or differentiate this research from prior works in the field.
   - The authors have expanded the literature review and added supplemental references to support the work.

4) Could the authors please clarify why electrolysis (wind) and electrolysis (grid mix) were not included in the sensitivity analysis shown in Figure 3?
   - The authors thank the reviewer for this comment and have added the electrolysis (wind) case to the sensitivity analysis, shown in Figure 3.

However, the (grid mix) was excluded as it already displayed the highest emissions ($kgCO_{2e}$ /kgH_2) in the base case with 2% leakage, which also represents the lower limit of leakage hydrogen leakage used for electrolysis. As such the authors chose to highlight more viable clean hydrogen production cases in the sensitivity analysis.

5) In the Methods - Production section, which explains the system boundaries, it would enhance the readability of the text to provide a separate description for each figure. Rather than stating that Figures 5, 6, and 7 display the system boundaries and then offering a combined description, addressing each figure individually will make the explanation clearer and more organised.
    - The authors have added more detailed descriptions about each of figures 5, 6, and 7 individually in the methods sections.
6) I think the authors didn't give enough credit to the recent literature on green hydrogen supply chains for the hard-to-abate sector. A straightforward search on search engines like Google Scholar shows this. I searched for "green hydrogen supply chains for the hard-to-abate sector" and I think the authors should use more recent papers (2023-2024) in their manuscript.
    - The authors have added more references and expanded the literature review across the manuscript.