Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

18th Aug 20

Dear Mrs Schomberg,

First of all, please allow me to apologise for the delay in sending a decision on your manuscript titled "Using Life Cycle Impact Assessment to assess the spatially explicit water scarcity footprint for the example of a Lithium-ion-battery storage". It has now been seen by 3 reviewers, and I include their comments at the end of this message/attached. 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. In particular, please clarify and sharpen your motivation and conclusions, compare to previous work where appropriate, and ensure the methods and terms are all clearly explained to a level where the research is reproducible. Please highlight all changes in the manuscript text file.

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) and the completed checklist:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me 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,

Heike Langenberg, PhD

Chief Editor
Communications Earth and Environment

On Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

In the event that your manuscript is accepted, we will provide detailed guidance on our journal policies and formatting. You may however wish to ensure that the manuscript broadly complies with our house style at this stage. See our style and formatting guide Communications Earth & Environment formatting guide for reference. The main points are as follows:

* ABSTRACT: less than 150 words and accessible. It should include the background and context of the work, the phrase ‘Here we’ (present/show/suggest) to indicate where the description of your own work starts, and then the methods/data, main results and conclusions of the paper.

*The text must be split into:
- INTRODUCTION (<1000 words): includes the background and rationale for the work. The final paragraph should be a brief summary of the main results and conclusions. The results of the current study should only be discussed in this final paragraph.
- RESULTS: split into subheaded sections; ensure that the subheadings are no longer than 60 characters including spaces.

- DISCUSSION: without subheadings.
- METHODS: split into subheaded sections; ensure that the subheadings are no longer than 60 characters including spaces

* SUPPLEMENTARY INFORMATION should be organised logically, with all items labelled as one of the following item types, and cited in the main article:
- Supplementary Figures, labelled and referred to as i.e. Supplementary Figure 1 throughout both the Supplementary Information and the main text
- Supplementary Tables, labelled as above
- Supplementary Notes, labelled as above
- Supplementary Discussion
- Supplementary Methods
- Supplementary References

Data: All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, and a list of examples, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.
In addition, Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).
In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The paper introduced a spatially explicit water scarcity footprint and applied this method to the example of a Lithium-ion-battery storage. It has good innovation in both method and practical application. Overall, the text is well arranged, and the structure is reasonable. Therefore, I recommend this article be published after some revisions.

1) Abstract: The content of the 1) Abstract is a little bit too long, so I suggest to simplify it. In addition, I suggest adding 1-2 policy implications based on the findings of this study.

2) In the Introduction section, the authors made a comprehensive literature review, but some important and related references might be missed:
Virtual scarce water embodied in inter-provincial electricity transmission in China, https://doi.org/10.1016/j.apenergy.2016.11.052
Scarcity-weighted global land and metal footprints. https://doi.org/10.1016/j.ecolind.2017.08.004
Scarcity-weighted fossil fuel footprint of China at the provincial level, https://doi.org/10.1016/j.apenergy.2019.114081

3) Table 2: the authors noted that min*-max**. Is there any quantitative explanation for this?

4) Discussion: I suggest adding more specific policy recommendations based on the new findings of the study.

Reviewer #2 (Remarks to the Author):

1. The research mainly focus on the Li-ion, and there are no more contents about Copper and Aluminum, but these two materials are shown in the Fig.3 and Fig.4 suddenly. It makes readers confused.
2. Table 2 lists some sub-indicators. Are they existed in the previous references? Or they are created for this research? It is better to define clear.
3. In section 2.2, what the differences between equations (3), (4) and (5)? There are many terms which are hard to understand.
4. In section 3.1, Fig.3 contains many contents which should be explained more. Moreover, how to decide the weight?

5. Fig.4 also needs more explanations. Authors just mentioned the circle in the map, but what is the meaning about the color (several kinds of red, yellow and green) in the different place?
6. Considering authors use LCA method to assess, it will be better to do an uncertainty analysis for some key indicators.
7. About the section of discussion, the data shortages are talked about much, but the discussion for this research is not enough. Authors could add some comparison with previous references to discuss the new finding of this research.

Reviewer #3 (Remarks to the Author):

Please see the attached review report

Dear authors,

Thanks for submitting this manuscript. It is an interesting study. However, this research needs a significant revision to sharpen the focus and its unique contribution. Currently, it does not seem so. Overall, there are four fundamental issues that need to be better clarified and addressed.

(i) The reasons for conducting the current research is not sufficiently justified; There are a few misconceptions in the current manuscript as further explained below in my specific comments

(ii) The framework is not transparent enough: the "net" water withdrawal or "water consumption" has been addressed in the current AWARE framework. If you would like to add "net" green water, i.e. the anthropogenic influence on green water demand "the baseline" from natural vegetation due to land cover change, I suggest adding them explicitly

(iii) If you have generated an alternative water scarcity factor that addresses "net green water", I think you should compare with the AWARE approach that only addresses "irrigation water".

(iv) The discussion on "grey" water footprint based on the dilution concept from the "water footprint network" does not conform with the LCA norms. Water pollution reduces potential water availability and meanwhile induce potential human health and ecosystem problems. If you want to address "grey" water in the lens of "scarcity", I think you should develop a consistent approach as how irrigation water consumption is handled by AWARE.

Some specific comments are given below:

Line 16: (1) "The risk that may arise from human water use regionally must be clearly classified in accordance with LCA standards "

Endpoint is not the same as "Risk".

Line 17: (2) The blurring of existing WF indicators, especially "blue" and "green" water, must be avoided

Green and blue water are clearly defined. Furthermore, the green and blue water is mainly used in WFA, rather than in the LCA domain.

Line 19 : (3) LCA-WF analyses must be adapted for spatially explicit LCIA

I don't see a problem. This has been routinely applied in the LCA domain. Why this is considered as a limitation?

Line 19 : Hence, a new water scarcity footprint approach for LCA (LCA-WSF) is presented to assess the probability of on-site and remote freshwater scarcity for humans and nature caused by water use along anthropogenic supply chains in a spatially explicit way

As argued above, the rationale for this objective is not justified.

Line 35: "*It is 52 million m^3 of globally weighted demineralised water per Li-ion-battery storage* "

What is the unit of li-ion battery storage?

Line 188: equation (1)

As argued above, if you want to add the “net green water” induced scarcity, please do it explicitly. For example, see a similar publication that addresses green and blue water issues.

S. Rost, D. Gerten, A. Bondeau, W. Lucht, J. Rohwer and S. Schaphoff, Water Resources Research, , DOI:10.1029/2007WR006331.

Rebuttal Letter

A point-by-point response to issues raised by the referees on the manuscript *Using Life Cycle Impact Assessment to assess the spatially explicit water scarcity footprint for the example of a Lithium-ion-battery storage*

We thank the reviewers for their valuable feedback. We have considered every comment, addressed all issues and modified the manuscript accordingly. In addition to the revised manuscript, we also provide a version with all changes highlighted – additions to the original manuscript are indicated in green and deletions in red.

In the following we respond to the reviewers point-by-point. Please note that reviewers' comments are formatted in normal font-style and our answers in italic. The line numbers and references in this document refer to the PDF of the revised manuscript without track changes.

Answers to Reviewer #1

Comment R1.1: The paper introduced a spatially explicit water scarcity footprint and applied this method to the example of a Lithium-ion-battery storage. It has good innovation in both method and practical application. Overall, the text is well arranged, and the structure is reasonable. Therefore, I recommend this article be published after some revisions.
Answer R1.1: *We thank you for your recommendation.*

Comment R1.2: 1) Abstract: The content of the 1) Abstract is a little bit too long, so I suggest to simplify it. In addition, I suggest adding 1-2 policy implications based on the findings of this study.
Answer R1.2: *We shortened the abstract to 150 words (in accordance with the guidelines of the Journal) and added a short recommendation (L 21-22), also in chapter 5 "Discussion". However, we must point out that the focus of our work is on the further development of scientific assessment methods and that we can and wish to make only indicative policy recommendations.*

L 11-22: *"To assess anthropogenic contributions to regional water scarcity along global supply chains, the life cycle water footprint is complemented by 1) a classification of the risk from human water use, 2) comprehensive conceptualisation of water use and 3) spatially explicit impact assessment. The presented midpoint water scarcity footprint approach for LCA assesses the risk of on-site and remote freshwater scarcity caused by supply chain water use spatially explicit. For a 2 MWh Li-ion battery storage, the quantitative Water Scarcity Footprint, comprising physically used water, accounts for 33,155 m^3, regionally weighted by AWARE, with highest contributions from Chilean lithium mining. The qualitative Water Scarcity Footprint, the virtual volume required to dilute pollutant emissions to safe concentrations, is 52 million m^3 of AWARE weighted demineralised water with highest contributions from copper and aluminium mining operations. For the assessment of global material supply, we recommend to consider the spatially explicit water scarcity footprint."*

Comment R1.3 2) In the Introduction section, the authors made a comprehensive literature review, but some important and related references might be missed:
Virtual scarce water embodied in inter-provincial electricity transmission in China,
https://doi.org/10.1016/j.apenergy.2016.11.052
Scarcity-weighted global land and metal footprints.
https://doi.org/10.1016/j.ecolind.2017.08.004
Scarcity-weighted fossil fuel footprint of China at the provincial level,
https://doi.org/10.1016/j.apenergy.2019.114081
Answer R1.3:. *Thank you for providing the links. We added the references to the revised manuscript.*

L 84-85: "*The energy transition in Western industrialized nations should help to lower their fossil fuel footprint*[24] *and minimize harmful environmental effects caused by greenhouse gases."*

L 427-428: "*Other spatially explicit studies on water footprints and other footprints also attach great importance to this difference*[49]*."*

L 462-464: *"Zhang et al. 2017*[54] *analysed the water footprint of inter-provincial electricity transmission in China and found that 12.7 % of the national total thermoelectric water consumption are transferred as virtual water across provinces."*

Comment R1.4: 3) Table 5: the authors noted that min*-max**. Is there any quantitative explanation for this?

Answer R1.4: *For processes with no specific location we used minimum and maximum geogenic background concentrations for aluminium in groundwater that were derived from a literature research to be able to specify a range. This is an attempt to cope with uncertainties. We added an explaining sentence in chapter 3.2 "Qualitative Water Scarcity Footprint of the modelled Li-ion-battery storage".*

> ***L 358-360:*** *"These values were determined in a literature search by comparing aluminium concentrations in groundwater in different countries (Supplementary Table 2)."*

Comment R1.5 4) Discussion: I suggest adding more specific policy recommendations based on the new findings of the study.

Answer R1.5: *We restructured chapter 5 "Discussion" and added some policy relevant recommendations (see also Comment R1.2).*

> ***L 475-476:*** *"We regard the avoidance of problem shifting as a crucial task on the way to a sustainable and long-term global energy transition."*
>
> ***L 481-483:*** *"To evaluate product water footprints and identify critical hotspots, it is crucial to consider virtual dilution of pollution in order to capture scarcity of (clean) water sufficiently."*

Answers to Reviewer #2

Comment R2.1: 1. The research mainly focus on the Li-ion, and there are no more contents about Copper and Aluminum, but these two materials are shown in the Fig.3 and Fig.4 suddenly. It makes readers confused.

Answer R2.1: *We did not focus on lithium exclusively, but the global lithium supply chain was the only commodity we regionalised ourselves. The rest of the upstream supply of the Li-ion-battery storage was modelled with the LCA database ecoinvent 3.5. In the supply chain analysis, we considered all commodities. After lithium mining, copper and aluminium mining and refining are responsible for the second highest water consumption in the supply chain. We added an explaining sentence.*

> ***L 302-304:*** *"The evaluation thus takes into account the entire supply chain, as modelled with ecoinvent 3.5, not only the regionalised lithium input. All processes that contribute more than 1 % to the total quantitative and qualitative WSF are shown in the evaluation of the results."*

Comment R2.2: 2. Table 2 lists some sub-indicators. Are they existed in the previous references? Or they are created for this research? It is better to define clear.

Answer R2.2: *The two main indicators are derived from the presented grid cell water balance within this study. The sub-indicators are partly known from former studies. This is now comprehensively addressed in the chapter "Distinction of relevant water flows and deduction of WSF (sub-)indicators".*

> ***L 179-202:*** *"The water balance shows, which water flows are relevant to identify the contribution of the sum of all water-using processes in a references area to water stress. The same water flows are used to describe the water use of a single process (e. g. a case study for which a WSF should be calculated). If they are weighted according to the regional water stress, water footprint indicators are obtained. They are grouped into two LCA-WSF midpoint indicators: 1) The quantitative Water Scarcity Footprint WSF_{quan} comprises all physical volumes of water use. According to the physical water balance (Figure 2 and equation (2)), used water is the portion of water taken from AMD_i that is not returned. It includes evapotranspiration losses (e_p), water transfers ($trans_p$) and product incorporated water (out_{inc}) per FU. Thus, the abstraction or intake of water on the input side of a water-using process per FU is indirectly considered as water use by accounting of the resulting output flows. Evapotranspiration loss e_p refers to consumptive, evaporative water use and is already well-known from former W(S)F studies[7,8]. Evapotranspiration from plant systems is included in this indicator, which represents the former "green" water[2]. The indicator $trans_p$ accounts for water that is removed from the hydrological water cycle by water transfers, e. g. through water pipelines. Product incorporated water out_{inc} represents water that is bound to the output product flow. For example, concentrated Li-brine, the output product of the first refinement step in lithium production, has a water content of approximately 90 %weight. 2) The qualitative Water Scarcity Footprint WSF_{qual} comprises all virtual dilution volumes (VDV) per FU. Different methodological approaches for the assessment of water quality exist[21,22,34], and the concept of virtual dilution is best suited here to assess the contribution of water pollution to a potential change of natural freshwater availability that exceeds the SOS: Each emission to water represents an additional burden ("material emission to water" Figure 1) and, in practical terms, reduces the availability of water with adequate quality. To ensure that the water quality of AMD_i is not reduced any additional emission would have to be diluted. Table 2 summarises the sub-indicators and establishes their relationship to the SDGs."*

Comment R2.3: 3. In section 2.2, what the differences between equations (3), (4) and (5)? There are many terms which are hard to understand.

Answer R2.3: *Equation (3) is the "original" formula to calculate the "grey water footprint" according to Hoekstra et al. 2011. In Equation (4) and (5) we present our new approach for the calculation of the "virtual dilution volume", which is a centrepiece of our study. We moved all detailed explanations and derivations in the supplementary material and reduced the number of equations by explaining equation 3 in the text to help the reader to understand the need for an extension of the current approach (L 211-212).*

Comment R2.4: 4. In section 3.1, Fig.3 contains many contents which should be explained more. Moreover, how to decide the weight?

Answer R2.4: *We added some explanations in the caption. The text also contains explanations (L 321-345). How we performed the weighting with CF_{AWARE} is explained in chapter 2.3 in detail.*

> ***L 379-390:*** *"Figure 3: The sankey diagram in the centre shows the distribution of process water uses greater than 1 % along the supply chain of the Li-ion-battery-storage in m^3 from left to right. Processes are represented by boxes, abbreviations see below. Inputs with no provider are direct inputs. Water flows are weighted with the CF_{AWARE} of the respective region if known. Flows weighted with a CF_{AWARE} < 5 are classified as uncritical (green), with 5-10 as semi-critical (yellow) and with > 10 as critical (red, see also chapter 2.3). There is only one small flow in green from "Li – Guemes, AR" to "cathode prod". The small figure on the bottom right shows all flows unweighted for visual comparison. The three bar charts on the bottom left illustrate the effect of weighting for the three greatest flows in numbers: The left number represents the unweighted evaporative water loss, respectively, whereas the right number is the unweighted evaporation multiplied by the CF_{AWARE}, which is 89 for Atacama, Chile, 88 for Zabuye, China, and 25 for Rest-of-Asia (RAS). Abbreviations: prod = production, liq = liquid, elec prod = electricity production, roll = rolling. Regions: CL = Chile, CN = China, AR = Argentina, RNA = Rest-of-North-America, RAS = Rest-of-Asia, RoW = Rest-of-World."*

> ***L 264-280:*** *"Within LCIA, quantitative results from the inventory analysis are multiplied with the CF_{AWARE}, thus transforming them into globally weighted, theoretical volumes with respect to regional conditions. The SOS for LCIA is defined here in accordance with Alcamo et al. 2003[44] who defined severe water scarcity as a withdrawal-to-availability ratio greater than 0.4[3]. However, for the AWARE approach the SOS has not yet been defined. By transferring the definition of the SOS by Alcamo et al. 2003[44] to the AWARE method (Supplementary Table 2), a CF_{AWARE} of 5 is obtained as the limit between water stress and no water stress as a counterpart to a withdrawal-to-availability ratio of 0.4. CF_{AWARE} between 5 and 10 represents moderate and CF_{AWARE} > 10 severe water stress. Hence, the CF_{AWARE} of a respective basin defines its water stress level and indicates whether the combined water consumption of*

water using processes leads to an exceedance of the SOS by reducing AMD_i (Figure 2). We have translated this classification into an AWARE map (underlying Figure 4), where basin CF_{AWARE} < 5 are coloured in green, CF_{AWARE} 5-10 in yellow and CF_{AWARE} > 10 in red. Because of the wide range, CF_{AWARE} 10-100 is divided into three ranges (10-30, 30-60 and 60-100) with darkening shades of red. Table 3 compares the DPSIR nomenclature with the equivalents at catchment and grid cell level and those used throughout this study. Table 4 provides an overview of the different specifications of WaterGAP2, the AWARE method and the presented approach."

Comment R2.5: 5. Fig.4 also needs more explanations. Authors just mentioned the circle in the map, but what is the meaning about the colour (several kinds of red, yellow and green) in the different place?

Answer R2.5: *We added some explaining sentences on our AWARE map with new colours in chapter 2.3 to make the reader familiar with the used colour scheme and added a legend in Figure 4.*

***L 274-277:** "We have translated this classification into an AWARE map (underlying Figure 4), where basin CF_{AWARE} < 5 are coloured in green, CF_{AWARE} 5-10 in yellow and CF_{AWARE} > 10 in red. Because of the wide range, CF_{AWARE} 10-100 is divided into three ranges (10-30, 30-60 and 60-100) with darkening shades of red."*

Comment R2.6: 6. Considering authors use LCA method to assess, it will be better to do an uncertainty analysis for some key indicators.

Answer R2.6: *We carried out a Monte Carlo Simulation for all (sub-)indicators to provide the uncertainties and added a new section on the uncertainties.*

***L 405-416**: "Uncertainties are determined by Monte-Carlo-Simulation (MCS), "a stochastic method to estimate the uncertainty of the model output"[47], using the simulation tool of the software openLCA (https://openlca.org) and the ecoinvent 3.5 database. It contains uncertainties for most data, while for newly created inventory data for the global lithium supply (Supplementary Chapter 3.1) no uncertainties can be determined and a log-normal distribution with a standard deviation of 1 is assumed. This is in line with the recommendations of the LCA guidelines[48]. For the product system Li-ion-battery storage, including the entire supply chain with approximately 110,000 linked processes, the uncertainties are huge (relative standard deviation (RSD) of 60 % for WSF_{quan} and of 450 % for WSF_{qual}). Lee et al. 2018[47] carried out an uncertainty analysis with AWARE for a case study in Korea and also revealed high RSD values with MSC (177 % and 185 %). They found that MSC can have* *problems to display the distribution function of the CF_{AWARE} correctly. This is supported by Hung & Ma 2009[49] who generally note, that the selection of the LCIA method is an important source of uncertainty."*

Comment R2.7: 7. About the section of discussion, the data shortages are talked about much, but the discussion for this research is not enough. Authors could add some comparison with previous references to discuss the new finding of this research.

Answer R2.7: *We restructured chapter 5 "Discussion", shortened the part about data shortages and added comparisons with previous references and highlighted our new findings.*

L 419-436: *"4.1 Conceptual Innovations - The presented LCA-WSF can comprehensively assess the risk of natural freshwater scarcity for humans and nature caused by water use associated to a distinct global supply chain in a spatially explicit way. A precondition is to regionalize and conceptualize the LCA water inventory by using the water flows we identified in the risk analysis. This was carried out for the lithium supply chain. From the identified water flows new WF (sub-)indicators were derived. These are weighted in a spatially explicit LCA, for which the AWARE software implementation was adapted. Hence, hotspots of water use can be identified along the supply chain for unweighted, purely physical water volumes as well as regionally weighted volumes. Other spatially explicit studies on water footprints and other footprints also attach great importance to this difference[49]. However, the regionalisation of the upstream supply chain has not been the focus of most analyses of the WF of energy systems for different reasons[50–53]. Different kinds of water use in the course of human-induced processes can be illuminated with the help of newly deduced sub-indicators (evapotranspiration losses, product incorporated water, water transfers, virtual dilution volumes), while uniting them under a common risk, which is the reduction of available water remaining if it results in an exceedance of the SOS. Previous water footprint studies have placed less emphasis on this. Inseparable forms of freshwater (former blue and green water) are no longer distinguished, which in the past often led to confusion and ambiguity in WF studies."*

L 437-459: *"4.2 Data shortages: Challenges still arise from data shortages. Within the scope of this study, only the inventory data for Li-mining have been enhanced and regionalised. Any other relevant mining processes within the analysis, for example copper mining, rely on data that have not been further regionalised so far. The contribution of Li-mining may be overestimated compared to other mining resources. For better-resolved results, more detailed regionalisation of more processes along global supply chains is required; an effort the LCA community is continuously working on. This analysis gives a first hint which processes contribute the most and should be focused on, e. g. "treatment of sulfidic tailings", weighted with a CF_{AWARE} of one here, would reveal even higher LCA-WSFs in regions with high CF_{AWARE}.*

Figure 3 shows that the production of liquid oxygen and nitrogen is responsible for a relative high share (5.8 %), of the total WSF_{quan}. The authors presume a mistake in the ecoinvent 3.5 database in this special case (Supplementary Table 8-13). Moreover, the underlying hydrological modelling data do not contain all kinds of human water consumption, e. g. mining activities are not considered (Table 4). First calculations indicate that CF_{AWARE} may be underestimated by up to 100 % in some basins due to that. Virtual dilution volumes outnumber physical volumes by far. This is because aluminium emissions along global supply chains are high and the suggested $c_{targ,s}$ of 0.2 mg/l[41] is low. In addition, the variable $c_{geo,s}$ has a decisive influence on the final result, that spans from 15, calculated with high $c_{geo,s,}$ to 80 million unweighted m^3, calculated with low $c_{geo,s}$, so it must be determined with sufficient accuracy. The data basis for geogenic background concentrations on a global level should be further improved.-To measure, assess and reduce product water footprints more research is needed in particular in the field of water use in the mining sector. Water pollution from diffuse sources, such as leakage from stockpile overburdens, may be a serious threat to water resources and a subject to future research.

L 462-483: *4.3 Findings and Recommendations: Zhang et al. 2017[54] analysed the water footprint of inter-provincial electricity transmission in China and found that 12.7 % of the national total thermoelectric water consumption are transferred as virtual water across provinces. This indicates that water use plays an important role in the electricity sector in general. The presented study goes a step further and for the first time investigates the remote impacts of an electric storage technology, a Li-ion battery storage, along its regionalised upstream supply chain. The hotspots of water use along the global supply chain of the modelled Li-ion battery storage are mainly associated with mining activities. Lithium brine mining in Chile and in China are responsible for the greatest evapotranspiration losses along the supply chain of the Li-ion battery, while the probability of natural freshwater scarcity for humans and nature is very high in these countries. Satisfying the global lithium demand by extracting lithium there or in regions with similar conditions will probably cause problem shifting: Climate footprints may be reduced by using electric vehicles in European countries, but in turn, the probability of natural freshwater scarcity will increase in lithium supplying countries. More attention should be paid to this fact before politicians and companies in Western nations increasingly focus on electric mobility. We regard the avoidance of problem shifting as a crucial task on the way to a sustainable and long-term global energy transition. The reduction of water quality by other mining processes like copper or aluminium extraction is another critical issue within this nexus as the associated volumes can be huge: The virtual dilution required along the supply chain of the Li-ion battery storage is in the order of magnitude of 23 % of the German total annual drinking water demand. However, impacts from water pollution on regional freshwater scarcity have not been part of LCA WF so far, as the VDV has not been assessed in an integrated manner before. To evaluate product water footprints and identify critical hotspots, it is crucial to consider virtual dilution of pollution in order to capture scarcity of (clean) water sufficiently.*

Answers to Reviewer # 3

Comment R3.1 Dear authors,

Thanks for submitting this manuscript. It is an interesting study. However, this research needs a significant revision to sharpen the focus and its unique contribution. Currently, it does not seem so. Overall, there are four fundamental issues that need to be better clarified and addressed.

Answer to R3.1 *Thank you for taking your time to review our manuscript and point out important issues. We addressed and clarified the points you raised.*

Comment R3.2 (i) The reasons for conducting the current research is not sufficiently justified; There are a few misconceptions in the current manuscript as further explained below in my specific comments.

Answer to R3.2 *Thank you for drawing attention on the innovation of our work. We revised chapter 1.2 "Requirements for a modified water scarcity footprint concept" to highlight it and sufficiently justify our contribution.*

> ***L 46-76:*** *"Despite these general guidelines, there are still many conceptual inconsistencies, particularly noticeable when comparing different systems. In order to determine spatially explicit WSFs of product supply chains, this research wants to overcome the following issues:* ***1) Diverging classifications of the risk associated with human water consumption:*** *The risk classification spans the frame for goal and scope of a life cycle wide WSF. Different W(S)F studies refer to different burdens or damages or define "water scarcity" differently. Table 1 gives an overview of-classifications of the potential burden (midpoint) and the potential (damage), referred to as "risk" in general in the following, of some selected studies. While it becomes evident from Table 1, that there is not one common risk related to human water consumption, there is a general perception of "water scarcity" and thus supply risk. As a first step, this study classifies a risk of human water consumption at midpoint level for LCA applications and then goes one step further by defining impacts as exceedance of the Safe-Operating-Space (SOS), which is derived from the SDGs.* ***2) Lack of comprehensive conceptualisation of water use in LCA within a consistent hydrological framework:*** *Blue, green and grey water have been established as commonly used sub-indicators for the W(S)F. However, it has often been discussed whether green water does contribute to environmental water flows and water scarcity at all or if it is more a matter of land use change assessment[11]. From a systems perspective, blue*

and green water are inseparably linked. In LCA, the distinction between blue and green water is not consistent because the term blue water refers to the source of the water, while green water refers to the fact that it has been used by plants. The indicator "grey water" (as per definition of Hoekstra et al. 2011[20]), representing a virtual volume that is initially not a real environmental flow, has often been critically reviewed as well[21,22]. Nevertheless, it offers the opportunity to quantify the impact on water quality on a volumetric basis[23]. As reduced water quality can lower water availability for users with higher demands for quality, it can contribute to the risk of "water scarcity". This study balances natural and process water flows within the classified risk and comprehensively conceptualizes water use in LCA against the background of a consistent hydrological framework. After that, sub-indicators of the WSF are derived from this. ***3) Lack of applied regionalisation:*** *While the locations of a production facility or a final consumer are often known within life cycle wide WSF assessments, the upstream supply chains are not or only partly spatially explicit. However, identifying the place of water use is crucial for an impact assessment with respect to regional water supply conditions. Some conceptual, data and software modifications are necessary to implement a spatially explicit impact assessment of the supply chain."*

Comment R3.3 (ii) The framework is not transparent enough: the "net" water withdrawal or "water consumption" has been addressed in the current AWARE framework. If you would like to add "net" green water, i.e. the anthropogenic influence on green water demand "the baseline" from natural vegetation due to land cover change, I suggest adding them explicitly
Answer to R3.3: *We understand from your comment that we need to clarify that we focused on two different things at the same time: comprehensive conceptualisation of water use in a consistent hydrological framework and the assessment of regional water scarcity using the existing AWARE LCIA method. We revised chapter 1.2 "Requirements for a modified water scarcity footprint concept" accordingly and explained how we deal with "green water" in the main text and the supplement*

L 69-71: *"This study balances natural and process water flows within the classified risk and comprehensively conceptualizes water use in LCA against the background of a consistent hydrological framework. After that, sub-indicators of the WSF are derived from this."*

L 175-178: *"Since it is necessary to consider all water-using processes in order to identify the potential contribution to water stress, water flows are not related to a previous, potentially natural or reference state, but are counted as such (Supplementary chapter 2.2)."*

L 188-189: *"Evapotranspiration loss e_p refers to consumptive, evaporative water use and is already well-known from former W(S)F studies*[9,10]*. Evapotranspiration from plant systems is included in this indicator, which represents the former "green" water*[2]*."*

Supplementary L 42-66: ***"****The former WF-indicator green water is no longer considered separately, which is an important innovation compared to previous concepts. As Figure 2 shows the water flow balance of water-using processes can be fully described by the variables water intake in_p, outflow out_p to AMD_i, water transfers beyond basin boundaries $trans_p$, evaporation losses e_p and outflow as product-incorporated water out_{inc}. If one of the output variables is increased, the water intake from AMDi is also increased and thus the water stress level of the respective basins. This means that a process-related calculation of these output water flows can sufficiently describe the contribution of the respective process to water stress. It is not necessary to differentiate between blue and green water. The use of water by plants in the form of evapotranspiration is described in this framework in the indicator evaporation losses e_p. This is relevant 1) for the calculation of a water scarcity footprint for a case study and 2) for the determination of the water stress level of a reference area: In the first case, transpiration by plant growth is considered in the indicator e_p, if it is relevant at any stage of the supply chain of the respective case study. To determine the water stress level, water use has to be compared to natural water availability. Water use includes all water-using processes in the reference area (human and natural), also evaporation losses by plant growth. Since access to soil moisture and shallow groundwater resources is linked to land use, there is another point to consider here: To identify the potential of water-using processes within a reference space to reduce the natural water availability the entirety of all water-using processes is considered. Shifts between the processes are not visible if they do not represent a change in total. An example should illustrate this: If a forest is cleared and instead a plantation with the same water demand is established on the same area, the contribution to water stress does not change, although the change in land cover is associated with other environmental impacts. However, these impacts must be assessed, for example, via the land footprint, not via the water footprint. This also means that the water demand of the newly created plantation is not related to the water consumption of the pre-existing forest (in our example this would be 0), but the water demand as such is counted."*

Comment R3.4: (iii) If you have generated an alternative water scarcity factor that addresses "net green water", I think you should compare with the AWARE approach that only addresses "irrigation water".

Answer to R3.4: *We did not generate an alternative water scarcity factor, but postulate to include all forms of water consumption in the LCA inventory on the one hand and assess it with AWARE on the other hand. The AWARE method addresses water consumption from agriculture, households,* *manufacturing and electricity generation which is compared with the natural water availability globally on grid cell level. The method assesses all LCA water inventory flows. We revised chapter 1.2 "Requirements for a modified water scarcity footprint concept" to clarify that.*

> ***L 58-71*: *2) Lack of comprehensive conceptualisation of water use in LCA within a consistent hydrological framework:*** *Blue, green and grey water have been established as commonly used sub-indicators for the W(S)F. However, it has often been discussed whether green water does contribute to environmental water flows and water scarcity at all or if it is more a matter of land use change assessment[11]. From a systems perspective, blue and green water are inseparably linked. In LCA, the distinction between blue and green water is not consistent because the term blue water refers to the source of the water, while green water refers to the fact that it has been used by plants. The indicator "grey water" (as per definition of Hoekstra et al. 2011[20]), representing a virtual volume that is initially not a real environmental flow, has often been critically reviewed as well[21,22]. Nevertheless, it offers the opportunity to quantify the impact on water quality on a volumetric basis[23]. As reduced water quality can lower water availability for users with higher demands for quality, it can contribute to the risk of "water scarcity". This study balances natural and process water flows within the classified risk and comprehensively conceptualizes water use in LCA against the background of a consistent hydrological framework. After that, sub-indicators of the WSF are derived from this.*

Comment R3.5: (iv) The discussion on "grey" water footprint based on the dilution concept from the "water footprint network" does not conform with the LCA norms. Water pollution reduces potential water availability and meanwhile induce potential human health and ecosystem problems. If you want to address "grey" water in the lens of "scarcity", I think you should develop a consistent approach as how irrigation water consumption is handled by AWARE. Some specific comments are given below:

Answer to R3.5: *After a careful re-consideration of all remarks on the conceptual framework, we do not see a conceptual problem with including the grey water footprint approach into LCA. It is a chance to (1) express water pollution in volumes of water (for example Van Vliet, Flörke & Wada 2017), depending on the regional conditions, and (2) assess this volume with respect to regional water scarcity on midpoint level. This ambition is also in line with the SDG framework. We highlighted that our WSF sub-indicators refer to different impacts in Table 2 and discussed the results with respect to that.*

Comment R3.6: Line 16: (1) "The risk that may arise from human water use regionally must be clearly classified in accordance with LCA standards ". - Endpoint is not the same as "Risk".

Answer R3.6: *Thank you for this remark. To align the different nomenclatures in a better way, we adapted the wording in chapter 1.2 and Table 1 (L 77).*

> ***L 50-53:*** *"Different W(S)F studies refer to different burdens or damages or define "water scarcity" differently. Table 1 gives an overview of classifications of the potential burden (midpoint) and the potential (damage), referred to as "risk" in general in the following, of some selected studies."*
> ***L 55-57:*** *"As a first step, this study defines a risk of human water consumption at midpoint level for LCA applications and then goes one step further by defining the impact as exceedance of the Safe-Operating-Space (SOS), which is derived from the SDGs."*
>
> ***L 112-114:*** *"The concept provided here goes further and compares this change of the state to what is regarded the SOS, as outlined by the SDGs. Here, we consider as impact the risk of an exceedance of the SOS."*
>
> ***L 124-129:*** *"This goes beyond conventional LCIA methods, where the SOS is usually not considered. Within LCA framework the classified risk can be located at midpoint level. The presented midpoint LCA-WSF assesses the on-site and remote probability of natural freshwater scarcity for humans and nature caused by water use along human supply chains in a spatially explicit way. "Natural freshwater" refers to basin-specific water in its naturally occurring water quality."*

Comment R3.7: Line 17: "(2) The blurring of existing WF indicators, especially "blue" and "green" water, must be avoided." - Green and blue water are clearly defined. Furthermore, the green and blue water is mainly used in WFA, rather than in the LCA domain.

Answer R3.7: *Thank you for this notice. We revised the section.*

> ***L 58:*** *"2) Lack of comprehensive conceptualisation of water use in LCA within a consistent hydrological framework"*
> ***L 62-64:*** *"In LCA, the distinction between blue and green water is not consistent because the term blue water refers to the source of the water, while green water refers to the fact that it has been used by plants."*

Comment R3.8: Line 19 : "(3) LCA-WF analyses must be adapted for spatially explicit LCIA" - I don't see a problem. This has been routinely applied in the LCA domain. Why this is considered as a limitation?

Answer R3.8: *We do not see this as a limitation, on the contrary, we demand that regionalisation is actually implemented in LCA supply chains. Especially in the field of mining activities the upstream supply is not regionalised. We see this as an issue in water footprint analysis. We present the methods and data that are necessary to regionalise the upstream supply with lithium, which is an important input to our case study. We addressed this in chapter 1.2 "Requirements for a modified water scarcity footprint concept" and chapter 2.3 "Regionalisation through combination of regionalised inventory and Life Cycle Impact Assessment".*

> ***L 72-76:*** *"3) Lack of applied regionalisation: While the locations of a production facility or a final consumer are often known within life cycle wide WSF assessments, the upstream supply chains are not or only partly considered spatially explicit. Identifying the place of water use is crucial for an impact assessment with respect to regional water supply conditions. Some conceptual, data and software modifications are necessary to implement a spatially explicit impact assessment of the supply chains."*
>
> ***L 249-253:*** *"2.3 Regionalisation through combination of regionalised inventory and Life Cycle Impact Assessment - To perform a regionalised LCIA the inventory of the case study is regionalised by implementing the world lithium production on mine site level to the ecoinvent 3.5 database (Supplementary Chapter 3.1)."*

Comment R3.9: Line 19 : "Hence, a new water scarcity footprint approach for LCA (LCA-WSF) is presented to assess the probability of on-site and remote freshwater scarcity for humans and nature caused by water use along anthropogenic supply chains in a spatially explicit way." - As argued above, the rationale for this objective is not justified.

Answer R3.9: *We revised chapter 1.2 "Requirements for a modified water scarcity footprint concept" to justify our objective (see comment to answer R3.2). We outlined our objective explicitly there by addressing the issues of the existing approaches. We identified and comprehensively described three issues: Diverging classifications of the risk associated with human water consumption, Comprehensive conceptualisation of water use in LCA within a consistent hydrological framework and Lack of applied regionalisation.*

Comment R3.10: Line 35: "It is 52 million m3 of globally weighted demineralised water per Li-ion-battery storage." - What is the unit of li-ion battery storage?

Answer R3.10: *The functional unit of the LCA is one Li-ion battery storage, designed for a daily energy feed-in of 2 MWh, which corresponds to 1.5 t lithium carbonate. We could only add a short explanation in the abstract due to the word limit of 150. Chapter 3 "Results" provides an extensive explanation.*

> ***L 16:*** *"a 2 MWh Li-ion-battery storage"*
>
> ***L 305-308:*** *"The FU of the Li-ion-battery was chosen to ensure comparability to other electrical energy storage technologies and is the amount of usable electricity, which can be provided based on a unified energy feed-in of 2 MWh per day[46]. The resulting storage consists of 34,800 kg Li-ion-battery cells, requiring 1523 kg of lithium carbonate."*

Comment R3.11: Line 188: equation (1) - As argued above, if you want to add the "net green water" induced scarcity, please do it explicitly. For example, see a similar publication that addresses green and blue water issues.

S. Rost, D. Gerten, A. Bondeau, W. Lucht, J. Rohwer and S. Schaphoff, Water Resources Research, DOI:10.1029/2007WR006331.

Answer R3.11: *Thank you for sharing this reference. Adding the net green water induced scarcity is not the aim of our study. Our framework assesses the risk of natural freshwater scarcity for humans and nature by water use along human supply chains. To do so, two steps are necessary: 1) For the product system that needs to be evaluated, e. g. a Lithium-ion-battery storage, all physical and virtual water flows related to the supply chain have to be considered spatially explicit (also evapotranspiration losses by plant growth, if relevant for the case study). 2) To assess the risk of freshwater scarcity, the water stress level of a reference area has to be determined by comparing water use to natural water availability. Water use includes all water using processes within the reference area (human and natural), also evapotranspiration losses by plant growth. We clarified this in chapter 1.2 "Requirements for a modified water scarcity footprint concept" to justify our objective (see answer to comment R3.2), in the main text (see below) and in the supplement, where we addressed the green water issue explicitly (see answer to comment R3.3).*

L 179-182: *"The water balance shows which water flows are relevant to identify the contribution of the sum of all water-using processes in a reference area to water stress. Therefore, the same water flows are used to describe the water use of a single process (e. g. a case study for which a WSF should be calculated). If they are weighted according to the regional water stress, water footprint indicators are obtained."*

18th Nov 20

Dear Mrs Schomberg,

Your manuscript titled "Extending Life Cycle Impact Assessment to assess the spatially explicit water scarcity footprint for the example of a Lithium-ion-battery storage" has now been seen by our reviewer 2, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to 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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Best regards,

Heike Langenberg, PhD

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REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

Thank you for considering the comments. The revised manuscript is improved a lot, and I am impressed by your revise. Therefore, I recommend this article be published after these revisions.