# Critical review report of the study:
# "Life cycle assessment of ammonia fuel"

By Miguel Brandão (chair), Romain Sachi, Rob Stevens

19th December 2024

## 1. Introduction

The present document reports the review made of a life cycle assessment (LCA) study of ammonia fuels. The LCA study in question (Schmidt et al., 2024) was performed by Jannick Schmidt, Karen-Emilie Trier Kreutzfeldt, Freja Konradsen, Simon Vemmelund, and Mathilde Nilsson, from 2.-0 LCA consultants, and commissioned by Mærsk, as part of a broader project aimed at comprehensively assessing the potential environmental impacts of using ammonia as a shipping fuel in comparison with very low sulphur fuel oil (VLSFO), following the Stepwise LCIA endpoint method. This is the review of the revised version, sent on 20th November.

The LCA study reviewed consists of the first iteration. Furthermore, results are estimated for the distribution of 1 MJ of ammonia fuel and compared with a more traditional way of producing shipping fuel (i.e., VLSFO).

The study represents a comparative assertion meant to be disclosed to the public, which, according to ISO 14044 (2006b), requires a third-party critical review panel.

## 2. Scope of the review

This review characterises the study against a fixed set of criteria commonly used in LCA reviews and can be found in the ISO standard 14071 (ISO, 2014). These characteristics cover each of the four phases of LCA, and this review is structured around those: 1) goal & scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation.

This critical review ensures that the methods used to carry out the LCA are consistent with the ISO standards - 14040 (ISO, 2006a), 14044 (ISO, 2006), as well as technical specification (TS) 14071 (ISO, 2014) – and are scientifically and technically valid. It also ensures that the data used are appropriate and consistent with the goal and scope of the study. Finally, this review ensures the LCA report is transparent and consistent. All these features are required by TS14071 (ISO, 2014) and represent the checks and balances that ensure the quality of the study.

This review is performed based on expert reviews by three experts whose expertise is complementary to the applied methods and sector to which the methods are applied. It has been performed at the end of the study, but changes are expected to occur after the production of this report, which will be re-assessed as follows (5-stage procedure) for each iteration:

1. Reviewers read and comments on the report
2. Study authors went through reviewer comments one by one and made a revised report and an itemized reply
3. Reviewers read the authors' itemized reply and gave remaining comments
4. Authors went through the remaining issues the reviewers identified and made a reply
5. Reviewers read the author's revised itemized reply and made the final review statement (i.e. this statement).

This review report corresponds to step 5 above and pertains to the final iteration. It excludes a detailed assessment of the life cycle inventory (LCI) model and of the individual data sets, but, as required by TS14071 (ISO, 2014), it covers all aspects of the LCA's definition of scope and life cycle inventory (LCI), including assumptions, data appropriateness and reasonability, calculation procedures and calculated LCI results. Furthermore, life cycle impact assessment (LCIA) results and interpretations made of those also subject to our review.

It is outside the scope of this review to address the goals chosen for the LCA study in question, as it is impossible to verify or validate them. The responsibility for those, as well as how the LCA results are used, lie with the commissioner of the LCA study. Specific comments are provided in Table 1.

## 3. Review of LCA study of ammonia fuels

### 3.1 Goal and scope definition

LCA practice is standardised by the International Organization for Standardisation (ISO) in ISO14040 (ISO, 2006a) and ISO14044 (ISO, 2006b). These standards include the terminology and requirements for LCA studies, such as the process for conducting LCA studies, methods, data, evaluation, documentation, etc. ISO compliance ensures that the study adheres to those internationally-agreed rules and, thus, credibility and bias-freedom. However, it may not necessarily ensure scientific soundness and robustness.

This section of the study explains this particular stage and where it falls within the four phases of an LCA. It also includes a description of the critical review, the purpose of the study, contrasting modelling approaches, functional unit, system boundaries, geographical scope, temporal scope, background databases, cut-off criteria, data sources and quality, life cycle impact assessment methods (including the adopted environmental impact categories), and time-dependent emission factors.

The following has been verified:

- The study under review claims to be compliant with the above standards. This is indeed attested. However, claiming compliance with other methods, such as RED II, must be made clear, particularly where inconsistencies exist.
- It is specified that the study will go through a critical review.
- The study's goals and intended application and audience are formulated.
- Data collection follows concerns of consistency.
- The temporal scope is specified.
- The geographical scope is delimited to the world, with groupings of countries and regions.
- The functional unit is specified and appropriate, but the proportion of VLSFO in ammonia for electrolysis remains a question. It will be used for comparison purposes.
- It is clearly stated that the LCI model follows a consequential approach, and an explanation is given. In addition, an attributional approach to the carbon footprint is followed and explained.
- It is clearly stated that the LCIA method used is Stepwise 2006, and an explanation of the method and updates on nature occupancy and global warming potential are given. A comprehensive set (9) of environmental impact categories was adopted and identified, and the few (5) that were left out were justified based on the lack of associated elementary flows in EXIOBASE.
- The treatment of biogenic carbon and methane is not explained nor justified properly. It is set to 0 to ensure compliance with RED II.
- System boundaries delimitation: cut-off identified for both attributional and consequential models, although the two are inconsistent, which limits the comparison of models. A distinction is made between the foreground and background systems, and

the use of EXIOBASE ecoinvent for the background data, and a general description of that database. iLUC is integrated with EXIOBASE. It is not explained why ecoinvent is used for the attributional model and EXIOBASE for the consequential, as any differences could arise instead of differences between the two modelling approaches.

### 3.2 Life cycle inventory (LCI): framework and general and specific activities

This section describes the data and modelling in the reviewed LCA study. The consequential system model version used ensures consistency with the consequential approach, particularly how by-products and determining products are dealt with to avoid allocation.

Indirect land use changes (iLUC) – which are often neglected in LCA – are modelled consistently with the rest of the LCA model.

Other general activities related to production, such as electricity and natural gas, process steam, transport, and concrete, are described appropriately. Specific activities related to ammonia, hydrogen, nitrogen and VLSFO production are also described. The involved activities are described, and inventory summaries are shown.

### 3.3. Life cycle impact assessment (LCIA)

A very competent LCIA, including weighting via monetarization as per the Stepwise method, is applied, and its results are shown. This includes a detailed contribution analysis for 9 midpoint impact categories in terms of both dominant emissions and hotspots.

It is shown that the ammonia fuel produced via electrolysis is more environmentally efficient in some categories, like global warming, but not all. Conversely, desulphurisation appears to be the worst.

### 3.4. Interpretation

Relevant parameters are changed in a sensitivity analysis, which includes sensitivity, completeness, and consistency checks. Furthermore, limitations are identified. The results and reasons for them are discussed. The extrapolated conclusions are robust and rest on the analysis reported that preceded them.

## 4. Conclusions

The review of the study on ammonia fuels revealed a competent analysis that underwent the rigorous application of the aforementioned ISO standards. Thus, it can be inferred that the study reviewed is an ISO-compliant, consistent and scientific application of the LCA methodology. We therefore conclude that the study made so far is of high quality, and can support environmental decision making.

## References


Schmidt J, Trier Kreutzfeldt KE, Konradsen F, Vemmelund S and Nilsson M (2024) *2.-0 LCA consultants, Aalborg, 20th November 2024*. Final version. 2.-0 LCA consultants, Aalborg, Denmark.

ISO 14040 (2006) Environmental management – Life cycle assessment – Principles and framework. International Standard Organization (ISO), Geneve.

ISO 14044 (2006) Environmental management – Life cycle assessment – Requirements and guidelines. International Standard Organization (ISO), Geneve.

ISO 14071 (2014) Environmental management – Life cycle assessment – Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006. International Standard Organization (ISO), Geneve.

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15th August 2024

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The LCA study reviewed consists of the first iteration. Furthermore, results are estimated for the distribution of 1 MJ of ammonia fuel and compared with a more traditional way of producing shipping fuel (i.e., VLSFO).

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This review is performed based on expert reviews by three experts whose expertise is complementary to the applied methods and sector to which the methods are applied. It has been performed at the end of the study, but changes are expected to occur after the production of this report, which will be re-assessed as follows (5-stage procedure) for each iteration:

1. Reviewers read and comments on the report
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3. Reviewers read the authors' itemized reply and gives any potential remaining comments
4. Authors will go through any remaining issues the reviewer might have and make a revised LCA report and itemized reply
5. Reviewers read the author's revised itemized reply and makes the final review statement (applicable only to the final iteration).

This review report corresponds to step 1 above and pertains to the first iteration, which was sent on 11th July 2024. It excludes a detailed assessment of the life cycle inventory (LCI) model and of the individual data sets, but, as required by TS14071 (ISO, 2014), it covers all aspects of the LCA's definition of scope and life cycle inventory (LCI), including assumptions, data appropriateness and reasonability, calculation procedures and calculated LCI results. Furthermore, life cycle impact assessment (LCIA) results and interpretations made of those also subject to our review.

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- The treatment of biogenic carbon and methane is not explained nor justified properly.

It is set to 0 to ensure compliance with RED II.

- System boundaries delimitation: cut-off identified for both attributional and consequential models, although the two are inconsistent, which limits the comparison of models. A distinction is made between the foreground and background systems, and the use of EXIOBASE ecoinvent for the background data, and a general description of that database. iLUC is integrated with EXIOBASE. It is not explained why ecoinvent is used for the attributional model and EXIOBASE for the consequential, as any differences could arise instead of differences between the two modelling approaches.

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## References

Schmidt J, Trier Kreutzfeldt KE, Konradsen F, Vemmelund S and Nilsson M (2024) *2.-0 LCA consultants, Aalborg, 11th of July 2024*. First iteration. 2.-0 LCA consultants, Aalborg, Denmark.

ISO 14040 (2006) Environmental management – Life cycle assessment – Principles and framework. International Standard Organization (ISO), Geneve.

ISO 14044 (2006) Environmental management – Life cycle assessment – Requirements and guidelines. International Standard Organization (ISO), Geneve.

ISO 14071 (2014) Environmental management – Life cycle assessment – Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006. International Standard Organization (ISO), Geneve.

**Table 1: Detailed comments (ed: editorial; te: technical**

| Index | Paragraph/ Figure/Table | Type of comment | Reviewer comment | Reviewer recommendation | Author of the LCA study response |
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| Goal and scope definition | | | | | |
| #1 | Overall | te | Ammonia and urea production are tightly integrated because urea production uses both outputs of ammonia production, namely $NH_3$ and $CO_2$. Urea producers are said to be the single largest consumer of industrial $CO_2$. What are the consequences of investing in electrolysis-based or natural gas + CCS-based ammonia? Would if affect the supply of $CO_2$ for urea production? Would the $CO_2$ be supplied by other means (e.g., point source capture from other industrial emitters with conditioning and transport). Should it be included within the system boundaries of the consequential model? | This might not be an issue since the authors are modeling "additional capacity".<br><br>In case other $CO_2$ sources would be used, urea might be outcompeted by nitrate-based fertilisers, pending geographic adjustments in regulation. Europe already is a nitrate-based fertiliser market.<br><br>Check whether the (consequential) model should include these indirect effects. | The demand for ammonia as shipping fuel will not affect the production of fertilizer, since none of the inputs to the production are constrained. But to make this clear to the reader, this is specified in the report. |
| #2 | Terminology (various) | te | By-product: "Non-determining product…". Not clear to the reader what a non-determining | It is relevant to specify market trends since electricity, for example, is a market with a decreasing trend since 2008 in Europe. | The terminology is explained more precisely and is introduced throughout the report. |

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| | | | product is.<br>Consequential modelling: “This implies that the product is produced by new capacity (if the market trend is increasing).”. Or by extending the lifetime of existing capacity if the market trend is decreasing?<br>iLUC: “as the upstream life cycle consequences of the land use” → “as the upstream life cycle consequences of a change in land use”? | | Moreover, it is specified in section 3.1 weather the market for electricity is increasing or decreasing. |
| #3 | Executive summary – scope and boundary | te | “using the Stepwise life cycle impact assessment method” | Include a reference to the method documentation. | This is included, see section 1.10. |
| | Executive summary – scope and boundary | te | “Note, that the current production methods for ammonia and VLSFO will not necessarily be reflected in this study, as a change in demand will be met by new capacity, e.g., H2 from natural gas is assumed to be produced using autothermal reforming (ATR), while VLSFO is assumed to be produced through desulphurisation.” | Include an authoritative reference showing the evidence that supports this claim. Could not an increase in demand for ammonia lead to an increase in the build-up of SMR units? Even though this is subject to changes in the sensitivity analysis, please provide a more robust justification for this assumption.<br><br>Please state the assumed fate of sulphur, as it will not be discarded. It will likely be recovered and used for fertilizer, thereby displacing marginal sulphur production. | It is made clear, that the modelled production method for H2 from natural gas is based on discussions with project partners, while the production method for VLSFO is based on the literature presented in section 4.2.<br><br>It is true that sulphur is not landfilled. Sulphur is as by-product from several production systems and |

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| | | | | | there is produced more sulphur than there is a demand for. Thus, sulphur is sent to stockpiling, where it is stored until it is used in the future. This is consistent with the modelling of sulphur in Ecoinvent.<br>Thus, the model is updated with a process for stockpiling of sulphur, which replaced the landfill of sulphur. |
| #4 | Executive summary – function and functional unit (p.8) | te | "For ammonia to fulfil its function as a shipping fuel, ammonia needs to be ignited by a pilot fuel. It is assumed that VLSFO is the closest match to a pilot fuel in this LCA study. Thus, for the functional unit of 1 MJ shipping fuel, VLSFO accounts for 9.6% of the total fuel energy of 1 MJ ammonia". | This reationale appears to be flawed. The fact that pilot fuel is needed is precisely because ammonia is used. It is a consequence of it. Hence, the 9.6% energy-equivalent should be additional to the 1 MJ of ammonia fuel supplied, and not included in the functional unit, even though it might not make a significant difference (especially given all the uncertainty). | The relevant project partners have confirmed that both the pilot fuel and the ammonia is used to fuel the ship. Thus, as the functional unit is 1 MJ of shipping fuel, the share of pilot fuel is included in the functional unit. |
| #5 | Executive summary – sensitivity analysis (p.10) | te | "this report can therefore be viewed as optimistic" | A scientific study should not be optimistic nor pessimistic. If anything, cautious and conservative assumptions should be adopted. Optimistic assumptions may be misrepresented.<br><br>The assumption of 0.253 g $N_2O$ emitted per MJ of ammonia has the potential to change the conclusions. | The wording is changed, and the conclusion mentions the results with both that the 0.02 and 0.06 g N2O/kWh, with the first being the development target for the engine and |

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| | | | | If data exist that points towards low $N_2O$ emissions, please cite accordingly. | the second being the highest value for N2O/kWh assumed to be acceptable for the design of ammonia engines according to this report by Maersk Mc-Kinney Moller Center[1]. |
| #6 | Executive summary – G&S (Table 1.1) | te | "The marginal electricity mix is applied, which is determined by the electricity technologies which will respond to changes in demand for electricity." | For clarity, it may be worth highlighting the fact that changes in capacity building are captured, to differentiate that from short-term responses. | This is added, see section 3.1.1.1. |
| #7 | Executive summary – G&S (p. 17) | te | "The LCIA results can be recalculated to 1 TEUkm using a conversion factor of 0.291 MJ/TEUkm for ammonia with 9.6% e/e VLSFO and 0.275 MJ/TEUkm for VLSFO" | Annex 4 shows that the load factor of 85% is preserved when the ship is powered with Ammonia. Would not the load factor increase if you reduce the load by 912 TEU (i.e., presumably, one would lose 912 TEU from the 2,250 empty TEUs)? | It is correct that the load factor changes with the decrease in TEU. The appendix is updated to reflect this. |
| #8 | Executive summary – G&S (p. 18, Fig. 1.1) | te | The $H_2$ production is modelled as SMR, since this technology is considered the most widely used for $H_2$ production worldwide" | Inconsistent assumptions: the H2 used to desulphurize fuel oil is produced by SMR while the H2 used for producing Nh3 is produced by ATR. Please justify. If we keep this rationale, we might choose SMR for providing the H2 to produce the NH3. | The model is changed, so all H2 to desulphurization is produced using ATR without CCS. Note, that the H2 will not be produced from a facility with CCS, since a project partner has stated that CO2 is rarely stored, more often it is used in fertilizer |

[1] https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

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| | | | | | production or the food & beverage industry, or simply vented to the atmosphere. Thus, CCS is specifically required for H2 for blue ammonia due to decarbonization targets for shipping fuel. Therefore, even though the CO2 for H2 for desulphurization is captured and potentially utilized, it will most likely be emitted within a very short timeframe, which is equal to the CO2 being emitted at the facility. Thus, this is included in the modelling of H2 from ATR for desulphurization. |
| #9 | Executive summary – G&S (p. 19, Figure 1.2) | te | | Show the market value of the near-pure oxygen from the ASU.<br>There might be needed a clarification on Figs 1.2 and 1.3 on the sensitivity of energy needed to maintain -33°C. Boil off of NH3 is marginal. Check consistency with statement in Section 1.10. | The oxygen from ASU is utilized on the market, while the oxygen from electrolysis is not (Krishnan et al. (2024)[2] and Hydrogen Insight[3]). Note, that for the default scenario, nitrogen is the primary product from the ASU, thus, with oxygen being utilized, this changes |

[2] https://www.sciencedirect.com/science/article/pii/S0360319923053405

[3] https://www.hydrogeninsight.com/production/analysis-what-should-companies-do-with-the-vast-amounts-of-oxygen-produced-by-green-hydrogen-projects-/2-1-1654419 and https://www.hydrogeninsight.com/industrial/additional-revenue-stream-by-product-oxygen-from-300mw-green-hydrogen-project-sold-in-long-term-deal/2-1-1382545

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| | | | | | the modelling of ASU for blue ammonia, since the oxygen will be a by-product which can substitute the production of primary oxygen. Typically, oxygen is the primary product from ASU facilities, thus, when oxygen is a by-product in the foreground, it will substitute its primary production at another ASU facility. Moreover, it is modelled the other way around for the sensitivity analysis in section 8.13.2.4, where oxygen is assumed to be the primary product, and nitrogen is the by-product. |
| #10 | Executive summary – G&S (p. 21, Figure 1.4) | te | | Clarify why EXIOBASE is shown several times since EXIOBASE is not explicitly mentioned as a background database up to this point (only ecoinvent has been mentioned so far (p.8)). | It is specified throughout the report, when either EXIOBASE and Ecoinvent is used and the EXIOBASE logo is removed from the system boundary figures to limit confusion. |
| #11 | Executive summary – G&S (p. 22) | te | "The decisive factors for when results are not valid anymore are when the activities surrounding the fuel production change, namely when | It appears that the size of the change in demand may also invalidate these results (e.g., 1 MJ of additional shipping fuel vs. 1 EJ). A change in demand large enough may potentially restructure the supply chains entirely. Maybe a few words should be added about the importance of the scale of the change in demand and the assumption of | The aim of the study is to model the long-term effect of the marginal demand. Thus, the modelling will not change if the functional unit is 1 EJ |

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| | | | market responses to changes in supply and demand are different compared to what is modelled in the LCA." | linearity. | instead of 1 MJ.<br>The current modelling is based on discussions with the project partners and their expectations to the market changes based on the current decarbonization targets and how these targets are expected to affect the demand for ammonia as shipping fuel. Thus, the model will change, e.g., if the decarbonization targets are altered or if the expected market changes go in another direction. This is made clear to the reader in the report. |
| #12 | Executive summary – G&S (p. 22) | te | "The LCA study is based on foreground data from literature from 2001-2023, the most recent available data from the project partners, and the Ecoinvent v.3.8 database, which includes data from approx. 1990-2021. The background database, EXIOBASE 3.3.16 hybrid version, includes data for 2011. Yet, due to the importance of electricity for ammonia production, the LCI data | At this point it is still unclear if and how EXIOBASE is used, although this is made clear in the next section. Change the sequence, please. | The section describing the used background database is moved up, so it is now section 1.6, thus, it comes before temporal and geographical scope. |

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| | | | for the marginal electricity mixes in EXIOBASE has been updated with a time-series from 2017-2021 based on data from IEA (2023b), i.e., changes in electricity supply from different technologies in this timeframe. Moreover, the data for the production of wind and solar electricity has also been updated with LCI data from Bonou et al. (2016) and Frischknecht et al. (2020). This updated LCI data is further described in section 3.1." | | |
| #13 | Section 1.8 Background databases (p. 22) | te | "it has a much more complete geographical scope than any process database". If the authors list the advantages of an MRIO database of a process-based one, they should also list its disadvantages, in my opinion (e.g., lower technology resolution). | As the authors list the advantages of an MRIO database of a process-based one, they should also list its disadvantages, (e.g., lower technology resolution). | Disadvantages of EXIOBASE/MRIO is added to section 1.6 (which was previously 1.8). |
| #14 | Section 1.8 Background databases (p. 24) | te | "Hence, in general, a very large part of the economy is excluded from Ecoinvent." while | While this is true, it leads the reader to think that it equates to a large part of impacts being excluded, which is not necessarily the case (see Steubing et al. 2022). Hence, please make this sentence more neutral or provide a | The text is adjusted accordingly. |

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| | | | this is true, it leads the reader to think that it equates to a large part of impacts being left out. This is not necessarily the case (see Steubing et al. 2022). Hence, I suggest making this sentence a bit more neutral or providing a publication supporting this claim. | reference supporting this claim. | |
| #15 | Section 1.10 Data sources and quality (p. 24) | te | "Thus, the provided values are average/typical values for these two plant designs estimated by the project partners based on their most recent available data. This data is therefore deemed to be of high quality." | It appears that there aren't any large-scale production units for green hydrogen and ammonia. Hence, we suggest requalifying the data quality from "high" to something along the lines of "as high as possible given the technology's maturity level" regarding green hydrogen and green ammonia. | The text is modified in both section 1.10 and 9.2. |
| #15 | Section 1.11 Life cycle impact assessment method | te | "The weighting module is documented in Weidema (2009)." | The ISO standards exclude the use of weighting in comparative assertions. Please clarify that Stepwise was used at the midpoint level. | As weighting is not applied in the LCA study, any reference to the weighting module in Stepwise is removed. Moreover, it is made clear, that Stepwise is used at the midpoint. |
| #16 | Section 1.1 Life cycle impact assessment method | | "Yet, these impact categories are not included in this report, since EXIOBASE does not include important | This is a poor justification, given that ecoinvent does include these elementary flows. Please justify the use of EXIOBASE for completeness, despite the incomplete coverage of impacts that its use entails. | EXIOBASE is used due to its 0% cut-off criterion. However, it is a limitation of the study, that EXIOBASE does not |

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| | | | elementary flows” | If hydrogen leaks are modelled, considering the warming potential of hydrogen emissions to air may be scientifically advised. Sand et al (2023)[4] suggest a GWP100a factor of 11.6 kg $CO_2$-eq./kg $H_2$. Hydrogen leads to warming via the destruction of ozone in the upper atmospheric layer while also extending the lifetime of methane by delaying its oxidation to $CO_2$. This was tested in Section 7.1 but please address it here too.<br><br>It may be worth noting that ammonia-exhaust emissions would be detrimental to marine and aquatic species through water acidification and eutrophication. Acidification and eutrophication are included, but not freshwater/marine ecotoxicity. | include elementary flows which are of high importance for the excluded impact categories. This is made clear in the report.<br><br>The default results are updated so GWP100 of hydrogen is included. The sensitivity analysis therefore tests the influence of a 5% hydrogen slip. It is specified that EXIOBASE does not include emissions of hydrogen, thus, GWP100 for hydrogen is only related to the foreground system. |
| #17 | Section 1.12 Time-dependent emission factors for CO2 emissions | te | “[…] the aim of limiting temperature rise to 2°C as stated in the Paris Agreement.”. | Change to “[…] the aim of limiting temperature rise to 2°C <u>by 2100 compared to pre-industrial levels</u>**,** as stated in the Paris Agreement.”. | The text is modified to include this suggestion. |
| #18 | Section 3.1.1.1 Marginal electricity mix | te | “Furthermore, as grid electricity is one of the important inputs for ammonia produced with H2 from ATR, […]”: I understand the opposite from “To produce ammonia with H2 from | Include a paragraph that explains why past time-series are used as opposed to future ones, e.g., 2021-2030 | This is addressed in the section and there is a reference to the sensitivity analysis, which tests this. |

[4] https://www.nature.com/articles/s43247-023-00857-8

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| | | | ATR, the electricity inputs are modelled as electricity from grid throughout the life cycle. This is done, since the input of electricity to natural gas-based ammonia production is minor […]”. | | |
| #19 | Section 3.1.1.2 Electricity from wind | te | “Furthermore, the total annual production is calculated using the efficiency of each country’s current wind power based on data from Ember (2024) for the countries wind power capacity and wind electricity generation for 2021.” | Equation 3.1 gives the maximal power output of a wind turbine. In practice, a wind turbine does not produce at maximum output regardless of the wind speed. This relation is usually given by the turbine’s power curve. This should be made clearer. | The text is modified to explain the chosen approach in a better way. |
| #20 | Section 3.1.1.3 Electricity from solar | te | | Using solar arrays or wind turbine without a means of storing the produced electricity seems incorrect. In practice, this will probably lead to an accelerated degradation of the electrolyzer as well as a poor load factor. | Battery storage is too expensive, thus, hydrogen storage is used instead, as described in section 4.1.1.1. |
| #21 | Section 3.1 Attributional modelling of electricity | te | | The electricity sold though PPA and GO should be removed from the attributional mixes to avoid double counting. AIB[5] provides those for EU countries. If not, probably a sentence should be added as to why. | Since the aim of the attributional model is to be RED II compliant, the residual electricity mixes are applied since this is not a requirement in RED II for RFBNOs. |

[5] https://www.aib-net.org/facts/european-residual-mix

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| #22 | Section 3.2 Attributional modelling of natural gas | te | "Note, that the Ecoinvent activity is in m3, so it is converted to GJ using a density of 0.8 kg/m3 and a lower heating value of 49.5 MJ/kg for natural gas." | The density for natural gas in ecoinvent is 0.739 MJ/kg, with a LHV of 36 MJ/$Nm^3$ (hence, about 48.8 MJ/kg). | In Ecoinvent v3.8 cut off[6], the LHV for natural gas, high pressure, is set to 39 MJ/m3 and the density is not specified. Yet, 39 MJ/m3 and 0.8 kg/m3 provides an LHV of 48.75 MJ/kg. Thus, in order to be consistent with the 39 MJ/m3 from Ecoinvent v3.8, the density of natural gas is changed to 0.790 kg/m3, thus resulting in a LHV of 49.5 MJ/kg, which is applied for natural gas in both the consequential and attributional model. |
| #23 | Section 3.5.1.4 Attributional modelling of transport by pipeline | te | | $CO_2$ leakage should be listed in this table To transport 1 t of $CO_2$ over 1 km, one need to transport 1 * leakage rate t of $CO_2$ over 1 km (hence, the CAPEX should be scaled accordingly). | The LCI data in section 3.5.1.3 and 3.5.1.4 is adjusted so it fits with the default slip for gases of 0.3% applied throughout the study. |
| #24 | Section 3.7.1.3 Consequential modelling of concrete | te | | 14% of cement mass-wise seems a little weak. The weakest concrete recipe in ecoinvent (i.e., 20 MPa) has 18.7% mass-wise of Portland cement (i.e., Portland cement contains 95% by mass of clinker), and up to 35% for the strong ones (i.e., 50 MPa). Please double-check the concrete recipe used here. | Based on the Ecoinvent v3.8, which we have available, there is around 200-600 kg cement per m3, with a density around 2300-2400 kg/m3. Based on this, cement accounts for 9-25% mass wise. |

[6] https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/14395/documentation

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| | | | | | The influence of the concrete recipe has been tested: If the share of cement is increased to 28%, the GWP results change with less than 0.0002% and the results for terrestrial ecotoxicity (which is one of the impact categories most affected by the material inputs to CAPEX) change with less than 0.0001%.<br><br>Since the changes in results are minor, the current recipe is kept. |
| #25 | | te | "Note, that the 0.3% slip from Bertagni et al. (2023) relates to the slip of natural gas and ammonia. Yet, for this LCA study, it is assumed that the 0.3% is applicable for all gases within the product system." | A molecule of hydrogen is smaller (in volume) than a molecule of methane. Hence, while we agree to apply the same rate to all gases, please add a sentence to acknowledge the limitation of such assumption. | This is added to the report, e.g., see several of the sub-sections to section 4.1. |
| #26 | Table 4.1 | te | | 8kg of $O_2$ should be produced per kg $H_2$. Please include this in the table. Clarify whether the oxygen is liquefied and used later (i.e., allocation)? | The oxygen output from the electrolysis process is added to table 4.1. The output is modelled as being emitted to air, since Krishnan et al. (2024)[7] |

[7] https://www.sciencedirect.com/science/article/pii/S0360319923053405

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| | | | | | states that oxygen from electrolyser operators is currently vented into the atmosphere, thus supporting the current modelling. This is further supported by these two articles from Hydrogen Insight[8] |
| #27 | Table 4.1 | te | | 25.5 kg $H_2O$ per kg $H_2$ is high. The stoichiometry requires 9 kg $H_2O$/kg $H_2$, and industry reports and literature indicate a few kilograms more for cooling and cleaning purposes (i.e., 12-14 kg $H_2O$/kg $H_2$ in total). Please check this figure. | A project partner has confirmed that the initial input of water to the electrolysis process included the upstream water usage. This is corrected, so the applied input is 12.5 kg water/kg H2. |
| #28 | Table 4.2 | te | | Where is the compression considered? A PEM electrolyzer will usually output at 25-30 bar. A storage unit would probably operate at 250-700 bar. I see an input of electricity, but it is not clear whether this corresponds to compression, and if so, it is not clear how it has been calculated. | This comment has been discussed with the relevant project partners. They state that there aren't many actual examples on hydrogen storage, but for the current storage solutions the compression is <100 bar. But the partners also acknowledge that there is no set or standard pressure for this. The partners also explain that the chosen storage |

8 https://www.hydrogeninsight.com/production/analysis-what-should-companies-do-with-the-vast-amounts-of-oxygen-produced-by-green-hydrogen-projects-/2-1-1654419 and https://www.hydrogeninsight.com/industrial/additional-revenue-stream-by-product-oxygen-from-300mw-green-hydrogen-project-sold-in-long-term-deal/2-1-1382545

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| | | | | | pressure for a hydrogen plant linked directly to an ammonia plant will often only require storage for 8-12 hours, thus, the chosen storage pressure will mostly depend on the costs of storage at a certain pressure. Hydrogen stored for other purposes requires much longer storage times and can also face limitations on space, like when transporting hydrogen by truck. That's where hydrogen is stored at >250 bar.<br><br>The energy data for hydrogen storage is obtained from Andersen and Grönkvist (2019), which has the following data: 1, 1.2, and 1.6 kWh/kg H2 for 100, 200 and 700 bar, respectively, for large-scale storage of hydrogen. Andersen and Grönkvist (2019) also states, that 100 bar requires large storage volumes and thereby high operating costs, while the source also states that 700 bar is often used for truck |

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| | | | | | storage and not stationary storage. Moreover, the source describes that there is an underground steel cylinder in Sweden used for hydrogen storage which operates with a pressure of 200 bar. Yet, underground storage may not be applicable in all scenarios.<br>Based on this, the applied value of 1.6 kWh/kg H2 is kept, since it can be seen as a "worst case" estimate for the hydrogen storage process. This is also made clear in the report. |
| #29 | Section 4.1.1.1 Hydrogen from electrolysis | te | | We cannot find the LCI for the electrolyzer, and related parameters, such as the type of electrolyzer (PEM, AEC, SOEC), lifetime (and number of replacements over the lifetime), load factors, etc. In particular, the use of metals (i.e., Pt and Ir loading) and the lifetime assumed are the two most interesting aspects as they usually drive the GHG emissions of such installation. | This comment has been discussed with the relevant project partners and they have not been able to provide any information on this.<br><br>Moreover, as the electrolyser is assumed to be part of the ammonia plant, there is no specific LCI data applied for the CAPEX activity for electrolyser. Thus, none of these parameters are considered in the study. |

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| | | | | | This is a limitation of the study, however, when taking the small contribution from CAPEX activities into account, the specific information about the electrolyser is expected to have a minor influence on the results. |
| #30 | Section 4.1.1.2.1 Carbon capture and storage | te | "adding CCS to ammonia production plants typically increases the energy intensity by 3-7% for a 90-95% capture rate" | Antonini et al. (2021)9 find the impact of adding CCS to an ATR unit is very limited because of the absence of an external furnace. Note however that the numbers in Antonini et al. are based on a numerical simulation.<br><br>We cannot find figure for CO2/tNH3 emitted from ATR based H2/NH3. A high value of 99% CO2 capture could be used, which means that the figure needs to include some CO2 leakage as well. (this will not significantly impact the overall conclusion, pending gas exploration source and methane leakage), but it should be mentioned. | First part: This comment has been discussed with the relevant project partners. They state that all SMR and ATR facilities, which are designed to produce hydrogen for ammonia production, has a CO2 capture plant, since the ammonia synthesis reactor requires pure hydrogen and nitrogen. But the partners acknowledge that the CO2 is rarely stored, more often it is used in fertilizer production or the food & beverage industry, or simply vented to the atmosphere. Yet, since CCS is specifically required for blue ammonia if this fuel should meet the decarbonization targets for |

[9] https://pubs.rsc.org/en/content/articlelanding/2020/se/d0se00222d

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| | | | | | shipping fuel, the CCS is kept in the model, since the LCA study models new capacity.<br><br>Second part: Table 4.3 shows that 9.49 t $CO_2$ is sent to CCS per t $H_2$ produced. And since 0.18 t $H_2$ is required per t $NH_3$, this means that there is sent 9.49*0.18=1.7 t $CO_2$ to CCS per t $NH_3$. Since 90% of the $CO_2$ is captured, 0.17 t $CO_2$ is emitted to air per t $NH_3$. Yet, table 4.3 is missing a 0.3% slip of $CO_2$, which is added and the input to CCS is adjusted slightly. |
| #31 | Section 4.1.1.4 Nitrogen production for natural gas-based ammonia | te | "Any excess $O_2$ or Ar will be vented to the atmosphere, since the marginal effect of changing the demand for $N_2$ leads to excess $O_2$ and Ar." | A marketable product that can easily be stored (i.e., liquid oxygen) is probably not vented out to the atmosphere. | As described for comment #9, the model is changed, since oxygen from ASU is utilized on the market. Note, that for the default scenario, nitrogen is the primary product from the ASU, thus, with oxygen being utilized, this changes the modelling of ASU for blue ammonia, since the oxygen will be a by-product which can substitute the production |

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| | | | | | of primary oxygen. Moreover, it is modelled the other way around for the sensitivity analysis in section 8.13.2.4, where oxygen is assumed to be the primary product. |
| #32 | Section 4.4 Fuel combustion and ship parameters | | | The $N_2O$ emissions factor is assumed to be the same for diesel and ammonia engines. As sensitivity tests show, it is a critical parameter. However, the value used, 0.02 g $N_2O$/kWh, does not seem to represent a standard value for diesel ships (0.03g/kWh, according to [10]), but is also much lower than the target value for $NH_3$ ships used by the Maersk Mc-Kinney Moller Center working group on the topic (i.e., 0.06g/kWh)[11]. The report only says that “a project partner” gives this value for diesel ships and assumes it would be the same for $NH_3$ ships. It would be good to argue why this unidentified partner has more credible data than what is publicly available (and published by Maersk Mc-Kinney Moller Center, presumably affiliated with A.P. Moller Maersk A/S, one of the commissioners of the present study). Given the importance of the parameter, we suggest the authors reconsider the data source for one that may be more transparent, to increase the study results/credibility. | It is made clear, that the 0.02 g N2O/kWh is the development target for the ammonia engine. Moreover, the 0.06 g N2O/kWh from the report by Maersk Mc-Kinney Moller Center is included in the sensitivity analysis as an upper value, since the report states that higher N2O emissions will not be acceptable for new ammonia engine design. |
| #33 | Table 6.1 | | | Both wind- and solar-based fuels have a GWP of 12.6 $gCO_2$/kg $NH_3$. This might be due to regulation 2023/1185, but it is unclear if the figure complies with the ISO standards. | It is made explicitly clear, that the attributional results are RED II compliant and not ISO 14040/44 compliant throughout the report. |

[10] https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx
[11] https://cms.zerocarbonshipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf

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| #34 | Table 6.9 | | "In the studies by Liu et al. (2020) and DECHEMA (2022), it is only electrolysis, which is run on 'green' electricity with a carbon footprint of zero, while the energy for ASU and Haber-Bosch process stem from grid electricity mix." | The difference cannot be explained by the Haber-Bosch being run on grid electricity since these results describe the electrolysis-based $NH_3$ case. Hence, this factor-15 difference can only come from the ASU process, which seems unlikely. The authors should try to pinpoint more precisely the root of such a difference. Maybe the other studies add local energy storage for autonomous H2 production or account for a shorter electrolyzer lifetime? | The results for Liu et al. (2020) and DECHEMA (2022) are under column "carbon footprint of 'green' electricity is 0" in table 6.9. For these studies, it is not all processes which run on green electricity. For Liu et al. (2020), both the ASU and Haber-Bosch process is based on grid electricity. For DECHEMA (2020), all processes – except for electrolysis – are run on grid electricity. This is also described in the comment section in table 6.9. Lastly, neither Liu et al. (2020) or DECHEMA (2020) include any impacts from H2 storage, buildings, machinery etc. |
| #35 | Figure 7.3 to 7.27 | | | Setting the y-axis to zero would be more accurate. In some cases, the variation seems large, but it is, in fact, in comparison to the absolute total. | This comment is implemented were applicable. |

**Comments to second iteration of the LCA report**

We are generally satisfied with the way in which you addressed our 35 comments. However, there are 5 comments to which we would like further clarification/change:

<u>- #4: it must be clear that one of the alternatives being compared is not just ammonia but an ammonia-blend. This need to be made explicit throughout the report.</u>
Reply: In both the introduction, executive summary, and interpretation and conclusion, the share of VLSFO in ammonia is mentioned in the first paragraph. Moreover, all legends to figures mention the share of VLSFO where relevant, and the same goes for all tables. Lastly, the tables used to define the terms used in the report now include the share of VLSFO for ammonia fuel.

<u>- #29: it is unfortunate that no data on critical parameters exist or is made available by the project partners, which is recognized as a limitation of the study. Please report on this limitation.</u>
Reply: This limitation is mentioned in both chapter 9 and section 10.1

<u>- #32: we insist that an "optimistic" value should not be taken as the default value and instead be tested in the sensitivity analysis. Please swap the two values (0.06 as the default value and 0.02 in the sensitivity analysis).</u>
Reply: We have followed up with the relevant partners to check whether the 0.02 g N2O/kWh of ammonia is still the development target for the engine. The project partners state that 0.02 was a bit optimistic, however, 0.04 g N2O/kWh is achievable based on the current engine data available from engine tests. Thus, the default value is changed from 0.02 to 0.04 while the sensitivity analysis still applies the 0.06 value. This means that all GWP results have been updated in the report along with the sensitivity analysis focusing of changes in GWP results.

<u>- #33: please state that it only makes sense to compare attributional results to the REDII and consequential results cannot be compared with either.</u>
Reply: This is specified in the executive summary, introduction, section 1.3, as well as interpretation and conclusion (section 10.2).

<u>- #34: we insist that the authors should try to justify the large difference with published results, which can be 15- to 20-fold. The reasons identified by the authors do not hold, as they make the results lower, not larger.</u>
Reply: The detected reasons for differences between the studies have been added as a new column in both table 6.9 and 6.10. Moreover, the reasons for the differences have been described in more detail in section 6.4.