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Research Article

Revisiting the challenges of ozone depletion from a prospective LCA perspective

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Currently, the main focus of prospective LCA research is the assessment of climate change. Still, there is a lack of understanding regarding the specific challenges of other impact categories, for example, the ozone depletion potential (ODP). Therefore, this work presents a review of recent studies regarding current ozone layer trends, future ozone-depleting substance (ODS) life cycle modelling, and characterisation factors to define strategies for assessing the ODP in prospective LCA studies. It was found that the phase-out of ODS due to the Montreal Protocol is currently not well represented in background databases, potentially resulting in large overestimations of the ODP by banned substances. These overestimations will be more important for prospective studies as the use of banned substances decreases. The review has also shown that, to date, anthropogenic N_2O emissions, instead of halocarbons, are the most important contribution to ozone depletion. However, the current standard characterisation models for ozone depletion have not yet covered these emissions. In addition, several interlinkages with climate change were found. Based on these insights, recommendations are given for future work to improve the quality of inventory modelling and ODP impact assessment in prospective LCA. For example, strategies for N_2O characterisation in prospective LCA will require geographical, temporal and scenario-based differentiation, as the ODP of N_2O depends on the atmospheric temperature, CO_2, CH_4 and chlorine levels. More generally, this work showcases the importance of analysing the challenges of prospective LCA for each impact category individually and collectively, due to potential interlinkages.

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1. Introduction

Several challenges for prospective life cycle assessment (LCA) related to each of the four phases of LCA have been identified by previous reviews [1][2][3][4]. The strategies to address these challenges are specific to each environmental impact category. Currently, the main focus of prospective LCA research is the assessment of impacts on climate change. However, there is a lack of understanding regarding the specific challenges of other impact categories, for example, ozone depletion potential (ODP).

Anthropogenic emissions of ozone-depleting substances (ODS) in the last century have severely reduced the stratospheric ozone layer [5]. After the adoption of the Montreal Protocol [6] in 1987, which controls the production and consumption of nearly 100 ODS, stratospheric ozone recovery has been observed in most regions [5]. However, full recovery is only expected by the second half of this century and requires additional measures and continuous monitoring of ozone depletion threats [7]. For example, model simulations show that large-scale deployment of rocket launches, stratospheric aerosol injection and supersonic aircraft could considerably affect the stratospheric ozone chemistry and transport mechanisms [8]. Thus, the ozone depletion potential (ODP) remains an important impact category in Life Cycle Assessment (LCA).

Therefore, this work presents a review of peer-reviewed articles addressing the state-of-art of ozone layer science, future ODS life cycle compilation, and characterisation factors (CFs). The review aims to define strategies for assessing the ODP in prospective LCA studies.

2. Methodology

The latest scientific assessment of ozone depletion [8] was reviewed to identify the main challenges of ozone depletion assessment. This report is prepared every four years by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UN Environment) to inform the parties under the Montreal Protocol on the state of the art of ozone depletion.

In addition to the report, a search was done in the Web of Science and Scopus databases. The search in the title, abstract, and keywords considered the following string: "Life Cycle Assessment" AND "ozone depletion" OR "ozone layer depletion" AND characterisation OR "impact assessment method". After removing duplicates, 199 abstracts were found and screened to include articles that discuss the ozone depletion impact assessment methodology in LCA. From this screening, 18 works [9]

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[10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26] were retained and analysed to identify the main challenges related to prospective ozone depletion impact assessment. Additional relevant works [5][7][27] were found through backward snowballing. The assessment of the results considers the challenges of assessing ODP substances based on the life cycle inventory compilation, CFs at the midpoint and the endpoint level, and the interlinkage with other environmental impact categories.

3. Results

3.1. Life Cycle Inventory

Meaningful impact assessment starts with a relevant life cycle inventory. It was shown that the major contribution to ozone depletion for construction products [23] and heavy-duty transport [28]comes from background processes. As the background model is determining the results most, except for product systems that include refrigerants with high ODP in their foreground model, compiling accurate background databases is imperative for ozone depletion impact assessment. However, this review has shown that the phase-out of ozone-depleting substances (ODS) due to the Montreal Protocol is currently not represented in conventional LCA databases. For example, [20] found that generic pesticide datasets in the USEEIO database [29] contain Halon 1001, whereas the import and production of this substance have been banned in developed countries since 2005. They also found that using the ecoinvent database [30], the biggest impacts were linked to fugitive emissions of halon 1211 and halon 1301 from fire extinguishers and cooling systems (present in crude oil production and natural gas production installations). Imports and production of both halons have been banned in all countries since 2010 [6]. Although existing installations are still allowed to recycle halon 1211 and halon 1301, it can be expected that the stocks will steadily decrease in the coming years. To demonstrate the potential effect, [28] removed all halon 1301 emissions from three crude oil and natural gas production datasets in the ecoinvent 3.8 cutoff database. It was found that this decreased the ozone depletion impacts of heavy-duty transport by a factor of 1000. To conclude, using current background databases for ozone depletion impact assessment may result in large overestimations of the ODP by banned substances [17][25]. These overestimations will be more important for prospective studies as the use of banned substances will decrease.

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3.2. *Midpoint characterisation*

The existing ozone depletion midpoint characterisation models are robust and in agreement [9][16][18][21][25], although discrepant results were found when comparing older and newer methods [17]. [17]. [17]. As anthropogenic N_2O emissions, and not halocarbons, are the greatest source of human-induced stratospheric ozone depletion today [8], it has been suggested to include CFs for N_2O [13]. To the authors' best knowledge, ReCiPe [31] is the only impact assessment model that has preliminary CFs for N_2O emissions. However, their use requires careful interpretation since the N_2O CFs are quite sensitive to atmospheric conditions and concentrations of CH_4, CO_2, and halocarbons [5][7][27], which are considered the biggest source of uncertainty of future stratospheric ozone levels [8]. Hence, the ReCiPe CFs (0.007, 0.011, and 0.017 for the Individual, Hierarchist and Egalitarian view, respectively) are only valid for the IPCC A1B climate scenario (resulting in representative concentration pathway (RCP) 6.0) considered for the calculation of the CFs. Model simulations indicate that these CFs could vary from 0.015 for RCP 2.6 to 0.030 for RCP 8.5, considering an infinite time horizon [27].

Stratospheric aerosols are currently not considered in impact assessment models for ozone depletion, but it is known that they affect stratospheric temperature, transport, and chemical reactions in the atmosphere (e.g., ozone destruction and formation) [8]. Consequently, it is expected that large increases in stratospheric aerosols, for example, due to the large-scale deployment of rocket launches, stratospheric aerosol injection, and supersonic aircrafts, would affect the ozone layer. Currently, the number of studies and model simulations on the effects of aerosols on the ozone layer is limited [8]. Consequently, deriving CFs for aerosols is likely not yet feasible.

Another challenge related to midpoint characterisation is the selection of time horizons, reference and return years. The return year is when the Equivalent Effective Stratospheric Chlorine (EESC) level returns to the same level as the reference year. For calculating ODPs, 1980 was chosen by the WMO as a reference year, while an infinite time horizon is used. In contrast, ReCiPe uses a time horizon from 1980 to 2044, which is assumed to be the return year. The rationale is that as most ODS will be banned by 2040, any remaining ODS emission after this year will only have a neglectable effect on the ozone layer and will not cause damage [26]. However, stratospheric aerosols, which are not yet considered ODSs by the Montreal Protocol, could still significantly affect the ozone layer. In addition, the return year, which affects upper boundary of the integral for the ODP calculation, is scenario dependent. The latest scientific ozone layer assessment reports values ranging from 2050-2070 for mid-latitudes, and from 2070-2090 for the Antarctic vortex, depending on the scenario [8].

3.3. Endpoint characterisation

Results from different endpoint impact assessment models are more divergent [10], and their robustness is not yet considered mature enough for recommendation [15]. Except for LIME [9], other methods only assess the damage to human health, neglecting the effects of increasing UV-B on crops, marine life, and human-built materials [12].

3.4. Interlinkages with other impact categories

Analysis of the scientific assessment report [8] shows that ozone depletion is inherently linked to climate change since most ODS are also greenhouse gases (GHG). In addition, the banned chlorofluorocarbons (CFC) have been replaced by hydrofluorocarbons (HFC), which are gases with even stronger global warming potential (GWP). Since the Kigali amendment of 2016, these HFCs are also being phased out, although with a longer timeline than the CFCs [6]. Consequently, the Montreal Protocol affects not only ozone depletion, but also climate change.

Another link is related to CO_2 and CH_4 emissions, which increase climate change, but decrease ozone depletion due to stratospheric cooling, which alters ozone chemistry kinetics. N_2O emissions, on the other hand, increase both climate change and ozone depletion.

Climate change also accelerates the Brewer-Dobson circulation and stratosphere-to-troposphere transport of ozone. This is the most likely explanation as to why no significant ozone layer recovery has been observed at mid-latitudes, despite the decrease in ODS emissions. Thus, increasing climate change may increase tropospheric ozone concentrations, which contribute to the impact category photochemical ozone formation. The effect of climate change on ozone depletion will be scenario-dependent since the negative effect of increased stratosphere-to-troposphere transport may be compensated by the positive effect of CO_2 and CH_4-induced stratospheric cooling. These interlinkages are a part of the complex coupling between climate change and ozone depletion and continuous monitoring and improved modelling is required to understand these links better.

The substitution of banned ODS may also affect toxicity impact categories. For example, hydrofluoroolefins (HFO) are gradually replacing HFCs. However, certain HFOs are converted to trifluoroacetic acid (TFA) in the atmosphere, which is a toxic substance.

Note that indirect links between impact categories in LCA are traditionally excluded in characterisation models.

4. Proposed strategies

The combined effect of outdated background databases, incomplete impact assessment and the omission of assessing indirect links between impact categories in current ozone depletion impact assessment must be further investigated to understand their breadth. Here some strategies that could be developed to address the identified shortcomings are proposed.

Firstly, a prospective background scenario could be developed to account for ODS substitution, to the example of what has been done in premise [32]. Such a scenario should be temporally and geographically differentiated to account for the different timelines of the different countries and the emission lag for existing ODS stocks. It is expected that such a background scenario could affect both the climate change and ozone depletion impacts of a given product system.

Secondly, to address the challenges related to N_2O CFs, different scenarios could be developed in alignment with climate-chemistry models, as the ODP of N_2O depends on atmospheric temperature, CO_2, CH_4 and chlorine levels. Collaboration with atmospheric scientist will be required for the development of these CFs. It is important that scenarios for the background and the characterisation are consistent with each other and with existing climate change scenarios. It is therefore recommended to start from the existing shared socio-economic pathway (SSP) storylines and RCPs. Finally, a future development is the inclusion of CFs for stratospheric aerosols in life cycle impact assessment methods.

5. Outlook and conclusions

In our future work, a prospective Montreal Protocol scenario will be developed to be integrated in premise. The scenario will consider the dynamic substitution of ODS for different countries. N_2O CFs for different RCP scenarios will be derived from the existing literature and applied to a case study of a biorefinery. The combined effects of the improved background model and scenario-dependent CFs on the ozone depletion and climate change impacts of the biorefinery will be analysed.

More generally, this work showcases the importance of analysing the challenges of prospective LCA for each impact category individually and collectively, due to potential interlinkages. Therefore, reviews of the particular challenges of other impact categories are recommended.

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Declarations

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