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Progress in life cycle impact assessment: Water vapor emissions and respiratory inorganics

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Abstract: Life cycle assessment (LCA) is being included formally in EcoDesign regulations. Especially product carbon footprint will be mandatory in Europe. However, life cycle impact assessment including global warming potential (GWP) in LCA is hampered by several challenges. One of these is lack of water vapor characterization indexes for GWP. A life cycle inventory profile for air transport fuel including water vapor emissions is evaluated with state-of-the-art practice, i.e. EF Method and ILCD 2011 Midpoint+ and neglecting water vapors high altitude GWP compared to carbon dioxide. Then the characterization factor in GWP100 for water vapor and alternate normalization for particulates are introduced. The results are compared. The main findings are that the EF method and ILCD both generate rather realistic results for Particulate Matter and Respiratory Inorganics mid-point indicators, respectively, but the amount of premature deaths should be better allocated to different specific emissions, and that water vapor may dominate the GWP100 result over the usual carbon dioxide. LCIA mid-points need measurable and understandable bases. The common knowledge of water vapor's GWP100 should not be neglected in LCIA for air transport and beyond where relevant.

Keywords: characterization; life cycle assessment; life cycle impact assessment; normalization; particulate matter; respiratory inorganics; water vapor;

1. Introduction

Life cycle assessment (LCA) has turned out to be a preferred tool to measure especially product sustainability progress [1]. LCA is being included formally in EcoDesign regulations. Especially product carbon footprint will be mandatory in Europe. However, the sustainability assessment is rather scattered and no uniform accepted metric exist. Even the rather straightforward mid-point categories have methodological and measurement problems. In truth ensuring repeated measurement is one of the largest problems. It is important to agree on how repeatability and accountably can be achieved for all mainstream impact mid-point categories such as climate change and particulate matter/respiratory inorganics. These are allegedly two of the most robust of all mid-point categories. This is why the present research is important. The main purpose is to improve the climate change mid-point category GWP100 mid-point indicator by adding a relative characterization index for water vapor. Further the characterization and normalization procedures for the respiratory inorganics mid-point impact category used in the Environmental Footprint (EF) Method [2] (p. 208) is discussed in comparison to the particulate matter impact category of ILCD 2011 Midpoint+ [3].

Water vapor is a very common emission - e.g. from air conditioning, airplanes, irrigation and volcanos - and its characterization factors compared to carbon dioxide is known rather well (0.001 at Earth Surface [4] but around four times higher than carbon dioxide [5] (p. 2 Fig. 1) in the atmosphere. Moreover, stratospheric and tropospheric water vapor effects have been recognized earlier [6]. Still characterization factors for water vapor in GWP indicators are not used so far. This is similar to nitrous oxide which is excluded from the mid-point ozone depletion practice in both [2] and [3], despite that is has a known characterization factor [7]. The conflicting hypotheses in the present research are to which degree water vapor should and could be included in the GWP100 indicator – especially for aircrafts - and what are reliable ways to characterize PM2.5 (Particulate Matter <2.5μm)

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equivalents or single respiratory inorganic emissions at the mid-point. This research will show the effect of adding 4kg CO_2-equivalents/kg water vapor to emissions from airplanes. The differences between Particulate Matter [3] and Respiratory Inorganics [2] indicator results with alternate normalization factor per person for ILCD [3] are also investigated. The present normalization methods for particulate matter in ILCD and respiratory inorganics in EF both give reasonable results for particulate emissions compared to other impact categories. However, the new GWP100-index for water vapor is suggesting that it is an important greenhouse gas to be considered in LCA, at least for airplanes. Water vapor emissions dominate carbon dioxide for airplane greenhouse gases.

2. Materials and Methods

The hypothesis in this research is: including anthropogenic water vapor characterization factor gives new perspectives in global warming potential (GWP) indicator evaluations wherever water vapor is emitted. The research concerns the LCA elements characterization factors [8] (p. 32, Eq. 3), normalization [8] (p. 33, Eq. 5), and weighting [8] (p. 33, Eq. 6), for particulate matter and climate change.

Global emissions of air pollutants black carbon, carbon monoxide, nitrogen oxides, sulfur oxide, organic carbon, PM10 and PM2.5, all belonging to Particulate Matter in ILCD [3] were around 944 billion kg in 2015 [9]. As baseline, ILCD uses the value for just global emissions of PM2.5 to arrive at the global normalization factor per person. Here instead is proposed to use the sum of "all" air pollutants instead, similar to the sum of all global greenhouse gas emissions used for person normalization for climate change, 57400 billon kg.

The characterization factor for the GWP100 indicator for water vapor emitted near earth surface is assumed to be 0.001 kg CO2e/kg [4]. The impact of water vapor emissions is very sensitive to the altitude of emission, so for aircraft emissions, the GWP-index will be much higher [4]. For operation of aircrafts at high altitudes, ≈4 kg CO2e/kg water vapor is assumed based on the relation between the absorption of thermal radiation of water vapor and carbon dioxide [5] (p. 2, Fig. 1). It is judged that the integral area (representing absorption and scattering) of water vapor is ≈4 times larger than for carbon dioxide. However, both negative and positive forcings (from e.g. water vapor) may occur due to aircraft emissions in different parts of the year in northern mid-altitudes [10]. It can be argued that a smaller value than 4kg shall be used even for high altitudes due to cooling effects of water vapor in the troposphere. This will checked in a sensitivity analysis.

2.1 Inventory of emissions from air transport at high altitudes in the atmosphere

Table 1 shows a rather aged inventory which is still useful for the present research which deals with methodological principles.

Table 1. Typical emissions per kg fuel for air transport.

Emission	Emission index (g emission per kg fuel)	Reference
Soot	0.015	[11] (p. 370, Table 1)
Nitrogen oxides	18	[11] (p. 370, Table 1)
Sulfur dioxide	1	[11] (p. 370, Table 1)
Carbon monoxide	1.5	[11] (p. 370, Table 1)
Carbon dioxide	3150	[11] (p. 370, Table 1)
Water vapor	1260	[11] (p. 370, Table 1)

In Table 1 Soot is assumed to be Particulate Matter <2.5μm (PM2.5) for the sake of simplicity and that the points to be made do not require new measured data. Some of the substances emitted listed in Table 1 contribute to the ILCD impact categories "Photochem-

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ical ozone formation", "Acidification", "Terrestrial eutrophication" and "Marine eutrophication". The normalization and weighting and comparison to "Particulate Matter" and "Climate Change" is out of scope but will be commented shortly. The same applies for corresponding impact categories of the EF Method [2].

2.2 State-of-the art and proposed normalization and characterization factors.

Table 1 shows the different characterization indexes used for water vapor and normalization factors for Particulate Matter in ILCD.

. **Table 1.** Characterization factors for water vapor and normalization factors particulate matter

Category	Value	Proposed
GWP100	0 kg CO_2eq/kg for water vapor emissions characterization factor, 7760 kg CO_2eq/capita per year, normalization factor per person [2]	4 kg CO_2eq/kg for water vapor, 7760 kg CO2eq/capita per year
Particulate matter	3.8 kg PM2.5/capita per year, normalization factor per person [3]	127.6 kg particles and air pollutants/capita per year (person global normalization, 944.3 billion kg [9]/7.4 billion people).

Table 2 shows the characterization indices for particulate matter and respiratory inorganics used in the present research.

Table 2. Characterisation indices for emissions per kg fuel for air transport related to particulate matter and respiratory inorganics impact categories.

Emission	Characterization index (kg PM2.5-eq. per kg) [3]	Characterization index (disease incidents per kg) [12]
Soot	1	0.000238
Nitrogen oxides	0.00722	0.0000016
Sulfur dioxide	0.0611	0.000008
Carbon monoxide	0.000356	0

3. Results

Here follow the results for baseline and alternate normalization and characterization applied to airplane emissions.

Table 3 shows the equally weighted results of the inventory in Table 1 using data from [3] for ILCD for the characterization (Table 2) of all substances and normalization factors for both impact categories, particle matter and climate change. Those impacts categories have equal weight of 6.66.

Table 3. Baseline approach ILCD 2011 Midpoint+.

	Baseline GWP100 (kgCO2eq)	Baseline Particulate Matter (kgPM2.5eq)	Normalization baseline (mPts) sum	Weighting baseline (mPts)
Soot	≈0	1.5×10^{-5}	0.0543	0.36 for Particulate Matter
Nitrogen oxides	≈0	1.3×10^{-4}		
Sulfur dioxide	≈0	6.1×10^{-5}		
Carbon monoxide	≈0	5.3×10^{-7}		
Carbon dioxide	3.15		0.34	2.27 for Climate Change
Water vapor	0			

Table 4 shows the unevenly weighted results of the inventory in Table 1 using data from [3] for ILCD for the characterization factors per kg of all substances except water vapor. The normalization factor used for Particulate Matter in Table 4 is 7.83×10^{-3}capita/kg PM2.5eq. instead of 0.263 which is applied in Table 3. For Climate Change 1.28×10^{-4}capita/kg CO_2eq. [2] (corresponds to 7760 kg CO_2eq./capita) is used instead of 1.08×10^{-4} [3]. 9.54 and 22.19 [2] are used as weighting factors for Particulate Matter and Climate Change, respectively.

Table 4. Proposed approach for ILCD 2011 Midpoint +

	Modified GWP100 (kgCO2eq)	Baseline PM (kgPM2.5eq)	Normalization proposed (mPts) sum	Weighting proposed (mPts)
Soot	≈0	1.5×10^{-5}	0.0015	0.015 for Particulate Matter
Nitrogen oxides	≈0	1.3×10^{-4}		
Sulfur dioxide	≈0	6.1×10^{-5}		
Carbon monoxide	≈0	5.3×10^{-7}		
Carbon dioxide	3.15		1.04	23.4 for Climate Change
Water vapor	5.04			

As shown in Figure 1, the difference between Table 3 and Table 4 is that normalizing the emissions belonging to Particulate Matter impact category by the total amount (944.3 million tonnes per 7.4 billion people) decreases the importance of this category in ILCD evaluations.

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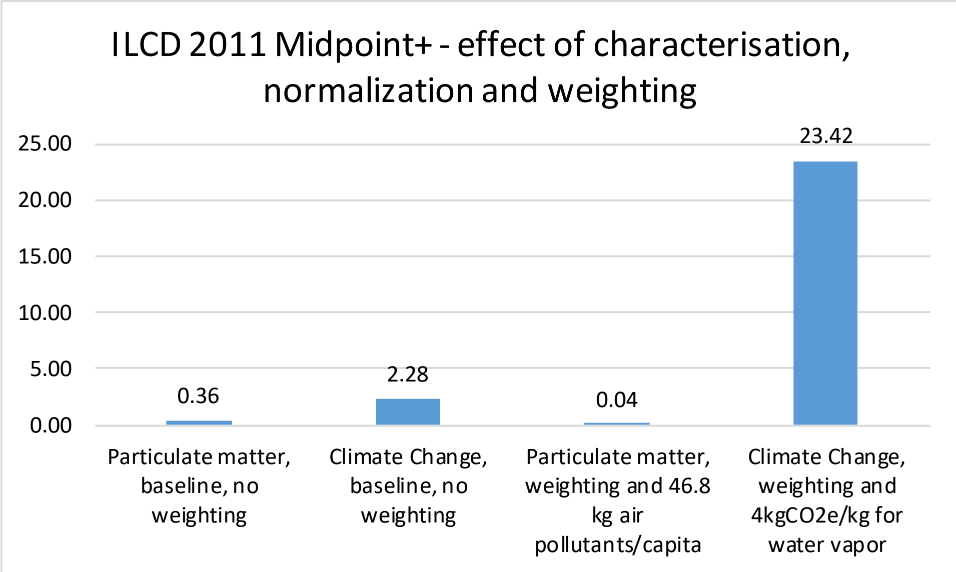

Figure 1. ILCD 2011 Midpoint+ results per kg fuel for air transport.

Table 5 shows the unevenly weighted results of the inventory in Table 1 using data from [2] and [12] for the EF Method for the characterization factors per kg of all substances. 9.54 and 22.19 [2] are used as weighting factors for Respiratory Inorganics and Climate Change, respectively. Carbon dioxide weighted result 0.4 in Table 5 is identical with Table 4 in which carbon dioxide is 0.4 of 1.04 mPts.

Table 5. Baseline approach EF Method.

	Baseline GWP100 (kgCO2eq)	Baseline Respiratory Inorganics (disease incidents, d.i.)	Normalization baseline (d.i.) sum	Weighting baseline (mPts)
Soot	≈0	3.57×10^{-9}	0.063	0.6 for Respiratory Inorganics
Nitrogen oxides	≈0	2.88×10^{-8}		
Sulfur dioxide	≈0	8×10^{-9}		
Carbon monoxide	≈0	0		
Carbon dioxide	3.15		0.4	9 for Climate Change
Water vapor	0			

Table 6 shows the unevenly weighted results of the inventory in Table 1 using data from [1] for the EF Method for the characterization factors per kg of all substances except water vapor. 9.54 and 22.19 [1] are used as weighting factors for Respiratory Inorganics and Climate Change, respectively. Climate change weighted result 1.04 in Table 6 is identical with Table 4 in which water vapor is 0.64 of 1.04 mPts.

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Table 6. Proposed approach EF Method.

	Baseline GWP100 (kgCO2eq)	Baseline Respiratory Inorganics (disease incidents, d.i.)	Normalization baseline (d.i.) sum	Weighting baseline (mPts)
Soot	≈0	3.57×10^{-9}	0.063	0.6 for Respiratory Inorganics
Nitrogen oxides	≈0	2.88×10^{-8}		
Sulfur dioxide	≈0	8×10^{-9}		
Carbon monoxide	≈0	0		
Carbon dioxide	3.15		1.04	23.4 for Climate Change
Water vapor	5.04			

As shown by Figure 2, the difference between Table 5 and Table 6 shows the effect of water vapor characterization, increasing the result by 160%. The weighted result for Respiratory inorganics seems more reasonable than for Particulate Matter in Table 4. However, the amount of global generated disease incidents from PM2.5 may be underestimated in the EF Method.

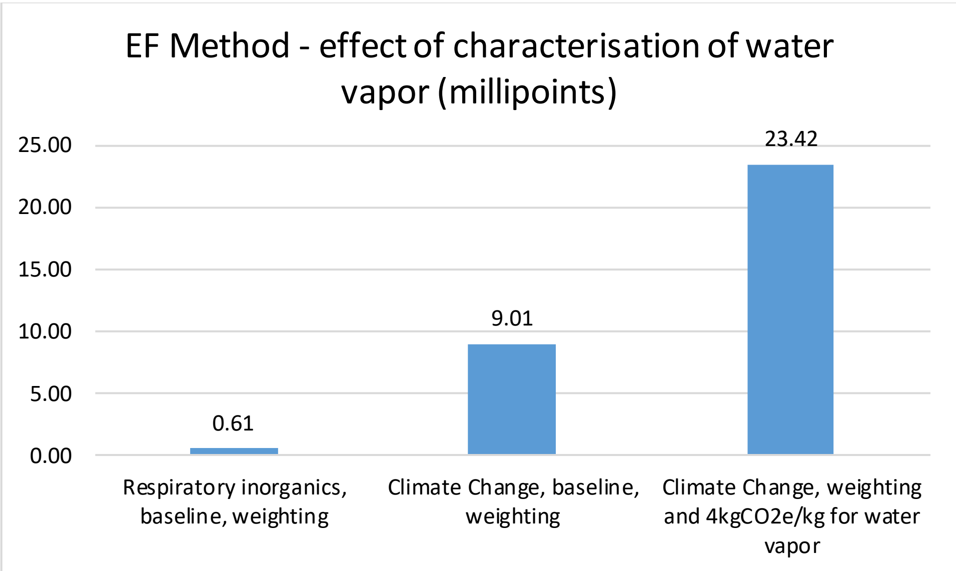

Figure 2. EF method results per kg fuel for air transport.

4. Discussion

Water vapor is emitted in a large number of processes used in Life Cycle Assessment such as transports, material production and certain power production. This is rooted in the combustion of hydrocarbons but also cooling. The effect of water vapor on GWP100 mid-point indicator results and weighted results should be investigated more in LCA and LCIA. Likely water vapor's share of most processes are similar to nitrous oxide when using 0.001 kgCO_2e/kg [4]. Then it may be ignored for ground level processes emitting water vapor. Air traffic stratospheric emissions is another story as far as the preliminary findings herein.

Table 6 and Figure 2 climate change weighted result 23.4 mPt for the EF method would decline to 12.6 mPt if 1kgCO2eq/kg is used instead of 4 for water vapor. Still, this is a 40% increase compared to the baseline in Table 5 and Figure 2. If the water vapor

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factor is reduced to 0.1kgCO_2eq/kg, 9.36 mPts results, i.e. a 4% increase compared to the baseline.

Opposite to carbon dioxide, water vapor has very different GWP depending on point of emission. Therefore scaled characterisation indexes for the mid-point indicator GWP100 should be developed and used. This is similar to particulates emitted near ground from automomobiles or trucks which (should) have other characterization indexes (disease incident/kg) than particles emitted from a very high chimney outside the city center. This is reflected in [12].

The EF method for Respiratory Inorganics - proposing disease incidents/kg factors for each substance belonging to respiratory inorganics - is similar to acidification in which the proton release potential of each acidifying substance is estimated. There is a trend away from PM2.5-equivalents and SO_2-equivalents moving towards measures without scaling on one substance.

Several issues remain to be discussed regarding characterization and normalization. PM2.5 is much analyzed for health and premature death consequences [13]. Other respiratory inorganics have similar properties as PM2.5. Is it better to have one impact category each for every respiratory inorganic substance (nitrogen oxides, carbon monoxide etc.) instead of merging them all into one impact category, Particulate Matter or Respiratory Inorganics? If the premature deaths due to PM2.5 can be isolated from deaths caused by other sources, why merge? ILCD Particulate Matter refers to health consequences and deaths of other substances compared to PM2.5. Therefore the normalization considers only the global emissions of PM2.5 (≈38.22 billion kg) and not "all" air pollutants which are included in the ILCD Particulate Matter mid-point category (944 billion kg per year). This normalization gives similar millipoint scores (0.36 and 0.6 millipoints) as shown by Tables 3 and 5. For EF Method Respiratory Inorganics, the normalization is based on global "all" disease incidents per year caused by "all" air pollutants, ≈4.39 million.

However, this value is less than half of recently estimated [13] global premature deaths due to PM2.5, ≈10.2 million.

For a more transparent normalization, it would be appropriate to focus on one air pollutant at a time as far as health impacts of respiratory inorganics.

Regarding the mid-point indicators ILCD Particulate Matter and EF Methods Respiratory Inorganics, a peculiar instance is that the mid-point is defined as disease incident which usually is an end-point.

Another issue is that the normalization for Particulate Matter in ILCD 2011 Midpoint+ is based on the emissions of PM2.5 alone. More fair is to add several (black carbon, carbon monoxide, nitrogen oxides, sulfur dioxide, organic carbon, PM2.5, and PM10 monitored in [9]) which belong to particulate emissions.

Perhaps it is more robust to estimate the disease incidents potential per each particle type per kg (EF Method) than relate each particles disease incidents potential compared to PM.2.5 (ILCD). Nevertheless, as shown by Table 2 both method (ILCD and EF Method) have a similar relative scoring e.g. for nitrogen oxides compared to PM2.5, 0.00722 for ILCD and 0.00672 for the EF Method. In fact, Particulate Matter in ILCD is based on the quantification of the impact of premature death or disability that particles and respiratory inorganics have on the global population in comparison to PM2.5. This is close to the disease incidents principle. The total global disease incidents due to smog and particles is monitored e.g. in cities. That is why disease incidents may be regarded as a mid-point, albeit caused by different kind of particles and substances.

For Respiratory Inorganics disease incidents for individual emissions is explained as "The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum risk-level" [14]. This disease incidents is used instead of kg PM2.5-equivalents. EF method and ILCD both generate rather realistic results for Particulate Matter and Respiratory Inorganics, respectively. The relation to other mid-point categories is current reasonable in [2] and [3] despite improvement potentials. Anyway, the amount of premature deaths should be better allocated to different specific emissions.

5. Conclusions

Water vapor may significantly increase the GWP100 indicator scores of air transport. Air pollutant respiratory inorganics including particles are rather well handled at the mid-point but more specific data for normalization would improve the mid-point indicators Respiratory Inorganics.

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