| | |
|---|---|
| **Titre:** Title: | Differentiation of greenhouse gases in corporate science-based targets improves alignment with Paris temperature goal |
| **Auteurs:** Authors: | Anders Bjorn, Shannon Lloyd, Urs Schenker, Manuele Margni, Annie Levasseur, Maxime Agez, & H. Damon Matthews |
| **Date:** | 2023 |
| **Type:** | Article de revue / Article |
| **Référence:** Citation: | Bjorn, A., Lloyd, S., Schenker, U., Margni, M., Levasseur, A., Agez, M., & Matthews, H. D. (2023). Differentiation of greenhouse gases in corporate science-based targets improves alignment with Paris temperature goal. Environmental Research Letters, 18(8), 12 pages. https://doi.org/10.1088/1748-9326/ace0cf |

| | |
|---|---|
| **URL de PolyPublie:** PolyPublie URL: | https://publications.polymtl.ca/54790/ |
| **Version:** | Version officielle de l'éditeur / Published version<br>Révisé par les pairs / Refereed |
| **Conditions d'utilisation:** Terms of Use: | |

| | |
|---|---|
| **Titre de la revue:** Journal Title: | Environmental Research Letters (vol. 18, no. 8) |
| **Maison d'édition:** Publisher: | IOP Publishing |
| **URL officiel:** Official URL: | https://doi.org/10.1088/1748-9326/ace0cf |
| **Mention légale:** Legal notice: | Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. |

ENVIRONMENTAL RESEARCH
LETTERS

**LETTER** • **OPEN ACCESS**

# Differentiation of greenhouse gases in corporate science-based targets improves alignment with Paris temperature goal

To cite this article: Anders Bjørn *et al* 2023 *Environ. Res. Lett.* **18** 084007

ENVIRONMENTAL RESEARCH
LETTERS

RECEIVED
25 April 2023

REVISED
12 June 2023

ACCEPTED FOR PUBLICATION
22 June 2023

PUBLISHED
11 July 2023

LETTER

# Differentiation of greenhouse gases in corporate science-based targets improves alignment with Paris temperature goal

**Anders Bjørn**[1,2,3,*], **Shannon Lloyd**[4], **Urs Schenker**[5], **Manuele Margni**[6,7], **Annie Levasseur**[8], **Maxime Agez**[9] **and H Damon Matthews**[3]

[1] Centre for Absolute Sustainability, Technical University of Denmark, Kongens Lyngby, Denmark
[2] Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[3] Department of Geography, Planning and Environment, Concordia University, Montréal, Canada
[4] Department of Management, Concordia University, Montréal, Canada
[5] Nestlé Research, Vers-chez-les-Blanc, 1010 Lausanne 26, Switzerland
[6] CIRAIG, Department of Mathematical and Industrial Engineering, Polytechnique Montréal, Montréal, Canada
[7] Institute of Sustainable Energy, School of Engineering, University of Applied Sciences (HES-SO) Valais, Sion, Switzerland
[8] Department of Construction Engineering, École de technologie supérieure, Montréal, Canada
[9] CIRAIG, Chemical Engineering Department, Polytechnique Montreal, Montréal, Canada
[*] Author to whom any correspondence should be addressed.

**E-mail:** anbjo@dtu.dk

**Keywords:** science-based targets, corporate GHG accounting, mitigation pathways

Supplementary material for this article is available online

## Abstract

Companies are increasingly setting greenhouse gas (GHG) emission reduction targets to align with the 1.5 °C goal of the Paris Agreement. Currently, companies set these science-based targets (SBTs) for aggregate GHGs expressed in $CO_2$-equivalent emissions. This approach does not specify which gases will be reduced and risk misalignment with ambitious mitigation scenarios in which individual gas emissions are mitigated at different rates. We propose that companies instead set reduction targets for separate baskets of GHGs, defined according to the atmospheric lifetimes and global mitigation potentials of GHGs. We use a sector-level analysis to approximate the average impact of this proposal on company SBTs. We apply a multiregional environmentally extended input output model and a range of 1.5 °C emissions scenarios to compare 1-, 2- and 3-basket approaches for calculating sector-level SBTs for direct (scope 1) and indirect (scope 2 and upstream scope 3) emissions for all major global sectors. The multi-basket approaches lead to higher reduction requirements for scope 1 and 2 emissions than the current single-basket approach for most sectors, because these emission sources are usually dominated by $CO_2$, which is typically mitigated faster than other gases in 1.5 °C scenarios. Exceptions are scope 1 emissions for fossil and biological raw material production and waste management, which are dominated by other GHGs (mainly $CH_4$ and $N_2O$). On the other hand, upstream scope 3 reduction targets at the sector level often become less ambitious with a multi-basket approach, owing mainly to substantial shares of $CH_4$ and, in some cases, non-$CO_2$ long-lived emissions. Our results indicate that a shift to a multi-basket approach would improve the alignment of SBTs with the Paris temperature goal and would require most of the current set of companies with approved SBTs to increase the ambition of their scope 1 and scope 2 targets. More research on the implications of a multi-basket approach on company-level SBTs for all scope 3 activities (downstream, as well as upstream) is needed.

## 1. Introduction

Corporate emissions often include methane ($CH_4$), nitrous oxide ($N_2O$) and other greenhouse gases (GHGs) in addition to $CO_2$. Yet, corporate emission reduction targets do typically not specify reductions of individual GHGs. Instead, these targets commonly involve a single percentage reduction of aggregated base year GHGs, expressed in $CO_2$-equivalent ($CO_2e$). Following the GHG Protocol (WBCSD/WRI

2004, 2013), this aggregation of GHGs is based on the 100 year global warming potential (GWP100) metric, which establishes equivalence between different GHGs, based on their contribution to cumulative radiative forcing over 100 years after a pulse emission (Forster *et al* 2021).

The use of a single emission metric, such as GWP100, has been criticized for failing to reflect how short-lived and long-lived GHGs contribute differently to warming over time (Levasseur *et al* 2016). For example, a global reduction in $CH_4$ would lead to a smaller mid-century temperature peak, but a higher long-term temperature, than the same $CO_2$e reduction in $CO_2$ (Sun *et al* 2021). Hence, it can be unclear if a given global aggregate $CO_2$e reduction pathway is compatible with the goals of the Paris Agreement (Fuglestvedt *et al* 2018, Abernethy and Jackson 2022). Another issue with global aggregate $CO_2$e emission pathways, including those currently used by the science based target (SBT) initiative (SBTi) (SBTi 2019, 2022, 2023a), is that information is lost about the differences in mitigation rates of the underlying GHG-specific pathways. Considering that $CO_2$ typically reduces faster than other GHGs in global 1.5 °C emission scenarios (Matthews and Wynes 2022), this current SBTi approach may lead to insufficiently ambitious SBTs for companies that predominantly emit $CO_2$.

Here, we propose that companies set SBTs for separate baskets of GHGs, defined according to the atmospheric lifetimes and global mitigation potentials of GHGs, and we demonstrate how this can be done. Our proposed multi-basket approach aims to improve the alignment of SBTs with the Paris temperature goal by making SBTs a function of the base year GHG mix of companies. We use a sector-level analysis to approximate the average impact of this multi-basket approach to company target setting for direct (scope 1) and indirect (scope 2 and upstream scope 3) emissions for all major global sectors for the years 2030, 2040 and 2050. This assessment involves the calculation of three sets of SBTs: 1-basket SBTs based on a single global aggregate $CO_2$e emission pathway, approximating SBTi's current approach (SBTi 2019); 2-basket SBTs inspired by the proposal of Allen *et al* (2022), where SBTs for short-lived and long-lived GHGs are calculated separately; and 3-basket SBTs based on a modification of the 2-basket approach placing $CO_2$ in a separate basket from other long-lived GHGs. We included the 3-basket approach in recognition that 1.5 °C emission scenarios generally involve higher reduction rates for $CO_2$ than other long-lived emissions (Matthews and Wynes 2022). In all cases, we calculated sector-level SBTs using the absolute contraction approach (Bjørn *et al* 2021). In addition to following a multi-basket approach to calculating SBTs, we deviated from SBTi's current guidance (SBTi 2023b) in several ways[10]. We did this to allow broader conclusions to be drawn from the study.

## 2. Methods

### 2.1. Establishing emissions baskets

We categorized emissions according to the six GHGs used in the multiregional environmentally extended input output model Exiobase v3.8.1 (Stadler *et al* 2018, 2021): $CO_2$, $CH_4$, $N_2O$, $SF_6$, HFCs and PFCs[11]. We then used the 100 year atmospheric lifetime threshold proposed by Allen *et al* (2022) to separate these emissions in short-lived and long-lived baskets for the 2-basket and 3-basket approaches (table 1).

### 2.2. Estimating base year emissions

SBTs are a function of base year emissions (Bjørn *et al* 2021). Here we used 2019 as a common base year, since it is the last year with reliable emission data not affected by the COVID-19 pandemic and following IPCC's presentation of scenarios in its last assessment report (IPCC 2022). We used four product-by-product arrays from Exiobase[12] v3.8.1 (Stadler *et al* 2018, 2021) to estimate direct emissions (scope 1), indirect emissions from purchased electricity, heat, steam and cooling (scope 2,) and other indirect, upstream emissions (upstream scope 3)[13] for 200 product classifications (products, in short) in 49 regions (44 countries and the remaining countries combined in 5 'rest of the world' regions) in the year 2019. The direct requirements matrix (***A***) specifies the amount of product inputs directly required per unit output of each product in each region. The factor production matrix (***F***) provides total direct environmental stressors (including individual GHGs)

---

[10] First, we calculated SBTs for entire sectors and their respective generic products—not specific companies. Second, we calculated SBTs using a more recent and broader range of 1.5 °C scenarios than those informing SBTi's absolute contraction approach at the time of writing (SBTi 2019). Third, we calculated SBTs in the same way for the years 2030, 2040 and 2050, although SBTi provides different guidance for calculating near-term targets (e.g. 2030) (SBTi 2023b) and long-term target, including net-zero targets (e.g. 2040 and 2050) (SBTi 2021a). For example, the SBTi guidance for setting net-zero targets distinguishes between emissions and removals and involves a cap on removals (SBTi 2021a). By comparison, our calculated SBTs concerns net-emissions, due to a lack of explicit information about carbon removal in the underlying 1.5 °C emission scenarios.

[11] Note that (unlike $CO_2$, $CH_4$, $N_2O$ and $SF_6$), HFCs and PFCs are classes of GHGs, representing hydrofluorocarbons and perfluorocarbons, respectively. Exiobase reports HFCs and PFCs in $CO_2$e, following GWP100.

[12] We follow the array notations of the pymrio module (Stadler 2021).

[13] Note that scope 3, as defined by the Greenhouse Gas Protocol (WBCSD/WRI 2004), also comprises indirect downstream emissions (e.g. from the use and subsequent waste management of sold product). However, due to limitations in Exiobase we only covered upstream scope 3 emissions in this study.

**Table 1.** GHGs in Exiobase and classifications according to the 2- and 3-basket approaches.

| GHG | GWP100 value (Forster *et al* 2021) | Atmospheric lifetime (year) | 2-basket classification | 3-basket classification |
|---|---|---|---|---|
| $CO_2$ | 1 | No value[a] | Long-lived | $CO_2$ (long-lived) |
| $CH_4$ | 27.9 | 11.8 | Short-lived | Short-lived |
| $N_2O$ | 273 | 109 | Long-lived | Other long-lived |
| $SF_6$ | 25 200 | 3200 | Long-lived | Other long-lived |
| HFCs | 1530 for HFC134a | 51 for HFC134a[b] | Short-lived | Short-lived |
| PFCs | 7380 for $CF_4$ | 50 000 for $CF_4$[c] | Long-lived | Other long-lived |

[a] $CO_2$ does not follow a first order decay function. We considered it long-lived following Allen *et al* (2022).

[b] Out of the 50 HFCs covered by IPCC AR6, 48 have atmospheric lifetimes below 100 years. Moreover, HFC134a, given as substance equivalent measure of HFC emissions in IPCC scenarios, has an atmospheric lifetime of 51 years. We therefore considered HFCs short-lived here.

[c] Out of the 19 PFCs covered by IPCC AR6, 12 have atmospheric lifetimes above 100 years. Moreover, $CF_4$, given as substance equivalent measure of PFC emissions in IPCC scenarios, has an atmospheric lifetime of 50 000 years. We therefore considered PFCs long-lived here.

from production of products in each region. The factor production coefficients matrix ($\boldsymbol{S}$) provides direct environmental stressors per monetary unit output of products. The global gross output vector ($\boldsymbol{x}$) provides the total amount of products produced in each region ($\hat{\boldsymbol{x}}$ is the diagonalized version of $\boldsymbol{x}$).

We first used an identify matrix ($\boldsymbol{I}$) to transform **A** into a total requirements matrix ($\boldsymbol{L}$—the Leontief inverse), which specifies the total (direct and upstream) amount of product inputs required per unit output of each product in each region (Miller and Blair 2009):

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \tag{1}$$

We then estimated emissions for each product and region as follows:

- We obtained scope 1 emissions directly from $\boldsymbol{F}$.
- We estimated scope 2 emissions by modifying $\boldsymbol{A}$ to include only the inputs from procuring electricity, heat, steam and cooling[14] ($\boldsymbol{A_u}$), modifying **S** to include only GHG emissions per unit output for these utilities ($\boldsymbol{S_u}$), and calculating emissions from these first-tier utility suppliers as follows:

$$\textbf{scope 2} = \boldsymbol{S_u} \cdot \boldsymbol{A_u} \cdot \hat{\boldsymbol{x}} \tag{2}$$

- We estimated upstream scope 3 emissions by subtracting scope 2 emissions (equation (2)) from total indirect upstream emissions via the following equation, where subtracting the identify matrix from the Leontief inverse gives just the indirect requirements per unit output for each product (hence, involving intentional double counting[15]):

$$\begin{aligned}\textbf{upstream scope 3} &= \textbf{total}_{\textbf{indirect}} - \textbf{scope 2} \\ &= \boldsymbol{S} \cdot (\boldsymbol{L} - \boldsymbol{I}) \cdot \hat{\boldsymbol{x}} - \textbf{scope 2}\end{aligned} \tag{3}$$

This resulted in 29 400 emission estimates for the year 2019 (200 products × 49 regions × three scopes), each covering the six GHGs in table 1, with 5099 instances of zero total emissions[16] due to the fact that not every product is produced in all 49 regions and that in some cases products do not have emissions in all three scopes.

### 2.3. Selecting emission scenarios and developing basket-level pathways

SBTs are based on global emission scenarios aligned with the temperature goal of the Paris Agreement (Bjørn *et al* 2021). As a basis for calculating SBTs in this study, we selected 69 of the 97 scenarios classified as 'immediate action to limit warming to 1.5 °C with no or limited overshoot (C1)' in the sixth assessment report of the Intergovernmental Panel on Climate Change (Byers *et al* 2022, IPCC 2022). This excludes 28 scenarios that did not include pathways for all six GHGs covered by Exiobase (table 1). For each scenario, we extracted emissions for the six GHGs in the year 2019[17]–2100 and classified each GHG according to the 2- and 3-basket approaches (table 1). For each scenario, we then used GWP100 values (Forster *et al* 2021) to aggregate the GHG-specific emission

---

[14] 'Electricity by coal', 'Electricity by gas', 'Electricity by nuclear', 'Electricity by hydro', 'Electricity by wind', 'Electricity by petroleum and other oil derivatives', 'Electricity by biomass and waste', 'Electricity by solar photovoltaic', 'Electricity by solar thermal', 'Electricity by tide, wave, ocean', 'Electricity by Geothermal', 'Electricity nec', 'Steam and hot water supply services'.

[15] As per the Greenhouse Gas Protocol (WRI/WBCSD 2011), a given emission source may be counted under the scope 3 emissions of multiple actors. For example, emissions from producing fertilizer are both part of the upstream scope 3 emissions of a farming activity and part of the upstream scope 3 emissions of a food processing activity that uses the output of the farming activity as an input. The Greenhouse Gas Protocol also involves intentional double counting between the scope 1, 2 and 3 emissions of different actors. For example, emissions from the electricity generation of a company both belong to that company's scope 1 emissions and to the scope 2 emissions of companies buying the electricity.

[16] Note that we encountered a few combinations of products and regions with zero production, but non-zero scope 1 emissions. We assumed that these non-zero scope 1 emissions were errors in Exiobase and replaced them by zeroes.

[17] The scenarios involve 5 or 10 year time steps. We therefore estimated 2019 values from linear interpolation between 2010 or 2015 and 2020 values.

pathways to a single $CO_2$e pathway for each GHG basket within the three basket approaches (table 1). The resulting basket-level global emission pathways formed the basis for the SBT calculations.

### 2.4. Calculating and comparing SBTs

For each emission scenario, we calculated SBTs for each product-region combination and basket-approach using the absolute contraction approach, which is the most common method behind approved SBTs (SBTi 2021b). This approach assigns emission allowances based on base year emissions requiring all companies to reduce emissions at the rate that is globally needed (i.e. emissions grandfathering). Accordingly, for each basket approach, we calculated SBTs for all relevant combinations of GHGs (G), related GHG baskets (table 1) (B), products (P), regions (R), emissions scopes (S), emission scenarios (ES) and target years ($y$):

$$\mathrm{SBT}_{\mathrm{G,B,P,R,S,ES,y}} = \mathrm{PE}_{\mathrm{G,B,P,R,S,ES,2019}} \cdot \frac{\mathrm{GE}_{\mathrm{B,ES,y}}}{\mathrm{GE}_{\mathrm{B,ES,2019}}} \tag{4}$$

where $\mathrm{PE}_{2019}$, the product emissions in the base year 2019, was estimated using Exiobase (section 2.2), and $\mathrm{GE}_{2019}$ and $\mathrm{GE}_y$ (with $y$ = 2030, 2040 or 2050), the global emissions in the base year and targets years, were sourced from the developed basket-level emission pathways (section 2.3). We then aggregated the calculated SBTs for emissions falling into the same GHGs basket, for a given basket approach. This resulted in up to 1676 769 SBTs for each basket and target year (69 scenarios × 24 301 non-zero emission estimates for the year 2019).

We demonstrate the application of the 1-, 2- and 3-basket approaches for deriving SBTs for an example product and region, i.e. 'Dairy products' in the United States. We chose this product, as we knew beforehand that its scope 1 and 2 emissions primarily involve $CO_2$ (related to process energy), while its upstream scope 3 emissions involve substantial shares of $CH_4$ and $N_2O$ (related to livestock farming and associated feed production). Hence, we expected substantial differences between multi-basket SBTs for scope 1, 2 and 3 emissions of US dairy products and, moreover, that these multi-basket SBTs would be different from the single-basket SBTs.

### 2.5. Analyzing differences between single-basket and multi-basket SBTs

We then investigated the impact of using the 2- or 3-basket approach instead of the 1-basket approach across all products, regions and scopes and investigated whether any patterns emerge from setting GHG-differentiated rather than GHG-wide SBTs. To do so, we normalized all calculated product-region SBTs by the 2019 emission estimates, thereby expressing them as targeted percentage reductions of 2019 emissions. We then calculated the percentage point differences between the normalized multi-basket SBTs and the corresponding normalized single-basket SBTs, to facilitate an identification of the products and emission scopes for which a multi-basket approach typically leads to substantially higher or lower reduction requirements than a single-basket approach.

For ease of interpreting results, we grouped the calculated target differences (between the single-basket and multi-basket approaches) for the 200 products into ten sectors: (1) fossil-based raw materials, (2) bio-based raw materials, (3) other raw materials, (4) fossil-based manufacturing, (5) bio-based manufacturing, (6) other manufacturing, (7) utility, (8) waste management, (9) transportation, (10) other services (see table S1 in the supplementary material for details). This classification was inspired by the concept of life-cycle stages in product-level life cycle assessment (ISO 2006a, 2006b, Hellweg and Milà I Canals 2014). Moreover, we differentiated the raw materials and manufacturing sectors according to the origin of materials (fossil, bio and other), which are known to have different mixes of GHGs (for example, the provisioning of bio-based materials typically involves higher levels of $CH_4$ and $N_2O$ than the provisioning of 'other' materials, such as aluminum ore). We then calculated medians and other summary statistics of the product-level target differences within each sector. We also calculated a weighted average target difference within each sector, using production in 2019 (reported as Euro value added in Exiobase) as weighting factor. In this way, the products and regions with high production have high influence on the weighted average target difference of a sector. In our discussion we reflect on what these sector-level results mean for company-level SBTs.

## 3. Results

### 3.1. Sectoral GHG mixes in 2019

A large difference in GHG mixes can be observed across sectors and emissions scopes (figure 1). While $CO_2$ makes up more than half of scope 1 emissions for seven of the ten sectors, other GHGs (mainly $CH_4$) dominate fossil-based and bio-based raw materials and waste management (figure 1(a)). Scope 2 emissions (figure 1(b)) are always dominated by $CO_2$ (around 99% for all sectors). The upstream scope 3 emission mixes (figure 1(c)) of manufacturing have 'echoes' of the scope 1 emission mixes of the raw materials used as inputs (lower $CO_2$ shares for fossil- and bio-based manufacturing than for 'other' manufacturing). While upstream scope 3 emissions are lower than scope 1 emissions for the raw materials sectors, upstream scope 3 emissions are highest in most of the remaining sectors, which rely more on upstream processes.

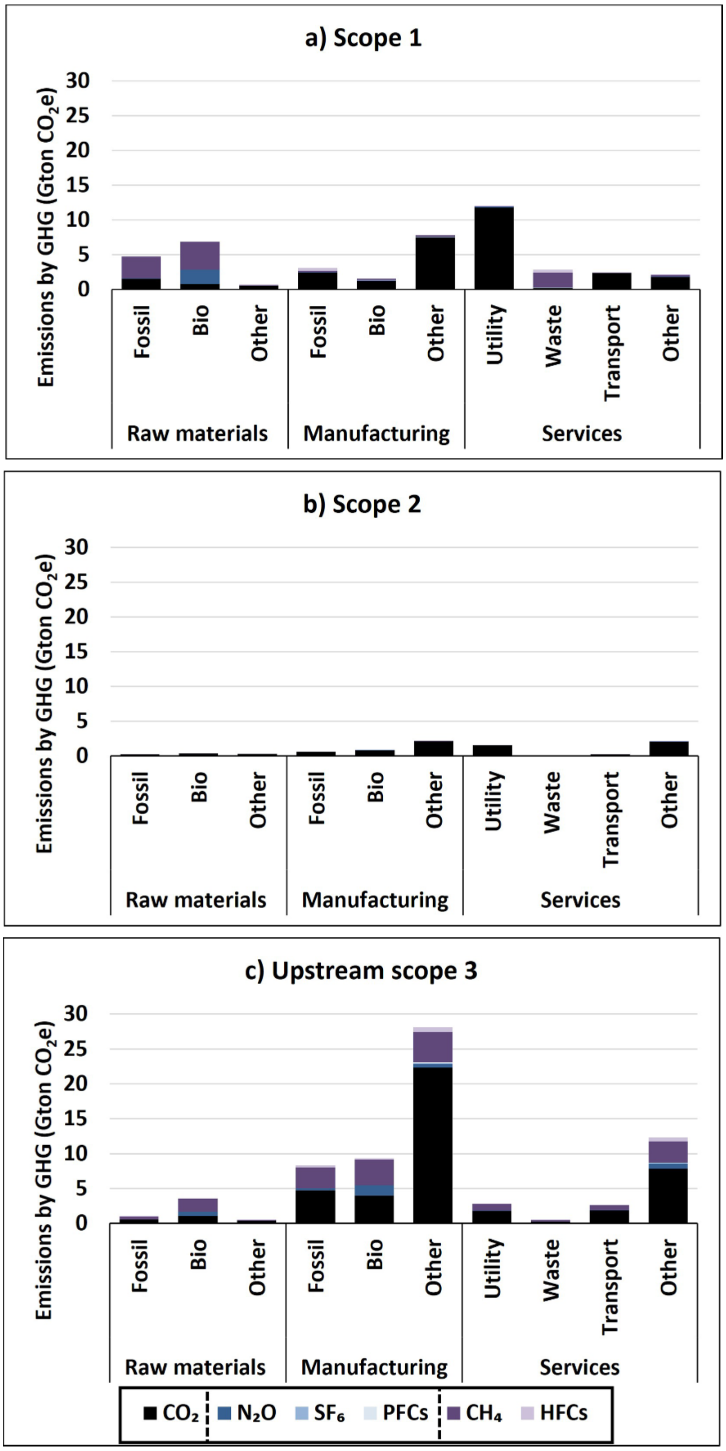

**Figure 1.** Estimated emissions for scope 1 (a), scope 2 (b) and upstream scope 3 (c) by GHG for the ten sectors in 2019. The coloring and dotted boarders in the legend indicate the GHG basket classifications, following table 1.

### 3.2. Global emission pathways for the 1-, 2- and 3-basket approach

The targeted reduction rates for individual GHGs vary considerably across the sixty-nine 1.5 °C emissions scenarios (figure 2(a)), with higher reductions generally required for $CO_2$, especially in later years (net-negative $CO_2$ emissions are required by 2050 in 36% of the 69 scenarios). In the existing 1-basket approach for setting SBTs (figure 2(b)), aggregate $CO_2e$ emissions gradually reduce over time with a median $CO_2e$ reduction of 82% in 2050 relative to 2019. In the 2-basket approach (figure 2(c)), long-lived emissions reduce more than short-lived emissions, especially in 2050 with median $CO_2e$ reductions of 91% vs. 52% relative to 2019. In the 3-basket approach (figure 2(d)), long-lived GHGs other than $CO_2$ ($N_2O$, $SF_6$ and PFCs) reduce much less than both $CO_2$ and short-lived emissions. This is an indication that the 3-basket approach is better than the 2-basket approach for aligning corporate emission reduction

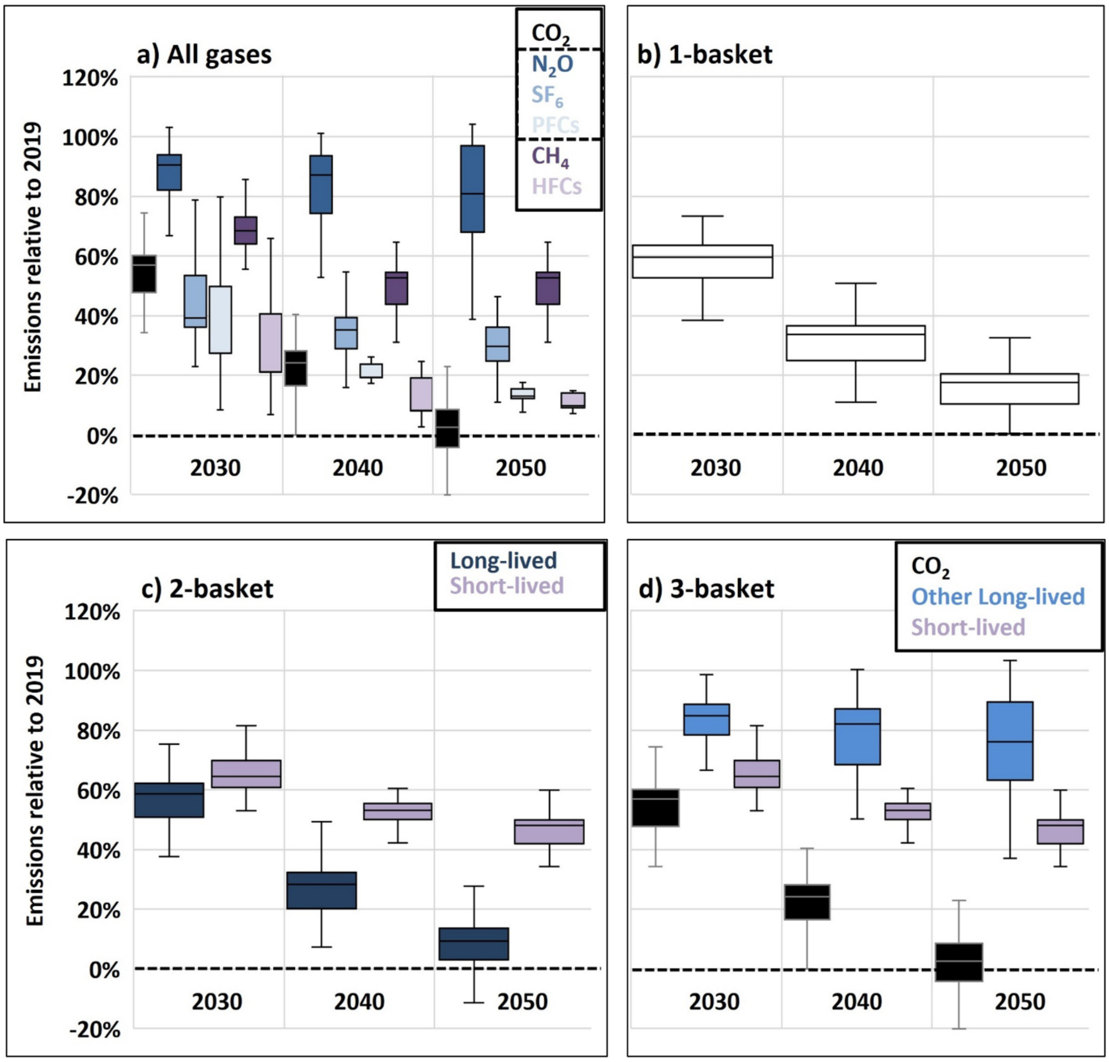

**Figure 2.** Emission reduction targets relative to 2019 for the sixty-nine 1.5 °C scenarios by GHG (a) and for the 1-, 2-, and 3-basket approaches (b)–(d). Boxes indicate 25–75th percentile ranges. Horizontal lines within boxes indicate medians. Whiskers (i.e. non-outlier ranges) indicate datapoints within 1.5-times the 25–75th percentile ranges. Outliers are not shown. The coloring and dotted boarders in the legend of figure 2(a) indicate the GHG basket classifications, following table 1.

targets with global mitigation needs, for example, by differentiating companies that mainly emit $CO_2$ from companies emitting substantial shares of $N_2O$ (further explored below).

### 3.3. SBTs for dairy products in the United States

Total 2019 emissions from US dairy products were 143Mt $CO_2$e (figure 3(a)), with $CH_4$ (a short-lived GHG) accounting for 52% (figures 3(b) and (c)). The $CH_4$ emissions were almost exclusively from upstream scope 3 (agricultural) activities, which accounted for 82% of total $CO_2$e (figures 3(d)–(f)).

The three considered basket approaches result in substantially different SBTs for US dairy products. For the common 1-basket approach (figure 2(b)), all GHGs must be reduced at the same rate (median 82% by 2050). Hence, the targeted percentage reduction for US dairy products is identical across all emissions (figure 3(a)) and scopes (figure 3(d)).

In the 2-basket approach (figure 2(c)), long-lived emissions must be reduced at a higher rate (median 91% by 2050) than short-lived emissions (median 52% by 2050). For US dairy products, this permits short-lived equivalent emissions to be nearly six times higher than long-lived equivalent emissions in 2050 even though the two baskets had similar equivalent emission levels in 2019 (figure 3(b)). Since most short-lived emissions are from upstream scope 3 activities, the aggregate reduction rate is lower for upstream scope 3 emissions than for scope 1 and 2 emissions (figure 3(e)).

In the 3-basket approach (figure 2(d)), $CO_2$ must be reduced at a much higher rate (median 97% by 2050) than other long-lived GHGs (median 24% by 2050). For US dairy products, this requires $CO_2$ emissions to be just 8% of other long-lived equivalent emissions in 2050 even though $CO_2$ emissions were more than double other long-lived equivalent

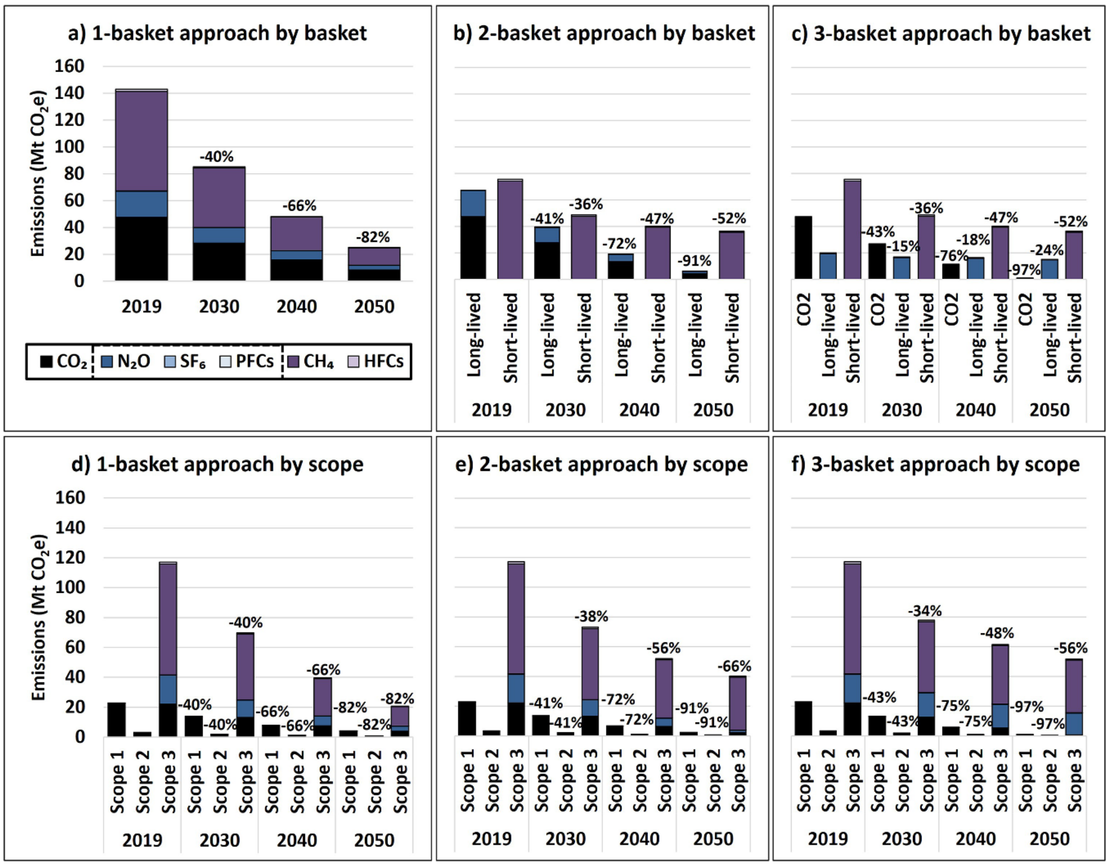

**Figure 3.** SBTs for US dairy products for different baskets of gases (a)–(c) and emission scopes (d)–(f). The columns indicate the median targeted emissions resulting from the application of the sixty-nine 1.5 °C scenarios (see figure 1) for each basket and year. The percentage reduction relative to 2019 is indicated above each column for 2030, 2040 and 2050. The coloring and dotted boarders in the legend indicate the GHG basket classifications, following table 1. Scope 3 refers to upstream scope 3 only.

emissions in 2019 (figure 3(c)). Since most scope 1 and 2 emissions are $CO_2$, the special treatment of $CO_2$ means an even higher aggregate reduction for scope 1 and 2 emissions compared to the 2-basket approach (97% instead of 91% by 2050) (figure 3(f)). The separate treatment of $N_2O$ (another long-lived gas) from $CO_2$ likewise results in an even lower aggregate reduction for upstream scope 3 emissions compared to the 2-basket approach (56% instead of 66% by 2050).

Overall, the high prevalence of $CO_2$ from scope 1 and 2 activities of US dairy products leads to a higher emission reduction requirement for these scopes when the 2-basket approach is used, and an even higher reduction requirement when the 3-basket approach is used (compare figures 3(d)–(f)). Conversely, the high prevalence of short-lived emissions (and non-$CO_2$ long-lived emissions) from upstream scope 3 activities leads to a lower emission reduction requirement for upstream scope 3 when the 2-basket approach is used, and an even lower reduction requirement when the 3-basket approach is used.

### 3.4. Normalized sector-level SBTs

Across the ten sectors, each covering multiple products and regions, the multi-basket approaches lead to higher 2050 reduction requirements for some emission scopes (medians and weighted averages above the zero lines in figure 4) and lower reduction requirements for others (medians and weighted averages below the zero lines in figure 4), depending on their GHG mixes (figure 1). The general pattern is similar to that observed for US dairy products—more aggressive scope 1 and 2 targets (due to the higher share of $CO_2$ emissions) and less aggressive upstream scope 3 targets (due to the higher shares of short-lived emissions and, in some cases, non-$CO_2$ long-lived emissions). The two main exceptions for scope 1 is fossil-based raw materials and waste management, which have less ambitious scope 1 targets for multi-basket approaches due to substantial shares of $CH_4$ (and HFCs for waste management) in their scope 1 GHG mixes (figure 1).

For each sector and scope, the 2- and 3-basket targets tend to both be more ambitious or both be less ambitious than the 1-basket target. The scope 1 targets for bio-based raw materials are the main exception, as they are generally more ambitious compared to single-basket targets when the 2-basket approach is used (median a bit above the zero line) but substantially less ambitious compared to single-basket targets when the 3-basket approach is used (median much below the zero line). This is because of the high

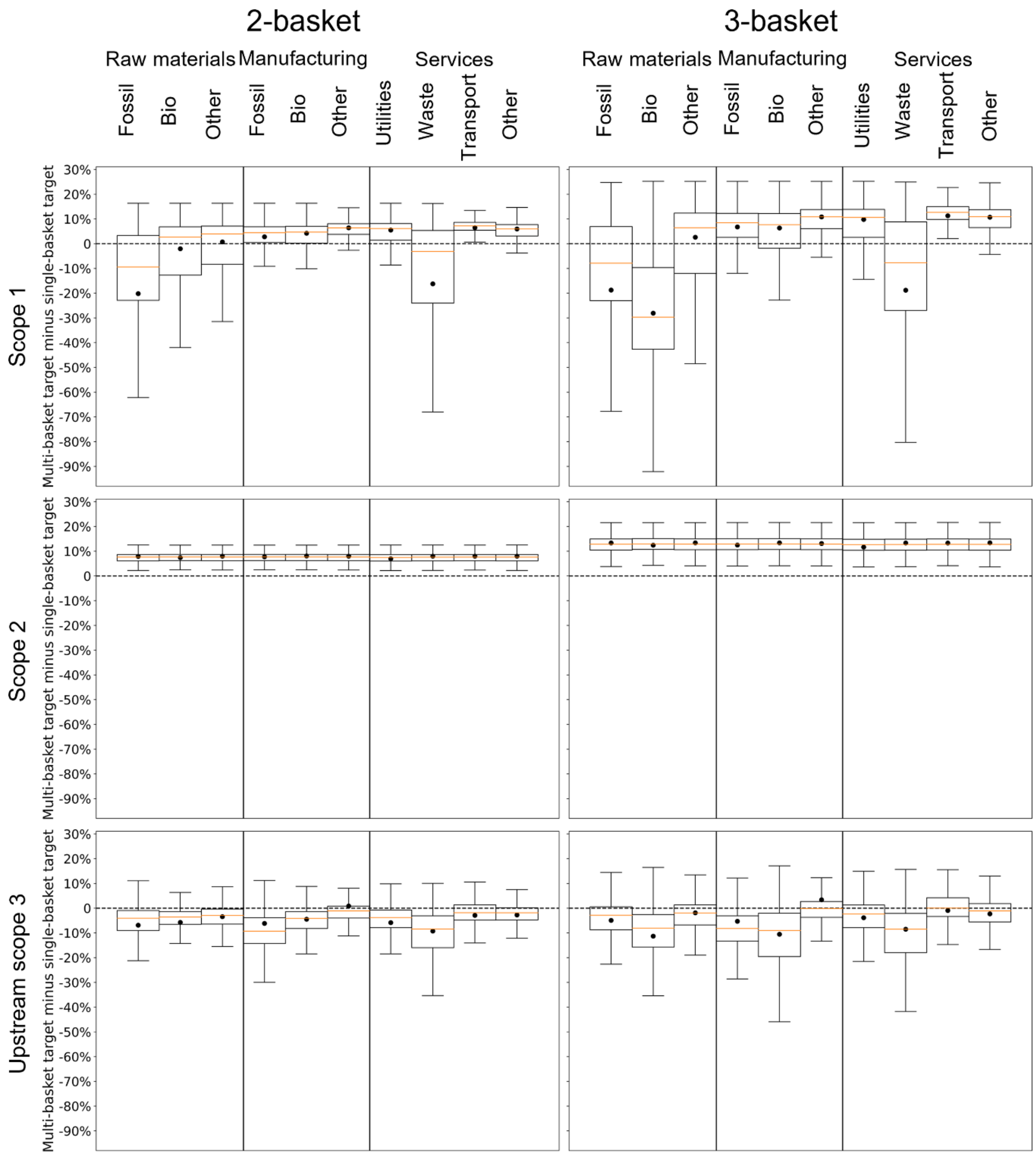

**Figure 4.** Difference between normalized sector-level SBTs in the year 2050 for the single-basket approach and the multi-basket approaches for then ten sectors. Each sector box covers SBTs for all relevant combinations of the sixty-nine 1.5 °C scenarios, the 49 regions, and the 7–36 Exiobase products covered by the sector. Boxes indicate 25–75th percentile ranges. Horizontal lines within boxes indicate medians. Black dots indicate production-weighted averages. Whiskers (i.e. non-outlier ranges) indicate datapoints within 1.5-times the 25–75th percentile ranges. Outliers are not shown. Values above the zero lines indicate that a multi-basket approach leads to higher reduction requirements than a single-basket approach and vice versa. The six charts cover the different combinations of the three emission scopes (rows) and the two multi-basket approaches (columns). Results for the targets years 2030 and 2040 are shown in figures S1 and S2 in the supplementary material.

share of $N_2O$ in 2019 scope 1 emissions in that sector (figure 1), which is part of the long-lived basket in the 2-basket approach and the other (non-$CO_2$) long-lived basket in the 3-basket approach (table 1), which have widely different reduction rates (compare figures 2(c) and (d)). Relatedly, the difference between the multi-basket and single-basket targets tends to be more pronounced for the 3-basket SBTs (medians and weighted averages further above or below the zero-line), since the 3-basket targets reflect higher reduction rates for $CO_2$ and lower reduction rates for other long-lived GHGs.

The weighted average target differences are close to the median target differences for most sectors and emission scopes (figure 4). This indicates that the normalized SBTs of products and regions with high production are generally close to the normalized SBTs of products and regions within each sector at large. Exceptions of this tendency include SBTs for scope 1 emissions of fossil-based raw-materials, for which the weighted average target differences are around double the median differences for both multi-basket approaches. This is because ‘Crude petroleum and services related to crude oil extraction, excluding surveying' is the Exiobase product contributing the most (61%) to the value added of the entire fossil-based raw-materials sector and this product has a substantially higher share of $CH_4$ in its scope 1 GHG mix (average over regions of 76%) than the average of all products in the sector (42%).

## 4. Discussion

We used a multi-basket approach to distinguish between short- and long-lived GHG emissions when calculating sector-level scope 1, 2 and 3 reduction targets. This showed that GHG basket-specific reduction targets in many cases are substantially different from targets calculated following the predominant single-basket approach.

### 4.1. Implications for company-level SBTs

The multi-basket approach generally leads to more aggressive reduction requirements for sector-level scope 1 and 2 emissions, due to the high share of $CO_2$ emissions typically in these scopes. Exceptions include the raw materials and waste management sectors, which would have a less aggressive scope 1 reduction requirement due to the high portion of non-$CO_2$ emissions. On the other hand, a shift to a multi-basket approach would in most cases allow less ambitious upstream sector-level scope 3 targets than a single-basket approach, due to the substantial shares of non-$CO_2$ GHGs in upstream scope 3 emission mixes across sectors. These sector-level findings indicate that most companies would likewise set more aggressive SBTs for scopes dominated by $CO_2$ emissions and less aggressive SBTs for scopes dominated by short-lived (and non-$CO_2$ long-lived emissions) if changing to a multi-basket approach.

If SBTs were implemented across all companies using the current single-basket approach, the net effect of the resulting emissions reductions would be generally aligned with the Paris temperature goal (assuming that all companies use the same emission allocation approach (Bjørn *et al* 2021), that they all meet their targets and that, in doing so, their combined reduction of individual GHGs is consistent with the global emission scenario(s) underlying their targets). However, SBTs have currently been approved for only a subset of the world's companies, and in general these companies belong to sectors with $CO_2$ as the dominant contributor to scope 1 and 2 emissions (SBTi 2022)[18]. As a result, if the current set of companies with SBTs were to shift to a multi-basket approach, this would require larger reductions in $CO_2$ compared to other gases, leading to more ambitious scope 1 and 2 targets across these companies. Following a similar logic, it may be tempting to conclude from our sector-level results that a multi-basket approach generally would allow for less ambitious company-level scope 3 targets than the current approved single-basket scope 3 targets. However, such a reasoning would rest on the assumption that scope 3 activities as a whole (downstream, as well as upstream) and across different company types have substantial shares of non-$CO_2$ emissions and this assumption has, to our knowledge, not yet been tested. Furthermore, it is important to stress that existing SBTi guidelines do not require targets for scope 3 to align with a 1.5 °C goal and as a result, approved scope 3 targets are already less ambitious than approved targets for scope 1 and 2 (Bjørn *et al* 2022c, 2023, SBTi 2023b). Consequently, our results suggest that across the current set of companies with approved SBTs, the use of a single-basket approach to target-setting has led to SBTs for scope 1 and 2 that in combination are less ambitious than what is required to align with the Paris temperature goal, while it is unclear how a shift to a multi-basket approach would affect current scope 3 targets.

A multi-basket approach would ensure a better alignment between companies' SBTs and the GHG-specific pathways of the underlying 1.5 °C scenarios and, as a result, generally increase target ambition for scope 1 and 2 emissions that are dominated by $CO_2$. We therefore encourage SBTi to implement a multi-basket approach in its target-setting guidance and methods.

### 4.2. Implications for corporate emission accounting

Implementing a multi-basket approach to emissions accounting and mitigation targets puts additional demands on companies and data providers. First, companies should disclose their emissions of each GHG, as already required by the GHG Protocol[19]. However, only 58% of the 2205 companies that disclosed GHG-wide scope 1 emissions in $CO_2e$ to CDP for 2019 also reported the corresponding GHG-specific scope 1 emissions (CDP 2020) (CDP did not ask companies for this GHG breakdown for scope 2 and 3 emissions). Hence, better compliance with the existing reporting requirements is needed.

For estimating indirect emissions (scope 2 and 3), companies typically require a combination of the scope 1 emissions of their suppliers and customers and generic datasets. The providers of these datasets should therefore enable GHG-specific accounting.

---

[18] Out of the 2,487 companies with approved SBTs as of April 4th, 2023, only 111 companies (4%) belonged to sectors related to food and tobacco production, mining and waste management, as per SBTi's sector classification (SBTi 2023a), which are the sectors that can be expected to have substantial shares of non-$CO_2$ emissions in scope 1, based on Exiobase (figure 1).

[19] In an amendment from 2013 to the Greenhouse Gas Protocol standard, companies are required to report 'Emissions data for all GHGs covered by the UNFCCC/Kyoto Protocol separately in metric tonnes and in tonnes of $CO_2$ equivalent.' (WBCSD/WRI 2004, 2013).

For scope 2 accounting, providers of region-specific average emission factors (used in the location-based accounting approach), providers of residual emissions factors and issuers of renewable energy certificates (used in the market-based accounting approach) should report each GHG separately (WRI 2015, Bjørn *et al* 2022a). For scope 3 emissions, resources such as the 'Scope 3 Evaluator' screening tool of the GHG Protocol (WBCSD/WRI/Quantis 2015) (which partially builds on environmentally extended input output modeling) could be updated to provide GHG-specific emissions estimates, in addition to the aggregate estimates currently provided.

Across all actors, a new standard for reporting fluorinated gases may be needed. Currently, companies, generic data providers (e.g. Exiobase) and scenario developers typically report fluorinated gases aggregated by classes based on molecular commonalities, such as HFCs and PFCs (see table 1). Corporate climate disclosure platforms, such as CDP, also asks companies to report fluorinated gasses aggregated by such classes. However, both HFCs and PFCs contain short-lived as well as and long-lived GHGs (see table 1). It may therefore be more useful to define classes of fluorinated gases according to atmospheric lifetimes (e.g. less than 100 years versus 100 years or more).

### 4.3. Future research

We demonstrated the multi-basket approach using the absolute contraction approach (implying emission grandfathering) and sixty-nine 1.5 °C scenarios. However, the multi-basket approach can be used with other emission allocation principles (such as those embedded in the sectoral decarbonization approach (Krabbe *et al* 2015, Bjørn *et al* 2021, Chang *et al* 2022, Bjørn *et al* 2022b)) and any emission scenario containing separate pathways for individual GHGs. Future studies should explore the implications of using a multi-basket approach with SBTi's emerging sector-specific target-setting framework, e.g. for forest, land and agriculture or for oil and gas (SBTi 2023c).

The multi-basket approach can also be used with alternative numbers and compositions of emission baskets. Future studies should investigate the most suitable basket configuration for the setting of emission reduction targets for specific actors and purposes. Considerations that may be important in such an assessment include (1) the threshold between short-lived and long-lived GHGs (the somewhat arbitrary and ambiguous 'around 100 years' threshold suggested by Allen *et al* (2022) makes it unclear what basket $N_2O$ belongs to, for example); (2) the GHG mix in the base year (there is no reason for a basket for GHGs that are not emitted by the type of actor in question); (3) the differences in the emission reduction rates of individual GHGs in 1.5 °C scenarios; (4) whether it is desirable to differentiate targets based on the underlying sources of emissions (e.g. fossil fuel use versus land-use emissions), as well as to offer separate targets for emissions and removals, so as to clarify efforts aimed at achieving net-zero emissions.

Our study involves the application of the well-known GWP100 metric in a new multi-basket approach to setting SBTs. This approach, inspired by Allen *et al* (2022), retains information about the atmospheric lifetimes of gasses (lost in a single-basket approach), and thereby about their different contributions to warming over time. By comparison, GWP with other time horizons than 100 years (Abernethy and Jackson 2022) and alternative metrics, such as the global temperature change potential (GTP) (Levasseur *et al* 2016), the GWP* (Lynch *et al* 2020) and the combined global temperature change potential (CGTP) (Collins *et al* 2020), involve different approaches to comparing the temperature effects of short-lived and long-lived GHGs. Future studies should explore the potential use of such alternatives to GWP100 in facilitating alignment of the emission reduction targets of individual actors with global 1.5 °C scenarios.

## 5. Conclusion

There is increasing attention to the different temperature effects of short-lived and long-lived GHGs and the different expected reduction potentials of the various GHGs (Collins *et al* 2020, Lynch *et al* 2020, Ou *et al* 2021, Allen *et al* 2022, Harmsen *et al* 2023, Ivanovich *et al* 2023). The current single-basket approach to setting SBTs does not adequately account for these differences. A multi-basket approach for setting GHG-differentiated SBTs offers a way to improve alignment of corporate targets with global emission scenarios. To enable a transition from single- to multi-basket SBTs, we call on companies and data providers to report emissions of each GHG and SBTi to introduce guidance for multi-basket corporate targets. Such actions would more effectively align corporate contributions to global mitigation plans.

## Data availability statement

The data that support the findings of this study are openly available at the following URL: https://zenodo.org/record/8024675.

## Acknowledgments

We thank two anonymous reviewers for their valuable comments. This research was funded by the Concordia University Horizon Fellows Program and Købmand Niels Erik Munk Pedersen Fonden.

## Competing interests

Anders Bjørn is a remunerated member of the Technical Council of the Science Based Targets initiative. The remaining authors declare no competing interests.

## ORCID iDs

Anders Bjørn https://orcid.org/0000-0001-9332-5346
Shannon Lloyd https://orcid.org/0000-0003-1058-6765
Urs Schenker https://orcid.org/0000-0002-9437-0904
Manuele Margni https://orcid.org/0000-0002-2475-0768
Annie Levasseur https://orcid.org/0000-0001-6968-8155
Maxime Agez https://orcid.org/0000-0003-0238-7352
H Damon Matthews https://orcid.org/0000-0003-3625-390X

## References

Abernethy S and Jackson R B 2022 Global temperature goals should determine the time horizons for greenhouse gas emission metrics *Environ. Res. Lett.* **17** 024019

Allen M R *et al* 2022 Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets *npj Clim. Atmos. Sci.* **5** 18–21

Bjørn A, Lloyd S M, Brander M and Matthews H D 2022a Renewable energy certificates threaten the integrity of corporate science-based targets *Nat. Clim. Change* **12** 539–46

Bjørn A, Lloyd S and Matthews D 2021 From the Paris Agreement to corporate climate commitments: evaluation of seven methods for setting "science-based" emission targets *Environ. Res. Lett.* **16** 054019

Bjørn A, Lloyd S and Matthews D 2022b Reply to comment on 'from the Paris Agreement to corporate climate commitments: evaluation of seven methods for setting "science-based" emission targets *Environ. Res. Lett.* **17** 038001

Bjørn A, Matthews H D, Hadziosmanovic M, Desmoitier N L R, Addas A and Lloyd S M 2023 Increased transparency is needed for corporate science-based targets to be effective *Nat. Clim. Change* accepted (https://doi.org/10.1038/s41558-023-01727-z)

Bjørn A, Tilsted J P, Addas A and Lloyd S M 2022c Can science-based targets make the private sector paris-aligned? A review of the emerging evidence *Curr. Clim. Change Rep.* **8** 53–69

Byers E *et al* 2022 AR6 scenarios database (https://doi.org/10.5281/zenodo.5886911)

CDP 2020 *CDP 2020 Annual Questionnaire—Public Responses. Investor Version and Supply Chain Version* (CDP)

Chang A, Farsan A, Pineda A C, Cummis C and Weber C 2022 Comment on 'from the Paris Agreement to corporate climate commitments: evaluation of seven methods for setting "science-based" emission targets *Environ. Res. Lett.* **17** 038002

Collins W J, Frame D J, Fuglestvedt J S and Shine K P 2020 Stable climate metrics for emissions of short and long-lived species-combining steps and pulses *Environ. Res. Lett.* **15** 024018

Forster P, Storelvmo T, Armour K, Collins W, Dufresne J-L, Frame D, Lunt D, Mauritsen T, Palmer M and Watanabe M 2021 The Earth's energy budget, climate feedbacks, and climate sensitivity *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V-P Masson-Delmotte *et al* (Cambridge: Cambridge University Press) pp 923–1054

Fuglestvedt J, Rogelj J, Millar R J, Allen M, Boucher O, Cain M, Forster P M, Kriegler E and Shindell D 2018 Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement *Phil. Trans. R. Soc.* A **376** 20160445

WRI 2015 *GHG Protocol Scope 2 Guidance: An Amendment to the GHG Protocol Corporate Standard* (World Resources Institute)

Harmsen M, Tabak C, Höglund-Isaksson L, Humpenöder F, Purohit P and Van Vuuren D 2023 Uncertainty in non-$CO_2$ greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility *Nat. Commun.* **14** 1–14

Hellweg S and Milà I Canals L 2014 Emerging approaches, challenges and opportunities in life cycle assessment *Science* **344** 1109–13

IPCC 2022 *Climate change 2022: mitigation of climate change. Working group III contribution to the sixth assessment report of the intergovernmental panel on climate change*

ISO 2006a Environmental management—Life cycle assessment—principles and framework ISO 14040:2006

ISO 2006b Environmental management—life cycle assessment—requirements and guidelines ISO 14044:2006

Ivanovich C C, Sun T, Gordon D R and Ocko I B 2023 Future warming from global food consumption *Nat. Clim. Change* **13** 297–302

Krabbe O, Linthorst G, Blok K, Crijns-Graus W, van Vuuren D P, Höhne N, Faria P, Aden N and Pineda A C 2015 Aligning corporate greenhouse-gas emissions targets with climate goals *Nat. Clim. Change* **5** 1057–60

Levasseur A *et al* 2016 Enhancing life cycle impact assessment from climate science : review of recent findings and recommendations for application to LCA *Ecol. Indic.* **71** 163–74

Lynch J, Cain M, Pierrehumbert R and Allen M 2020 Demonstrating GWP: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants *Environ. Res. Lett.* **15** 044023

Matthews H D and Wynes S 2022 Current global efforts are insufficient to limit warming to 1.5 °C *Science* **376** 1404–9

Miller R E and Blair P D 2009 *Input-Output Analysis. Foundations and Extensions* (Cambridge: Cambridge University Press)

Ou Y *et al* 2021 Deep mitigation of $CO_2$ and non-$CO_2$ greenhouse gases toward 1.5 °C and 2 °C futures *Nat. Commun.* **12** 1–9

SBTi 2019 *Foundations of Science-based Target Setting. Version 1.0* (Science Based Targets initiative)

SBTi 2021a *SBTi Corporate Net-zero Standard. Version 1.0. October 2021* (Science Based Targets initiative)

SBTi 2021b Understand the methods for science-based climate action (available at: https://sciencebasedtargets.org/news/understand-science-based-targets-methods-climate-action-1)

SBTi 2022 Science-based net-zero scaling urgent corporate climate action worldwide science based targets initiative annual progress report 2021 *Version 1.2—Updated June 2022* (Science Based Targets Initiative)

SBTi 2023a Companies taking action (available at: https://sciencebasedtargets.org/companies-taking-action/)

SBTi 2023b SBTi Corporate Manual *TVT-INF-002. Version 2.1* April 2023 (Science Based Targets initiative) (available at: https://sciencebasedtargets.org/resources/files/SBTi-Corporate-Manual.pdf)

SBTi 2023c Sector guidance (available at: https://sciencebasedtargets.org/sectors)

Stadler K *et al* 2018 EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables *J. Ind. Ecol.* **22** 502–15

Stadler K *et al* 2021 EXIOBASE 3 (3.8.1 (available at: https://zenodo.org/record/4588235))

Stadler K 2021 Pymrio—A Python based multi-regional input-output analysis toolbox *J. Open Res. Softw.* **9** 8

Sun T, Ocko I B, Sturcken E and Hamburg S P 2021 Path to net zero is critical to climate outcome *Sci. Rep.* **11** 22173

WBCSD/WRI/Quantis 2015 Scope 3 evaluator (available at: https://ghgprotocol.org/scope-3-evaluator)

WBCSD/WRI 2004 *The greenhouse gas protocol—a corporate accounting and reporting standard* Revised edn (Washington, DC: World Resources Institute; World Business Council for Sustainable Development)

WBCSD/WRI 2013 *Required greenhouse gases in inventories. Accounting and reporting standard amendment* (Washington, DC: World Resources Institute; World Business Council for Sustainable Development) (Accessed February 2013)

WRI/WBCSD 2011 *Greenhouse gas protocol corporate value chain (scope 3) accounting and reporting standard* (Washington, DC: World Resources Institute; World Business Council for Sustainable Development)