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Quantifying industry impacts on the Sustainable Development Goals

Sergej Lisowski [a,b,*], Jonas Bunsen [a], Markus Berger [a,c], Matthias Finkbeiner [a]

[a] Institute of Environmental Technology, Chair of Sustainable Engineering, Technische Universität Berlin, Office Z1, Strasse des 17. Juni 135, 10623, Berlin, Germany
[b] Department of Environmental Management Product, Volkswagen Aktiengesellschaft, Brieffach 011/1774, 38436, Wolfsburg, Germany
[c] Chair of Multidisciplinary Water Management, University of Twente, P.O. Box 217, 7500, AE Enschede, the Netherlands

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ABSTRACT

The private sector plays a crucial role in achieving the United Nations Sustainable Development Goals (SDGs). However, implementation of the SDGs into corporate strategies is low, and there are as yet no practicable methods to assess the impact of business activities on the SDGs. Therefore, this paper identifies influencing factors of industries on the official SDG indicators, and we develop a top-down method to quantify industry footprints vis-à-vis the SDGs, including the manufacturing and use phase and supply-chain effects. We apply the proposed method to case studies for 19 industries (which is the entire private sector, with the exception of services) and 28 environmental SDG indicators, covering topics such as greenhouse gas emissions, energy consumption, microplastic emissions, and land take.

First, the results show that the private sector has a high impact on the SDG indicators under analysis, with a total footprint of 66% for all industries on average. Second, large industries such as agriculture, construction, and motor vehicles usually have the highest footprints. Third, a few industries cause a major part of the footprint for each indicator, which means efficient improvements are indeed possible. Finally, every industry has some impact on any given SDG indicator, at least in a small way via the supply chain.

By quantifying footprints for the private sector, this paper demonstrates where responsibility for achieving the SDGs lies, it also supports companies in making decisions and implementing the SDGs in their strategy. In addition, this data-based assessment helps to avoid “SDG-picking”.

1. Introduction

In 2015, the United Nations (UN) adopted the Sustainable Development Goals (SDGs), which have since been described as a “guiding light” (Pineda-Escobar, 2019, p. 176) or “the closest thing to a strategy for planet Earth over the next 15 years that humanity has ever generated” (CISL, 2016, p. 10). This expresses both the high importance of the SDGs and their rather general character; to be effectively realized, the SDGs must become more specific. The SDGs, designed at the country level, are intended to be implemented by governments (Pineda-Escobar, 2019). The level of SDG implementation and performance is monitored via national (Miola and Schiltz, 2019; Raszkowski and Bartniczak, 2019; Allen et al., 2020) and international (OECD, 2019; Sachs et al., 2020; Lamichhane et al., 2021) reports, using selected SDG indicators. Following the adoption of the SDGs, these reports highlighted the progress towards achievement. Now, halfway to their target achievement date of 2030, it is soberingly clear that SDG achievement is in grave danger (UN, 2022). The Covid-19 pandemic and the war in Ukraine as well as their knock-on effects (on health services, supply chains, humanitarian situations, nutrition, energy security, inflation, etc.) have further contributed to this disillusionment. Climate change and other environmental issues have taken a back seat.

Another challenge is to achieve the top-down transfer of the global SDG framework to individual stakeholders at the national and lower levels (Bennich et al., 2020; Sullivan et al., 2018) so that these players can take action from the bottom up to actually achieve the SDGs (Gusmão Caiado et al., 2018). Many studies have highlighted the prominent role of the private sector (especially multinational enterprises) in achieving the SDGs (WBCSD & DNV-GL, 2018; Ivanaj et al., 2021; van der Waal et al., 2021). The UN itself has also encouraged companies to contribute to the SDGs by “[applying] their creativity and innovation to solving sustainable development challenges” (UN GA,

* Corresponding author. Institute of Environmental Technology, Chair of Sustainable Engineering, Technische Universität Berlin, Office Z1, Strasse des 17. Juni 135, 10623, Berlin, Germany.

E-mail addresses: sergej.lisowski@volkswagen.de (S. Lisowski), jonas.bunsen@tu-berlin.de (J. Bunsen), m.berger@utwente.nl (M. Berger), matthias.finkbeiner@tu-berlin.de (M. Finkbeiner).

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2015, p. 29). It is not yet clear how companies are supposed to realize this and contribute to the SDGs; this requires further research (Sullivan et al., 2018; Ike et al., 2019). Further research is also needed to identify which of the 169 SDG targets and 247 SDG indicators are influenced by which companies. This impact is generally industry/sector-specific; not all industries and companies influence all SDG topics equally (Schönherr et al., 2017). Moreover, impacts often originate from the supply chain, and are therefore not always directly transparent (GRI, UNGC & WBCSD, 2015). So far, companies have embraced their role primarily by means of communication in sustainability reports (Topple et al., 2017; Pineda-Escobar, 2019, 2019v; van der Waal et al., 2021). Studies conclude that companies' treatment of the SDGs has tended to be "symbolic" (Silva, 2021, p. 1) or "rhetoric" (van der Waal and Thijssens, 2020, p. 10). The terms "SDG washing" or "rainbow washing" have evolved in this context (Bridges and Eubank, 2019, p. 96; Beyne, 2020, p. 4).

There is a need for:

- Deeper corporate engagement with the SDGs. Most companies engage superficially at the overarching SDG goal level, while only a few companies – 11% (Pineda-Escobar, 2019), 13% (Silva, 2021), or 36% (WBCSD & DNV-GL, 2018) – have analyzed the SDGs at the target level.
- Stronger implementation of the SDGs into corporate strategy (Bridges and Eubank, 2019; Grainger-Brown and Malekpour, 2019; Ivanaj et al., 2021). Only a few companies – 13% (Scott and McGill, 2018, p. 7) or 23% (Ethical Corporation, 2019, pp. 10–14) – have derived quantified objectives from the SDGs.
- A way to translate SDGs into company practice (Topple et al., 2017, 2017v; van der Waal and Thijssens, 2020), e.g., by establishing a link between SDGs and companies and operationalizing the contributions a given company has made (Rashed and Shah, 2021; Silva, 2021).
- A practical method/tool to assess companies' impacts on the SDGs (Hacking, 2019; Henzler et al., 2020; Mansell et al., 2020).

To overcome these needs, we develop a method to quantify industry footprints on the SDG indicators and analyze which influencing factors of industries affect the SDGs. This paper is structured as follows: Chapter 2 presents the relevant literature. The method development is described in Chapter 3. Chapter 4 gives the industry footprints on SDG indicators and discusses these. Last, we draw conclusions from the findings of this paper and make suggestions for future research in Chapter 5.

2. Theoretical background

Before companies can implement the SDGs in their strategies and set quantitative objectives, they need to know:

- which SDGs they impact (relevant SDGs),
- how they have an impact (impact link), and
- the extent of their impact (quantification).

The SDG Compass (GRI, UNGC & WBCSD, 2015) and the sector roadmaps provide key guidance for implementing the SDGs in companies. The SDG sector roadmaps indicate the level of impact a given sector has on SDG targets in a qualitative materiality matrix (high, medium, low) and subsequently derive priority SDG targets. However, this approach does not operate at the indicator level, and impacts are only indicated qualitatively. This makes quantification challenging. Moreover, roadmaps are currently only available for a few sectors, e.g., chemicals (WBCSD, 2018), forestry (WBCSD, 2019), and electric utilities (WBCSD, 2021). To select relevant SDG indicators for an industry, Lisowski et al. (2020) developed a criteria-based approach and selected 31 relevant (in terms of influenceable) environmental SDG indicators for the automobile industry. Twenty-eight of these indicators address negative impacts (avoiding harm), while three cover positive impacts (doing good). However, impacts are not quantified as yet, and the results only apply to this one industry. Another way to identify and prioritize key issues related to the SDGs is materiality analysis (Whitehead, 2017; Ranängen et al., 2018). Materiality analysis is particularly suitable for strategic analyses at higher levels. However, it does not create an impact link between companies and the SDGs, and assessment tools are still needed to quantify impacts.

Impact assessment (IA) has been advocated as a key approach for implementing the SDGs in companies, given that IA allows companies to evaluate and manage their activities based on the desired outcome (González Del Campo et al., 2020; Kørnøv et al., 2020; Morrison-Saunders et al., 2020). As yet, the application of IA to the SDGs is largely a theoretical concept, which has only been used in individual subjects of the SDGs (Hacking, 2019). One of these subjects is infrastructure projects, with the resulting recognition that there is still a lack of "practical tools" (Mansell et al., 2020, p. 6413). In another study, Henzler et al. (2020) performed IA based on the SDGs and Life Cycle Assessment (LCA). They found that such assessments were labor-intensive and limited by data availability; that SDG-based approaches on LCA are still in their infancy; and that existing methods focus on specific SDGs and industries (Henzler et al., 2020). Additional methods to quantify the impacts of economic activities include environmentally-extended input-output analyses (EEIO) (Kitzes, 2013) and environmentally-extended multiregional input-output analyses (Bjelle et al., 2020). These analyses calculate footprints based on economic input-output databases and, by extension, the environmental impacts. Common footprints include, e.g., carbon and material footprints (Tukker et al., 2014; Valentina et al., 2019). One benefit of this type of analysis is the inclusion of the supply chain (Bjelle et al., 2020). EEIO has also been mentioned in the SDG Compass (GRI, UNGC & WBCSD, 2015) as a method to identify the impacts of companies along their value chain. So far, however, no EEIO analyses have been published concerning the private sector's impact on SDGs. This may be due to the limitation of the method to existing environmental extensions, since footprints can only be calculated for those. To overcome the limitations of quantitative tools (which are labor-intensive expert tools for specific subjects that are limited by data availability and cannot encompass normative societal value), Eriksson et al. (2019) developed a qualitative self-assessment tool for corporate impacts on the SDGs. However, qualitative approaches create difficulties in quantification and prioritization. Moreover, self-assessments depend on the expertise of the user, and bear the risk of focusing on known problems, while blind spots go unnoticed.

For quantitative assessments, additional data (referred to as "SDG-external data") must often be used due to the poor data availability for many SDG indicators (Allen et al., 2019; Lafortune et al., 2020; UN, 2022). The impacts of particular industries on the SDGs can then be quantified using data with contributors at the sectoral level; for example, Industry A causes 20% of total emissions, while Industry B causes 10%. However, using such data for different topics can be problematic, as it has to be derived from a variety of sources. Usually, the contributing industries are then aggregated heterogeneously, which leads to poor comparability between different topics. Often, small industries are not listed individually. IAs for small industries are then impossible. In addition, such data only reflect direct impacts, e.g., emissions from the manufacturing or use phase. These data do not include the supply chain, so upstream impacts due to consumption remain hidden.

This highlights the following research gaps: first, companies need support in identifying their impacts on the SDGs. Second, there is a lack of practicable methods to quantify the impacts of industries on the SDGs. These research gaps can be filled by answering the following research questions:

- What factors of business activity influence the SDGs?
- How can industry impacts on the SDGs be quantified?
- What are the impacts of different industries on the SDGs?

3. Method development and data collection

To answer these research questions, this paper elaborates a method that is based on:

- Impact quantification for a set of indicators, which enables quantification despite the labor-intensive character of data collection for such indicators;
- SDG-external data, which makes it possible to overcome the scarcity of SDG data;
- Input-output tables, which make it possible to include the supply chain.

We quantify the industry footprints on SDG indicators using a three-step method, which is shown in Fig. 1. First, Section 3.1 indicates the influencing factors (inputs or outputs of industries) that affect the SDG indicators under analysis, as well as source data (i.e., data on emissions or resource consumption) on the cause of these factors at the sectoral level. Influencing factors are those that cause changes in SDG indicators, while industries affect the source data via resource use and emissions. Then, to include the supply chain, we calculate consumption proportions between industries by using monetary input-output tables in Section 3.2. Finally, we quantify industry footprints by combining the actual emissions and resource consumption levels with consumption proportions between industries in Section 3.3. In addition, an example of the method is given in Section 3.4.

3.1. Identification of influencing factors and source data for the SDG indicators

Given that impact quantification is labor-intensive and data is often scare, it is necessary to focus on a selected set of the 247 official UN SDG indicators (UN, 2021). This subset, comprising the relevant environmental indicators for the automobile industry, consists of 28 “avoiding harm” indicators (24 are unique) that address negative impacts on the environment (Lisowski et al., 2020). The reason for using this indicator subset is because it contains fundamental (rather than industry-specific) environmental topics such as energy consumption, greenhouse gas (GHG) emissions, and waste generation. Besides, the relevance of this indicator subset for the automobile industry has already been proven; therefore, the subset’s relevance for other industries is analyzed here.

First, we derive the influencing factors by examining the computation methods of each indicator. The computation method defines the official calculation procedure of SDG indicators and is described in metadata of these (UN, 2021). We define “influencing factors” as environmental factors (emissions or resources) that are responsible for a change in the indicator on the one hand, and that are inputs or outputs of industries on the other. As inputs and outputs, these influencing factors are also compiled in an LCA as an inventory (Finkbeiner, 2014). Depending on the content of the indicators, four cases are distinguished to derive influencing factors:

C1: When an indicator measures resource consumption, emissions, or efficiencies as well as the impacts due to these, then the corresponding emissions or resources are used as the influencing factor.
C2: When an indicator measures environmental conditions, then factors that impact these conditions are used as the influencing factor.
C2a: Special case: when an indicator measures land area or consumption, then land take is used as the influencing factor.
C3: When an indicator measures waste, wastewater generation, or ratios thereof, then the absolute quantity of these values is used as the influencing factor.
C4: When an indicator measures something that is impacted by climate change, GHG emissions are used as the influencing factor.

Examples for each case are presented in Table 1. If indicators cover multiple topics, they can subsequently have multiple influencing factors. The influencing factors of each indicator are provided in Table S4.

Next, we retrieved data at the sectoral level for the European Union (EU or EU28) for the influencing factors. This data is referred to as “source data” in this paper, since it contains distributions concerning the originators of emissions and resource consumption patterns. Source data covers the manufacturing and use phases of the life cycle, e.g., raw

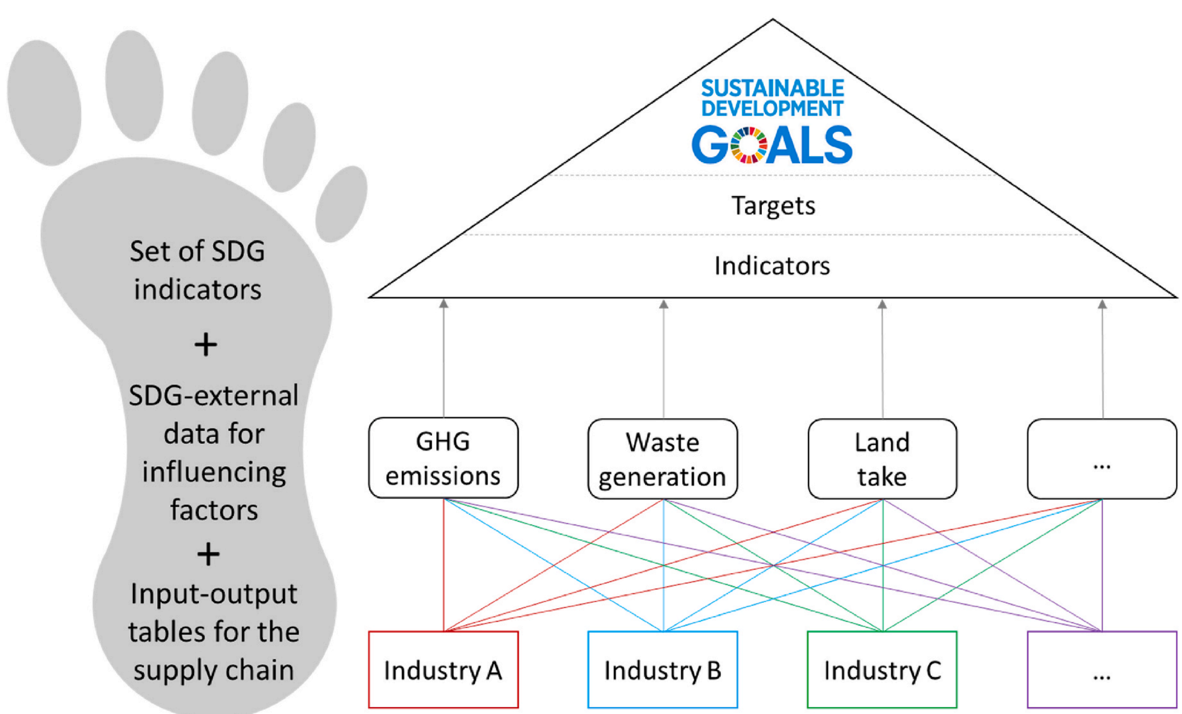

Fig. 1. Method to quantify industry footprints on SDG indicators.

Table 1
Examples for each case for deriving influencing factors.

Case	SDG indicator	Computation method (UN, 2021)	Environmental influencing factors
C1	7.3.1 Energy intensity measured in terms of primary energy and GDP	Energy used divided by gross domestic product (GDP)	Total final energy consumption
C2	14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations	Average marine acidity (pH) "caused primarily by the uptake of carbon dioxide from the atmosphere" (UN, 2021, *Metadata of Indicator 14.3.1, p. 1*)	CO_2 emissions
C2a	6.6.1 Change in the extent of water-related ecosystems over time	Wetland area and change in the extent of wetlands	Land take on wetlands
C3	12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment	Hazardous waste generated per capita; and proportion of hazardous waste treated	Hazardous waste generation
C4	1.5.1, 11.5.1 & 13.1.1 Number of deaths, missing persons, and directly affected persons attributed to disasters per 100,000 population	Number of deaths, missing persons, and directly affected people attributed to disasters	GHG emissions Disasters are differentiated, including extreme weather, extreme temperature, drought, and flood. GHG emissions cause climate change and, among other things, disasters such as extreme weather and temperatures (EC, 2021).

material consumption for manufacturing or emissions during the use of a product. Due to the scarcity of SDG data at the sector level from the UN, we supplemented it with additional SDG-external data. This data was collected from databases from the European Environment Agency (EEA, 2021), Eurostat (EU, 2021a), and the International Energy Agency (IEA, 2021a). If no perfectly matching source data could be found for an influencing factor, we used nearby data from these databases, if available, e.g., data on freshwater abstraction as a proxy for water used. If no source data could be found in these databases, studies were used with data for the EU or EU Member States. If multiple data sets were available, we used the most recently available data. Hence, most of the data used is for the year 2018 and for the EU28 (pre-Brexit). The next step was to prepare the data for further analysis.

- Data gaps in the recent distribution were filled with data from the past. If more than two gaps could not be filled in for a country, this country was excluded.
- Aggregated data was broken down according to the distribution in the EU or in neighboring countries. For example, for the energy consumption of all transportation, we used the energy consumption of each mode of transportation. We broke land take changes related to the expansion of transportation networks into road and rail according to the length ratio of these modes in the EU.
- For data given in ranges, the mean was used.
- Negative data values for emissions and land take was excluded.

Finally, originators that accounted for less than 1% of the total data were truncated from the source data. If the truncated data accounted for more than 10% of the total, we reduced the truncation criterion to 0.5%, so that at least 90% of the total source data was included in the analysis. Eutrophication was calculated using the eutrophication potential (PO_4-equivalent) from nitrogen (0.42) and phosphorus (3.06) emissions (EnArgus, *no year*). The environmental source data used is presented in Table S5 in the Supplementary Materials, with specifications for the region, the year, and the fraction analyzed after truncation (EEA, 2005; Sundt et al., 2014; Lassen et al., 2015; Magnusson et al., 2016; Boucher and Friot, 2017; Bertling et al., 2018; EEA, 2019; EEA, 2020a; EEA, 2020b; EU, 2021b; EU, 2021c; EU, 2021d; EU, 2021e; IEA, 2021b).

3.2. Calculation of consumption proportions between industries

When quantifying footprints, it is crucial to consider consumption between industries to incorporate the indirect impacts from the supply chain (in addition to the direct impacts from industries themselves). This paper accomplishes this by using monetary input-output tables. Of the databases with input-output tables (i.e., WIOD, Eora, and Exiobase (Tukker and Dietzenbacher, 2013)), this paper used Exiobase due to its advantages with respect to timeliness, its coverage of EU Member States, and its resolution, as well as its homogeneity with respect to products and the classification of industries. Exiobase version 3.8.1 (Stadler et al., 2021) contains estimated data until 2022, of which data for 2018 was used, due to its fit to the environmental source data. The database is divided into 49 countries or regions, with data available for 28 EU Member States, their 16 largest trading partners, and five rest-of-the-world regions. Furthermore, the product-by-product database distinguishes among 200 products that are linked to various industries and services, and seven demand types for each country/region (Stadler et al., 2021). The economic interactions of all countries are represented in the "technology matrix" (T-matrix), the final demand matrix (Y-matrix), and the total output (x-vector). The T-matrix contains 9,800 (200 times 49) rows and columns.

First, we compiled an input-output table for the EU with 200 rows and columns. We applied a production-based approach, because inputs and outputs generated in the EU count for both domestic consumption and exports (Harris et al., 2016). The T-matrix is compiled by combining the domestic data of each EU Member State as well as all exports of these Member States to $T_{EU,prod}$. Totaling the rows of the Y-matrix for each EU Member State forms the y-vector to $y_{EU,prod}$. The total output $x_{EU,prod}$ is calculated for the EU as the sum of the rows of $T_{EU,prod}$ and $y_{EU,prod}$. Then, economic proportions are calculated by dividing the elements of $T_{EU,prod}$ and $y_{EU,prod}$ by the elements of $x_{EU,prod}$ (row by row). These proportions show the relative amount of any one product that flows to other products (p_p) or the final demand (p_{fd}).

3.3. Quantification of industry footprints

The term "footprint" often refers to impacts on CO_2 or water equivalents; in this context, it refers to the impact on SDG indicators. A footprint is defined as an industry's share of the total impact on a given SDG indicator – i.e., the share of emissions or resources used over the entire life cycle. We calculated footprints for 19 industries: all 17 manufacturing industries in Exiobase, plus agriculture and mining. This selection represents the entire private sector, with the exception of services. The industries analyzed were derived from the product-by-product Exiobase segmentation (Stadler et al., 2021). Table 2 shows the industries analyzed and their products.

The footprints were quantified based on emissions and resource consumption from the source data. First, the originators in the source data of all influencing factors were allocated to the corresponding products in Exiobase's system, according to their denomination. For example, if "iron and steel" was an emitter in the source data, these emissions were allocated to "basic iron and steel" products. If "basic metals" was an emitter, then these emissions were allocated to all "basic metal" products. Due to this fine distinction, it was possible to allocate

Table 2
The industries analyzed and their Exiobase products.

Industry – short name	Industry – long name	Exiobase product number
Agriculture	Agriculture, forestry & fishing	1–19
Mining	Mining & quarrying	20–42
Food	Food, beverages & tobacco	43–54
Textiles	Textiles, wearing apparel & leather	55–57
Wood	Wood products	58–59
Paper	Pulp, paper products & printed matter	60–63
Energy	Coke, fossil & nuclear fuel	64–85
Chemicals	Chemicals	86–95
Plastics	Rubber and plastic products	96
Minerals	Non-metallic mineral products	97–103
Metals	Basic metals	104–116
Metal products	Fabricated metal products	117
Machinery	Machinery and equipment	118
Electr(on)ics	Electrical, electronical, medical & optical products	119–122
Motor vehicles	Motor vehicles, trailers and semi-trailers	123
Other transport	Other transport equipment	124
Furniture	Furniture; other manufactured goods	125
Electricity	Electricity, gas & steam	128–148
Construction	Construction work	150

almost 70 different contributors to Exiobase products for all the indicators. Originators without an industrial context, such as households, residential, commercial, institutional, and leisure activities, were not allocated; instead, they were excluded from further calculations (proportion = 0). Then, for the footprint of one industry, we determined the proportions of all the allocated originators to the given industry according to Section 3.2. Direct impacts, e.g., on the footprint of "agriculture" if "agriculture" is an originator, as well as indirect (supply chain) impacts, e.g., on the footprint of "agriculture" if "chemicals" was an originator in the source data, were attributed based on the proportions p_p. In addition, the final demand was attributed according to the proportion p_{fd} for direct impacts. Finally, we multiplied the individual proportions of one industry by the contributions of every originator in the source data and totaled them up. To quantify the footprints, these product totals of industries were divided by the total amount in the source data. Footprints of 19 industries on 28 SDG indicators were quantified using this method.

3.4. An example of the method

The method from Sections 3.1-3.3, with the data used and the outcome of each step, is demonstrated for one sample indicator in Fig. 2. This method was then used to quantify footprints for each indicator.

Explanation of the method:

- Identification of influencing factors
  - For marine acidity, the influencing factor is CO_2 emissions; increases in CO_2 emissions causes a rise in marine acidity.
- Identification of source data on the sectoral level
  - The actual source data for CO_2 emissions used in the study contains more than 40 contributors.
  - For demonstration purposes, the graphic depicts a simple example with three industries.
- Compilation of the EU input-output table
  - The actual input-output table used in the study contains 200 rows and 200 columns.
  - For demonstration purposes, the graphic depicts a simple input-output table for three industries.
- Calculation of consumption proportions between industries
  - This shows the proportions that flow from one industry to other industries by row as well as final demand (in the columns).
- Calculation of industry footprints for Industry A:
  - Industry A's own emissions are attributed by $\frac{1}{4}$.
  - Emissions generated by Industries B and C (as suppliers of Industry A) are attributed by $\frac{1}{5}$ and $\frac{1}{6}$, respectively.
  - Emissions from Industry A due to final (consumer) demand are attributed to $\frac{1}{8}$.

The example demonstrates the redistribution of impacts between industries as a result of incorporating a given industry's supply chain. Since Industry A supplies more than 60% of its production to other industries, its footprint is smaller than its share according to the source data – in other words, its impact is smaller than the source data would seem to indicate. In contrast, the footprints of Industry B and C are accordingly higher than their shares in the source data. In fact, Industry C has a footprint greater than zero, despite the fact that it does not generate any emissions according to the source data.

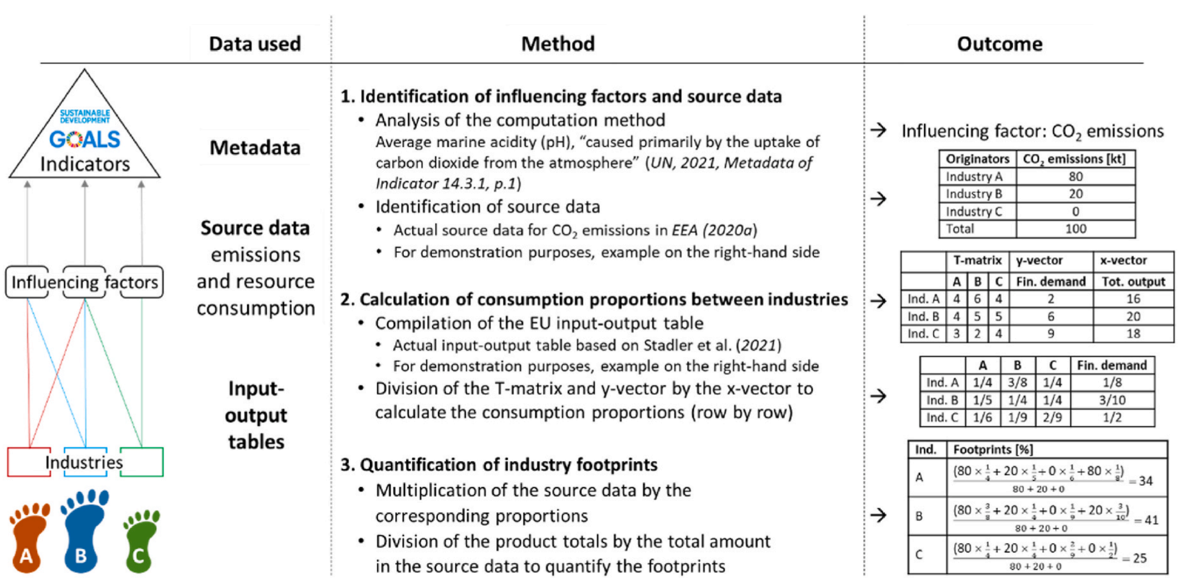

Fig. 2. Example of the method for Indicator 14.3.1 – Average marine acidity (pH).

4. Results and discussion

Applying this method resulted in industry footprints that are presented and discussed in Section 4.1. Subsequently, Section 4.2 and Section 4.3 discuss the method as well as the data used.

4.1. Industry footprints on the SDG indicators

The footprints of the 19 industries on the 28 analyzed SDG indicators as well as the influencing factors per indicator are shown in Table 3. Indicators with identical influencing factors are grouped. Indicators with multiple influencing factors are listed multiple times for completeness.

For each SDG indicator, the second column lists the influencing factors of industries. First, it shows that some influencing factors affect several indicators, e.g., GHG emissions. GHG emissions impact the three identical indicators 1.5.1, 11.5.1 & 13.1.1 (affected persons attributed to disasters), because GHG emissions cause climate change and, among other things, disasters such as extreme weather and temperatures (EC, 2021). GHG emissions also impact indicator 13.2.2 (total GHG emissions) and indicator 15.5.1 (Red List Index), since climate change is a threat to organisms. Second, the table demonstrates that some indicators e.g., such as 14.1.1, 15.2.1, 15.3.1, and 15.5.1, have several influencing factors. Indicator 15.5.1 encompasses various processes that affect organisms, "including habitat destruction and degradation, over-exploitation, invasive alien species, human disturbance, pollution and climate change" (UN, 2021, *Metadata of Indicator 15.5.1, p. 4*). Indicators 14.1.1, 15.2.1, and 15.3.1 contain different subtopics by UN definition (UN, 2021). The rationale for the selection of the given influencing factors for all indicators is shown in Table S4. Indicator 14.1.1 b has only one influencing factor (microplastic emissions), but due to the data basis, seven footprints were calculated for different countries and regions. The impact of each row on the SDGs is therefore different. The following columns in Table 3 present the footprints per industry on the SDG indicators, analyzed as a heatmap. For each influencing factor, the highest value has the most saturated red and the lowest footprint has the most saturated green. It results in large footprints for agriculture in eutrophication as well as nitrogen and phosphorus emissions; for motor vehicles in microplastic, CO_2, and GHG emissions; and for construction in raw material consumption, land take and waste generation. Many smaller footprints can be seen for the wood, plastics, and minerals industries. The last column indicates the total footprint of all industries on the SDG indicators, as a row sum. This shows which indicators are strongly influenced by the entire industry. With a total footprint of almost 81%, industry plays the major role in impacting wood consumption and land on wetlands. The remaining 19% results from other economic participants, such as services, the public sector, and households. In contrast, wastewater generation (33%) and PM2.5 emissions (37%) are influenced much less by industry. This is because both these influencing factors are driven by activities from private households and residential, commercial & institutional activities – more than 50% of the emissions in the source data. On average, the industries analyzed in this study represent 66% of the overall footprint, and thus have a major impact on the SDG indicators analyzed. Table S6 provides an overview of the industries with the largest footprints for each influencing factor and the largest contributions to the environmental source data, each as hotspots.

While it is unsurprising that agriculture would have a large footprint with respect to eutrophication, motor vehicles for GHG emissions, and construction for waste generation, it is interesting to observe that a few industries dominate the footprints. Indeed, just a few industries are responsible for a major part of the total footprint for any given influencing factor. For example, motor vehicles, electricity, and agriculture produce almost 48% of total GHG emissions, while the remaining 16 industries together are responsible for 28%. This finding can be harnessed to enhance environmental protection: Adaptations in a few high-

Table 3
Industry footprints on the SDG indicators [%]; largest footprints per row in red and smallest in green.

Indicators	Influencing factors	Agri-culture	Mining	Food	Textiles	Wood	Paper	Energy	Chem-icals	Plastics	Minerals	Metals	Metal products	Mach-inery	Electr. goods	Motor vehicles	Other transp.	Furni-ture	Elect-ricity	Const-ruction	Total
1.5.1, 11.5.1, 13.1.1, 13.2.2 & 15.5.1	GHG emissions	9.32	0.25	4.43	0.47	0.19	0.74	3.72	3.10	0.64	2.24	2.37	1.43	1.38	1.45	21.71	0.41	0.42	16.49	4.66	75.43
3.9.1 & 11.6.2	Particulate matter (PM)2.5 emissions	5.56	0.08	4.26	1.15	0.14	0.61	0.78	0.87	0.39	0.23	0.42	0.57	2.06	2.95	12.32	0.78	0.89	2.16	0.71	36.93
6.3.1	Wastewater generation	0.29	2.52	3.70	0.20	0.11	5.65	4.43	4.31	0.70	0.31	2.44	0.83	0.66	0.82	0.59	0.17	0.24	3.72	0.83	32.51
6.3.2	Nitrogen load per ha	50.43	0.10	9.29	0.36	0.04	0.16	0.22	0.47	0.10	0.07	0.12	0.16	0.53	0.78	0.57	0.17	0.22	0.34	0.28	64.42
	Phosphorus load per ha	41.50	0.10	8.25	0.51	0.06	0.25	0.34	0.56	0.16	0.11	0.19	0.26	0.86	1.27	0.94	0.28	0.35	0.53	0.43	56.97
6.4.1 & 6.4.2	Freshwater abstraction	22.56	1.23	6.46	0.95	0.24	0.79	0.89	1.23	0.51	0.50	0.97	0.73	1.72	2.40	1.77	0.54	0.71	26.46	2.93	73.58
6.6.1	Land take on wetlands	0.38	15.89	9.33	3.24	0.37	1.58	4.37	2.61	1.03	1.26	1.43	1.46	5.38	8.09	8.20	2.08	2.51	1.64	9.69	80.53
7.3.1	Total final energy consumption	2.26	0.30	4.54	1.47	0.18	0.70	4.84	1.80	0.55	0.26	0.45	0.67	2.75	3.82	26.86	1.03	1.15	0.43	1.09	55.13
8.4.1, 8.4.2, 12.2.1 & 12.2.2	Raw material consumption	6.49	1.50	13.44	1.30	0.37	0.27	3.26	1.28	0.26	0.76	0.32	0.69	2.55	2.13	3.31	0.71	1.64	3.29	30.84	74.42
9.4.1	CO_2 emissions, fuel combustion	2.48	0.25	2.28	0.53	0.21	0.38	3.65	2.36	0.58	1.51	2.45	1.03	1.49	1.56	28.60	0.46	0.46	21.83	4.32	76.44
11.3.1, 15.3.1 & 15.5.1	Total land take	0.20	10.71	4.78	1.66	0.19	0.79	2.58	1.38	0.53	0.77	0.79	0.75	2.82	4.14	11.78	1.09	1.29	1.03	20.07	67.36
11.6.2	PM10 emissions	15.10	0.09	6.69	1.45	0.16	0.72	0.96	1.10	0.47	0.27	0.48	0.66	2.52	3.65	12.47	0.96	1.10	1.96	0.81	51.62
12.4.2	Hazardous waste gen.	0.32	9.63	0.65	0.25	0.15	0.42	4.98	4.11	1.78	0.71	2.13	2.74	1.58	1.81	1.59	0.46	0.37	7.65	20.93	62.24
12.5.1	Waste gen.	0.18	17.54	2.02	0.17	0.10	0.23	2.62	1.74	0.64	0.94	1.22	1.12	0.47	0.49	0.41	0.12	0.22	3.93	38.86	73.02
14.1.1 a & 15.5.1	Eutrophication – nitrogen & phosphorus load	48.32	0.10	9.04	0.40	0.04	0.18	0.25	0.49	0.12	0.08	0.14	0.19	0.61	0.90	0.66	0.20	0.25	0.38	0.32	62.66
14.1.1 b	Microplastic emissions: Global, to oceans	0.09	0.05	0.08	33.77	0.02	0.12	0.06	0.12	0.15	0.05	0.10	0.13	0.51	0.27	33.12	0.14	0.13	0.09	0.21	69.20
	NO	0.13	0.12	0.36	1.28	0.06	0.14	0.18	0.27	2.57	0.11	0.21	0.31	1.04	0.68	55.10	0.25	0.21	0.32	4.10	67.43
	NO, to the sea	0.20	0.21	0.64	1.41	0.08	0.21	0.26	0.47	4.75	0.16	0.34	0.42	1.30	0.97	57.88	0.31	0.30	0.40	4.84	75.16
	DK	0.16	0.09	0.62	6.12	0.07	0.19	0.06	0.42	6.13	0.13	0.14	0.40	1.27	0.95	58.31	0.33	0.34	0.17	1.73	77.64
	DK, to aquatic environment	0.10	0.09	0.18	1.80	0.03	0.07	0.11	0.15	0.88	0.07	0.17	0.22	0.96	0.51	61.83	0.24	0.14	0.17	0.42	68.14
	SE	0.10	0.07	0.18	5.50	0.03	0.07	0.08	0.15	1.09	0.07	0.14	0.23	1.01	0.53	66.20	0.26	0.15	0.14	0.46	76.47
	DE	1.56	0.07	1.45	0.43	0.08	0.28	0.29	0.46	3.33	0.14	0.18	0.44	1.54	1.46	54.81	0.46	0.46	0.31	4.58	72.33
14.3.1	CO_2 emissions	2.30	0.27	2.17	0.52	0.22	0.85	3.34	3.39	0.73	2.70	2.83	1.69	1.64	1.71	26.10	0.49	0.50	19.81	5.52	76.76
15.1.1 & 15.2.1	Land take on forests	0.18	19.84	3.32	1.14	0.17	0.58	3.55	1.25	0.39	1.13	0.93	0.59	1.96	2.79	15.03	0.74	0.93	1.79	17.33	73.63
15.2.1 & 15.3.1	Wood consumption	29.66	0.15	5.81	1.06	9.55	3.93	0.09	0.62	0.35	0.19	0.21	0.25	1.08	0.39	2.03	0.15	7.56	1.39	16.34	80.81
15.4.2	Wood and crops consumption	24.89	0.10	40.69	1.71	1.81	0.84	0.07	0.45	0.12	0.09	0.12	0.10	0.15	0.22	0.87	0.07	1.71	0.55	4.35	78.89

impact industries can substantially improve the overall environmental condition. Nevertheless, there is a large number of small footprints, but all calculated footprints are still greater than 0. So, even if industries do not make any contributions according to the original source data, small footprints can be attributed to them due to economic links with other industries via the supply chain. This means that every industry can contribute to the improvement of environmental conditions, at least in a small way via the supply chain. It is striking that motor vehicles generally have large footprints on all the indicators analyzed. At first glance, this could be due to the indicators, which had been specifically selected for the automobile industry. However, on further examination, it is apparent that the influencing factors were chosen generically, without any focus on a particular industry. Therefore, the selection of influencing factors does not explain the large footprints of this single industry. Possible reasons for the frequent large footprints of motor vehicles include the size and diversity of the automobile industry. It is one of the largest industries in the EU, it uses many different raw materials and causes high emissions. If the industry as a whole is a contributor in the source data, the economic size of the automobile industry will result in high average proportions attributed to it. In addition, how a contributor is allocated to a given industry may have an influence; for example, roads are allocated to motor vehicles even though they are also used otherwise. Also, the classification of automobiles as consumer goods fosters frequent large footprints. If we attribute supply-chain effects to industrial sectors, the footprints of consumer-goods industries will be larger, because supply-chain impacts (often in the form of intermediate goods) are attributed to the downstream industry. Furthermore, the large footprints (55–66%) of motor vehicles on microplastic emissions in EU Member States are striking. This can be explained by microplastic emissions from tire and road wear being assigned exclusively to motor vehicles, rather than to plastics as well. This could also be due to uncertainties in the determination of microplastic emissions. Since this field is relatively young and it is difficult to precisely determine microplastic emissions to the environment, data must be estimated in some cases, and gaps still exist (Magnusson et al., 2016; Bertling et al., 2018). At the same time, it must be noted that the footprint of motor vehicles is considerably larger than the next largest contributor in all the studies analyzed. Even if the microplastic emissions from tire and road wear were overestimated, the impact of motor vehicles on microplastic emissions would still be high.

The footprints illustrate the relevance of the indicators selected for other industries as well, in addition to the motor vehicle industry. In particular, big industries (agriculture, food, and construction) exhibit large footprints for a variety of indicators. However, smaller industries also have large footprints in specific areas, e.g., electricity for freshwater abstraction, and mining for land take. Overall, the indicators used in this study were suitable for analyzing all industries. They provided an overview of impacts from various industrial sectors; all industries had footprints greater than 1%, and half of the industries analyzed had large footprints for many indicators. At the same time, it is evident that no industry had large footprints for all indicators, and that smaller industries, by total output, were less likely to have large footprints. For further industry-specific analyses, it therefore would make sense to adjust the indicator selection according to these footprints.

4.2. Discussion of the method developed

The method developed here allows researchers to overcome typical problems with respect to impact assessment concerning the SDGs (labor intensity, data scarcity, and the lack of supply-chain inclusion). This is possible because the method quantifies impacts according to a set of indicators, using SDG-external data and input-output tables. This in turn identifies industry-level impacts on the SDGs, and is also the first method to quantify them. It provides a consistent, and therefore comparable, impact quantification for all industries, on a wide variety of environmental topics. The footprints have broad comparability and demonstrate the impact industry has on the SDGs, since they are calculated based on official UN SDG indicators. Furthermore, this method offers advantages over qualitative assessments. On the one hand, it provides fluent gradations (0–100%) in the level of impact. On the other hand, it is less dependent on the user due to the attribution of actual environmental data. Since the environmental source data is attributed to a given industry based on its economic consumption vis-à-vis other industries (input-output tables), impacts resulting from the supply chain can be included. That means footprints can be quantified even for industries that do not show up as contributors in the environmental source data, allowing researchers to identify "blind spots". One example of this would be the footprint of motor vehicles with respect to the generation of waste and wastewater, since most of the impact depicted in these footprints originates from the supply chain. Moreover, using an indicator set that represents a criteria-based selection from all SDG indicators ensures that not only topics with high popularity or data availability are addressed. Examples from this paper include calculations of footprints for issues such as microplastic emissions and land take, which receive less attention in the SDG "sector roadmaps". Moreover, although the calculations of the footprints were initially based on relevant indicators for the automobile industry, the footprints demonstrate that these indicators are relevant for most other industries, too. This is due to the fundamental character of the environmental issues encompassed in those indicators. Rather than being confined to a specific industry, these issues depict inputs or outputs for almost all industries, e.g., energy consumption, GHG emissions, and waste generation. Also, due to the interlinked nature of the economy and by including the supply chain, the method allows the calculation of small footprints even when an industry does not show contributions in the environmental source data. Finally, quantifying footprints via inputs and outputs provides a sound foundation for determining impacts. Inputs and outputs represent the inventory, which can be extended to impacts via impact factors.

This method also entails limitations. The first is the assumed proportionality between environmental and economic data, even though the actual proportions of environmental burdens may differ from the economic ones, e.g., for particularly environmentally intensive (or friendly) products. Another limitation is the attribution of impacts via a production-based approach (domestic consumption plus exports), which leads to imprecision, e.g., since emissions in the use phase are caused by products that are in fact used (consumption-based). Footprints for consumer-goods industries (e.g., food and motor vehicles) are systematically larger than industries that typically produce intermediate goods (e.g., plastics and metals). This is because an industry's final demand is attributed to the industry itself and because impacts of the supply chain are incorporated. Turning to the study's geographic scope, the footprints are only valid for the EU28 region. From a sustainability perspective, the indicator set in this study is limited to "only" indicators that have a direct impact on the environment. It would be helpful to consider social and economic indicators and the interactions between them as well. Then, indicators that have indirect impacts as well as the institutional partners (from industry, politics, education, etc.) need to be identified and evaluated. Furthermore, this work focuses on indicators that have a negative impact (reduce harm). For the transformation of the economy, necessary to fully achieve the SDGs, the positive side (doing good) must be considered, too. This requires adjustments in the method, e.g., by measuring the potential for sustainable agriculture and renewable energies. Turning to computational questions, another limitation may arise from the selection of influencing factors. We determined the influencing factors based on their fit to the indicators' computation methods and data availability at the sectoral level. As a result, the influencing factors have a good fit for most indicators. However, in a few cases, the influencing factors are close in terms of content, but differ slightly due to data availability. For example, wastewater generation was used as the influencing factor for indicator 6.3.1 (proportion of wastewater treated), and wood consumption was used as the influencing factor for indicators

15.2.1 (biomass stock) and 15.3.1 (carbon stock). Furthermore, we cannot be certain that all influences were taken into account. Some indicators include several topics and can be influenced by more than the influencing factors selected, e.g., 1.5.1 affected persons attributed to disasters, 14.1.1 (b) plastic debris density, or 15.5.1 biodiversity. For indicator 1.5.1, additional influencing factors could include flood regulation or river straightening for water-related disasters. However, these influencing factors do not correspond to the criterion defined in the method's "inputs or outputs of industries". For indicator 14.1.1 (b), additional influencing factors could include plastic emissions coarser than microplastic. We used microplastic because it can be ingested and is therefore potentially harmful to organisms. However, even if data for all influencing factors on each indicator were available, it would be very complex to identify the single best fitting influencing factor (e.g., what is the best fitting single influencing factor on disasters or biodiversity?) or to calculate a single-score footprint for each indicator. Finally, it must be taken into account that the various industries cannot control (and thus reduce) their footprints completely independently, since the entire life cycle is taken into account. A part of any footprint is "bought" via the supply chain, and would have to be reduced via collaborative activities. Another part of each footprint originates during the use phase. To reduce this, not only efficient products, but also customer support and action for efficient use (e.g., proper operation and maintenance) or partnerships with third parties would be necessary (e.g., operation of an electrical device with renewable energy).

4.3. Discussion of the data used

To overcome the scarcity of SDG data, we used SDG-external data to quantify industry footprints for the 28 indicators more comprehensively. The data mainly refers to the EU28 and the year 2018, allowing a comparable assessment. The slight lag is common for environmental data. Data for nitrogen and phosphorous load refer to 2001–2005, and data for microplastic emissions do not refer to a specific year. For a few influencing factors (nitrogen and phosphorous load, wastewater generation, and freshwater abstraction), data was only available for a subgroup of the EU (12–21 countries) or individual European countries and the world as a whole (microplastic emissions). Moreover, classification of the environmental source data can influence footprints. If the classifications in the environmental data are not accurate, e.g., industries were combined or split without being marked accordingly, proportions will be imprecise as well. Furthermore, the degree of resolution in the source data is heterogeneous. For example, GHG emissions data has high resolution for the individual industries, while in the energy consumption and freshwater abstraction data, the total industry is given as the polluter. The high aggregation of industrial sectors leads to increasing uncertainty since average values are then used, e.g., as a proportion of the total industry instead of the proportion of a particular industry. The data preparation process to handle data (in)availability, such as by filling gaps with past data or by excluding countries due to a lack of data (for wastewater generation and freshwater abstraction) or breaking down aggregated data (for energy consumption and land take), may also have influenced the footprints.

5. Conclusions and outlook

The private sector has a prominent role in achieving the SDGs. However, the implementation of the SDGs into corporate strategies is still low. This is because companies need support in identifying their impacts related to the SDGs, and indeed there is a lack of practicable methods to quantify these impacts related to the SDGs. To overcome these hurdles, this paper has identified influencing factors of industries on SDG indicators and illustrated a method to quantify industry footprints concerning the SDGs, including the manufacturing and use phase and supply-chain effects. The study then quantified the footprints of 19 industries (which is the entire private sector, with the exception of services) for 28 environmental SDG indicators for the EU. These indicators deal with frequently addressed issues, such as greenhouse gas emissions, energy consumption, and raw material consumption, as well as with issues that are often poorly addressed, such as microplastic emissions and land take.

First, the results show that the private sector indeed has a high impact on the SDG indicators under analysis, with industry representing 66% of the total footprint on average. Industry had a particularly large influence (81% of the total footprint) on indicators for wood consumption and land take on wetlands. In contrast, the indicators for wastewater generation (33%) and PM2.5 emissions (37%) were much less influenced by industry. The remaining proportions were influenced by other economic actors, such as the service industry, the public sector, and households. Second, the impacts on the SDG indicators vary per industry. Large industries most frequently have the highest footprints, such as agriculture with 48% of the footprint related to eutrophication, and motor vehicles with 66% of the footprint related to microplastic emissions. However, smaller industries also have large footprints in specific areas, e.g., electricity's role in freshwater abstraction, or mining's role in land take. Third, a few industries cause a major part of the footprint for any given indicator. This opens up the opportunity for efficient environmental protection, since improvements in a few high-impact industries could substantially improve the overall environmental condition. Lastly, the footprints reveal that every industry impacts environmental conditions, at least in a small way via its supply chain.

To our knowledge, this paper is the first to quantify industry footprints related to the SDGs. In doing so, it overcomes typical problems in impact assessment on the SDGs (labor intensity, data scarcity, and the lack of supply-chain inclusion). By using the official UN SDG indicators and applying the method consistently for all industries, it was possible to ensure high comparability of the different footprints. As a result, this paper highlights various industries' responsibility for achieving the SDGs, and it supports companies in making decision and implementing the SDGs in their strategy. In addition, this data-based assessment helps to avoid "SDG-picking".

In light of the findings in this paper, future research can investigate these topics, among others:

- The quantification of footprints for further regions by applying this method;
- The calculation of impacts by multiplying the footprints (inventory of inputs and outputs) by impact factors;
- The appropriate prioritization of topics for industries, by using footprints and other criteria;
- The quantification of footprints at the company level, by further breaking down industry footprints or by using a company's own environmental data.

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CRediT authorship contribution statement

Sergej Lisowski: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft. **Jonas Bunsen:** Data curation, Formal analysis, Software, Writing – review & editing. **Markus Berger:** Methodology, Supervision, Writing – review & editing.

Matthias Finkbeiner: Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All used data is given in the references

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136661.

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