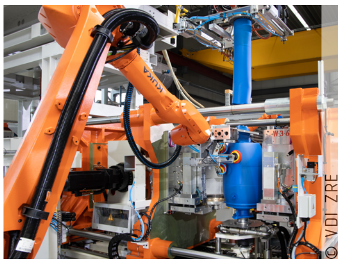
VDI Zentrum Ressourceneffizienz

On behalf of:

Federal Ministry
for the Environment, Nature Conservation,
Nuclear Safety and Consumer Protection

Development of a Standardised Procedure for Determining the Greenhouse Gas Emissions Saved by Material Efficiency Measures (ESTEM)

Final Report



Baden-Württemberg
MINISTERIUM FÜR UMWELT, KLIMA UND ENERGIEWIRTSCHAFT

Hamburg
Behörde für Umwelt, Klima, Energie und Agrarwirtschaft

Rheinland-Pfalz
MINISTERIUM FÜR KLIMASCHUTZ, UMWELT, ENERGIE UND MOBILITÄT

Bayerisches Staatsministerium für Umwelt und Verbraucherschutz

HESSEN
Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Wohnen

January 2024

VDI ZRE Study: Development of a Standardised Procedure for Determining the Greenhouse Gas Emissions Saved by Material Efficiency Measures (ESTEM)

Authors:

Prof Dr Mario Schmidt (project management), Dr Christian Haubach, Dr Philipp R. Schäfer
Steinbeis Transfer Centre for Marketing, Logistics and Corporate Management at Pforzheim University of Applied Sciences

Prof Dr Liselotte Schebek, Dr Vanessa Zeller, Laura Goellner, Dipl.-Wirt.-Ing., Tabea Hagedorn, M.Sc.
Technical University of Darmstadt, IWAR Institute, Department of Material Flow Management and Resource Economics

Sofia Haas, M.Sc., Dr Anika Neitz-Regett
Research Centre for Energy Economics (FfE) e. V. Munich

Dr Moritz Nill, Hubertus Drinkuth, Yi Ding
Systain Consulting GmbH Hamburg

Contact:
Jakob Rothmeier, VDI Zentrum Ressourceneffizienz

We would like to thank Prof Dr Christoph Helbig, Chair of Ecological Resource Technology at the University of Bayreuth, for reviewing this study.

The study was commissioned by the VDI Zentrum Ressourceneffizienz (Competence Center for Resource Efficiency) on behalf of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, in cooperation with the Baden-Württemberg Ministry for the Environment, Climate Protection and the Energy Sector, the Bavarian State Ministry for the Environment and Consumer Protection, the Hamburg Ministry for the Environment, Climate Protection, Energy and Agriculture, the Hessian Ministry for Economic Affairs, Energy, Transport and Regional Development and the Rhineland-Palatinate Ministry for Climate Protection, Environment, Energy and Mobility, Energy and Mobility Rhineland-Palatinate.

The study was funded by the participating state ministries.

Editorial:

VDI Zentrum Ressourceneffizienz (Competence Center for Resource Efficiency)
Bülowstraße 78 | 10783 Berlin | Tel. +49 30-2759506-505
zre-info@vdi.de | www.resource-germany.com

VDI ZRE Publications:
Studies

Development of a Standardised Procedure for Determining the Greenhouse Gas Emissions Saved by Material Efficiency Measures (ESTEM)

Final Report

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

APOS	Allocation at the point of substitution
BAFA	Bundesamt für Wirtschaft und Ausfuhrkontrolle (Federal Office for Economic Affairs and Export Control)
B2B	Business-to-Business
B2C	Business-to-Consumer
BSI	British Standards Institution
CF	Carbon Footprint
CFF	Circular Footprint Formula
CFP	Carbon Footprint of Products
CHP	Combined Heat and Power
CL	Cooling Lubricants
CO_2	Carbon dioxide
CO_{2e}/CO_{2eq}	Carbon dioxide equivalents
EF	Emission Factor
EoL	End-of-Life
EPD	Environmental Product Declaration
ERP	Enterprise Resource Planning
EU	European Union
HFC	Hydrofluorocarbons
GHG	Greenhouse Gas

GWP	Global Warming Potential
PFHC	Partially Fluorinated Hydrocarbons
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KrWG	Kreislaufwirtschaftsgesetz (German Circular Economy Act)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OECD	Organisation for Economic Co-operation and Development
OEF	Organisation Environmental Footprint
OEFSR	Organisation Environmental Footprint Sector Rules
PAS	Publicly Available Specification
PCF	Product Carbon Footprint
PE	Polyethylene
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PP	Polypropylene
PVC	Polyvinyl Chloride

REZ	Ressourceneffizienzzentrum Bayern (Resource Efficiency Centre Bavaria)
RFID	Radio-Frequency Identification
SBTI	Science Based Targets Initiative
SF_6	Sulphur hexafluoride
SME	Small and medium-sized enterprises
UBA	Umweltbundesamt (Federal Environment Agency)
UNEP	United Nations Environment Programme
VDI	Verein Deutscher Ingenieure e. V. (Association of German Engineers)
VDI ZRE	VDI Zentrum Ressourceneffizienz GmbH (VDI Competence Center for Resource Efficiency)
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

Excel® is a trademark of Microsoft®.

ABSTRACT

The aim of the project was to uniformly estimate the climate impact of measures from the field of operational material efficiency by developing a calculation procedure and the ESTEM tool. It is aimed at applicants and consulting firms for the funding of projects and the carbon accounting of measures in the context of consulting projects on material efficiency in manufacturing companies. Furthermore, the tool can be used within companies in order to make comparative assessments of measures. A standardised calculation procedure is used to quantify the total GHG emissions caused by the use of materials and energy as well as by the direct release of greenhouse gases (GHG). This allows projects and measures aimed at material efficiency in a business environment to be compared in terms of their climate impact and their potential for mitigating the climate impact.

The ESTEM calculation procedure is easy to apply and requires little methodological knowledge, meaning that it can be used in particular by small and medium-sized enterprises, for example, when applying for state support measures. For this purpose, an Excel®-based tool as well as an instruction guide is provided, with which the emission reduction of material efficiency measures can be calculated.

The procedure mainly asks for data on the change in energy and material use resulting from the implemented material efficiency measure and combines this data with standardised emission factors. Users are asked to answer ten key questions and to provide information on the scope of the planned material efficiency measure.

This final report contains the results from the field analysis, workshop discussions with expert audiences, the actual development of the method and the case studies. The final report is supplemented by the Excel®-based ESTEM tool and the accompanying instruction guide.

FOREWORD

In the spring of 2020, at the beginning of the corona pandemic, the VDI Zentrum Ressourceneffizienz GmbH (VDI ZRE) invited tenders for a study, financed by the five federal states of Baden-Wuerttemberg, Bavaria, Hamburg, Hesse and Rhineland-Palatinate. VDI ZRE acted as a project management agency on behalf of the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). The aim of the invitation to tender was to develop a standardised procedure for determining the greenhouse gas emissions saved by material efficiency measures in industrial production. The defined procedure is intended to create a high degree of comparability of the greenhouse gas emissions saved by each material efficiency measure. This should make it possible to determine the global contribution to emission reductions from material efficiency measures that are implemented in German industrial production. The main target group of the study comprises small and medium-sized enterprises (SME), particularly those who carry out resource efficiency measures and wish to calculate the greenhouse gas emissions saved. The expectation of the ministries involved is that this kind of standardised procedure will help in particular with the evaluation of applications for material efficiency measures within the framework of funding programmes.

At the end of August 2020, the contract was awarded to a consortium under the leadership of the Steinbeis Transfer Center Marketing, Logistics and Company Planning at Pforzheim University. The consortium included the Department of Material Flow Management and Resource Economy at the IWAR Institute of the Technical University, the Forschungsstelle für Energiewirtschaft e. V. in Munich and the Systain Consulting GmbH in Hamburg.

Over the next two years, in numerous discussions and expert meetings held within the consortium, together with the contracting authorities and within the professional community, a procedure was developed with which it is possible to achieve the desired goal simply, transparently, with a clear direction, with little effort and in a way that is appropriate for the target group. Thus, the ESTEM calculation procedure was not only described abstractly as a guide to the method, as was originally planned, but implemented in a practical Excel® -based tool that is made available upon conclusion of the project. This was only possible because emission factors were also updated during the project and made available free of charge via the so-called BAFA list. There is still considerable work to do in the future with regards to data, so that the goal - allowing small and medium-sized enterprises to initiate, apply for and implement material efficiency measures and thereby obtain knowledge about their saved greenhouse gas emissions - can be fulfilled comprehensively. Only in this way can the topic of resource efficiency in production become an integral part of and make a significant contribution to the national climate protection strategy.

I would like to take this opportunity to thank all the colleagues involved for their commitment and contributions, the ministries involved from the federal states for the trust they have placed in us and for the stimulating discussions, VDI ZRE for the professional organisation in the project setting and the interested parties involved for their suggestions and critique.

Prof. Dr. Mario Schmidt

Pforzheim, 31st July 2022

1 THE RELEVANCE OF MATERIALS FOR CLIMATE PROTECTION

1.1 Introduction

The use of materials in companies plays a significant role in their carbon footprint. In most industries, it is the greenhouse gas (GHG) emissions associated with the extraction and processing of materials – both of raw materials as well as semi-finished products and other intermediate products – that account for the largest share of the climate footprint. These are so-called upstream scope 3 emissions (Figure 1). Many companies now also see their responsibility for climate protection in this scope 3 area. This is largely driven by the requirements of stakeholders, in particular via the demands of customers vis-à-vis supplying companies, e.g. the automotive industry.

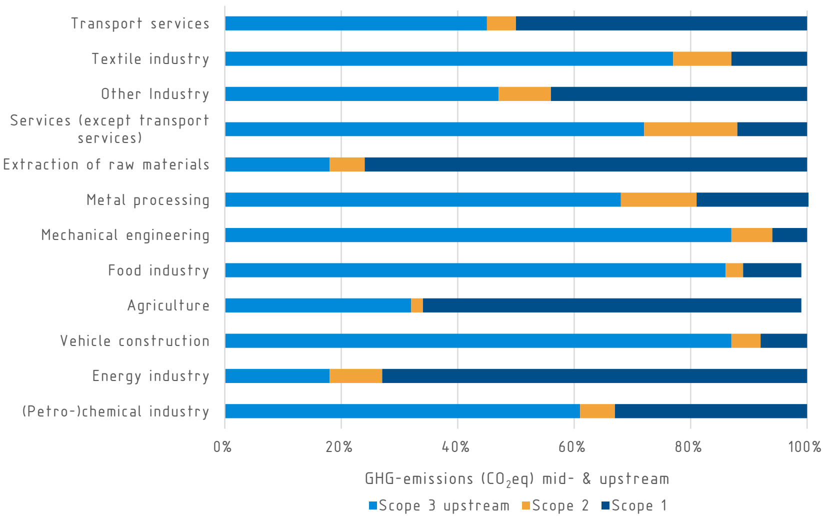


Figure 1: Ratio of the scope 1, 2 and 3 emissions (without downstream) of CO_2 equivalents in various economic sectors in Germany[1] [2]

[1] Based on Schmidt et al. (2021), p. 1694.

[2] Deviation from 100% due to rounding.

Currently, most companies want to prepare a comprehensive assessment of their carbon footprint in order to examine how they can achieve "climate neutrality". To this end, numerous areas of action are examined. There is currently a great deal of uncertainty among companies in particular with regard to the “ecological backpack” of their intermediate products. Reliable public data is hard to come by. There is also a lack of expertise with regards to methods.

The following questions come up again and again:

- What materials are used and what GHG emissions are linked to them?
- Can the burden be eased by substituting materials?
- Where do the materials come from and would, for example, sourcing from Europe be more climate-friendly than sourcing from Asia?
- What are the benefits of using more secondary materials?

The question of the impact of climate protection measures in the corporate sector is also gaining importance due to various initiatives. The Science Based Targets Initiative demands an absolute reduction of scope 3 emissions of at least 2.5% per year[3]. Representing these changes correctly in the context of corporate balance sheets is a major challenge given the accuracy of the emission inventories. Methods that focus on individual measures and map their change in terms of emissions will make more sense here. The goal must be to actually (and not just on paper) save as large an amount of GHG emissions as possible.

Nevertheless, comprehensive inventories are of great importance in order to analyse influencing factors and long-term trends. Even at national level, the material-related emissions are not negligible. Yet they are not included in conventional territorial inventories. To illustrate the relevance of these emissions, which are caused by economic activity in Germany but can occur globally, calculations were carried out using input-output models, which are presented here as impetus for the topic. The calculations were

[3] **Cf. Science Based Targets Initiative (2021).**

performed by the project partner Systain Consulting. These models are not looked at further in the present report for the evaluation of measures, but are an important addition to the assessment of the relevance of material efficiency.

The traditional GHG inventories of individual countries only take into account the direct, territorial GHG emissions that are released in that country. However, the German economy is deeply integrated in the global economic structure via imports and exports of raw materials as well as intermediate and final products. For a comprehensive understanding of the causes and for better strategies to combat climate change, it is therefore necessary to obtain a life cycle view ("from cradle to grave") of the goods and services consumed in Germany. An analysis of the GHG emissions of the German economy that includes the supply chain is possible with the help of the extended input-output analysis. This is particularly helpful for an improved understanding of the significance of material use in the German economy with regard to the carbon footprint (CF). This methodology is briefly presented below. With the help of such a model, the following central questions can then be answered for the German economy:

- How high are the GHG emissions from final demand compared to direct emissions?
- How much of the emissions are imported?
- What emissions are caused by exports?
- What share of emissions is attributable to the use of materials?
- Which metals are of particular importance here?

The results were obtained using the input-output analysis approach, which is presented below.

1.2 GHG accounting with extended input-output models

The scope of German territorial GHG emissions refers to the GHG emissions released in Germany within one year. A GHG balance that also covers the supply chain, on the other hand, includes the cumulative GHG emissions ("GHG backpack") of all goods and services used in Germany in a year. This final use of goods includes household and government consumption, business investment and exports (see Figure 2).

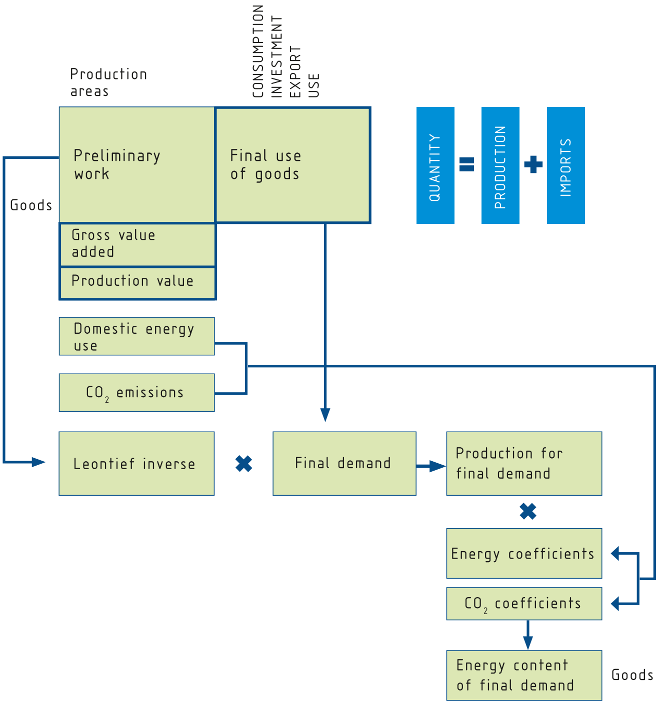


Figure 2: Schematic diagram on determining GHG emissions from final demand[4]

Extended input output models make it possible to provide, for the goods used – measured in euros – emission factors in kg CO_{2e} per euro which cover the entire supply chain and thus the cumulative life cycle emissions.

[4] Based on the German Federal Statistical Office (2020).

In the first step, the so-called Leontief inverse is used to determine the net value added that is caused by demand in Germany, but also in the supplier countries, on the basis of statistical information on the economy (input-output calculations, import statistics). In the second step, the GHG emissions caused are quantified using sector-specific and, if necessary, country-specific emission values[5].

The multi-regional input-output model of the OECD[6] was used for the analysis, together with GHG emissions extensions of the EU research project Exiobase[7] – in each case for the year 2016. The advantage of a multi-regional input-output model is that the upstream chain of goods is broken down into individual countries across the entire value creation structure and thus specific differences of individual manufacturing countries, e.g. in the electricity mix, are explicitly taken into account. Another advantage of the multi-regional model, at least in the structure used here, is gained from the uniform model structure with 150 sectors and 49 countries and the resulting possibility to reveal the structure of GHG emissions for all goods in detail.

In contrast, the German Federal Statistical Office uses a different model to determine CO_2 emissions, but does not include other greenhouse gases. A comparison of our results when only CO_2 is included showed a large degree of consistency with the results of the hybrid input-output model from Destatis[8].

---

5 Cf. Eurostat (2008).

6 Cf. OECD (2015).

7 Cf. Stadler et al. (2018), p. 502.

8 Cf. German Federal Statistical Office (2020), p. 18.

1.3 The GHG import and export inventory of Germany

The results of the input-output analysis are broken down in Figure 3 according to both imported and domestic emissions and the emission content of final demand goods and that of exports. It can be seen that GHG emissions (Mt CO_{2e}) associated with imports and exports play a central role.

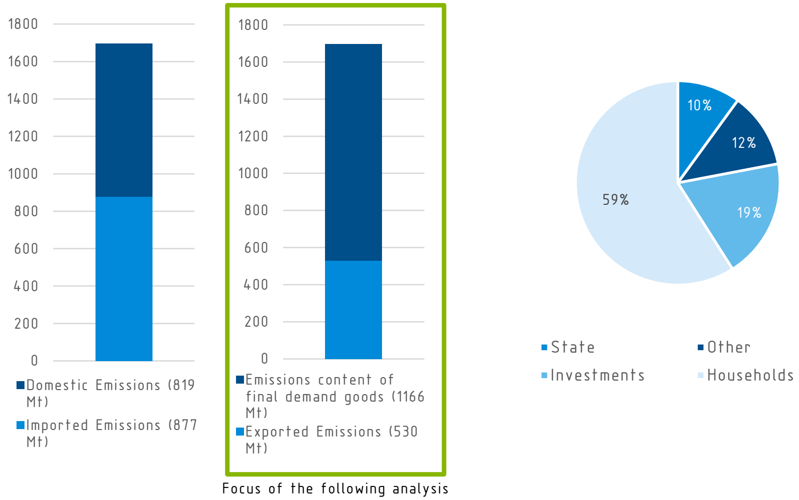


Figure 3: GHG inventory (Mt CO_{2e}) for German final consumption in 2016, emission content of goods excluding their use and thus excluding direct emissions from private households and private individual transport[9] [10]

The emissions associated with imports ("imported emissions") are one third greater than the emissions from exports ("exported emissions"). A closer look at only those emissions generated by final demand shows that emissions from domestic final demand result predominantly from household consumption, followed by investment.

Figure 4 meanwhile illustrates which goods and services dominate the GHG footprint of final consumption. For the sake of clarity, the individual

[9] Own calculations based on Systain's estell model, henceforth cited only as "estell (2021)".

[10] Deviation from 100% due to rounding.

economic sectors listed in the OECD model have been assigned to superordinate groups of goods.

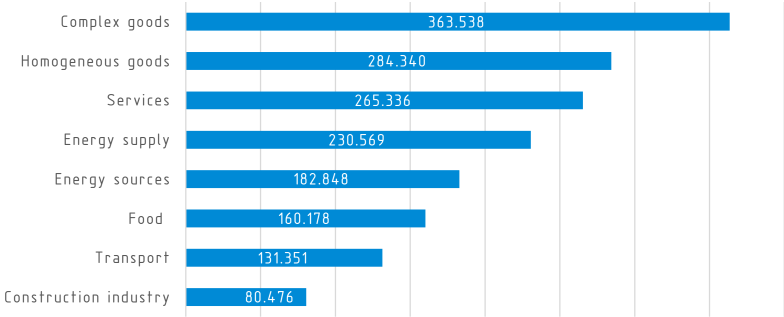


Figure 4: GHG emissions from final demand by groups of goods in kt CO_{2e} [11]

In the case of complex goods, it is automotive production and mechanical engineering in particular that contribute to the GHG footprint; in the case of homogeneous goods, it is mainly chemicals and metal production. Services are also a significant contributor to GHG emissions. In this case the total contribution is higher than that of energy supply. Particularly relevant in the context of services are health care, buildings and hotels, and restaurants.

In the following, we will focus in particular on the first two groups of goods and take a closer look at chemicals, metal production, automotive manufacturing and mechanical engineering.

1.4 Breakdown of GHG emissions in selected economic sectors

The GHG emissions of the selected economic sectors were evaluated from three perspectives. Firstly, it was investigated which inputs cause the GHG emissions. This view helps to understand whether the carbon footprint is determined by scope 1 ("own site emissions"), scope 2 ("utilities") or the supply chain of certain intermediate products.

[11] Cf. estell (2021).

This gives an insight into whether improvements can be made via energy efficiency measures or via measures that increase resource efficiency. This represents the second view, which sorts the above-mentioned emissions generators into three groups:

- Emissions that can be addressed by energy efficiency measures – "addressable by energy efficiency". These are scope 1 and scope 2 emissions.
- Emissions that can be addressed by resource efficiency measures – "addressable by resource efficiency". These include emissions that occur during the production of materials (plastics, glass, metals, textiles, etc.).
- All other sources of emissions

The third view then examines whether GHG emissions occur domestically - i.e. in Germany ("domestic emissions") - or abroad ("foreign emissions").

This analysis helps to better assess the role of international supply chains in the respective economic sectors.

1.4.1 Metal production

In metal production, the carbon footprint is largely dominated by scope 1 emissions (27%) and the sourcing of metals (22%). Significant contributions also come from the provision of energy sources (16%) and electricity (14%) as well as metal raw materials (7%). A picture thus emerges that the GHG emissions can be addressed in particular through energy and resource efficiency. About one third of the life cycle emissions are released abroad.

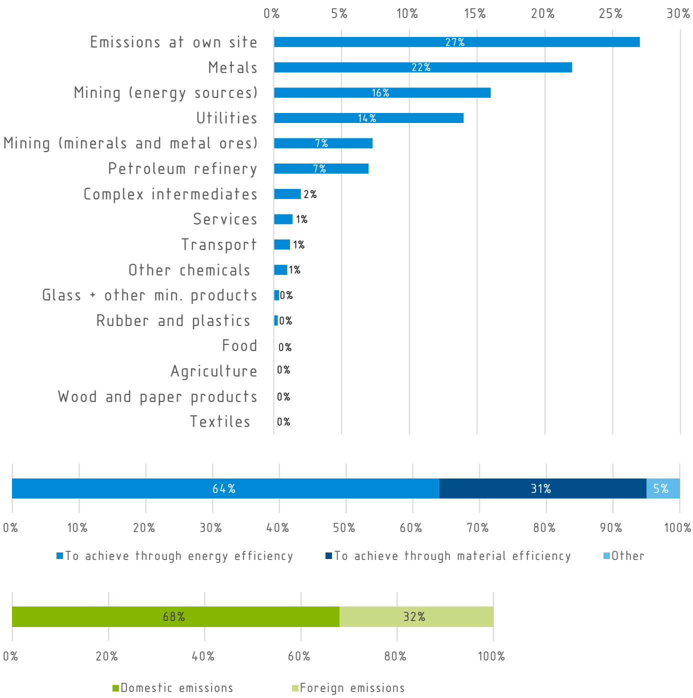


Figure 5: Analysis of emissions occurring in metal production[12 13]

[12] Cf. estell (2021).

[13] Presentation based on rounded values.

1.4.2 Automotive industry

The breakdown of cumulative GHG emissions from the automotive industry, on the other hand, looks very different. This is dominated by the sourcing of complex intermediate products (44%) - i.e. subcomponents such as gearboxes, wheels, cables, etc. Another important source of emissions are metal inputs (19%) - in particular steel and aluminium inputs for the car body. This means that only a small proportion of GHG emissions can be reduced through material or energy efficiency measures. Other concepts are necessary for complex intermediate products. With regard to the international breakdown of GHG emissions, however, the picture is comparable to the analysis results for metal production: Here, too, about one third of the GHG emissions are released abroad.

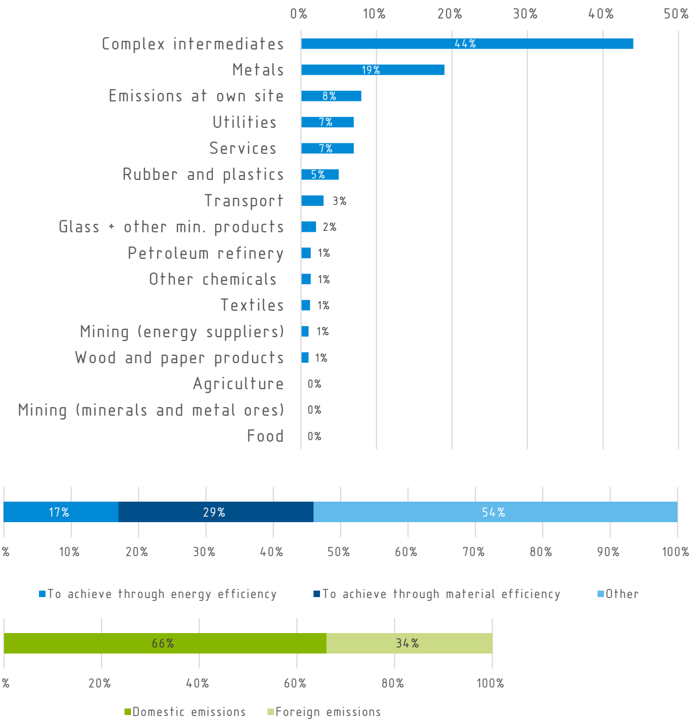


Figure 6: Analysis of emissions occurring in automotive production[14] [15]

[14] Cf. estell (2021).

1.4.3 Chemical industry

The largest emission drivers in the chemical industry are chemical inputs (26%) and GHG emissions at companies own sites (26%), followed by emissions from energy inputs for electricity (11%), energy sources (9%) and feedstock (5%). Thus, the chemical industry has good opportunities to reduce GHG emissions through energy or material efficiency measures. About one third of the life cycle emissions are released abroad.

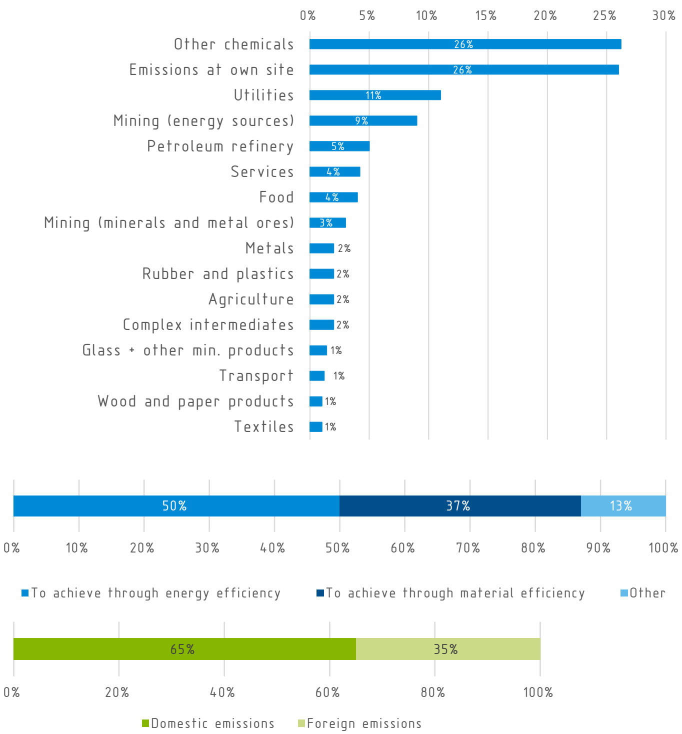


Figure 7: Analysis of emissions occurring in the chemical industry[16] [17]

[15] Presentation based on rounded values.

[16] Cf. estell (2021).

[17] Presentation based on rounded values.

1.4.4 Mechanical engineering

In mechanical engineering, the main contribution to GHG emissions results from the sourcing of metal raw materials (38%) and complex intermediate products (27 %). Meanwhile, electricity consumption accounts for about one tenth (11%) of GHG emissions. Therefore, material efficiency measures in particular are the first resort for reducing GHG emissions. In mechanical engineering, too, about one third of the GHG emissions occur abroad.

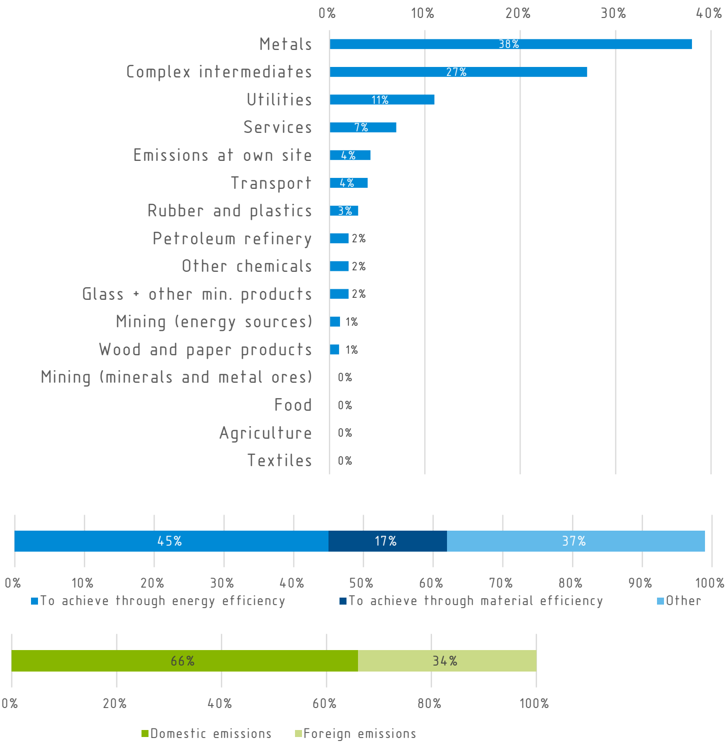


Figure 8: Analysis of emissions occurring in mechanical engineering[18] [19]

[18] Cf. estell (2021).

[19] Presentation based on rounded values.

1.5 GHG emissions from German metal input

As has been shown, the input of metals plays a decisive role in the GHG footprint of German final consumption. The following examines which metals are predominantly involved. For this purpose, the model for the German GHG footprint was evaluated to determine which metal inputs with their cumulative GHG footprint contribute to the footprint as a whole and to what extent. Here, the calculation is limited to the granularity of the model for the breakdown of the individual metals: A distinction can be made between various specific metals (steel, aluminium, copper, cast metal) and other metals (lead, zinc, tin).

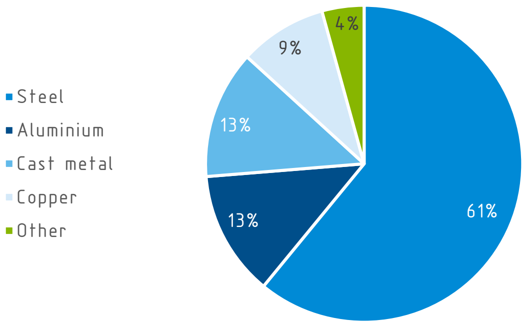


Figure 9: Detailed analysis of metal production in Germany[20]

It can be seen from Figure 9 that GHG emissions due to metal inputs are predominantly due to steel (61%), metal castings (13%), aluminium (13%) and copper (9%). Other metals only play a minor role (4%). This analysis also highlights how it makes sense to focus GHG reduction measures on the bulk metals of steel, aluminium and copper.

[20] Cf. estell (2021)

1.6 Summary and conclusions

The analysis using a multi-regional input-output model for Germany allows interesting and important insights into the GHG emission breakdown of German final consumption. It can be seen that imports and exports of emissions play a major role in understanding GHG emissions. The imported emissions are similar in size to the territorial emissions (excluding direct emissions from households) and about one third higher than the exported GHG emissions. It is therefore important that the discussion on climate protection does not continue to ignore GHG emissions related to imports and exports, because life cycle emissions are also of central importance for climate protection on a global scale.

Another important insight that emerges from the life cycle perspective is the great significance of intermediate products that companies source for their activities. Sourced goods - both homogeneous and complex - are by far the most important source of emissions for German final consumption - much more relevant than the electricity industry or transport. This in turn underlines the importance of the task of the present research project: to advance climate protection through improved resource efficiency. In addition to goods, services also contribute to the GHG footprint to a considerable extent. The economic sectors of health and social services, but also the hospitality industry, must not be excluded from climate protection measures.

The central sectors of the German economy - automotive, mechanical engineering, chemicals and metal production - show a common characteristic with regard to their respective GHG emission breakdown: They generate about one third of their GHG emissions abroad. In other respects, the causes of GHG emissions vary greatly, and so do the measures relevant to combating climate change: While the greatest potential in metal production lies in energy efficiency, the greatest reduction leverage in mechanical engineering and the chemical industry can be achieved through material efficiency. In the automotive industry, on the other hand, where the footprint primarily arises from complex intermediate products and the utilisation phase of the products, more far-reaching measures are necessary.

2 ASSESSMENT METHODS AND TOOLS, DATABASES AND OTHER PROJECTS

2.1 Assessment methods

2.1.1 Overview

The “assessment methods” comprise technically accurate life cycle inventories or inventory analyses that describe the emissions and, at mid-point level, the environmental impacts. In the case of climate protection, these are the emissions of greenhouse gases in kg of carbon dioxide equivalents (CO_{2e}).

There are a number of standards, norms, guidelines and recommendations for the life cycle assessment or greenhouse gas assessment of products, processes and companies/organisations (see Figure 10). The standards of the International Organization for Standardization (ISO) are of central importance here. They form the basis for most of the other standards. The following figure shows the existing documents as well as their object of investigation and the relationships between the methodology documents. The methodology documents and the most important technical terms are briefly described in the following chapters.

In addition to these concrete method proposals, there is also the standard ISO 14080:2018. It provides a framework and principles for the development, identification or extension of methodologies with regard to climate-relevant measures. These include relevance, consistency, comparability, compatibility, completeness, conservatism, accuracy, practicality, flexibility, credibility and transparency. These guidelines and principles are very general in nature and provide a rough framework for methodology development. For example, ISO stipulates that the applicability of a newly developed methodology must be appropriately tested before it is used.

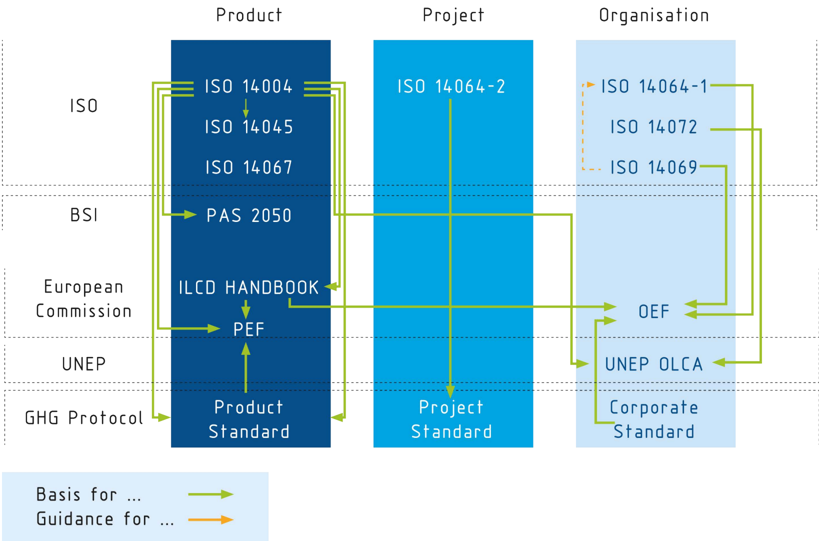


Figure 10: Interrelationships of norms and standards according to areas of application (own figure)

The ISO also prescribes which aspects have to be considered and/or included in the definition of the target and assessment framework. This concerns, among other things, the baseline definition, for which ISO 14064-2:2020 provides a relatively detailed specification. According to this definition, the baseline indicates the state that would have arisen without the measure. Existing and planned changes (strategic or political) also have to be taken into account. Similarly, it must be possible to adapt the baseline to unforeseen changes in the economic system so that such changes are not attributed to the measure.[21]

Within the framework of this project, the development of the methodology to quantify the GHG savings of material efficiency measures will take into account the recommendations of ISO 14080.

[21] Cf. ISO 14064-2:2020, p. 20.

2.1.2 Definition of key terms

Carbon footprint / greenhouse gas footprint
The sum of greenhouse gases that are directly and indirectly emitted or removed by a defined object (product, activity, person, company, etc.).

Corporate carbon footprint / organisational carbon footprint
The sum of greenhouse gases that are directly and indirectly emitted or removed by an organisation over a defined period.

Direct greenhouse gas emissions
Greenhouse gas emissions originating from greenhouse gas sources that are directly owned or controlled by a company.

Indirect greenhouse gas emissions
Greenhouse gas emissions resulting from an organisation's operations and activities that are from greenhouse gas sources not owned or controlled by the organisation.

Organisational Life Cycle Assessment (O-LCA) / corporate life cycle assessment
Compilation and assessment of input and output flows and potential environmental impacts of activities that are wholly or partly attributable to the organisation. A life cycle perspective is adopted.

Product carbon footprint
Sum of greenhouse gases that are directly and indirectly emitted by a product over its entire life cycle.

Life cycle assessment
Compilation and assessment of input and output flows and potential environmental impacts of a product system over its life cycle.

Environmental footprint / ecological footprint

The environmental footprint can be seen as the result of a life cycle assessment. In contrast to the carbon footprint, the environmental footprint is based on several indicators that represent the potential environmental impacts.

System boundaries

Boundaries that define, based on defined criteria, which processes are part of the system under review (e.g. product system).

Allocation

Allocation of the input or output flows of a process or a product system to the product or product system under review and to one or more other products or product systems.

Baseline / reference scenario

The hypothetical scenario that best reflects the conditions that would most likely occur in the absence of the carbon offset project. It should describe as best as possible the situation without the carbon offset project. It serves as a reference to quantify the impact of the carbon offset project.

Life cycle view / perspective

The complete consideration of the consecutive and interrelated stages of the life cycle from the extraction or production of raw materials to their use and final disposal.

Functional unit

Quantified benefit of a product or service system for use as a unit of comparison of life cycle assessments.

Greenhouse gas projects / climate protection project

Activity or activities that deviate from the reference scenario and lead to a reduction in greenhouse gas emissions or an increased removal of greenhouse gases.

Cradle-to-gate

The cradle-to-gate approach (from the cradle to the factory gate) is part of the entire life cycle. It encompasses the extraction of the required raw materials up to the provision of the finished product. In this case, the use and end-of-life phases are not part of the scope of investigation.

Cradle-to-grave

The cradle-to-grave approach (from the cradle to the grave) covers the entire life cycle.

2.1.3 Brief description of selected assessment methods

Product level

European Commission – Product Environmental Footprint (2013) (PEF)

The European Commission's guidance on calculating the environmental footprint of products has been developed with the primary aim of providing a uniform European methodology to quantify the impact of products on the environment. The methodology follows the principle of "comparability over flexibility", i.e. the comparability of the studies has top priority.

The European Commission defines the Product Environmental Footprint (PEF) as "[...] a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. PEF information is obtained for the overarching purpose of seeking to reduce the environmental impacts of goods and services taking into account supply chain activities (from extraction of raw materials, through production and use, to final waste management). This PEF guide provides a method for modelling the environmental impacts of the flows of material/energy and the emissions and waste streams associated with a product throughout its life cycle."[22]

[22] European Commission (2013), p. 9.

In addition to the concrete instructions for calculating the environmental footprint of products (PEF method), the guide includes instructions for developing calculation methods for specific product categories. These product categories are in turn to be embedded in so-called product category rules (Product Environmental Footprint Category Rules, PEFCR). They are to be understood as specific additions to the general PEF method, which are intended to increase the reproducibility, consistency, relevance and, in particular, the comparability of PEF studies.

The PEF method is based on the established methodological guidelines for life cycle and GHG assessments, such as ISO 14040/44, ISO 14067, the ILCD Handbook and the product-specific standard of the GHG Protocol. In the meantime, an updated description is available.[23]

GHG Protocol – Product Life Cycle Accounting and Reporting Standard
The GHG Protocol - Product Life Cycle Accounting and Reporting Standard was published in its first version in 2008 by the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). It includes concrete guidelines for quantifying and reporting on greenhouse gas emissions and savings associated with a specific product. The target group is companies and other organisations of all sizes and countries. The primary objective of the standard is to provide a general framework for companies to make informed decisions in the development, sales, manufacturing and use of products that lead to a reduction in greenhouse gas emissions.

The standard focuses only on the actual greenhouse gas emissions and removals that occur or are generated during the product life cycle. The avoidance or reduction of emissions is not covered by the standard. The quantification of offsets is also not the subject of the standard.

The standard is based on the methods for the preparation of life cycle assessments and/or greenhouse gas inventories ISO 14040/44 and PAS 2050.

[23] Cf. EU PEF (2021).

European Commission – International Reference Life Cycle Data System (ILCD) Handbook

The International Reference Life Cycle Data System (ILCD) Handbook was published in 2010 to complement the general life cycle assessment framework of ISO 14040/44. One of the purposes of the handbook is to provide users with supportive guidelines for the wide range of activities covered by the ISO standard. In addition to a detailed guide, a simplified guide is also included. The handbook covers all aspects of conducting a life cycle assessment:

- the definition of the goal and the target group,
- the collection of data on resource consumption and emissions that can be attributed to a specific product,
- the calculation of the contribution to the environmental impact,
- the verification of the soundness and significance of the results and conclusions, and
- the reporting and verification to ensure transparency and quality.

The handbook is part of the European Commission's efforts to promote sustainable consumption and production structures.

British Standards Institution – PAS 2050

The PAS 2050 was developed in response to stakeholder requests for a common methodology for calculating the life cycle greenhouse gas emissions of products and services. The PAS 2050 provides a carbon accounting methodology that organisations can use to better understand the greenhouse gas emissions of their value chain. However, the primary objective of the PAS is to provide a uniform basis for quantifying greenhouse gas emissions. The standard was developed in 2008 by the British Standards Institution (BSI) as the first defined standard for the carbon footprint of a product or service and was revised in 2011.

The PAS 2050 builds on the ISO standards 14040/44 and represents a simplified form of the ISO standards. The widespread use of the PAS confirms the need of organisations for a clear and simple method for the carbon accounting of products as another option to a comprehensive life cycle assessment (according to ISO standard).

ISO 14044:2006 + A1:2018 + A2:2020: Life cycle assessment
Together with ISO 14040, ISO 14044 represents the standard for performing an ISO-compliant life cycle assessment. The first publication of the standard dates back to 2005, and the current revision is from 2020.

The life cycle assessment method is used to quantify the potential environmental impacts (multi-criteria) of a product or service along its entire life cycle, i.e. from the extraction of the necessary raw materials to its use and disposal. The potential environmental impacts are always considered in relation to a reference unit, the so-called functional unit, which indicates the concrete benefit of a product or service.

A life cycle assessment study comprises four phases: (1) Determination of the objective and scope of the study, (2) life cycle inventory phase (inventory of input and output data of the system under review), (3) impact assessment and (4) evaluation.

ISO 14067:2018: Carbon footprint of products
The ISO 14060 family of standards addresses the quantification, validation, verification, monitoring and reporting of greenhouse gas emissions. ISO 14067 "[...] defines the principles, requirements and guidelines for quantifying the carbon footprint of products. The aim of this document is to quantify greenhouse gas emissions associated with the life cycle stages of a product, starting with resource extraction and raw material sourcing, through the stages of production, use and end of life of the product."[24]

ISO 14045:2012: Eco-efficiency assessment
ISO 14045 is the international standard for the eco-efficiency assessment of product systems. According to the definition of the standard, the eco-efficiency assessment is "[...] a quantitative management tool that enables the examination of the environmental impacts over the life cycle of a product system in relation to the associated benefits of the overall system for

[24] ISO 14067:2018, p. 11.

stakeholders. [...] The benefits of the product system may be chosen to reflect, for example, its efficiency in terms of resources, production, distribution or use, or a combination thereof. This benefit may be expressed in monetary units or other aspects of benefit. Usually, the economic efficiency of the product (benefit) is considered in relation to its impact on the environment."[25]

In the eco-efficiency assessment, the environmental impacts are quantified using the life cycle assessment method. The corresponding ISO standards ISO 14040/44 apply here. This means that the central principles of a life cycle assessment also apply to an eco-efficiency assessment, such as the life cycle perspective, the holistic approach, the functional unit approach, the iterative character and the goal of transparency.

Project level

ISO 14064-2:2019: Specification with guidance at the project level for the quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements.
The ISO 14060 family of standards addresses the quantification, validation, verification, monitoring and reporting of greenhouse gas emissions. As part of this family, ISO 14064-2 is dedicated to projects. ISO 14064-2 "[...] specifies principles and requirements for determining the baseline and for the monitoring, quantification and reporting of project emissions. [It] focuses on GHG projects or project-based activities that are specifically developed to reduce GHG emissions and/or enhance GHG removals. It forms the basis for GHG projects to be verified and validated."[26]

GHG Protocol – The GHG Protocol for Project Accounting
The GHG Protocol for Project Accounting provides specific concepts and methods for quantifying and reporting on GHG projects. The projects can include mitigations in greenhouse gases in the sense of reductions as well as greenhouse gas removals or storage.

[25] ISO 14045:2012, p. 5.
[26] ISO14064-2:2019, p. 9.

The protocol has the following goals:

- Establish a credible and transparent approach to quantifying and reporting GHG reductions from GHG projects,

- Increase the credibility of carbon accounting for greenhouse gas projects through the application of common accounting concepts, procedures and principles, and

- Provide a platform for harmonising different project-based GHG initiatives and programmes.

The target group of the protocol is project developers and/or those responsible for the project. However, it can also be of interest to numerous other addressees. The protocol can be used in support of the ISO 14064-2 standard.

Organisation level

: Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removals
The ISO 14060 family of standards addresses the quantification, validation, verification, monitoring and reporting of greenhouse gas emissions. As part of this family, ISO 14064-1 is dedicated to the organisation or corporate level. The ISO 14064-1 "[...] specifies the principles and requirements for the design, development, management and reporting of an organisation's GHG inventories. It includes requirements for setting limits on greenhouse gas emissions and removals, quantifying an organisation's greenhouse gas emissions and removals, and identifying specific measures or activities undertaken by the organisation to improve greenhouse gas management. It also includes requirements for and guidance on the quality management of GHG inventories, reporting, conducting internal audits and the organisation's responsibilities in relation to verification activities."[27]

ISO/TR 14069:2013: Greenhouse gases – Quantification and reporting of greenhouse gas emissions for organizations – Guidance for the application of ISO 14064-1
This technical report describes the principles, concepts and methods relating to the quantification and reporting of direct and indirect greenhouse gas (GHG) emissions for an organisation. This includes direct (scope 1) as well as indirect emissions (scope 2 and 3). The technical report is designed to serve as guidance for the application of ISO 14064-1 and thus support or facilitate its application.

The synopsis does not take the technical report into account, as the underlying ISO 14064-1 is now more up-to-date (2018) than the technical report (2013).

[27] ISO 14064-1:2018, p. 9.

European Commission – Organisational Environmental Footprint (2013) (OEF)

The European Commission's guidance on calculating the environmental footprint of organisations has been developed - as a counterpart to the PEF - with the primary aim of providing a uniform European methodology to quantify the impact of organisations on the environment. As with the PEF methodology, the organisation-specific methodology also follows the principle of “comparability over flexibility”, i.e. the comparability of the studies has top priority.

The European Commission defines the Organisational Environmental Footprint (OEF) as "[...] a multi-criteria measure of the environmental performance of organisations when providing goods or services, taking into account the entire life cycle. OEF studies are created for the overarching purpose of seeking to reduce the environmental impacts of organisations’ activities taking into account all supply chain activities (from extraction of raw materials, through production and use, to final waste management). These organisations include, among others, companies, public administration bodies and non-profit institutions.”[28]

On the one hand, the OEF guide contains the methodological basis for calculating an OEF. On the other hand, it contains instructions for the development of so-called sector rules, which serve the calculation of the environmental footprint of sector-specific organisations (Organisation Environmental Footprint Sector Rules, OEFSR). Analogous to the PEFCRs, the OEFSRs - by focusing uniformly on the most important impact categories and processes of a sector - are intended to enable the comparability of OEFs from within the same sector.

The OEF guide is based on the established methodological guidelines, such as ISO 14064: 2006, ISO 14069:2010, the ILCD Handbook and the organisation-specific standard of the GHG Protocol.

[28] European Commission (2010), p. 110.

ISO/TS 14072:2014: Environmental management – Life cycle assessment – Requirements and guidelines for organisational life cycle assessment

This technical specification provides requirements and guidelines for the application of the life cycle assessment standards ISO 14040 and ISO 14044 at the organisational level. In particular, the application of the life cycle assessment method, the advantages of applying the method and the choice of system boundaries are expanded in this document.

ISO/TS 14072 can be applied to all organisations. With appropriate justification, this technical specification may also be applied to sub-divisions of an organisation.

GHG Protocol – A Corporate Accounting and Reporting Standard

The Corporate Accounting and Reporting Standard was first published in 2001 and revised in 2004. It provides a step-by-step guide for companies and other organisations to quantify and report their own greenhouse gas emissions. The standard is complemented by numerous calculation tools listed on the GHG Protocol website.

Extensive stakeholder consultation was undertaken in the development and revision of the standard. This intensive stakeholder involvement and the strong practical orientation of the standard are reasons for its very broad application.

United Nations Environment Programme (UNEP) – Guidance on Organizational Life Cycle Assessment

This guide from the UNEP "[...] describes three different ways in which organisations can broaden their analytical horizons and implement the O-LCA approach, building on existing experience with individual environmental assessment methods. Recommendations for small, medium and large organisations also provide guidance for practical implementation. Specific recommendations for different use cases underline that there is no 'universal concept' for the application of O-LCA. In addition, eleven case studies from pioneers of the O-LCA method illustrate the benefits of applying a multi-criteria environmental assessment method for organisations and their value chain."[29]

The guide is based on ISO 14040/44 and aims at harmonisation with ISO 14072 and/or to be understood as a supplementary document to this guideline. It aims to create consistency and credibility and to enable easier and wider application of O-LCA. In this way, the guide is intended to support users from the field in overcoming the most important methodological challenges in the course of applying O-LCA.

2.1.4 Synopsis of methods

The methods described above are compared in the following synopsis in terms of their key methodological principles.

[29] UNEP (2015), p. 12.

Table 1: Synopsis of methods for assessment methods at product level

	ISO 14044	ISO 14045	ISO 14067	PAS 2050
Reference object	Product/service	Product/service	Product/service	Product/service
Life cycle perspective	Yes	Yes	Yes	Yes
Application	Identify opportunities to improve the environmental performance of products. Comparative statements with additional requirements. Information for decision makers.	The eco-efficiency assessment is a quantitative management tool that enables the examination of the environmental impacts over the life cycle of a product system in relation to the associated benefits of the overall system for stakeholders.	Information for decision makers. Performance monitoring. Comparative statements with additional requirements.	The method is intended for internal assessment, e.g. – To facilitate the assessment of alternative product configurations or benchmarking; – Performance monitoring, including identification of opportunities to reduce GHG emissions; – Facilitating the comparison of GHG emissions of goods and services.
Target audience and communication	B2B and B2C	B2B and B2C	B2B and B2C	Communication requirements not specified
Functional unit	The functional unit must be consistent with the objective and scope of the study. It must be clearly defined and measurable. After the functional unit is chosen, the reference flow must be defined.	The functional unit must be consistent with the objective and scope of the study. It must be clearly defined and measurable.	Clearly defined and measurable	Refers to the functional unit as the unit of study. Very little information and guidance.
System boundaries	Iterative process: - Initial system boundaries are defined based on the objective and scope of the study. - Final system boundaries are defined after initial calculations and the sensitivity analysis. If processes, life cycle phase, etc. are excluded, this must be justified accordingly.	Corresponds to ISO 14044	When quantifying a CFP, the entire life cycle of a product is considered, including raw material extraction, design, production, transport/delivery, use and end-of-life treatment. The exclusion of life cycle stages, processes, inputs or outputs within the system under consideration is only allowed if it does not significantly alter the overall conclusions of the CFP study. Any decision to exclude life cycle stages, processes, inputs or outputs must be clearly stated and the reasons for the exclusion and its implications must be explained.	From sourcing of raw materials to end-of-life and disposal. Enables cradle-to-grave and cradle-to-gate analyses. Other additional requirements apply. Exclusions from the system boundary: – Capital goods, – Process inputs in the form of human energy, – Transport service by animals, – Transport of the consumer to and from the point of sale (could be included after verification), – Transport of employees.
Cut-off criteria	Allowed - based on mass, energy or environmental relevance.	Choice of cut-off criteria must be in line with the objective of the study.	Allowed - if insignificant for carbon footprint.	5% of global warming potential (all emissions that contribute significantly (i.e. >1% of emissions) and at least 95% of total emissions must be included.
Modelling approach (attributional, consequential)	Includes principle for calculating the environmental impact of products. Avoidance of allocation is the preferred approach.	Includes principle for calculating the eco-efficiency of product systems.	Includes principle for calculating GHG emissions (climate change) of products. Avoidance of allocation is the preferred approach.	Attributive approach. Avoidance of allocation is the preferred approach.

	ISO 14044	ISO 14045	ISO 14067	PAS 2050
Data quality	Data quality requirements should be specified for the following criteria: – Time-related coverage – Geographical coverage – Technological coverage – Precision – Completeness – Consistency – Data sources – Information uncertainty There are no minimum requirements for data quality. For comparative statements, the aforementioned criteria must be taken into account.	Preferably scientific data Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Corresponds to ISO 14044	Adopted from ISO 14044. No minimum requirements specified for data quality.
Data type and data collection	Primary data: collected (measured, calculated or estimated) at production sites associated with the process modules within the system boundary. Secondary data: Data from other sources (e.g. literature or databases). No recommendation for a specific data source. For the choice of secondary data, the user must meet the specified data quality requirements. Template for data collection: see ISO/TR 14049	Environmental assessment pursuant to ISO 14044	Corresponds to ISO 14044	Primary activity data is required for all processes in which the performing organisation has ownership rights or which are performed by it. For inputs where primary activity data cannot be obtained, secondary data must be used. Secondary data should preferably meet the requirements of the PAS standard. Secondary data must be selected on the following basis: 1) Data quality requirements according to ISO 14044, 2) Secondary data from peer-reviewed publications together with data from other expert sources are preferred. Template for data collection: included in the PAS-2050 guide.
Allocation	Wherever possible, allocation should initially be avoided by means of process subdivision or system expansion. If this is not possible, physical relationships (e.g. mass, energy) between products or functions should be used to allocate inputs and outputs. If physical relationships cannot be established, other relationships must be used instead (e.g. economic value).	No allocations are made to adjacent systems. Choice of cut-off criteria must be in line with the objective of the study.	Corresponds to ISO 14044	Further developed from ISO 14044: 1. Allocation of co-products is avoided by subdividing process modules into sub-processes or by expanding the product system, 2. If case 1 does not apply: Allocation according to additional requirements, 3. If there are no additional requirements, priority is given to the economic value.
Allocation for recycling	This issue is addressed separately; general principle of avoiding allocation but no specific rule provided – no formula.	Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Substitution of primary production of avoided product. It follows ISO 14044. Annex C which contains the formulas, informative.	Provides equations to calculate emissions – distinguishes between recycled content method and approximation method (for closed-loop recycling). (Sets out criteria as to where to apply 0/100,100/0).
Fossil and biogenic carbon emissions and removals	No provision.	Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Removals and emissions shall be reported separately for both fossil and biogenic sources.	Both carbon emissions and removals are included in the assessment (mandatory), except biogenic emissions and removals from food and feed (which is not mandatory).

	ISO 14044	ISO 14045	ISO 14067	PAS 2050
Direct / indirect land use change	No provision.	Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Direct land use change: Uses IPCC guidelines Indirect land use change: Will be considered once an internationally agreed method has been established.	Direct land use change: Specifically includes emissions from land use change that occurred within the past 20 years. Indirect land use change is excluded.
Carbon storage and delayed emissions	No specific provision / information provided. However, interpretation of the definition of LCA provided suggests that carbon storage and delayed emissions are excluded from the usual scope of study.	Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Carbon storage shall be reported separately.	Any impact of carbon storage is included in the inventory but must also be recorded separately. Weighting factors for delayed emissions are not included in the inventory result, but a method is provided (in Annex B) if organisations wish to apply them. If so, this must be recorded separately to the inventory result.
Emissions off-setting	No provision.	Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Shall not be included in the impact assessment (outside the product system).	Shall not be included in the impact assessment.
Review and reviewer qualifications	Provides requirement for comparative studies: If the study is intended to be used for a comparative assertion to be disclosed to the public, interested parties shall conduct this evaluation as a critical review, and provide general information as to the type of review.	A critical review can be performed by a qualified internal or external reviewer. In both cases, the review must be carried out by a qualified reviewer independent of the eco-efficiency assessment. The review, comments of the producer(s) and any responses to recommendations of the reviewer(s) must be included in the eco-efficiency assessment report.	Provides for different verification schemes depending on the type and intended application of the study: Declaration, assertion, labelling.	Independent third party certification body accredited to provide assessment and certification to the PAS 2050. There are other possibilities for verification, including self verification and non-accredited body verification, depending on intended communication.
Consideration of scope 3 (upstream and downstream)	Dependent on system boundaries	Dependent on system boundaries	Dependent on system boundaries	Cradle-to-grave covers upstream and downstream; no downstream for cradle-to-grave
Bottom up / top down	Bottom up	Bottom up	Bottom up	Bottom up
Consideration of baseline	No baseline guidelines. Systems must be compared using the same functional units and equivalent methodological specifications, such as performance, system boundary, data quality, allocation procedures, criteria for assessing inputs and outputs, and impact assessment.	Corresponds to ISO 14044 (environmental assessment pursuant to ISO 14044)	Corresponds to ISO 14044	No baseline guidelines. For product comparisons: - Same data quality - Same system boundaries - Suitable and same functional unit
Presentability of individual measures, especially from VDI 4800/4801	Simple, as life cycle assessment	Simple, as based on life cycle assessment	Simple, as based on life cycle assessment	Simple, as based on life cycle assessment

	GHG Protocol Product Standard	EU PEF	ILCD Handbook
Reference object	Product/service	Product/service	Product/service/system
Life cycle thinking	Yes	Yes	Yes
Application	Performance tracking include identifying GHG reduction opportunities. Provide GHG emissions data to business and interested stakeholders through public reporting. Additional types of communication (e.g., labels, claims) are supported by the standard with additional specifications (e.g. product rules). Comparative assertions (as defined by ISO 14044) are not supported.	In-house applications may include support to environmental management, identification of environmental hotspots, environmental improvement and performance tracking. External applications (e.g. B2B, B2C) cover a wide range of possibilities, responding to customer and consumer demands, marketing, benchmarking, environmental labelling, etc.	Analyse environmental life-cycle performance of products for improvement (performance tracking), comparisons, customer information (business customers). Including comparative assertions with additional requirements.
Target group and disclosure	B2B and B2C	B2B and B2C	B2B and B2C
Functional unit	The magnitude, duration or lifetime, and the expected level of quality of the function or service. Separate reference flow for supporting the data collection.	The unit of analysis for a PEF study shall be defined according to the following aspects: The function(s) / service(s) provided: “what”; The magnitude of the function or service: “how much”; The duration of the service provided or service life time: “how long”; The expected level of quality: “how well”. An appropriate reference flow shall be determined in relation to the unit of analysis. The quantitative input and output data collected in support of the analysis shall be calculated in relation to this flow.	The functional unit must be consistent with the objective and scope of the study. It shall be clearly defined, both in terms of quantitative and qualitative aspects. What? How much? How long? How well? Separate reference flow for supporting the data collection.
System boundaries	From raw material acquisition through to end-of-life and disposal. Attributable processes required, relevant non-attributable processes recommended. Allows for both cradle-to-grave and cradle-to-gate analyses.	The system boundaries shall include all processes linked to the product supply chain relative to the unit of analysis. Cradle-to-grave as default approach, or different if otherwise specified in PEFCRs. The processes included in the system boundaries shall be divided into foreground processes (i.e. core processes in the product life cycle for which direct access to information is available) and background processes (i.e. those processes in the product life cycle for which no direct access to information is possible).	From raw material acquisition through to end-of-life and disposal. Iterative, focused on most relevant processes. Include all relevant processes (both attributable processes and non-attributable processes).
Cut-off criteria	Not allowed	Not allowed	Cut-off criteria should consider the quantitative degree of completeness with respect to the overall environmental impacts of the product system. For comparative studies the cut-off shall also always relate to mass and energy.
Modelling approach (attributional, consequential)	Attributional approach, plus direct system expansion for multi-product processes and closed-loop approximation for recycling (following the requirements of the standard).	Takes elements from both attributional and consequential modelling approaches.	Attributional approach plus substitution for end-of-life and other multi-product processes. Avoidance of allocation is the preferred approach.

	GHG Protocol Product Standard	EU PEF	ILCD Handbook
Data quality	Five data quality indicators shall be used to assess data quality: – Technological representativeness – Time-related representativeness – Geographical representativeness – Completeness – Reliability For significant processes, companies shall report a descriptive statement on the data sources, the data quality, and any efforts taken to improve data quality.	Data quality is assessed against the following criteria: – Technological representativeness – Geographical representativeness – Time-related representativeness – Completeness – Parameter uncertainty – Methodological Appropriateness and Consistency Data quality requirements shall be met (for both specific and generic data) by any PEF study intended for external communication. In the final Resource Use and Emissions Profile, for the processes or activities accounting for at least 70% of contributions to each impact category (based on the screening exercise, if conducted), both specific and generic data shall achieve at least an overall "good quality" level. A semi-quantitative assessment of data quality shall be performed and reported for these processes. [...] With respect to the level at which assessment of data quality shall be conducted: – For generic data, shall be conducted at the level of the input flows, e.g. purchased paper used in a printing office; – For specific data, shall be conducted at the level of an individual process or aggregated processes, or at the level on individual input flows.	Modified from ISO 14044 (applies to both primary and secondary data): – Technological representativeness – Geographical representativeness – Time-related representativeness – Completeness / Precision
Data type and data collection	Primary data are required for all processes under the reporting company's ownership or control. Secondary data: The best quality data is recommended, with primary data preferred if available. The methodology guide acknowledges that the data management plan should include a data collection template. However, no example is provided in the standard.	Specific data shall be obtained for all foreground processes and for background processes, where appropriate. However, in case generic data is more representative or appropriate than specific data (to be justified and reported) for foreground processes, generic data shall be also used for the foreground processes. Generic data should be used only for processes in the background system, unless (generic data) are more representative or appropriate than specific data for foreground processes, in which case generic data shall also be used for processes in the foreground system. Generic data (provided they meet the data quality requirements specified in this guide) shall, where available, be sourced from: – Data developed in line with the requirements for the relevant PEFCRs – Data developed in line with the requirements for PEF studies – ILCD Data Network (data that comply with ILCD requirements for Situation A) – ILCD. Data collection template: the template provided is informative.	Primary data: Primary data for the foreground system and main background processes preferred; secondary data can also be used, provided it is ILCD-compliant and has good and demonstrable representativeness for those processes/products. For all other data needs, the best quality, ILCD-compliant secondary data is preferred. Remaining data gaps shall be filled using "data estimates" of minimum quality. The methodology guide acknowledges that the data management plan should include a data collection template.
Allocation	Adopted from ISO 14044: – Companies shall avoid allocation wherever possible by using process subdivision, redefining the functional unit, or using system expansion. – If allocation is unavoidable, companies shall allocate GHG emissions and removals based on the underlying physical relationships between the studied product and co-product(s). – When physical relationships alone cannot be established, companies shall select either economic allocation or another allocation method that reflects other relationships between the studied product and co-product(s).	The following decision hierarchy shall be applied for resolving all multi-functionality problems: (1) subdivision or system expansion; (2) allocation based on a relevant underlying physical relationship (substitution may apply here); (3) allocation based on some other relationship.	Further developed and specified from ISO 14044: – Avoiding allocation by subdivision or virtual subdivision. – Substitution / system expansion (also of wider functions) of market mix. – Causal physical relationship allocation, e.g. mass, energy. – Economic allocation.

	GHG Protocol Product Standard	EU PEF	ILCD Handbook
Allocation for recycling	Either the closed-loop approximation or recycled content method shall be used. If neither method is appropriate, other methods - consistent with ISO 14044 - may be used if disclosed and justified in the inventory report.	Specific guidance (including formula!) provided, also accounting for energy recovery.	Substitution of market average primary production of avoided product
Fossil and biogenic carbon emissions and removals	Both carbon emissions and removals from fossil and biogenic sources are included in the inventory results and reported separately for transparency (mandatory unless not applicable).	Removals and emissions shall be reported separately for both fossil and biogenic sources.	Removals and emissions shall be reported separately for both fossil and biogenic sources.
Direct / indirect land use change	Direct land use change: required when attributable. Additional guidance for calculation available, data sources refer to IPCC. Indirect land use change is not required.	Greenhouse gas emissions from direct land use change shall be allocated to goods/services for 20 years after the land use change occurs using the IPCC default values table. Indirect land use change: Greenhouse gas emissions that occur as a result of indirect land use change shall not be considered in the default EF impact categories.	Direct land use change: Specific IPCC-derived guidance with default table; allocated to products for 20 years after land use change (can be adjusted in case of better specific, reviewed data). Indirect land use change is considered under consequential modelling, but not for product level (attributional-based) LCAs.
Carbon storage and delayed emissions	Carbon that is not released as a result of end-of-life treatment over the time period of the study is treated as stored carbon. The time period should be based on science insofar as possible, or be a minimum of 100 years. Delayed emissions or weighting factors (e.g. temporary carbon) shall not be included in the inventory results, but can be reported separately.	Credits associated with temporary (carbon) storage or delayed emissions shall not be considered in the calculation of the PEF for the default impact categories, unless otherwise specified in a supporting PEFCR.	Excluded from the usual scope of study. However, if included because part of the goal of study, the ILCD Handbook provides detailed operational guidance. Similar to the recommended approach in the PAS 2050 for methods by which carbon storage impacts are calculated. Differentiate temporary storage from permanent storage if guaranteed for over 10 000 years.
Emissions offsetting	Shall not be included in the impact assessment	Shall not be included in the impact assessment	Shall not be included in the impact assessment
Review and reviewer qualifications	Assurance is required and can be achieved through: – First party verification – Third party verification – Critical review	Unless otherwise specified in relevant policy instruments, any study intended for external communication shall be reviewed by an independent and qualified external reviewer (or review team). A study to support a comparative assertion intended to be disclosed to the public shall be based on relevant PEFCRs and reviewed by an independent external reviewer together with a stakeholder panel. Minimum requirements on reviewer qualifications apply.	Provides minimum requirements for review type, reviewer qualifications and how to review (e.g. for a general LCA study, independent external review is a minimum requirement).
Consideration of scope 3 (upstream and downstream)	Cradle-to-grave covers upstream and downstream; no downstream for cradle-to-grave	Cradle-to-Grave covers upstream and downstream	Cradle-to-Grave covers upstream and downstream
Bottom up / top down	Bottom up	Bottom up	Bottom up
Consideration of baseline	No baseline guidelines, but specifications for comparative assessments: - Same system boundaries - Same allocation methods - Same time-related and geographical scope of study, - etc. (p. 115 ff.).	PEFCR (Product Environmental Footprint Category Rules) are developed for better comparability of products. No information on a baseline is provided.	No baseline guidelines, but specifications for comparative assessments (P. 145 ff.)
Presentability of individual measures	Simple, as based on life cycle assessment	Simple, as life cycle assessment	Simple, as life cycle assessment

Table 2: Synopsis of methods for assessment methods at project level

	ISO 14064-2	GHG Protocol Project Protocol
Reference object	Project	Project
Life cycle thinking	No provision.	No provision.
Application	Quantifying, monitoring and reporting activities/projects that reduce GHG emissions or increase GHG removals.	A credible and transparent approach to quantifying and reporting GHG reductions from GHG projects. Increase the credibility of carbon accounting for GHG projects by applying common accounting concepts, procedures and principles; and Provide a platform for harmonisation between different project-based GHG initiatives and programmes.
Target audience and communication	Diverse target audiences	Diverse target audiences
Functional unit	No provision.	No provision.
System boundaries	No system or project boundary defined, but relevant sources, sinks and storage: Relevant QSS include those that are "controlled" by the project applicant, those that are "associated" with the project through material or energy flows, and those that are "influenced" by the project.	All activities associated with the GHG mitigation project must be recorded. All primary (intended) and secondary (unintended) effects must be recorded.
Cut-off criteria	No specifications	Non-significant secondary effects should be cut off.
Modelling approach (attributional, consequential)	No specifications on the method The following principles must be observed: - Relevance - Completeness - Consistency - Precision - Transparency - Conservatism	Reference to different standards and tools of the GHG Protocol Initiative for GHG quantification. The following principles must be observed: - Relevance - Completeness - Consistency - Precision - Transparency
Data quality	Define and apply quality management procedures for managing data and information.	Data quality and collection are subject to the above principles.
Data type and data collection	Data can be determined quantitatively and/or collected or estimated.	Data quality and collection are subject to the above principles.
Allocation	No provision.	No provision.
Allocation for recycling	No provision.	No provision.
Fossil and biogenic carbon emissions and removals	No provision.	No provision.
Direct / indirect land use change	No provision.	No provision.
Carbon storage and delayed emissions	No provision.	No provision.

	ISO 14064-2	GHG Protocol Project Protocol
Emissions off-setting	No provision.	No provision.
Review and reviewer quali-fications	Validation and verification according to ISO 14064-3	Minimum reporting requirements, no information on third-party verification
Consideration of scope 3 (up-stream and downstream)	No provision.	Recorded via secondary effects
Bottom up / top down	No provision.	No provision.
Consideration of baseline	Reference scenario: should take into account the likely future developments and fulfil the principle of conservatism. Scenario can be static and dynamic. The following must be taken into account: - Project description, - existing and alternative project types, activities and technologies that deliver equivalent types and quantities of products or services, - availability, reliability and limitations of data; - other relevant information regarding current or future conditions such as legal, technical, economic, socio-cultural, environmental, geographic, site-specific and temporal assumptions or projections. Includes guidance on how to determine the scenario	Extensive baseline information (two methods for GHG determination are proposed, Chapters 8 and 9). Baseline can be static and dynamic, a time frame must always be specified for which the baseline is valid.
Presentability of individual measures, espe-cially from VDI 4800/4801	Purpose of the ISO standard, focus on climate protection projects	Purpose of the protocol, focus on climate protection projects

Table 3: Synopsis of methods for assessment methods at organisation level

	ISO 14064-1	ISO 14072	GHG Protocol Corporate Standard	UNEP OLCA	EU OEF
Reference object	Organisation	Organisation	Organisation	Organisation	Organisation
Life cycle perspective	Optional	Yes	Optional, at least scope 1 and 2	Yes	Yes
Application	Organisational design, development, management and reporting of GHG emissions for the purpose of corporate risk management, voluntary initiatives, GHG markets, or regulatory reporting.	Recording the environmental impact of organisations, taking into account the life cycle perspective. Can be applied to environmental management, strategic management decisions, reporting, etc.	Intended to support accounting and disclosure for internal use and external applications.	Numerous applications: - Insights into the value chain and internal activities - Identification of environmentally relevant hotspots - Measuring environmental performance - Support for strategic decision-making	In-house applications may include support to environmental management, identification of environmental hot-spots, environmental improvement and performance tracking. External applications (e.g. B2B, B2C) cover a wide range of possibilities, from responding to customer and consumer demands, to marketing, benchmarking, environmental labelling, etc.
Target audience and communication	B2B and B2C	B2B and B2C	B2B, B2C, business to interested stakeholders through public reporting.	B2B, B2C, business to interested stakeholders through public reporting.	B2B and B2C
Functional unit	Does not use "functional unit" and "reference flow" concept.	functional unit = reporting unit (e.g. "Hosting all the clients of the Hotel Group during one year, over the world, considering all the basic services including restoration")	Does not use "functional unit" and "reference flow" concept.	Which organisation, which activity, which year, which consolidation method (system boundaries)?	Functional unit concept (organisation as goods/services provider) and reference flow concept (product portfolio = sum of all goods/services produced/provided by the organisation in the reporting period).
System boundaries	The organisation shall aggregate greenhouse gas emissions and removals at the facility level using one of the following approaches: - Control approach, - Equity share approach.	Cradle-to-gate possible if no influence on use and EOL Control approach (operational or financial) or equity share	Boundaries defined based on "equity share approach" or control criteria.	Cradle-to-gate possible if no influence on use and EOL Control approach (operational or financial) or equity share	The system boundaries shall include both organisational boundaries (related to the defined organisation) and OEF boundaries (specifying the aspects of the supply chain to be considered in the study). "Control approach" (financial and/or operational control).
Cut-off criteria	Based on considerations of materiality, feasibility and cost effectiveness	Corresponds to ISO 14044	Discouraged	Corresponds to ISO 14044	Not allowed
Modelling approach (attributional, consequential)	No provision.	Corresponds to ISO 14044 Top-down and hybrid approaches also allowed	– Provides modelling spreadsheets with embedded (but customisable) default emission factors that are applied to activity data. – Provides 15 categories (e.g. business travel, investment) for modelling scope 3 emissions, with recommended inclusions for each.	Corresponds mainly to ISO 14044 for LCA Top-down and hybrid approaches also allowed	Takes elements from both attributional and consequential modelling approaches.
Data quality	Requires data management plan and uncertainty assessment. Refers to ISO 14064-3 for validation / verification requirements.	Corresponds to ISO 14044	Recommends qualitative data quality scoring for scope 3 calculations. Specifies criteria for a data management plan. Guidelines on the GHG website for uncertainty assessments	Corresponds to ISO 14044	Data quality is assessed against six criteria (technological, geographical and time-related representativeness, completeness, parameter uncertainty and methodological appropriateness and consistency). Data quality requirements are mandatory for OEF studies intended for external communication, recommended for studies intended for in-house applications. For the processes accounting for at least 70% to each impact category, "good quality" required for both specific and generic data based on a semi-quantitative assessment. [...]

	ISO 14064-1	ISO 14072	GHG Protocol Corporate Standard	UNEP OLCA	EU OEF
Data type and data collection	Specific data: Required for corporate activities within the system boundary Generic data: Should be derived from a recognised source and be current and appropriate	Corresponds to ISO 14044	Specific data: Provides guidance on collection of specific data for corporate scope 3 activities Generic data: Provides description of generic data for each category in scope 3. Preferred sources: internationally recognised government or peer-reviewed sources.	Corresponds to ISO 14044	Specific data: Required for all foreground processes and for background processes, where appropriate. However, in case generic data is more representative or appropriate than specific data (to be justified and reported) for foreground processes, generic data shall be used for the foreground processes too. Generic data: Should be used only for background processes. Generic data shall, where available, be sourced from: – Data developed in line with the requirements for the relevant OEFSRs, – Data developed in line with the requirements for OEF studies, – ILCD Data Network, – ELCD. Data collection template: the template provided is informative.
Allocation	No provision.	Corresponds to ISO 14044 Sensitivity analysis when different methods are applicable	Adopts ISO 14044. Calculation tool for stationary combustion provides 2 allocation options.	Corresponds to ISO 14044 Sensitivity analysis when different methods are applicable	OEF multi-functionality hierarchy: (1) subdivision or system expansion; (2) allocation based on a relevant underlying physical relationship (here substitution may apply); (3) allocation based on some other relationship.
Allocation for recycling	No provision.	Corresponds to ISO 14044	Adopts ISO 14044. Calculation tool for stationary combustion provides 2 allocation options.	Corresponds to ISO 14044	Specific guidance (including formula!) provided, also accounting for energy recovery.
Fossil and biogenic carbon emissions and removals	Shall be recorded and documented separately	No provision.	No provision.	No provision.	The capture and release of CO_2 from biogenic sources must be recorded separately in the resource use and emissions profile.
Direct / indirect land use change	No provision.	No provision.	Reference to IPCC	No provision.	Greenhouse gas emissions that occur as a result of direct land use change shall be allocated to products for (i) 20 years after the land use change occurs or (ii) a single harvest period from the extraction of the evaluated product (even if longer than 20 years) and the longest period shall be chosen. For details, see Annex VI. Greenhouse gas emissions that occur as a result of indirect land use change shall not be considered unless OEFCRs explicitly require to do so. In that case, indirect land use change shall be reported separately as “Additional Environmental Information”, but it shall not be included in the calculation of the “Greenhouse gas” impact category.

	ISO 14064-1	ISO 14072	GHG Protocol Corporate Standard	UNEP OLCA	EU OEF
Carbon storage and delayed emissions	Report separately	No provision.	Carbon storage and removal must be reported separately.	No provision.	Credits associated with temporary carbon storage or delayed emissions shall not be considered in the calculation of the default EF impact categories. These shall be reported in the "Additional Environmental Information" if required by the OEFSRs.
Emissions offsetting	Reductions from purchased credit or other external projects must be documented and reported separately.	No provision.	Provision of guidance for accounting	Report separately	Shall not be included in the impact assessment.
Review and reviewer qualifications	Review report or third party verification statement should be available for public assertions. Required level of validation and verification depends on several criteria.	Corresponds to ISO 14044	Provides detailed guidance, but not a requirement.		OEF studies intended for external communication require review by an independent and qualified external reviewer (or review team). OEF studies intended to support a comparative assertion require review by 3 independent external reviewers. Minimum requirements on reviewer qualifications apply.
Consideration of scope 3 (upstream and downstream)	Direct (scope 1) mandatory and indirect emissions (scope 2 and 3) and thus upstream and downstream optional	Upstream optional, depending on whether cradle-to-gate or cradle-to-grave	Scope 3 optional	Upstream optional, depending on whether cradle-to-gate or cradle-to-grave	"Cradle-to-grave" as default, but only cradle-to-gate defined as a must
Bottom up / top down	No provision.	Bottom up, top down, hybrid	Bottom up (scope 3 calculator also uses top down)	Bottom up, top down, hybrid	Bottom up
Consideration of baseline	Information for determining the base year	Reference year	Reference year or average of several years Definition, but no guidance for baseline	Reference year	No provision.
Presentability of individual measures, especially from VDI 4800/4801	Not possible/difficult, as it relates to the organisation	Not possible/difficult, as it relates to the organisation	Not possible/difficult, as it relates to the organisation	Not possible/difficult, as it relates to the organisation	Not possible/difficult, as it relates to the organisation

2.1.5 Conclusions

The evaluation of the relevant standards and recommendations reveals the absence of explicit methods that lend themselves to an emissions calculation of material efficiency measures. In principle, LCA or PCF can of course be used for such purposes. However, the effort is considerable and requires expertise. There are no easily applicable procedures for the practice. In addition, the standards are formulated so openly that many methodological specifications depend on the respective application case. This makes it difficult to compare the results of different measures. Nevertheless, some important recommendations can be derived from the standards and adapted to the scope of application here:

- For carbon accounting, the system boundaries, the reference objects (or functional units) and the reporting period must be chosen in a plausible and comprehensible manner.

- It must be possible to reproduce the calculations, i.e. all assumptions and methodological specifications must be documented.

- In addition to CO_2 emissions, the other greenhouse gases must also be taken into consideration in carbon accounting. These are primarily methane and nitrous oxide (dinitrogen monoxide), but also sulphur hexafluoride (SF_6), partly fluorinated hydrocarbons (PFHCs) and hydrofluorocarbons (HFCs) in accordance with the Kyoto Protocol. Emissions are to be reported in CO_2 equivalents. The Global Warming Potential (GWP) according to the recommendations of the IPCC is to be used for the calculation (IPCC 2013).

- If no substitution of CO_2 emissions of fossil origin by CO_2 emissions of biogenic origin (or vice versa) is to be expected, only the CO_2 emissions of fossil origin are taken into account. No such distinction is made for the other greenhouse gases; in their case, all emissions are always to be included.

- If biogenic CO_2 emissions are taken into account, they must be reported separately - in addition to fossil emissions.

- The long-term binding of CO_2 in biogenic systems or in non-biogenic systems or their delayed emission are not to be taken into account.

- Compensations or offsets of emissions are to be excluded as a matter of principle.

- The use of electricity is generally based on the German electricity mix; the sourcing of green electricity is not taken into account. This facilitates the comparability of different measures and prevents misinterpretations.

- If a process or production system produces more than one product and the emissions or consumption (e.g. of energy) cannot be clearly allocated to the products, an allocation must be carried out. In this process, the emissions (or consumption) are distributed proportionally to the products. The distribution key should be based on the benefit of the products in the technosphere, which is usually the quantities (in kg, m^3, kWh, etc.) or the market value.

- Recycling systems are calculated with a cut-off approach, i.e. in simple terms: The expenses and/or emissions in the "first life" of a material are not counted towards the second life of the material. This tends to favour secondary materials in their carbon footprint. The rule is preferred to more complex calculations (such as in the PEF) mainly for reasons of practicability.

- Measured or empirically determined values of consumption and emissions are to be preferred to default or generic values. The data sources shall be documented transparently. In the case of generic data, quality-assured and up-to-date databases should be used.

The corresponding recommendations are discussed again in Chapter 4.2 on the ESTEM calculation procedure.

2.2 Databases

2.2.1 Overview and requirements

The preparation of life cycle assessments and greenhouse gas inventories is very data-intensive. For each material and for each energy input of the system under investigation, it must be known which environmental impacts and/or greenhouse gas emissions are associated with it. This is referred to as the background data. To obtain this data, special databases are usually used.

Since the project is aimed at German companies, background data for the German region is primarily required. Here, the use of electrical energy in particular plays a central role. The materials used in companies do not necessarily have to originate in Germany. For example, metals - at least their ore concentrates - come almost exclusively from other regions of the world. The background data therefore has to ensure a high level of global coverage, especially for materials. The up-to-dateness of the data also plays a decisive role. The best example of this is the dynamically changing electricity mix. For example, one kWh of the German electricity mix in 2015 released about 30% more greenhouse gas emissions than the electricity mix of 2019.[30] As the focus of the project is on material efficiency measures, in addition to a high degree of global coverage and the use of current data, it is also important that the database covers all the necessary materials. More detailed information about this can be found in Chapter 2.2.3.

The two most well-known and widely used databases are the ecoinvent database of the non-profit association ecoinvent and the GaBi database of Sphera Solutions GmbH (formerly Thinkstep AG). Both databases offer a comprehensive, up-to-date and consistent pool of data with a high degree of sectoral and global coverage. In addition to the market leaders, there are numerous other LCA databases on the market. Among these are the free databases, such as ProBas of the Federal Environment Agency. However, these databases have significant disadvantages in terms of scope and up-to-

[30] **Cf. IEA and OECD (2020).**

dateness. Another, relatively new database is carbonminds. This database offers a very comprehensive and highly differentiated database for the chemical industry. The high level of differentiation according to different chemicals, manufacturing variants and production countries and locations is made possible by comprehensive model calculations. In addition, numerous free and fee-based databases are available for different regions of the world, but these are not considered here due to the above-mentioned requirements of German and global coverage.

In addition to the LCA databases, there are the input-output databases that are based on economic statistics (see previous chapter), which have been expanded to include environmentally relevant key figures (environmental impact per monetary unit of production output). One example is the Exiobase database, which was developed by several European research institutes. This data is used for so-called environmental input-output analyses. Such analyses have the great advantage that complex systems can be analysed relatively easily and quickly. Even processes that do not have any classic physical data parameters, such as services or development services, can be analysed. The disadvantages of this analysis lie in particular in the limited depth of detail (which is due to the highly aggregated data basis) and in the uncertainty due to the evaluation using monetary values, which are subject to natural fluctuations. These analyses are therefore much less suitable for evaluations of material efficiency measures, which always require a very high level of detail and accuracy.

2.2.2 Comparison of databases

The most important databases and their key data are listed in Table 4. As explained in Chapter 2.1, due to the aforementioned requirements of high global coverage, high up-to-dateness and broad material coverage, it is mainly the ecoinvent and GaBi databases that are suitable for further consideration. However, both databases are also very cost-intensive to purchase. The ProBas database (also incorporates other free databases, including GEMIS) also offers global coverage and acceptable material coverage. It is also free of charge, but has significant disadvantages in terms of the up-to-dateness and methodological consistency of the data.

Table 4: The most important environmental databases and their key data

	eco-invent	Thinkstep GaBi	ProBas UBA	GEMIS	car-bonminds	JRC
Type of data	LCI data	LCI data	LCI data	LCI data	LCI data	LCI data
Region	Global, divided into coun-tries/regions	Global, divided into coun-tries/regions	Global, divided into coun-tries/regions	Global, divided into coun-tries/regions	Global, divided into coun-tries/regions	Europe, divided into coun-tries/regions
Sub-ject to charg-es	Yes	Yes	No	No	Yes	No
Up-to-date-ness	Regularly updated	Regularly updated	Partially outdated	Partially outdated	Regularly updated	Discontinued
Data rec-ords	19000	15000	16000	10000	30.0000	500
Sec-tors	Comprehen-sive	Comprehen-sive	Comprehen-sive (contains other DBs incl. GEMIS)	Energy in particular	Chemicals	Comprehen-sive

	exiobase	Federal Commons	IDEA	CaLC	The ICE Database
Type of data	Input-Output	LCI data	LCI data	LCI data	Energy / CO_{2eq}
Region	Global, divided into coun-tries/regions	USA	Japan	Global, divided into coun-tries/regions	No differenti-ation
Sub-ject to charg-es	No	No	Yes	No	No
Up-to-date-ness	Sporadically updated	Regularly updated	Regularly updated	Partially outdated	Regularly updated
Data rec-ords	200 products	9200	3800	Not specified	200 materials
Sec-tors	Comprehen-sive	Comprehen-sive	Comprehen-sive	Comprehen-sive	Comprehen-sive

The example of aluminium is used to illustrate the degree of coverage of the three databases ecoinvent, GaBi and ProBas:

- ecoinvent offers a total of 183 data records on 44 products and processes (raw materials, intermediate products, semi-finished products, scrap groups, etc.) relating to the raw material aluminium. 50 of these data records are market data records, which indicate the average production or consumption mix of a country or region. These market data records are particularly necessary when no specific information on the exact origin of the materials is known (e.g. recycling share, production process, etc.). The ecoinvent database also provides coverage of up to eleven countries/regions for the key products, such as primary aluminium. The data is verified externally according to a standardised procedure and is thus quality-assured. Since the individual sub-processes can also be viewed, the database is transparent and comprehensible.

- With 133 products and processes, the GaBi database offers a much broader selection. This high number is due in particular to the large number of different aluminium alloys that GaBi offers from primary and secondary sources (ores and scrap). However, despite the wide range of products and processes, the number of data records is similar to ecoinvent with 211 records. This is directly due to the fact that GaBi offers country coverage of up to a maximum of five countries/regions. In addition, only eleven market data records are available.

- The ProBas database offers a total of 55 data records on aluminium. These data records mainly cover the raw material aluminium (primary and secondary). Hardly any products or intermediate products are included. For primary aluminium, the ProBas database covers eight countries/regions. The main shortcoming of the data records is their up-to-dateness. Only twelve data records have 2020 or 2030 as the reference year. However, these are not current data records, but future scenarios for these years that were already created several years ago.

In addition, the database as a whole is supplied by a large number of very heterogeneous sources and therefore exhibits some methodological inconsistencies. The data is also not externally peer-reviewed, as it is for the ecoinvent database.

In summary, it can be said that ecoinvent provides a particularly broad global coverage as well as a large number of market data records. The product and process depth is also high. GaBi offers a very high degree of product and process depth, but has disadvantages in terms of global coverage and market data records. ProBas only contains the essential products and processes and has acceptable global coverage. However, the up-to-dateness and quality of the data are currently not acceptable.

In the following Figure 11, some data records of the ProBas database (without the incorporated databases) are compared to those of the ecoinvent and GaBi databases. The blue data points show the comparison between ecoinvent - ProBas, and the orange data points the comparison between GaBi - ProBas. If the points lie on the straight line, the values of the two databases compared are identical, whereby it must be noted that the scale is double-logarithmic. One “box” corresponds to a deviation by a factor of 10, a third of a "box" corresponds to a deviation by 100% (factor 2).

Even between the values of ecoinvent and GaBi, large deviations can occur (e.g. pumice or construction gravel). This highlights the (in)accuracy of corresponding calculations when generic data is used. The values from ProBas tend to follow a similar course as the values from GaBi and ecoinvent. However, some data points deviate significantly from the straight line. Since it is a log-log scale, even small deviations from the straight line mean significant differences in the values.

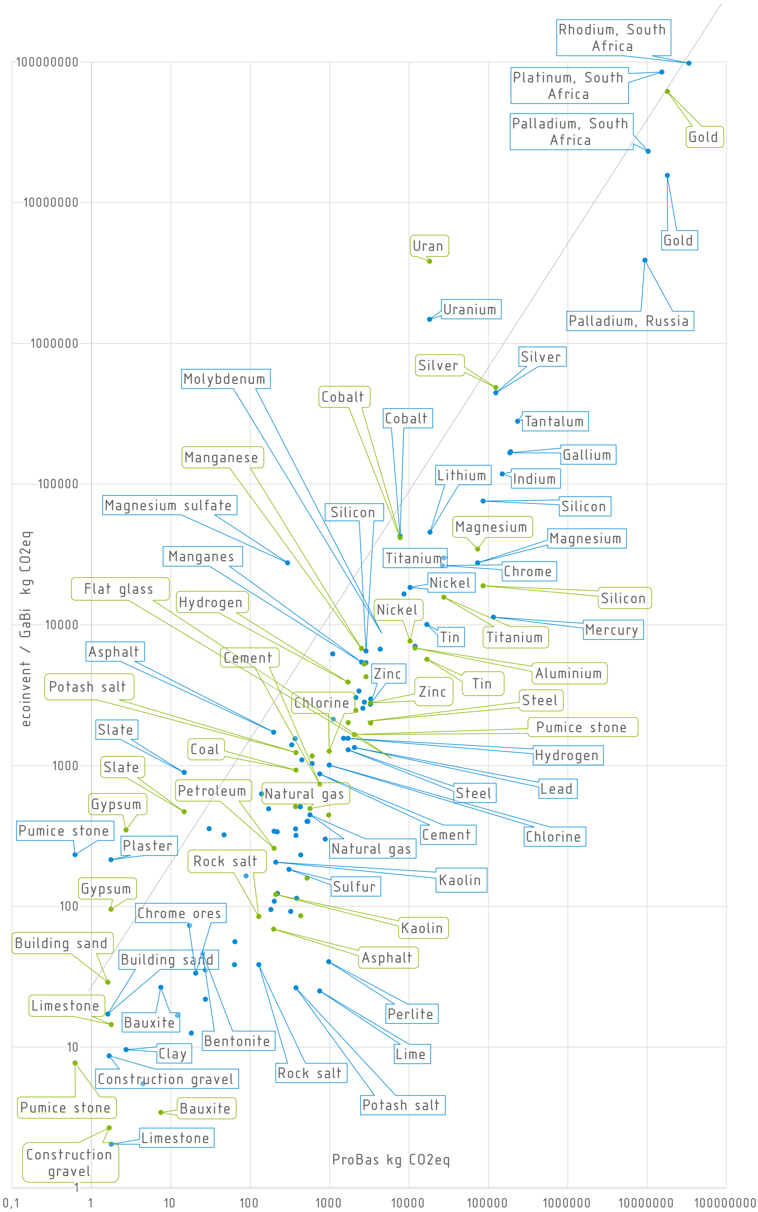


Figure 11: Comparison of selected ProBas data with the ecoinvent (blue) and GaBi (green) databases (own figure)

This database comparison also shows that the GaBi database does not contain any data records for some of the materials listed in ProBas and ecoinvent (e.g. tantalum, gallium, indium, chromium, numerous ores and ore concentrates, etc.).[31]

During the course of the project, it also became apparent that there is a great deal of interest in freely available data on emission factors. In the meantime, this wish has been partly fulfilled with the BAFA list[32]. In addition, the ProBas database is set to be upgraded in the future. All current developments have been taken into account in the development of the ESTEM calculation procedure (see Chapter 4.4).

2.2.3 Material taxonomy

In the context of this project, material taxonomy means the granularity or level of detail of the materials available in the databases. How deep should the level of detail be? For example, are the most common metals sufficient or must they be broken down to the last special alloy? In order to be able to answer these questions, two things need to be investigated: firstly, how much the materials differ in their GHG emissions and which criteria are decisive for this. Secondly, it must be investigated which materials used by German companies account for the largest shares of total emissions and thus have the greatest relevance.

Differences and important factors influencing the GHG emissions of the materials

Figure 12 shows the GHG emissions of some of the most common material groups. The most important materials of the respective groups are shown as range points (e.g. PE, PP, PVC, etc. for plastics). The data used for this are values averaged over world production.

[31] The Professional Database and all Extension Databases were taken into account. Data on demand is excluded from the analysis.

[32] Cf. BAFA (2021).

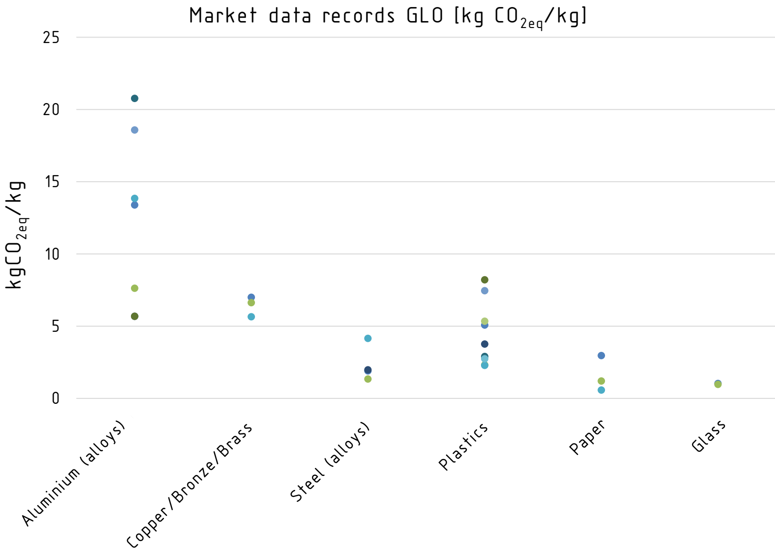


Figure 12: Scatter range of global average GHG emissions in kg CO_{2eq} per kg for individual materials from the most common material groups (ecoinvent V 3.7) (own figure)[33]

This chart shows:

(1) In some cases, the GHG emissions of the different material groups differ greatly from each other. This is directly attributable to the different efforts required in their production. For example, aluminium has to be electrolytically refined with very high energy input, whereas paper and glass can be produced with relatively little energy.

(2) It is also clear to see that the ranges of the respective materials within the group can vary greatly in their GHG emissions. This is essentially due to the following things:

33 Editorial note: Due to usage rights, the values are anonymised.

- A material group contains similar, but not identical materials (e.g. different plastics, which are also produced differently in some cases, or different alloys).

- The same materials can also be produced using different production techniques and/or from different raw materials (e.g. scrap or ore).

- The processing stage of the materials can also have an impact on GHG emissions. This is discussed in more detail in the following chapter.

Another influencing factor that does not come into play in this global average consideration is the region of material production. Different countries/regions of the world have different electricity mixes with varying GHG emissions. This will also be discussed in detail in the next chapter.

In Figure 13, five “special material groups” from Figure 12 are added. This shows that the GHG emissions of such special materials can deviate significantly from the usual material groups and must therefore be treated separately if they are relevant for the studies in question.

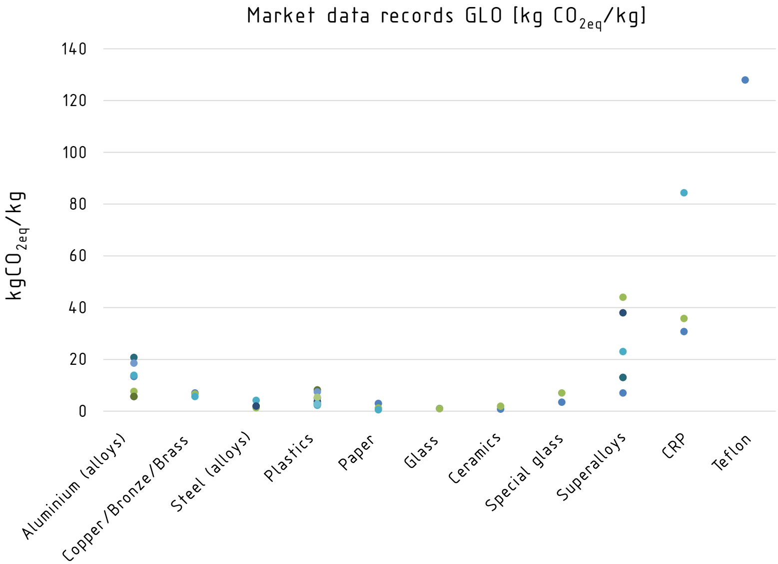


Figure 13: Scatter range of global average GHG emissions in kg CO_{2eq} per kg for individual materials from the most common material groups and for five special material groups (ecoinvent V 3.7; GaBi database) (own figure)[34]

The fact that metals cannot be grouped together in one material group is already clear from Figure 12 and Figure 13. A more comprehensive analysis of this can be found in the logarithmic representation based on Nuss and Eckelmann (2014) in Figure 14.

This shows that, depending on which ones are examined, metals can cause GHG emissions of between 0.3 kg CO_{2e}/kg to 35,000 kg CO_{2e}/kg in their production. The typical bulk metals such as iron or aluminium are located on the right-hand side of the diagram. Technology and precious metals are mainly found on the left-hand side in the area of high emissions. A differentiated consideration of metals is therefore imperative.

[34] Editorial note: **Due to user rights, the values are anonymised.**

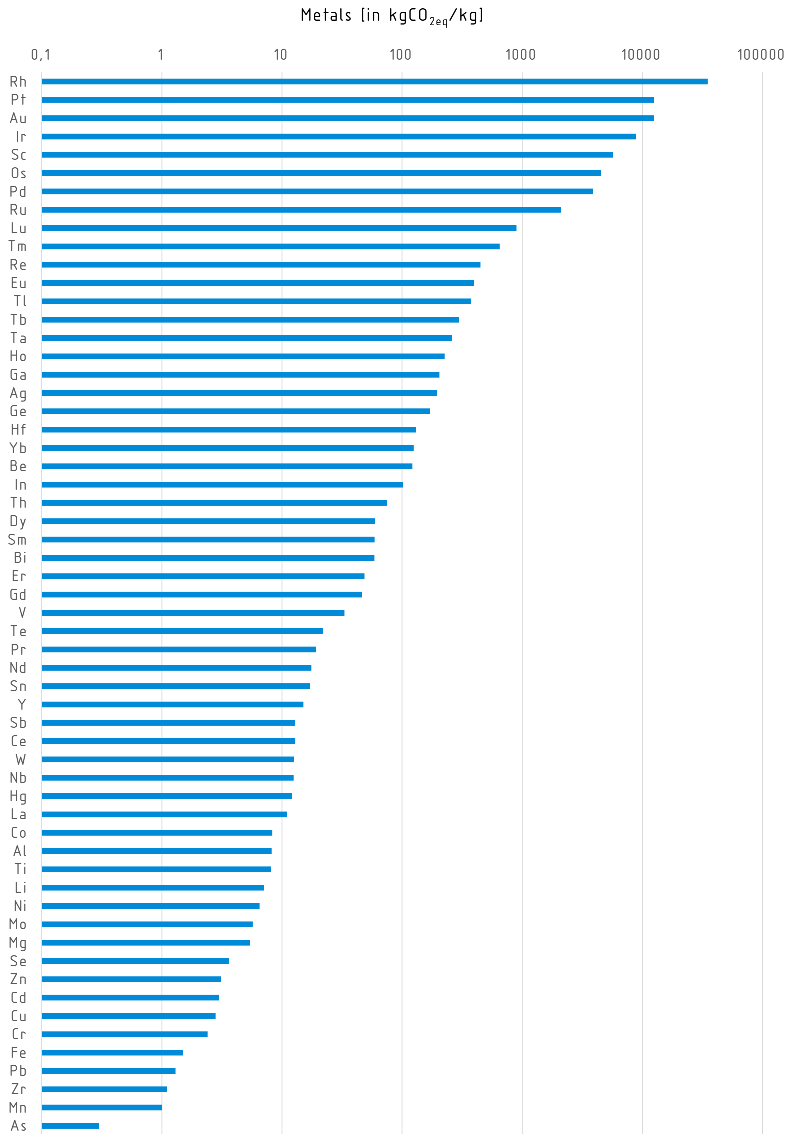


Figure 14: Scatter range of average GHG emissions in kg CO_{2eq} per kg of metals[35]

[35] Own figure based on Nuss and Eckelmann (2014).

Key influencing factors

Using metals as an example, the most important factors influencing the GHG emissions of materials, which were already identified in the previous chapter, are examined in more detail below.

Different alloys

Figure 15 shows the GHG emissions of various steel alloys. This shows that the GHG emissions of most alloys are very similar. Only the stainless steel alloys deviate from this. In this case, it is advisable to provide a higher level of detail and distinguish between ordinary steel or ordinary steel alloys and stainless steel alloys. The situation is similar for other metals. In the case of aluminium, for example, a distinction should be made between casting alloys and wrought alloys.

Figure 15: Scatter range of German average GHG emissions in kg CO_{2eq} per kg of various steel alloys (GaBi database) (own figure)[36]

[36] Editorial note: **Due to usage rights, the values are anonymised.**

Different production routes

Using the example of copper, the influences of the different production routes on the resulting GHG emissions are illustrated in Figure 16. While the global average value across all countries and production routes is about 7 kg CO_{2e}/kg copper, the value for copper extracted from a gold mine can be about 2 kg CO_{2e}/kg. The other extreme is found for copper as a by-product of platinum extraction with approx. 15 kg CO_{2e}/kg.

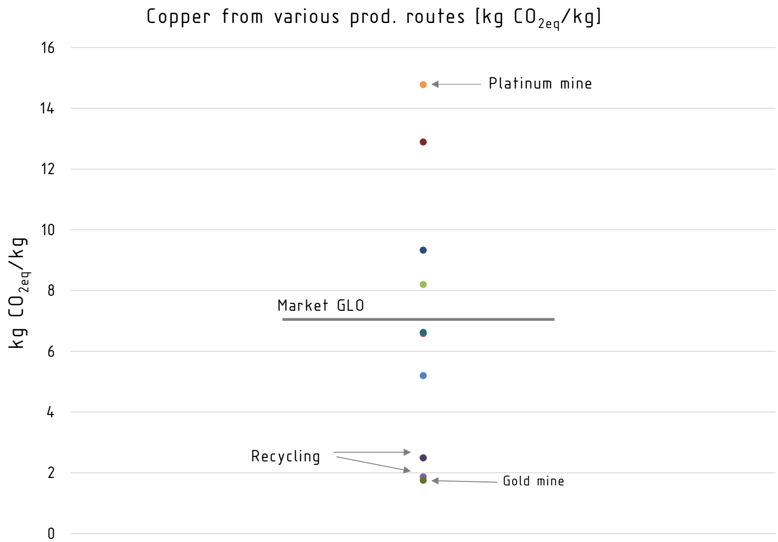


Figure 16: Scatter range of the average GHG emissions of various copper production routes and the global market average (ecoinvent V 3.7) (own figure)[37]

A differentiation according to production routes is recommended based on this evaluation. At this point, however, the question of practicability must also be raised. Only a few companies can trace their materials back to their exact origin and therefore do not have the necessary information to differentiate according to specific production routes. Providing consistent and sound global averages of key materials across primary production routes is therefore seen as an appropriate tool here. In the case of recycling, mean-

[37] Editorial note: **Due to usage rights, the values are anonymised.**

while, a differentiated consideration is suggested, as the use of recycled materials is mostly known to companies and/or even represents a popular measure for reducing GHG emissions.

Different processing stages

In Figure 17, the example of steel shows the extent to which GHG emissions can vary at different processing stages. Although the differences are not as great as, for example, for different production routes, the two extremes still differ by about 100%. Since it can be assumed that companies have knowledge about the processing depths of the materials they use, it is recommended to make a rough differentiation, e.g. on the basis of the three stages of processing depth or according to the most common processing types (pipes, coils, etc.).

Figure 17: Scatter range of global GHG emissions in kg CO_{2eq} per kg of steel products with different processing depths (ecoinvent V 3.7; worldsteel) (own figure)[38]

[38] Editorial note: Due to usage rights, the values are anonymised.

Different production regions

Different regions of the world have different electricity mixes with different GHG emissions as well as different environmental standards. This has a direct impact on the GHG emissions of the materials and goods produced in the regions. This is illustrated below in Figure 18 using aluminium as an example.

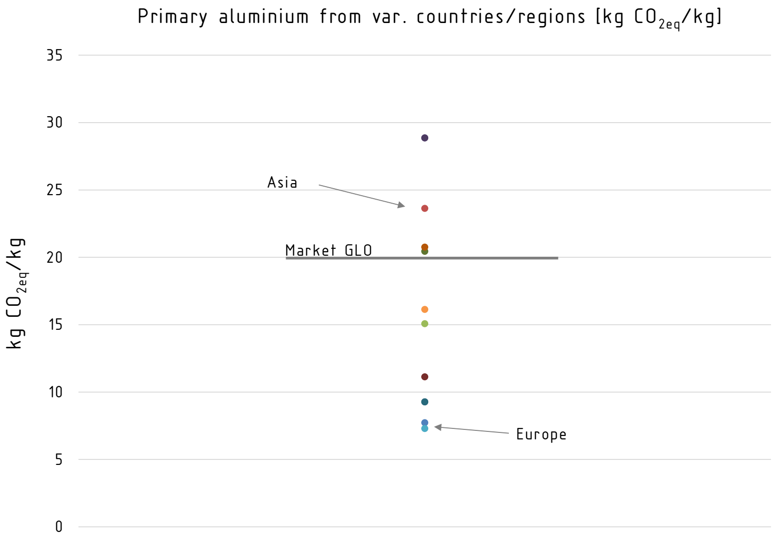


Figure 18: Scatter range of GHG emissions in kg CO_{2eq} per kg of primary aluminium from different production countries/regions and the global market average (ecoinvent V 3.7) (own figure)[39]

Similar to the case of the different production routes, the GHG emissions also deviate significantly from the global average value in a differentiated consideration of regions. However, unlike in the case of production routes, companies can usually determine from which countries/regions their purchased goods and materials originate. A differentiated consideration by country or region of origin is thus classified as necessary and practicable.

[39] Editorial note: **Due to usage rights, the values are anonymised.**

2.2.4 Conclusions

In principle, the professional databases provide an extensive pool of data relating to materials. The quality and up-to-dateness of the data varies, which is why the selection is difficult for non-experts. One has to be able to rely on having chosen the right data records. The freedom of choice in methodological assumptions of LCA and PCF (e.g. attributional vs. consequential or various allocation rules) tends to lead to errors. Moreover, the assumptions and empirical data incorporated into the data records are not always fully comprehensible. This makes it difficult to compare results.

LCA or CF data is highly dependent on the following factors:

- The choice of technology and level of modernisation in production; this depends largely on the year and country of the survey,
- the energy mix used,
- coverage of the relevant input and output flows in the respective processes,
- market composition; this can change within a few years,
- determination and allocation in multi-product systems (e.g. in the recycling sector, but also in the use of biogenic raw materials); they are often used based on different rules and with a lack of transparency,
- consistent linking of all data records in a kind of "world model".

Regarding the last point, it should be said that according to standard LCA methodology, all data records are linked in an overall model. However, this requires not only a collection of data, but also the possibility for a computational linkage. This is essential if, for example, the respective country-specific processes for electricity generation or the current steel data are also to be taken into account for the production of materials.

With regard to material taxonomy, the origin of the materials is often more decisive than the variation in the composition and quality of the materials. For the differentiation of materials, one should also be guided by their absolute relevance for the climate. For example, the consideration of different processing stages or alloys makes sense for steel or aluminium, but is rather irrelevant for technology metals.

From these points it follows that the LCA or CF data for materials should at least

- be up-to-date and from a comparable reference period,
- include the respective production chain with the corresponding current and country-specific energy mixes,
- take into account the supply situation, e.g. in Europe or Germany, according to the current market composition,
- take into account a minimum set of relevant input and output flows in their production chain (e.g. all major GHG emissions),
- focus on material flows relevant for climate protection,
- transparently document all assumptions, especially on allocations.

Furthermore, it would be preferable if the data came from a uniformly linked and common overall model (see above).

These points show how it is inappropriate to search for and compile data more or less randomly from arbitrary sources, and illustrate the need to establish comparable levels of up-to-dateness, quality and consistency. To this end, a methodically coordinated procedure as well as a certain longevity in the provision of quality-assured data are obligatory.

Since professional databases are associated with considerable costs, many users in practice resort to freely available data. Here, the stipulated requirements with regard to quality, up-to-dateness and methodological consistency of the data are rarely met. However, it is important that alternatives are made available especially for small and medium-sized enterprises that do not want to or cannot afford the corresponding software and data from professional providers.

In a project of the Federal Environment Agency from 2011, the ifeu Institute Heidelberg created eco-profiles of around 130 different materials (see Table 5), some of which were also made available in ProBas.[40] These profiles cover a large part of the most important imported goods and can be used as a guide to the carbon footprint of materials. However, the data has not been updated since then and therefore does not meet the above requirements.

It would be conceivable to make such standard data available again for a limited set of materials (approx. 200 - 300 materials). The data would have to be updated or newly collected, quality assured and transparently documented. This has already been done in part with the BAFA list[41]. It would also make sense to take into account the reference period and origin as well as to update the data on a regular basis in order to reflect the dynamics of the energy transition in Germany and other countries. Furthermore, the data should be integrated into a consistent calculation environment (see above). Above all, however, it would be important to make this data permanently available.

The selection could include raw materials in the narrower sense (e.g. metals), but also semi-finished or intermediate products that are important for the industry, and ideally be based on the absolute contribution to the national GHG inventory. In addition, the data collected should not only refer to GHG, but also include other important environmental impacts. The associated effort is not significantly greater, but could conversely serve as an aid if environmental trade-offs arise.

[40] Cf. Giegrich et al. (2012), p. A1 – A131.

[41] Cf. BAFA (2021).

Table 5: Selection of environmental profiles created by IFEU 2011[42]

Metals and ores	Mineral raw materials	Semi-finished and finished goods
Aluminium	Andalusite, disthene	Cotton fabric
Arsenic	Asbestos	Fuel elements
Bauxite	Asphalt	Computers
Lead	Barite	Flat glass
Chromium	Barium carbonate	Laptops
Chromium ores	Building gravel	LDPE
Iron	Building sand	PET
Iron ore (2)	Bentonite	Cars
Gallium	Pumice stone	Steel
Gold	Borates	Styrene
Ilmenite concentrates	Industrial diamonds	Newsprint
Indium	Fluorspar	Naphtha
Iridium	Rock flour	Ethylene
Cobalt	Gypsum	
Cobalt ores	Mica	
Copper	Graphite	**Energy raw materials**
Copper ores & conc. (4)	Potash salt	Natural gas
Lithium	Lime	Crude oil
Magnesium	Limestone	Hard coal
Manganese	Kaolin	Uranium
Manganese ore	Diatomaceous earth	
Molybdenum	Chalk	
Molybdenum ore	Cryolite	**Biotic raw materials**
Nickel	Clay	Field bean
Niobium and tantalum conc.	Magnesium carbonate	Forage crop (silage maize)
Osmium	Magnesium sulphate	Vegetables (white cabbage)
Palladium (2)	Natural stone, unbroken	Cereals (winter wheat)
Platinum (2)	Pegmatite sand	Grassland
Mercury	Perlite	Root crops (potato)
Rhodium (2)	Phosphate (2)	Commercial crops (rape)
Ruthenium	Quartz, quartzites	Hardwood
Selenium	Quartz sand	Softwood
Silver	Slate	Fruit (apple)
Silicon	Emery, corundum, garnet	Beet leaf
Tantalum	Evaporated salt	Straw (winter wheat)
Thallium	Silimanite	
Titanium	Soapstone	
Bismuth	Chippings, grains of marble	**Other**
Tungsten	Rock salt	Chlorine
Zinc	Talc, talcum	Phosphorus, white
Zinc ores	Peat	Oxygen, liquid
Tin	Trass	Sulphur
	Tuff	Nitrogen, liquid
	Vermiculite	Hydrogen
	Cement	UCTE electricity

[42] Cf. Giegrich et al. (2012).

More detailed or other data records (e.g. subdivision of the metal data records into the different alloys and processing forms) would still have to be created by appropriate professional providers. It is important not to create a competitive situation here.

The discussion about the different databases is ultimately essential for the development of a calculation tool, as appropriate data has to be integrated here. Please refer to Chapter 4.4 on this topic.

2.3 Assessment tools

2.3.1 Overview and requirements

Today, a variety of software solutions and simple web tools are available in different forms for preparing life cycle assessments and GHG inventories: From freely accessible and very simple CO_2 calculators that allow private individuals to estimate their personal carbon footprint, to commercial software solutions and web tools for the comprehensive calculation of corporate carbon footprints, to expert tools from the field of life cycle assessment. In addition to these offerings, there are also numerous service offerings available on the market for the preparation of corporate carbon footprints and life cycle assessments.

The requirements of the project for the assessment tool result from the discussion about the methods, the required data and easy handling for users in the companies. With regard to the objective of the project, the software solutions and web tools for the calculation of the corporate carbon footprint are of particular importance. They can usually be used without significant prior knowledge and allow an initial assessment.

LCA tools, on the other hand, are much more complex, but allow for more flexible and detailed analyses and are generally suitable for mapping complex situations or measures. Since they require considerable expertise and the objective of the project is to make their use as low-threshold as possible, even for laypersons, they have been left out of the following detailed analysis. In Table 6, which provides an overview of the most important key data of the numerous assessment tools, they are, however, listed for the sake of completeness.

Table 6: Available assessment tools and their key data

Tool	SMART 3	CO_2-Rechner (CO_2 calculator)	Eco-cockpit	CCF. Navi	ECO-SPEED Business	Foot-print Manager Foot-print Expert	Scope 3 Evaluator	ESM Software
Provider	myclimate	KlimAktiv	Effizienz-Agentur NRW	Energie-Agentur NRW	Ecospeed	Carbon Trust	GHG Protocol, Quantis	WeSustain GmbH
Application	CCF (Scope 1,2,3)	CCF (Scope 1,2,3)	CCF (Scope 1,2,3), PCF	CCF (Scope 1,2,3)	CCF (Scope 1,2,3), PFC, PEF	CCF (Scope 1,2,3), PCF	CCF (Scope 1,2,3)	CCF (Scope 1,2,3)
Method	GHG Protocol, ISO 14064	GHG Protocol, ISO 14064	GHG Protocol	ISO 14064, GHG Protocol	GHG Protocol, ISO 14040/44, 14064, 14067	GHG Protocol, PAS 2050, ISO 14067	GHG Protocol	Not specified
Application	Various incl. Dyson, Lufthansa	Various incl. Schaeffler, Melitta	Various incl. Roth, Dyckhoff	Not specified	Various incl. Stawag, Sparda Bank	Various incl. Samsung, Danone	Not specified	Various incl. ThyssenKrupp
Commercial	Yes	Yes	No	No	Yes	Yes	No	No
Software	Web-based	Software as a Service	Web-based	Web-based	Web-based	Cloud-based	Web-based	Web-based
Language(s)	Multi-language	German	German	German	Multi-language	English	English	German
User-friendliness	High	High	High	High	High	High	High	High
Configurability	Individually configurable	Div. licensing models	None	None	Customising possible	Not specified	Not specified	Not specified
Databases used	ecoinvent	GEMIS, data from studies, public data (incl. IEA)	GEMIS, ProBas, Ökobaudat	GEMIS	None	Not specified	Mainly IO data (WIOD), ecoinvent (V2.2.), eGRID	DEFRA, ecoinvent

Table 6: Available assessment tools and their key data (continued)

Tool	SCO_2PES	CCalC2	GaBi	GEMIS	umberto	OPEN LCA	Símpa Pro	ease-tech
Provider	Global Climate	University of Mancheste r	Sphera	IINAS	IFU	Green Delta	Pré Sustainabi lity	ESATECH
Application	CCF (Scope 1,2,3)	LCA	LCA	LCA	LCA	LCA	LCA	LCA (heterogen eous material flows, waste managem ent)
Method	Not specified	ISO 14044, PAS 2050	ISO 14040/44	ISO 14040/44	ISO 14040/44	ISO 14040/44	ISO 14040/44	ISO 14040/44
Application	Not specified	Not specified	Various incl. VW	Not specified	Various incl. Miele	Various incl. BASF	Various incl. Huawei	Mainly research
Commercial	Yes	No	Yes	No	Yes	No	Yes	Training subject to a charge
Software	Software as a Service	Software	Software	Software	Software	Software	Software	Software
Language(s)	German, English	English	Multi-language	German	English, German	English	Multi-language	English
User-friendliness	High	Medium	Complex, expert tool	Complex, expert tool	Complex, expert tool	Complex, expert tool	Complex, expert tool	Complex, expert tool
Configurabil ity	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Databases used	Based on monetary data	CCalC database, ecoinvent	GaBi, ecoinvent, USLCI database	GEMIS	GaBi, ecoinvent	Numerous databases possible	Numerous databases possible	Numerous databases possible

2.3.2 Brief description and evaluation of the most important assessment tools

The first screening of the assessment tools available on the market shows that the methodological and conceptual differences are only very minor. The basic structure is always the same:

(1) The required physical data is collected or entered into the categories provided for this purpose (e.g. energy consumption, material use, etc.). Via this entry into defined categories (e.g. external electricity purchase, own generation, material purchase, etc.), an allocation to the scope categories takes place automatically.

(2) In the background, the entered data is linked to the LCI or CO_{2e} data of a stored database. Only the Scope 3 Evaluator, which is made available via the GHG Protocol Initiative and Quantis, supplements this procedure with an extended input-output analysis based on monetary data for some of the scope 3 categories.

In a further step, selected assessment tools were examined in more detail in several categories relating to practicability. For this purpose, a direct exchange with the providers as well as direct tests of the tools took place. The selection of the tools was based, among other things, on the general market penetration of the tools, the relevance of the tools for relevant stakeholders and (potential) users (which come from other projects of the authors, including 100 companies) and their expert assessments. Four of the six tools examined in more detail (the CO_2 calculator from KlimAktiv, Smart 3 from myclimate, Sco$_2$pes from Global Climate and ecocockpit from efa-nrw) were also presented by the companies or institutions in the course of the project workshop on 26 January 2021.

The qualitative findings of this analysis are summarised in the following Table 7. A detailed description of the results is also given below.

Table 7: Evaluation results of the tools

	CO_2-Rechner (CO_2 calculator)	SMART 3	Eco-cockpit	Ecospeed business	Scope 3 Evaluator	Sco2pes
User-friendliness	Very high	High	Very high	High	Medium	High
Implementation effort	Very low	Low	Very low	High	Low	Very low
Quality of results	Medium	Medium	Medium	No data	Low (Scope 3 comprehensive)	Very high
Presentation quality	High	Medium	High	Very high	Medium	High
Integratable in ERP system	Planned	API interface	None	Semi-automated	None	Yes

KlimAktiv – CO_2 calculator for enterprises

User-friendliness

The web-based tool is simple and intuitive to use. The user interface is self-explanatory. There are only a few processing steps, which have a logical sequence. A negative aspect is that the units of the data to be entered are fixed. There is no possibility to change them (e.g. from kWh to MJ) and thus spare the users possible conversions. One advantage is that the most important information on the background data can be called up for each data record entered. A graphical representation of the GHG emissions for the respective category/sector (purchasing, transport, production, etc.) is already available when entering the data.

Users are provided with a quick guide and a detailed manual.

Implementation effort

The implementation effort can be classified as very low. By preselecting the industry, the most important or typical input options for the respective industry are preselected. For example, in the classic service industry there are hardly any material selection options, whereas in the mechanical engineering industry this selection is much more extensive. The tool is thus kept intentionally simple and lean. The data is entered manually; basic knowledge is advantageous for this.

Quality of results

By rounding to two decimal places, the results suggest an accuracy that can never be true in such analyses. In addition, some of the underlying databases are very outdated, which further reduces the quality of the results.

The possibility to assess the quality of the entered data via three categories (high, medium, low) during data entry has no effect on the result, but is merely a visual aid, e.g. for external experts.

Currently, only the upstream of scope 3 is recorded via the background data (e.g. the ecological backpack of materials). There was no possibility to record the downstream (especially the use phase).

Presentation quality

The assessment tool allows two graphical representations: Bar chart and pie chart; bars by sector, pie chart by scopes. In addition, explanations of the scopes are given. Output of the results as a PDF document is possible.

Integratable in ERP system / interface for data import?

Being planned/developed

myclimate – Smart 3

User-friendliness

The Smart 3 tool is relatively simple and intuitive to use. The clarity and general presentation quality of the tool are to be classified as rather low. The units are not variable, which can make data entry difficult. Data is entered in direct comparison to the data of the previous year. An additional Excel® document is provided for recording the commuting of employees.

Users are provided with a detailed manual.

Implementation effort

The implementation effort can be classified as low. The data is entered manually. Especially when evaluating the results, at least basic knowledge is necessary.

Quality of results
By rounding to two decimal places, the results suggest an accuracy that can never be true in such analyses.

Currently, only the upstream of scope 3 is recorded via the background data (e.g. The ecological backpack of materials). There is no possibility to record the downstream (especially the use phase).

Presentation quality
The tool offers four graphical representations. These includes time series analyses, breakdown by sectors/categories, scopes, etc. The input data and data analyses can be exported to Excel®.

The general data analysis or evaluation is unclear and relatively complex. There are numerous evaluation options (free selection of the years to be analysed, scopes, input data, etc.) that are not intuitive to use.

Integratable in ERP system / interface for data import?
API interface

Effizienz-Agentur NRW – ecocockpit

User-friendliness
The ecocockpit is simple and very intuitive to use. The tool is laid out in an extremely clear way and the presentation quality is very good. Some of the units can be changed, which can facilitate data entry. When entering data, the underlying background database is displayed (mostly GEMIS) as well as its quality assessment.

Users are provided with a detailed manual.

Implementation effort
The implementation effort can be classified as very low. The data entry is manual and can be carried out without prior knowledge.

Quality of results

Currently, only the upstream of scope 3 is recorded via the background data (e.g. the ecological backpack of materials). There is no possibility to record the downstream (especially the use phase).

Presentation quality

The presentation of the results is very clear and sufficient, although only one graphical representation is available. The general data preparation is very good. By dividing the total greenhouse gas emissions into percentages for the input data (electricity, materials, etc.), hotspots can be identified quickly and easily. The results are also presented in such a way that they can be easily understood by laypersons (e.g. comparison with easy-to-understand examples).

Integratable in ERP system / interface for data import?

Cannot be integrated, no interfaces for data import.

Ecospeed – Ecospeed Business

User-friendliness

Ecospeed Business is a clearly laid out web tool, but requires a short introduction and familiarisation phase. The structure is not very intuitive. The tool is designed to be managed centrally (important basic settings, electricity mix, etc.). Data entry by the respective departments (e.g. production) should then take place decentrally. Joint work in the tool/project is possible. Different access authorisations can be assigned.

A manual is available. In addition, a comprehensive introduction to the tool is provided.

Implementation effort

The implementation effort is quite high. The structure is modular; for example, individual accounting units/divisions (production, development, etc.) have to be defined in advance. It can then be selected which categories are relevant for the respective accounting unit (buildings, materials, energy, mobility). Data can be entered directly in the tool (for experts) or via a special input screen in table form (for laypersons).

The settings to be made by the division are relatively comprehensive and require specialist knowledge. For example, the efficiency levels of self-consumption CHP plants can be variably defined.

Quality of results

Background data for different energy mixes are available and can be variably compiled if necessary. The basis is IPCC data.

Beyond that, no background data is stored. Ecoinvent is to be introduced in May 2021 as an additional option. Ecospeed says it wants to keep the tool very transparent and consistent. That is why there is no background data so far. This means that at present, only scope 1 and scope 2 can be modelled (based on the energy data).

Presentation quality

The presentation quality and possibilities are very comprehensive and cover all conceivable options. Data export to Excel® is possible.

Integratable in ERP system / interface for data import?

No standard interface, usually semi-automated interfaces are implemented during customising.

GHG Protocol/Quantis – Scope 3 Evaluator

User-friendliness

For the most part, the Scope 3 Evaluator is clearly laid out, but not always intuitive to use. One advantage is that some units can be set variably. Monetary data (for the input-output analysis) can only be specified in US dollars.

Implementation effort

Users are asked about numerous specifics of the company (use of energy, purchase of goods, organisational structure, etc.). This manually entered data is linked by the tool to data from input-output statistics (in the case of monetary data) and LCI data (in the case of physical data). The tool is not intended for data documentation or for larger amounts of data. For categories that contain extensive data, it is suggested that only the 5, 10 or 20 most important items are used. Basic knowledge is an advantage.

Quality of results

The tool is basically intended to provide a first rough estimate of scope 3 emissions. Even though the tool follows the GHG Protocol recommendations, in many cases the calculated GHG emissions are only estimates and do not guarantee compliance with the scope 3 standard.

The Scope 3 Evaluator uses the World Input-Output Database and the Open IO Database. Scope 1 and 2 are quantified either via direct input of emissions or input of company data (monetary or physical). If this is not possible, scope 1 and scope 2 emissions can be estimated via sector-specific statistics. The tool distinguishes according to 15 scope 3 categories.

Presentation quality

The presentation is of medium quality. The results are presented in a general overview of the scopes and in a detailed list of the 15 scope 3 categories. Data export to Excel® is possible.

Integratable in ERP system / interface for data import?

Cannot be integrated, no interfaces for data import

Global Climate – Sco$_2$pes

User-friendliness

The Sco$_2$pes tool is very user-friendly and intuitive to operate. An integrated tool is available for calculating transport distances (road and air), among other things. The entry of suppliers makes it easy to record the transport routes.

Support is available.

Implementation effort

The implementation effort is reduced to a minimum through the direct import of the accounting data (in particular raw materials and supplies, energy inputs, etc. are stored in the accounting system). The subsequent manual entry of data that is not automatically imported from accounting is simple and intuitive. Basic knowledge is an advantage, but not necessary. Authors' assessment: For SMEs, this method of data transfer from accounting can be practicable; for larger companies and groups, the data stored in accounting is so diverse that the method is likely to reach the limits of practicability.

Quality of results
The software uses the ecoinvent database and accounting input data (e.g. material purchases by units of mass). As long as the accounting data is available in the units that match the LCA database, a very high quality of results can be assumed.

Presentation quality
The tool offers a very high presentation quality in graphical and tabular form, data export via Excel® is possible.

Integratable in ERP system / interface for data import?
SAP interface to ERP system and accounting system, further interfaces being planned (e.g. Microsoft Dynamics).

2.3.3 Conclusions

Currently, no simple software tools can be identified specifically for the area of climate effectiveness of material efficiency measures. The quality of the tools depends not only on their usability, but also on the methods and data on which they are based. In particular, the comparability of the results generated is likely to be severely limited. Ultimately, the methodological approach of the ESTEM calculation procedure cannot be covered by tools available on the market, which is why a pragmatic tool solution was developed in the ESTEM project (see Chapter 4.2).

2.4 Other projects

In order to record the initial situation, an overview was compiled of completed and ongoing projects that deal with the further development of methods, databases and tools for the evaluation of material efficiency measures. A systematic meta-study was conducted for this purpose. The procedure for conducting the meta-study is shown schematically in Figure 19 and Table 13.

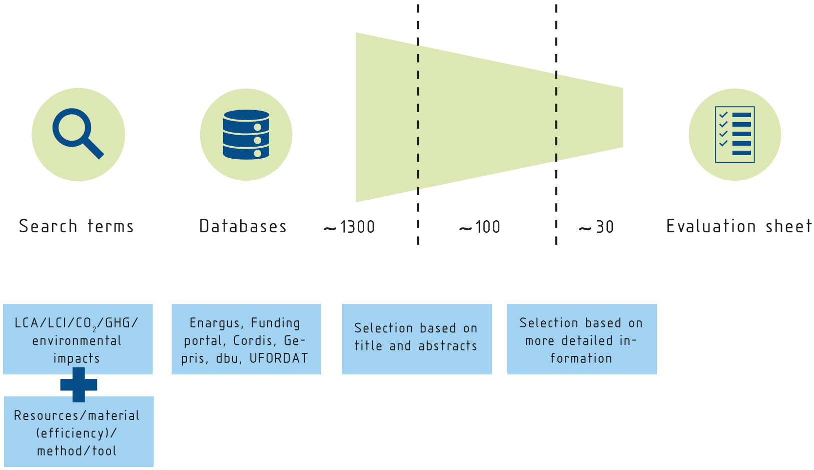


Figure 19: Conducting the meta-study

The projects were evaluated with regard to the following categories:

- Title, authorship, institutes/companies, period,
- Further developed method/database/tool,
- Data basis: Background database or own data,
- Object of study and scope of study (e.g. system boundary, location, time-related reference),
- Consideration of a baseline/reference state,
- Included materials and raw materials as well as industries.

The analysis shows that a large number of the projects examined are concerned with the further development or application of methods (14 projects), of which just under half use the method of life cycle assessment. While the development of a calculation tool is the subject of seven projects, two projects deal with the further development of databases. The most frequently used database is ecoinvent, followed by GaBi, or a combination of different databases.

In the projects, different definitions are given for the reference state or baseline. Depending on the project, the baseline is defined as conventional construction method, original technology, technological status before the measure or already existing real process. Most of the 14 projects analysed focused on individual sectors, such as the construction industry, the timber industry, or on individual raw materials, such as metals.

On this basis, it was finally classified which existing projects have the same characteristics as the ESTEM project. For this purpose, it was examined whether a method was newly developed in the project, whether material efficiency measures were the focus, whether a top-down or bottom-up approach was pursued, whether GHG emissions were calculated and whether the target group was companies. From this evaluation, it can be concluded that none of the projects had the same focus as the ESTEM project. This finding confirms the uniqueness and novelty of the project and makes it clear that the development of the methodology cannot be based exclusively on existing previous work, and that the development of a new approach is necessary.

3 ANALYSIS AND EVALUATION OF MATERIAL EFFICIENCY PROJECTS

3.1 Objectives and selection of the case studies

3.1.1 Objectives

In the following, 25 case studies of material efficiency projects in companies are evaluated with regard to the methods, data and tools used there to determine the greenhouse gas emissions saved. This evaluation serves as a basis for developing framework conditions and conceptual building blocks for the development of a standardised procedure for determining GHG emissions.

The material efficiency projects under consideration are analysed with regard to the following criteria:

I: General information (relating to the project)

- Characterisation of the company under consideration (industry, size, region)
- Brief description of the respective material efficiency measure(s) implemented in the project
- Analysis of the assessment method(s), database or assessment tools used to determine the GHG emissions saved

II Specific information (relating to each measure identified in a project)

- Focus (process-related, product-related, organisation-related)
- Considered scope of the system boundaries (impact on the raw material extraction, production, use and/or disposal phase, regional or global saving)

- Materials/material classes/material uses affected by the measure
- Definition of a current state as the reference state
- Specific data used for the assessment of the measure and the associated methods of data collection

For the evaluation of the project-related and specific information, the contents of the practical examples under consideration were clustered according to various characteristics relating to the company, measures and assessment methods

3.1.2 Selection of the case studies (material efficiency projects)

The selection of case studies for the ESTEM project took place in the period from October to November 2020. For this purpose, a total of 44 written documents on material efficiency projects from funding programmes of the participating federal states as well as two projects funded by the Federal Environment Agency were provided for pre-selection by the federal states involved in the project. From the submitted documentation, 25 case studies were selected so that the greatest possible representativeness could be achieved with regard to the participating federal states and the material efficiency measures implemented.

3.2 Methodical preparation of the evaluation of the case studies

Overview of the evaluation procedure

An initial review of the 25 case studies was carried out with regard to the objectives described above and the relevant criteria for the evaluation. On this basis, issues were identified that needed to be looked at in more detail or methodologically elaborated in order to carry out the evaluation. These issues concern on the one hand the terminology used, and on the other hand the verification of the completeness and, if necessary, the extension of the catalogue of VDI Guideline 4800[43], which was to be used as a basis for the identification of measures.

The procedures described below were developed for the aforementioned issues and were applied in the course of the evaluation.

Terminology

The catalogue used as the basis for evaluating measures of the material efficiency projects is presented in VDI Guideline 4800 as Table 1 (Figure 20) with the heading “Strategies for increasing resource efficiency”. Instead of the term “strategy” used in VDI Guideline 4800, the term "measure" is used in the present project, as this is more common in general usage for the circumstances described in VDI 4800.

Figure 20 shows the catalogue of VDI 4800:2016, which is referred to hereafter as the “VDI 4800 catalogue of measures”.

A further necessity for a terminological definition arose from the finding, after an initial review of the case studies, that the measures in the VDI 4800 catalogue were regularly combined in practice and not encountered individually. An earlier study on resource efficiency in the context of Industry 4.0[44] also came to a similar conclusion. With this in mind, the term "practical application" was adopted for the combination of measures.

A practical application “refers to the combination or expression of different measures or strategies encountered within actual companies”[45].

[43] Cf. VDI 4800:2016.
[44] VDI Zentrum Ressourceneffizienz GmbH (2017).
[45] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017), p. 75.

No.	Strategy	Related to		influencing parties in the company						Life phases with relevant effects					Life cycle analysis		
		Product	Production	Product development	Factory planning	Operations planning	Purchasing/Procurement	Production	Sales	Raw material processing	Product manufacturing	Use	Recovery/disposal	Transport	Required	conditionally required	Not required
1	Material choice / material substitution	●		●						●	●	●	●	●	●		
2	Lightweight design	●		●						●		●		●		●	
3	Mission match and safety	●		●						●		●					●
4	Miniaturisation	●		●						●	●	●	●	●	●		
5	Production-oriented product design	●		●		●		●			●					●	
6	Use-oriented product design	●		●								●		●	●		
7	Extension of technical lifetime	●		●						●	●				●		
8	Extension of product service life	●		●						●	●					●	
9	Product service systems (dematerialisation)	●		●						●	●	●		●		●	
10	Cascading use of products	●		●						●	●					●	
11	Reparability	●		●						●	●					●	
12	Recycling-oriented product design	●		●									●		●		
13	Adding instructions on user behaviour to the manual	●		●								●					●
14	Resource-efficient packaging design	●		●				●	●	●	●			●		●	
15	Manufacturing process selection and optimisation		●		●	●		●			●					●	
16	Equipment dimensioning		●		●						●						●
17	Minimisation of machine volume		●	●	●	●		●			●					●	
18	Substitution of auxiliary materials and operating supplies		●				●	●		●	●				●		
19	Dry machining and minimum quantity lubrication		●		●			●		●	●						●
20	Minimisation of planned loss		●	●		●		●		●	●						●
21	Minimisation of planned scrap		●			●				●	●						●
22	Avoidance of losses due to rework		●	●				●		●	●						●
23	Avoidance of losses due to disposal of finished products		●					●		●	●						●
24	Avoidance of losses due to disposal of purchased materials		●				●	●		●	●						●
25	Avoidance of losses due to improper storage or obsolescence		●				●	●		●	●						●
26	Reduction of energy consumption		●		●			●			●					●	
27	Efficient energy supply		●		●						●					●	
28	Use of process heat and waste heat		●		●			●			●					●	
29	Efficient building infrastructure		●		●			●			●					●	
30	Efficient building envelope		●		●			●			●				●		
31	Efficient cleaning		●	●	●			●		●	●		●			●	
32	Manufacturing-process related recirculation		●		●			●		●	●			●		●	
33	Cascading use of auxiliary materials and operating supplies																
34	Efficient transport		●		●		●	●	●	●	●			●			●
35	Complete and unambiguous product documentation		●	●	●	●		●			●						●
36	Detailed task descriptions and structured shift handovers		●		●	●		●		●	●						●
37	Employee qualification/employee potential		●	●				●			●						●

Figure 20: VDI 4800 Strategies for increasing resource efficiency (overview) [46]

Review of the VDI 4800 catalogue of measures for completeness

The VDI 4800 catalogue of measures was checked for completeness with regard to two topics, digitisation and circular economy.

[46] VDI 4800:2016, p. 38 f. Reproduced with permission of the Verein Deutscher Ingenieure e.V.

Digitisation

With regard to the question of whether the VDI catalogue should be expanded to include one or more measures from the context of digitisation, the relevant experience available at the TU Darmstadt from other research projects was called upon, in particular the study on resource efficiency in the context of Industry 4.0[47]. Based on the literature evaluation carried out there and the case studies examined, it can be said that independent digitisation measures for resource efficiency cannot be identified. Instead, digitisation measures have the function of an enabler for measures that are already known or listed in the VDI 4800 catalogue of measures:

For example, they lead to a reduction of scrap in production or to an increase in the energy efficiency of machines. For this reason, the VDI 4800 catalogue of measures is not expanded to include digitisation measures.

Circular economy

In order to review the topic area of "circular economy measures", the definition of waste management measures in § 6 (1) KrWG (Federal Circular Economy Act) was used, which were broken down into measures of prevention in the run-up to the generation of waste and measures of recycling in the sense of closing material cycles. As a result of this breakdown,

I. measures already contained in the VDI 4800 catalogue of measures were formulated more specifically or subdivided into more specific measures
   - Subdivision of measures 1 and 18 with regard to substitution by a) renewable raw materials, b) secondary raw materials
   - Conceptual clarification of measure 32 on production-related recirculation

[47] **VDI Zentrum Ressourceneffizienz GmbH (2017).**

II. additional circular economy measures were defined:
- **Measure 38:** Recycling of production waste
- **Measure 39:** Avoidance of waste through recycling of in-house materials

Adding these modified and new measures results in an extension of the VDI 4800 catalogue of measures that was used for the evaluation of the case studies.

3.3 Results of the case study evaluation

3.3.1 Overview of the presentation of results

The results are clustered around the themes of company, assessment method and practical applications/measures, as shown in Figure 21.

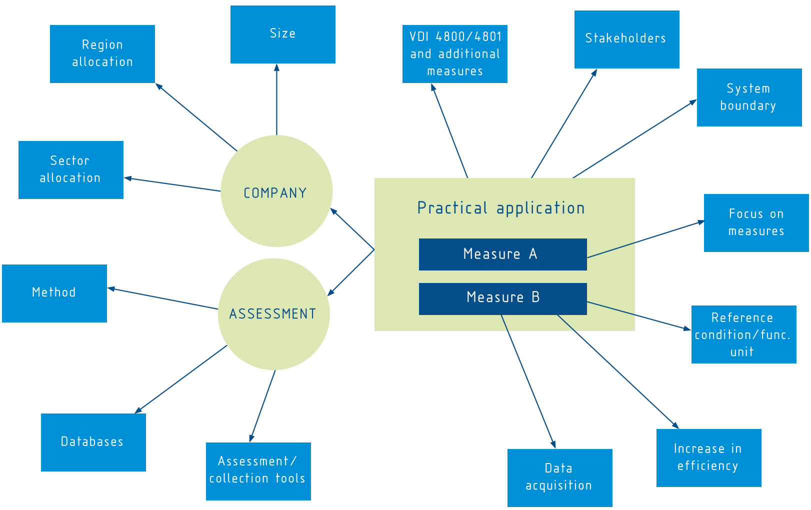
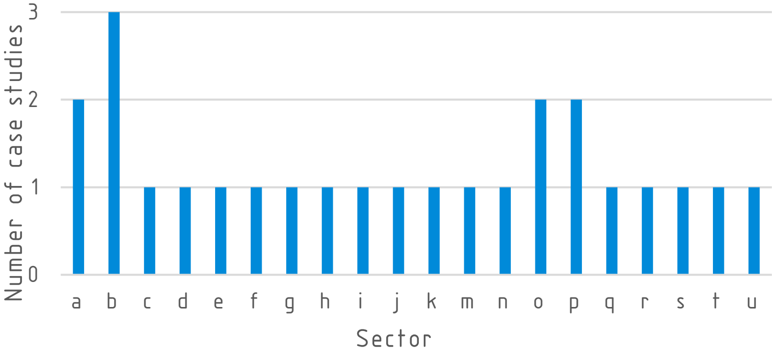


Figure 21: Representation of the clustering in relation to the themes of company, assessment methods and practical applications/measures (own figure).

The quantitative evaluation is presented in the following sections on the specified clusters. The other sections contain a summary of further qualitative results of the evaluation as well as the identification of topics for further method development.

3.3.2 Company-related information

The 25 case studies examined can be assigned to a total of 20 different sectors (Figure 22). Due to the broad distribution, each sector is represented by only one or a few case studies, so that no insights into sector-specific measures could be derived.



a Chemical industry
b Electrical industry
c Production and initial processing of other non-ferrous metals
d Automotive engineering
e Precision mechanics industry
f Production of coatings, printing inks and mastics
g Production of plastics
h Production of metal constructions
i Production of sheets, foils, hoses and profiles from plastics
j Production of other non-metallic mineral products
k Food production - coffee
m Mechanical engineering - manufacture of packaging machines
n Mechanical engineering - manufacture of web-type materials
o Metal production and processing
p Metalworking industry
q Mineral oil processing industry
r Surface finishing
s Surface finishing and heat treatment; mechanics
t Recovery of sorted plastics
u Writing instrument manufacturers

Figure 22: Sector composition of the evaluated case studies (own figure)

The case studies examined include small, medium and large enterprises. Small enterprises are those whose headcount is <50, medium enterprises are those whose headcount is >50 and <250, and large enterprises are those whose headcount is >250. The distribution can be seen in Figure 23. In terms of regional distribution, the examples come from the federal states of Hamburg, Hesse, Rhineland-Palatinate, Bavaria and Baden-Wuerttemberg.

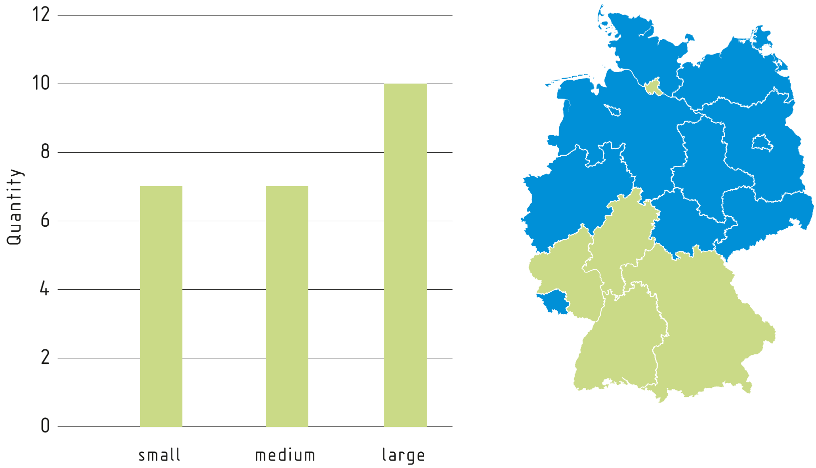


Figure 23: Company size and regional allocation of the case studies examined (own figure)

3.3.3 Assessment methods

The overview of the assessment methods used is shown in Figure 24:

No calculation	10				
CO_2 calculation	15	Number of complete LCA	4		
		Number of incomplete CO_2 calculations*	11	Only energy sourcing	4
				Consideration of individual materials	7

Identification of 36 specific emission factors in total
- Materials
- Energy-related (electricity, natural gas)

* (material/energy requirement* of specific emission factors from the literature)

Figure 24: Overview of assessment methods used (own figure)

In the 25 case studies examined, the CO_2 emissions saved are determined in 15 cases, four of which are based on a complete life cycle assessment (LCA). In the remaining eleven cases, the savings caused by the respective measures are determined with the help of specific emission factors. In four cases, only the GHG reduction achieved through energy savings is taken into account, i.e. material savings are not considered. In seven cases, the GHG reduction achieved through material savings is determined using emission factors from the literature. The necessary expenses, such as machine procurement, additional requirements for other operating materials, etc., have not been determined for the most part and are therefore not offset against the CO_2 savings achieved. A total of 36 specific emission factors were encountered in the case studies. Of these, nine emission factors are attributable to electricity and seven to natural gas.

Figure 25 shows the average specific emission factors used in the case studies, including their standard deviation. For five of the nine emission factors used, no sources are given, which means that it is not possible to check the causes of the deviation. In the case of natural gas, it was not always stated whether the specific emission factors refer to kWh_{el} or kWh_{th}.

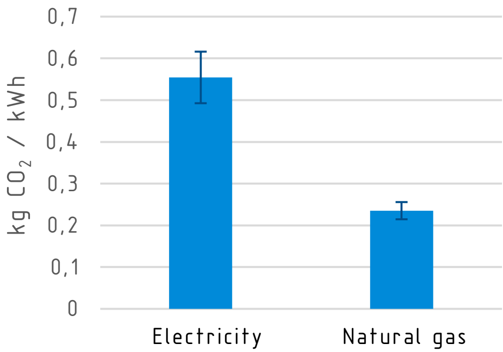


Figure 25: Specific emission factors for electricity and natural gas (own figure)

Emission factors for materials were given for 20 different materials. The data origin was only specified in about one third of all cases. In the case studies, two tools used to calculate CO_2 savings could be identified: the Excel® -based CO_2 calculator provided by the Infozentrum Umwelt-Wirtschaft Bayern and the calculation software GEMIS[48].

[48] Cf. Bayerisches Landesamt für Umwelt (2021).

3.3.4 Practical applications and measures

Within the scope of the study of the 25 case studies, 42 practical applications were identified. These comprise a total of 106 measures to increase resource efficiency (see Figure 26).

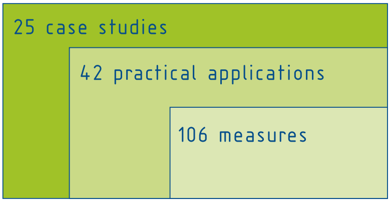


Figure 26: Case studies, practical applications and measures examined (own figure)

Different contributors are involved in the assessment, implementation and identification of material and resource efficiency measures within the company. An overview can be found in Table 8. The largest group of contributors involved is that of the external consultants. They were involved in 13 of the 25 case studies.

Table 8: Contributors involved

Internal					
Corporate management	**R&D**	**Procurement**	**Sustainability/Environmental Management**	**Operational area**	**Diverse (without specific allocation)**
3	2	2	1	2	3
External					
Delivering	**Customers**	**Advisory**	**Research facilities**	**Other**	
2	2	13	3	1 (General contractors)	

The distribution of the identified practical applications varies. The largest share is accounted for by process-related measures, just under half are product-related and just under a third are organisational measures to increase material and resource efficiency (see Figure 27).

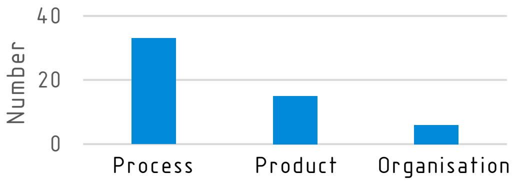
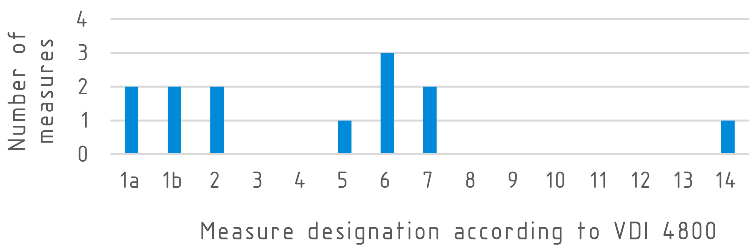


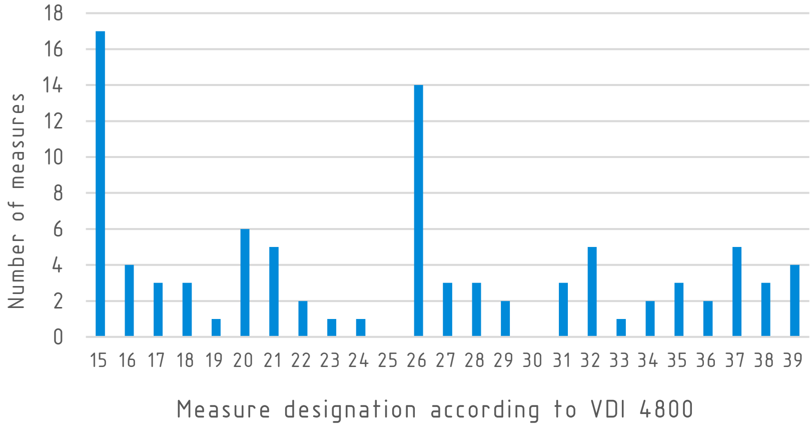
Figure 27: Focus of the practical applications (own figure)

The distribution of the groups of measures is shown in Figure 28 and Figure 29:



1a	Material choice/material substitution	8	Extension of product service life
1b	Use of secondary raw materials	9	Product service systems (dematerialisation)
2	Lightweight design	10	Cascading use of products
3	Mission match and safety	11	Reparability
4	Miniaturisation	12	Recycling-oriented product design
5	Production-oriented product design	13	Adding instructions on user behaviour to the manual
6	Use-oriented product design	14	Resource-efficient packaging design
7	Extension of technical lifetime		

Figure 28: Product-related measures (own figure)



15	Manufacturing process selection and optimisation
16	Equipment dimensioning
17	Minimisation of machine volume
18	Substitution of auxiliary materials and operating supplies
19	Dry machining and minimum quantity lubrication
20	Minimisation of planned loss
21	Minimisation of planned scrap
22	Avoidance of losses due to rework
23	Avoidance of losses due to disposal of finished products
24	Avoidance of losses due to disposal of purchased materials
25	Avoidance of losses due to improper storage or obsolescence
26	Reduction of energy consumption
27	Efficient energy supply
28	Use of process heat and waste heat
29	Efficient building infrastructure
30	Efficient building envelope
31	Efficient cleaning
32	Manufacturing-process related recirculation
33	Cascading use of auxiliary materials and operating supplies
34	Efficient transport
35	Complete and unambiguous product documentation
36	Detailed task descriptions and structured shift handovers
37	Employee qualification/employee potential
38	Recycling of production waste
39	Avoidance of waste through recycling of in-house materials

Figure 29: Process-related and organisational measures (own figure)

The proportion of measures in small enterprises are shown in Figure 30. With regard to the distribution of measures, it should be noted that small enterprises prefer to implement energy-related measures rather than product-related ones. This mainly concerns companies in the following sectors:

- Production and initial processing of other non-ferrous metals
- Production of coatings, printing inks and mastics
- Production of sheets, foils, hoses and profiles from plastics
- Metal production and processing
- Surface finishing
- Recovery of sorted plastics

Here it can be assumed that a considerable proportion of the companies do not have their own product development, but produce as suppliers or in contract manufacturing.

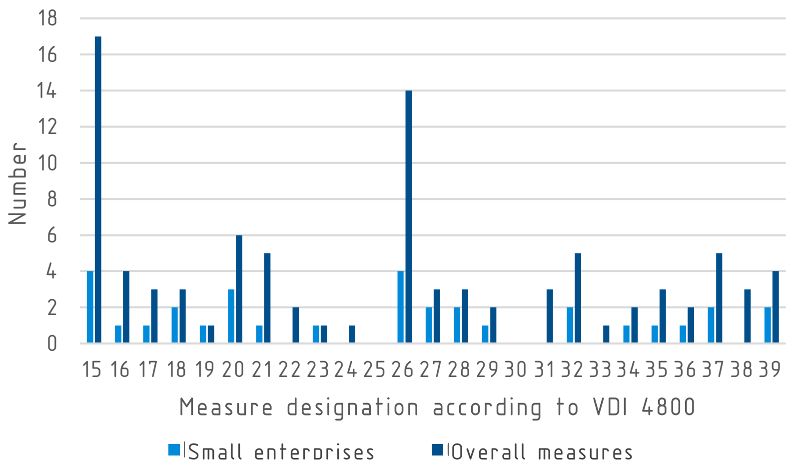


Figure 30: Proportion of measures in small enterprises (own figure, key in Figure 29)

The results for medium-sized enterprises are shown in Figure 31 and Figure 32. These are mainly attributable to the following sectors:

- Chemical industry
- Electrical industry
- Automotive engineering
- Production of plastics
- Production of metal constructions
- Mechanical engineering - manufacture of packaging machines

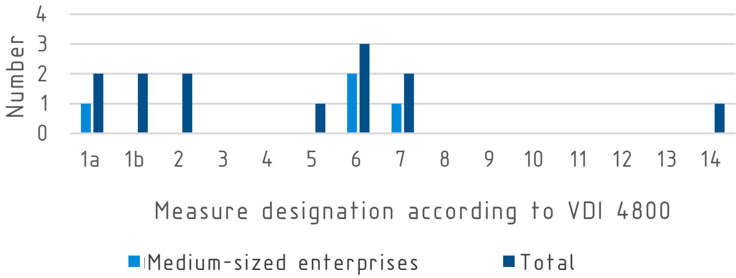


Figure 31: Product-related measures in medium-sized enterprises (own figure, key in Figure 28)

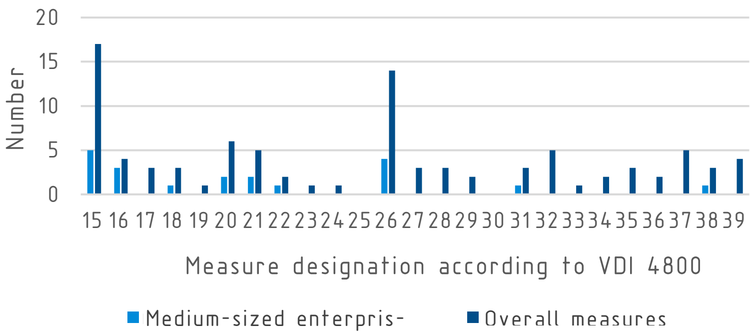


Figure 32: Process-related measures in medium-sized enterprises (own figure, key in Figure 29)

Here, the focus is obviously on product innovations that lead to savings for customers or facilitate marketing through the selection environmentally friendly materials.

The results for large enterprises are shown in Figure 33 and Figure 34. These are mainly attributable to the following sectors:

- Chemical industry
- Electrical industry
- Precision mechanics industry
- Food production - coffee
- Metal production and processing
- Metalworking industry
- Mineral oil processing industry
- Writing instrument manufacturers

Here, too, the picture is similar to that of the medium-sized enterprises.

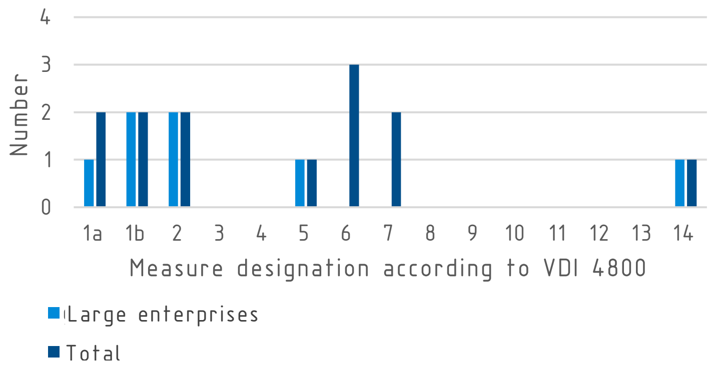


Figure 33: Product-related measures in large enterprises (own figure, key in Figure 28)

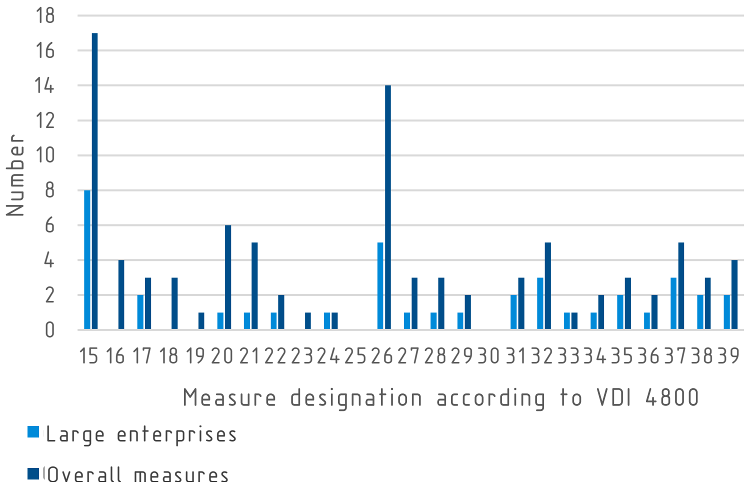


Figure 34: Process-related measures in large enterprises (own figure, key in Figure 29)

3.3.5 Miscellaneous

In addition to the quantitative evaluation described above, the following findings can be described qualitatively.

The role of digitisation in the case studies was examined. The following examples, among others, were found:

- Use of RFID tags for optimised component cleaning,
- Optimisation of mould arrangements by means of programming, so that there is less waste,
- Use of robots with optimised motion sequences,
- Time-distance optimisation of logistics processes.

The measures to increase resource efficiency with the help of digitisation are mainly achieved through optimisation software. Another area of application is the continuous tracking of components in the manufacturing process in order to make individual production settings appropriate for the component: e.g. selection of a suitable cleaning program and based on the most cleaning-intensive component. Overall, the evaluation confirms that digitisation can be used as an enabler for almost all resource efficiency measures.

Furthermore, the question of the collection and processing of operational data ("foreground data") was investigated. Generally speaking, no usable information was found on this in the evaluated case studies.

The topic of increasing efficiency is described in detail in the case studies. However, there is no calculation of "resource efficiency" in the definition of VDI 4800.

4 ESTEM CALCULATION PROCEDURE

4.1 Initial situation

As described in Chapter 2.1, extensive practical experience, proven calculation procedures and even internationally used standards and norms are available for the accounting of GHG emissions. Nevertheless, carbon accounting in any specific case is not trivial, and the result depends on numerous assumptions and stipulations. The most important influencing factors are briefly described below.

4.1.1 Choice of system boundaries

In the carbon accounting of GHG emissions, the decisive factor is the subject to which the inventory relates (see Figure 35). It can be an individual site, an entire company, a product or a process. In the case of material efficiency measures, as listed in Figure 20, very diverse subjects form the reference point. This is why VDI 4800, for example, distinguishes between reference to a product or production[49].

In addition, there are different inventory boundaries (see Figure 35). They are particularly important in the context of the Greenhouse Gas Protocol with its distinction between scope 1, scope 2 and scope 3. With regard to the organisational reference, the simplest form is accounting for a single site or "gate-to-gate" accounting. For products, a life cycle assessment according to the "cradle-to-grave" approach is common.

[49] Cf. VDI 4800:2016, p. 38.

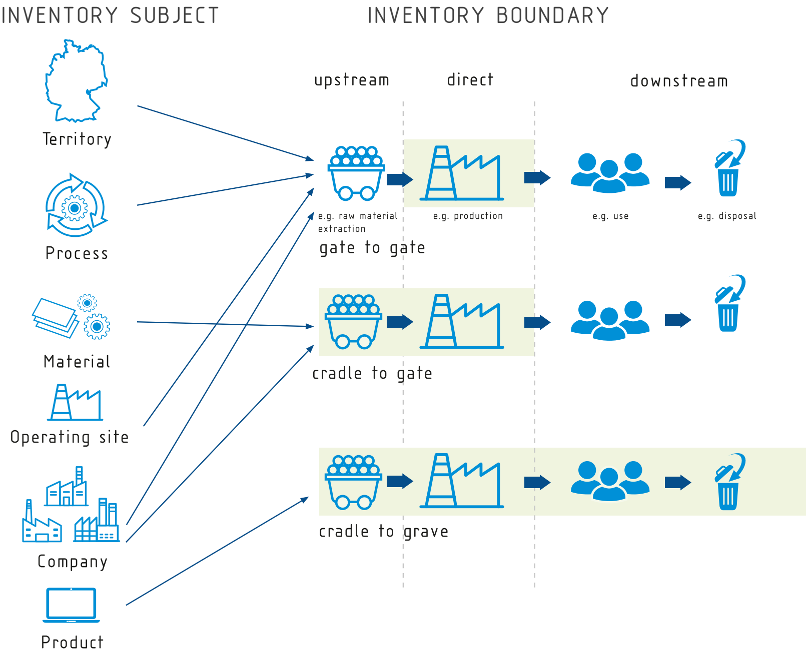


Figure 35: Inventory subjects and possible inventory boundaries (own figure)

The climate relevance of material efficiency measures is about the global environmental impact. The place of the cause (e.g. the production of a product) and the place of its effect are not united and therefore do not usually coincide. For this reason, the choice of system boundaries within which emissions are to be accounted for is based on a life cycle concept (see Figure 36): "System means all upstream and downstream processes required for this benefit, including the associated infrastructure"[50]. Strictly speaking, this principle is applicable to all inventory subjects, but requires careful selection of the system parts that are affected by a measure, for example. This is to avoid misinterpreting emission reductions in system parts and overlooking displacement effects to other system parts.

[50] Cf. VDI 4800:2016, p. 18.

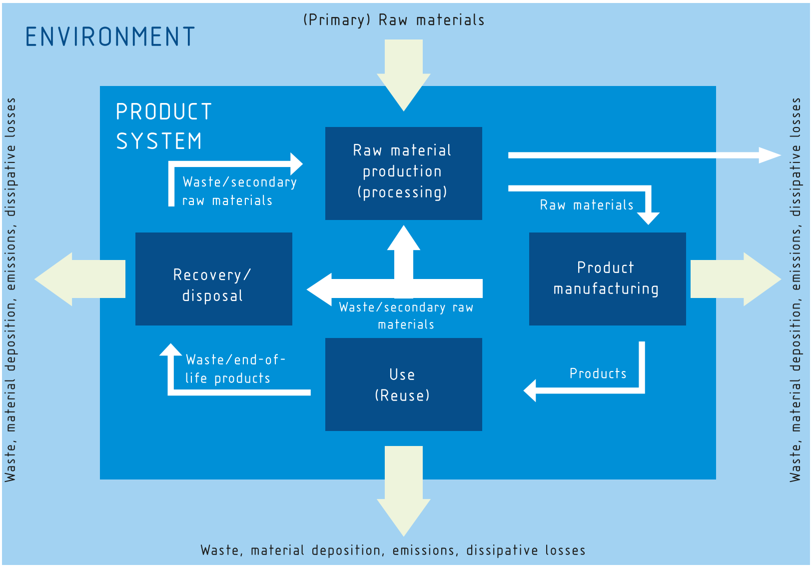


Figure 36: Life cycle concept based on the product system from VDI 4800, Sheet 1[51]

The correct choice of system boundaries depends on the individual case. After all, this is a crucial step in the system analysis (e.g. according to ISO 14040 or 14067) and is by no means trivial. Thus, VDI 4800 only offers reference points as to which life cycle phases are to be considered for different types of resource efficiency measures. The larger the inventory area selected, the greater the effort required to collect data. If one wants to keep this effort low within the framework of a simple assessment method, the system boundaries should be chosen to be as extensive as necessary and as narrow as possible. The system parts that make a significant contribution to the change in the emission inventory should be taken into account.

It was agreed with the contracting authorities of the present project to choose the system boundaries and the calculation procedure in such a way that the GHG emissions affected by a measure are recorded globally, meaning, for example, that emissions abroad that occur through the provision of a material should be taken into account in the inventory. This specification

[51] VDI 4800:2016, p. 19. Reproduced with permission from the Verein Deutscher Ingenieure e.V.

is important so that mitigation potentials cannot be directly counted towards national or regional mitigation targets, as these targets usually refer to geographical inventory boundaries and do not take foreign emissions into account.

4.1.2 GHG reference scenario

GHG mitigation measures require reference to a benchmark that can be used to assess the effectiveness. On the one hand, it should be possible to assess the relative effectiveness (i.e. the reduction rate of emissions), but on the other hand also the absolute reduction quantity. In addition, there is the time dimension in which the reductions are considered.

Chapter 3.2.6 of ISO Standard 14064-2 describes a reference scenario as the hypothetical reference case "that best represents the conditions that would most likely occur in the absence of a proposed mitigation project"[52]. It continues: "A greenhouse gas reference scenario can be static (remain unchanged during the project period) or dynamic (change over the project period)."[53] And: "In developing the GHG reference scenario, the proposer of the project must select the assumptions, values and procedures which ensure that reductions in GHG emissions or increases in removals are not overestimated, [sic!] and justify them".[54]

Since the calculation of emissions E is mostly the product of the two factors activity A and emission factor EF, the variability of both factors must be taken into account in a reference scenario.

The emission factor usually represents the technical system, i.e. how much GHG is emitted by a facility per unit of benefit or how much GHG emissions are caused by the production of a unit of material or product. Material efficiency measures typically start with this factor and influence it. This is also affected by external influences, such as when the emission factor for externally sourced electricity changes (see Figure 37).

---

[52] ISO 14064-2:2019, p. 20.
[53] ISO 14064-2:2019, p. 33.
[54] ISO 14064-2:2019, p. 33.

It is assumed that within the framework of funding projects, not only the specific emissions (per unit of benefit) are to be reduced, but that a contribution to the absolute reduction of GHG emissions is aimed for. This has been agreed with the contracting authorities of this project. The emissions are therefore related to a reference period (e.g. one year). This means that changes in the activity are also relevant. For example, the sales volume of a product may increase significantly, possibly even as a rebound effect of the measure.

According to ISO 14064-2, the assumptions for the reference scenario should be selected in such a way that the reductions from the measures are not overestimated. If absolute emission quantities (and not specific ones) are assumed, the activity has a decisive influence: What sales figures or production quantities does a company anticipate? Assumptions have to be made and justified here, which can lead to great uncertainties when longer periods of time are involved. Making an appropriate forecast is complex and depends on individual circumstances, which makes it difficult to compare different projects.

Another difficulty concerns the reporting period for emission reductions. ISO 14064-2 states: "The GHG reference period and the reporting period should be long enough to ensure that the variability of operations is accounted for by the GHG reference scenario and the performance indicators for project emissions". [55] Further specifications are not made.

[55] ISO 14064-2:2019, p. 55.

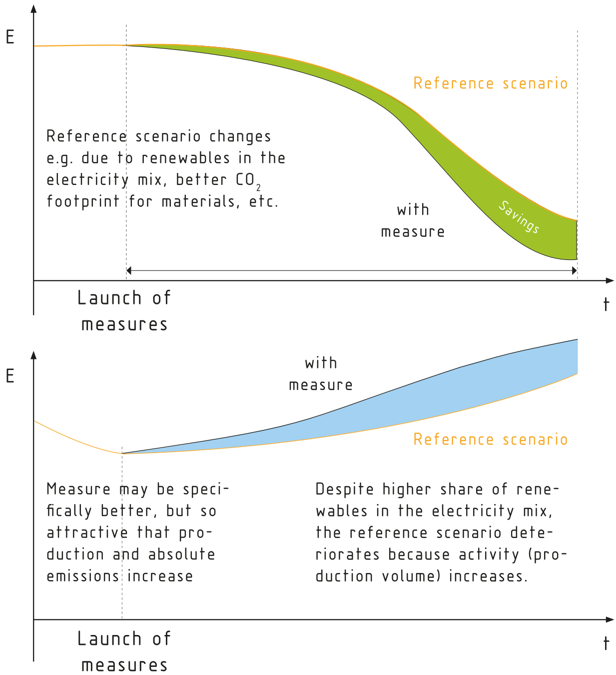


Figure 37: Possible emission trajectories of the reference scenario and the measure scenario (own figure)

Since comparability is required when selecting material efficiency projects and arbitrary assumptions must be avoided, it is important to set a uniform target here for a period under review.

4.1.3 Treatment of the end-of-life phase

End-of-life (EoL) measures generally include those measures that bring about changes in the treatment of materials or products after the end of the use phase. A distinction must be made here between measures that affect the EoL phase but are applied in other phases of the life cycle of materials or products, and measures that are only applied in the EoL phase itself. Figure 38 provides a graphical representation of this distinction and examples of measures in the various life cycle phases

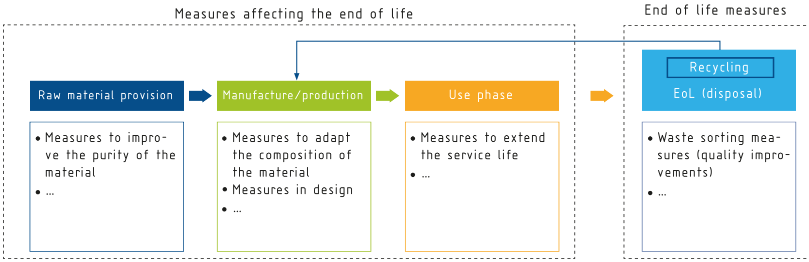


Figure 38: Measures in the life cycle of a product (own figure)

In the first case, which describes the upstream measures that have an impact on EoL, products can, for example, be designed in the development phase to be more durable and repair-friendly, or to be manufactured with reduced material inputs or more environmentally friendly raw materials. Such measures reduce the amount of materials or products to be disposed of after the use phase or reduce their harmful environmental characteristics.

In the second case, it is a matter of disposal measures in the narrower sense, i.e. measures for the recovery, treatment or disposal of waste. Objectively, this is the regulatory area of circular economy legislation (KrWG) and, from a legal perspective, the materials and products to be disposed have the character of waste. In the circular economy, the five-level waste hierarchy sets priorities between upstream measures in the production or use phase to avoid waste and various options for disposal. The highest priority is given to prevention, followed in priority by the material first and then the energy recovery from waste. Waste may only be disposed of if all these measures are out of the question or if there are reasons relating to environmental protection, health protection or economic feasibility.

In the LCA and also in the ESTEM calculation procedure, the upstream measures that already begin in the design or manufacture of products are accounted for on the input side. It is thus factored in that less material will be used in the system under review - in the case of auxiliary or operating materials, the company; in the case of products, the entire manufacturing process chain - and the waste produced is reduced to the same extent. This can go as far as the extreme case where an auxiliary material for production can be completely avoided and no waste is produced at all. An example of this is dry machining in metal-cutting production, which eliminates the use of cooling lubricants (CL) and thus the occurrence of used coolant emulsions.

In contrast, EoL measures in the narrower sense begin where waste already exists. The central measure here is material recovery, for which the term recycling is used synonymously in the KrWG. Recycling serves to close material cycles in the economy. This means that waste is returned to the economic cycle by being reprocessed and used again as secondary raw materials for production. This case is more complex in terms of carbon accounting and is presented below.

A generic representation of material cycles in the economy is shown in Figure 39. This illustrates - in a simplified way - the contributors involved in closing material cycles on the side of provision and use of secondary raw materials.

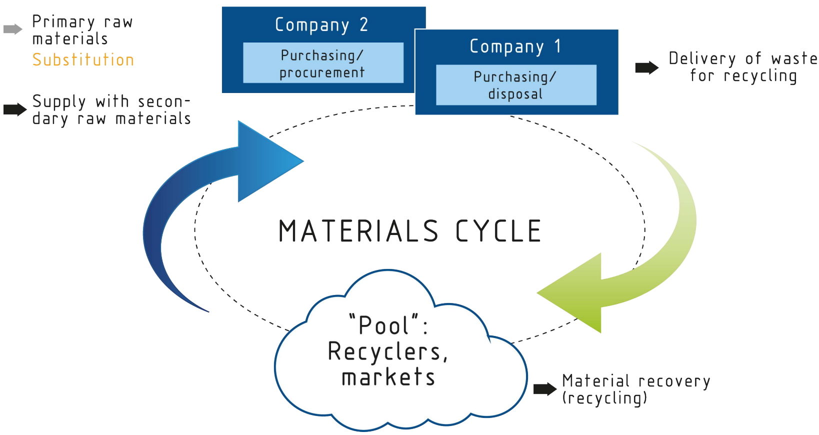


Figure 39: Material cycles in the economy (own figure)

It becomes clear that several contributors are involved in such material cycles. A company that generates waste must collect it separately and pass it on to a recycling company in a purposeful manner. Recycling can involve several technological steps in which one or more companies in the waste management industry can be involved. In the end, there is a producing company that, instead of being supplied with primary materials, decides to purchase secondary materials. Only through the cooperation of all these contributors can material cycles ultimately be successfully closed.

The mitigation of environmental impacts such as greenhouse gases in this kind of material cycle, the “secondary raw materials supply chain”, takes place through the last step, i.e. through the substitution of primary materials with secondary materials. To calculate the environmental impacts in the supply chain, the expenses for the production of the primary materials must first be known. Since these are no longer incurred through substitution, they are calculated as savings. These are the gross savings, which are matched against the expenses of recycling. For this purpose, all recycling processes and the necessary transport of materials have to be taken into account. After deduction from the gross savings, the net savings for the material cycle are obtained. However, this general pattern for substituting primary materials with secondary materials only takes place under certain market conditions. In the case of a measure involving the additional provision of secondary raw materials, there must also be an additional demand for secondary raw materials or, in the case of a measure involving the additional use of secondary raw materials, there must not be a shortage of secondary raw materials.

In the ESTEM calculation procedure, which enables carbon accounting of the measures of an individual company and does not address the situation of the markets, two essential questions arise here: 1) How high are the savings of the measures and 2) to which contributor within a material cycle should the savings resulting from substitution be attributed? A fundamental convention of life cycle assessment for such material cycles is that double counting must be avoided and that the physical mapping of flows must be correct.[56]. It follows that the sum total of environmental impacts such as greenhouse gases saved through substitution must not be attributed to all of the contributors, but must either be divided among several or be attributed to just one. In the field of life cycle assessment, there are various methodological approaches for such apportionments or attributions, which

---

[56] Cf. Pelletier et al. (2014), p. 396 and Allacker et al. (2014), p. 9.

have been the subject of scientific discussions for decades, but without a universally accepted methodological definition having been established to date.

In the following, the main approaches to recycling within LCA are briefly presented. The detailed description of the methods and their application in various guidelines can be found in Allacker et al. (2017) or also Ekvall et al. (2020)

Cut-off approach

A simple approach that is often used in practice in LCAs is the so-called cut-off approach. This approach is implemented in the ecoinvent database in a system model and is also recommended by the international Environmental Product Declaration (EPD) system, the PAS 2050 and the Greenhouse Gas Protocol. In the cut-off approach, the use of secondary materials is accounted for as follows: The secondary material only bears the environmental impacts from the upstream recycling process; no environmental impacts from its “previous life”, the primary material supply, are accounted for57. Whether the new product is recyclable again is not considered further, because there is a cut-off point between the examined and the subsequent life cycle.

The cut-off approach, also called the recycled content (or 100:0) approach, promotes the use of secondary material as long as recycling has a lower environmental impact than the production of the primary material. As a result, products made from primary materials tend to be rated lower, as the environmental impacts of primary material extraction are usually higher. Under the premises described above, this approach ultimately promotes the use of secondary materials and does not reward provision.

Recyclability approach

The recyclability approach is often found in LCA studies that deal with EoL in the narrower sense, e.g. in studies on improved sorting technology or new recycling processes. In this kind of waste management studies, the

[57] **The primary material thus bears 100% of the environmental impact of primary material production.**

use of secondary material is often not considered at all, but rather the provision of secondary material is addressed, which is accounted for according to the principle of recyclability: For the recyclable proportion of a waste, subsequent environmental impacts from recycling are taken into account and avoided environmental impacts through avoided primary material provision are credited. Therefore, the environmental impacts of a recyclable material are reduced. Using this approach, environmental impacts are shifted to the next and ultimately to the last life cycle, where only disposal remains. For this reason, the approach is also called the “avoided burden” (or 0:100) approach.

With this method, incentives are given for the provision of secondary materials, since the avoided environmental impacts through primary material substitution strongly improve the overall inventory, in some cases even presenting minus values. The use of secondary material is not promoted.

50:50 approach

The 50:50 approach was proposed, among others, as part of the first Product-Environmental-Footprint (PEF) method58. With this approach, the use and provision of secondary materials are accounted for as follows: Both environmental impacts from upstream or downstream recycling and the environmental impacts avoided through recycling are to be divided in a ratio of 50:50 between providers and users of the secondary material.[59]

In this approach, therefore, there is no preferential treatment and both the provision of the material and the use of the secondary material are promoted.

Circular Footprint Formula / “CFF” (20:8, 80:20) approach

The CFF is included in the proposals of the revised PEF methodology.[60] Instead of the fixed 50:50 split, this approach takes into account factors that are intended to reflect the relationship between supply and demand in a market. Here, a low value indicates that the demand is higher than the

[58] European Commission (2013).
[59] European Commission (2013), p. 84.
[60] Cf. Wolf et al. (2019), p. 2.

supply of the secondary material. A high value, on the other hand, indicates that supply is higher than demand. For the categories of metal, paper, plastic, batteries, building materials, glass and chemicals, default values of 0.2, 0.5 and 0.8 have been so far been assigned. Using these factors, both the supplying and the using product system are taken into account proportionally.

The CFF approach has the effect of promoting both the provision and use of the secondary material depending on the market situation and quality of the material.

Allocation-at-the-point-of-substitution (APOS) approach
The APOS approach also comes from the widely used ecoinvent database. The environmental impacts are attributed to recycling and disposal using the allocation factor of waste generation. This allocation is usually based on the economic value for a product and the secondary material that can be utilised.[61] Thus, the waste-generating product and the secondary material are each assigned a value. At the same time, the production of new products and the final disposal are each attributed to the life cycle in which they occur. In contrast to the cut-off approach, the largest part of the recycling process is often assigned to the life cycle in which secondary material is produced.

Depending on the allocation factor, the recycled material from this product may have a greater environmental impact than, for example, primary production. This happens when the production and use of a product have higher environmental impacts than the provision of material. Whether recycling is promoted for the provision of secondary material now depends on the assumed allocation factors.

Market model (0:100 or 100:0) approach
While the previous approaches are used in the so-called attributional LCA and are based on normative attribution, in the consequential LCA (c-LCA) recycling approaches are found that map the effects of a changed demand

[61] Cf. Weidema et al. (2013), p. 2.

or supply of secondary raw materials, taking into account the market situation. Whether a 0:100 or 100:0 approach is taken is thus not a general decision, but depends on the respective market situation. This kind of market model approach is also included in a system model in the widely used ecoinvent database.

To assess the market situation and subsequently select the approach, data on the supply and demand of secondary raw materials is needed. In a market where the supply of secondary raw materials is higher than the demand, the additional use of secondary raw materials is represented with the 100:0 approach. In a market where demand is higher than supply, this situation is represented with the recyclability approach (0:100). In addition, market constraints are taken into account in the modelling, which, for example, mean that the use of secondary material can lead to increased primary production. Further explanations on the principles of market-based modelling can be found in Weidema (2000) or Schrijvers et al. (2021).

Using the market model approach, either measures for the recyclability of the product or measures for the use of secondary materials are supported. If the supply of secondary raw materials is higher than the demand, their use is promoted. If the demand is higher than the supply, the recyclability of products is promoted. In order to implement this approach, additional data about the company is required to determine the market situation.

Double counting (100:100) approach

The double counting approach breaks the principle of physical correctness. The aim of the method is to create incentives for the joint fulfilment of goals beyond the LCA approach. Here, each contributor is credited with the full scope of positive and negative environmental impacts. This is based on the theory that all contributors play an essential role in jointly achieving the goals and are therefore assigned the same relevance, regardless of their own specific contribution. Only through joint action can the common goals be achieved. In the ESTEM project, the focus was on life cycle assessment approaches, so this approach is not elaborated on here.

4.1.4 Influence on the use phase of products

In the use phase of products, material efficiency measures can have two main effects:

(1) Change in the consumption of resources (energy, auxiliary and/or operating materials),
(2) Change in the useful life

A classic example of the first effect is the reduction of the material input in a product, which leads to a lower weight and thus to a reduction in energy consumption in the use phase. Furthermore, a change in product design can also result in a change in the use of operating materials, for example if fewer ink cartridges are required for printers. In order to quantify the asso-ciated reduction in GHG emissions, data from the use phase must be avail-able, e.g. on the usage patterns (of customers) and the associated use of energy and operating materials.

A greater challenge is the allocation of emissions. What we mean by this is that for the production of a sub-component, the contribution of this compo-nent to the total change in emissions in the product use phase has to be determined. The contribution of an injection pump to the subsequent emis-sions of a truck in its use phase can be cited as an example here. In the simplest case, the allocation could be made according to mass share or value share (of the injection pump in the truck). What would certainly make more sense is a functional allocation, which indicates what contribu-tion an injection pump can make to the truck's energy savings. However, such questions cannot be answered with simplified carbon accounting approaches, especially if they focus on material efficiency, and require detailed life cycle assessments or at least carbon footprints.

The inclusion of the product use phase also raises the question of the reference point for the emission inventory. In product-related life cycle assessments or carbon footprints, the total environmental impacts (or emissions) along the product life cycle are typically related to the functional unit of the product under consideration, i.e. to its use or, in the simplest case, to the product unit. If inventories are related to a period of time, the period of time would either have to be extended to include the use phase or, for example, emissions from the use phase would have to be allocated to the year of manufacture. Such approaches are complex, must be chosen on a case-by-case basis and thus make it difficult to compare different material efficiency measures.

The second effect, the extension of the useful life, can on the one hand lead to an increase in the total emissions during the operation of a product, but on the other hand the extension of the useful life can also bring about emission savings resulting from the postponement of the end of life and thus the postponement of the manufacture of a new product. In sum, fewer products have to be manufactured over time, which has a positive effect on the emission inventory during production. Such effects can only be mapped with complex models that incorporate purchasing and usage behaviour as well as feedback on supply and demand situations. In the context of life cycle assessments, such aspects are dealt with in so-called consequential LCAs.

4.1.5 Biogenic and fossil carbon emissions

With regard to CO_2 emissions, a distinction must be made between carbon sources of fossil and biogenic origin, i.e. from biomass. If carbon from biomass is burnt, only as much carbon dioxide is released as was previously absorbed from the atmosphere during photosynthesis. For this reason, many emission inventories neglect the sequestration of biogenic carbon and its release as CO_2. This is justified as long as this cycle is closed over shorter periods of time. However, if more biomass is burnt than is reproduced (e.g. through deforestation of rainforests) or, conversely, more carbon is bound in biomass than is burnt (e.g. through reforestation measures), then the biogenic carbon also has to be factored in.

In this case, ISO 14067 requires the CO_2 of biogenic origin to be reported additionally and separately from fossil CO_2 emissions: “If the biogenic carbon content of a product is calculated, it must be documented separately in the CFP study report, but it must not be included in the result for the CFP or partial CFP. Information on biogenic carbon content must be provided when studies are undertaken for the “cradle-to-gate” life cycle stage, as this information may be relevant for the rest of the value chain”.[62].

Nevertheless, materials or products made from biomass will also have a carbon footprint. This is made up of the fossil emissions associated with the cultivation and processing of biomass, as well as emissions of other GHGs (especially methane and nitrous oxide).

4.2 Principles of the ESTEM calculation procedure

The following requirements exist for the calculation procedure:

- **Comparability:** The procedure enables the comparison of GHG emissions saved by material efficiency measures proposed in government funding programmes mainly by small and medium-sized enterprises.

- **Simplicity:** The procedure is simple enough to be carried out by applicants (SMEs) with reasonable effort as part of a funding application.

- **Conservatism**: The assumptions and ultimately the results are conservative, i.e. the quantified savings are not overestimated by means of arbitrary assumptions.

- **Standardisation:** The procedure requires a high degree of standardisation, both in terms of the calculation steps and the underlying assumptions and data used.

For this purpose, procedural proposals were developed for the areas of system boundaries, reference scenario, allocations and biogenic emissions, which are presented below. They are implemented accordingly in the Excel® -based ESTEM tool, which is described in the accompanying guide.

The main approach underlying the proposed calculation procedure is a delta analysis: Applicants are asked which changes are brought about by their proposed material efficiency measure. For this purpose, the system

[62] **ISO 14067:2018, p. 55.**

within the boundaries of which the GHG emissions are accounted for is greatly simplified. Strict assumptions are made about the reference period in order to provide comparability. A detailed reference scenario is omitted, as only the changes are considered and the GHG emissions saved are assessed in absolute terms. For recycling measures, simplifying assumptions are also made which ensure easy use and avoid double counting. Emissions are calculated using standardised emission factors that are updated by the government.

4.2.1 Choice of system boundaries

A highly simplified scheme for dealing with system boundaries has been established (see Figure 40). The central assumption here is that in the case of material efficiency measures, the emission-reducing effect is caused in most cases by a change in the material flows. If a product becomes lighter due to lower material input or material change, this is reflected in the material input in the system (at the company), but may also have a significance for the use and disposal phase that needs to be taken into account. However, with this approach, it is difficult or impossible for those measures that are aimed at qualitative changes in product design, management or the type of use of the product to be mapped. Having said this, the quantification of the emission reduction from such measures is difficult to standardise and always requires a detailed and individual justification beyond this standardised calculation procedure.

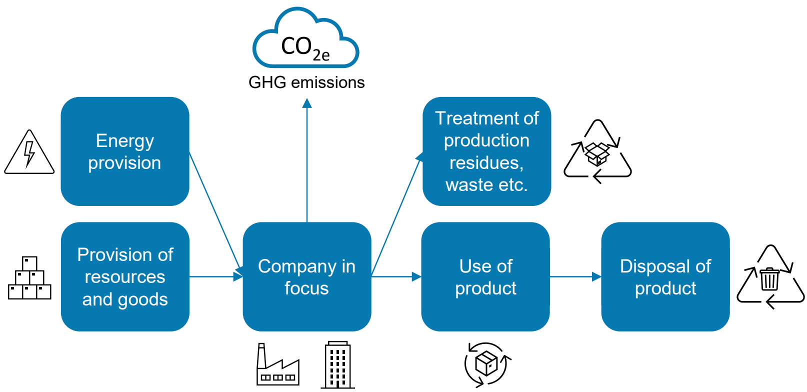


Figure 40: Simplified life cycle for the ESTEM system view (own figure)

If we consider one (applying) company - we shall call it the focal company here - we assume that emissions and the corresponding savings occur directly at the company (scope 1 in the nomenclature of the Greenhouse Gas Protocol). In addition, there are emissions from upstream processes for the provision of materials, goods and energy or energy carriers (scope 2 and scope 3 upstream). These emissions occur upstream from the company's perspective and can be quantified, for example, by the quantity used and the corresponding carbon footprints. The carbon footprints implicitly contain the information of the upstream chain, so that these do not have to be analysed in further detail.

It is more difficult to deal with emissions that occur “downstream” from the perspective of the focal company, i.e. in the use and disposal phase. In this case, some assumptions have to be made: Product sales volumes, product use patterns, disposal and recycling scenarios, etc. The carbon accounting of scope 3 downstream emissions is usually subject to assumptions and estimates for the future. For the present calculation procedure, it was agreed with the contracting authorities to make an assumption of ceteris paribus. This means that the production quantities, processes to be used and carbon footprints are based on the existing conditions at the time of application. This also applies, for example, to the provision of electricity from the national grid ("electricity mix").

Users of the calculation procedure are asked, on the basis of the individual system parts, what changes occur there as a result of a material efficiency measure. This is done by means of a catalogue of ten questions, which is also prepared accordingly in the ESTEM tool.

4.2.2 Delta analysis instead of reference scenario

The proposed calculation procedure is characterised by the fact that a reference scenario is not explicitly required, and instead only the changes or reductions in absolute GHG emissions compared to the status quo are accounted for. This implicitly assumes a “static reference scenario”, [63] namely

[63] ISO 14064-2:2019, p. 33.

a freezing of the current emission values against which the change is considered. However, the absolute emission values (e.g. of a company) are not collected, only the changes. Therefore, this method is not suitable for corporate reporting, where the relevance of a measure in relation to total emissions should always be considered. Here, the focus is exclusively on the question of how high the emission reductions are within the scope of a support measure in comparison with various proposed measures. This is why only the reduction quantities are taken into account. This simplifies the procedure considerably, as neither a reference scenario nor an overall inventory has to be drawn up.

Since the calculation procedure is aimed at material efficiency measures, the delta analysis is essentially mapped by a change in the activity ΔE, which includes in particular the material quantities used. The emission factors EF are assumed to be static and standardised by the calculation procedure. They represent the upstream chain of material provision, but also processes from the area of external energy provision, disposal or transport.

The change in emissions ΔE is then calculated as the product of the change in activity ΔE and the emission factor EF of this activity.

Measures such as the reduction of material input, material substitution or the increased use of recycled materials can be mapped in a simple and standardised way using suitable data records for emission factors. The challenge lies in providing sufficiently differentiated and comprehensive EF data records (see Chapters 2.2 and 4.4).

It is also necessary to define the reference unit to which the GHG emissions or the quantities of reduced emissions are related. In the case of measures with constant and continuous reduction, the choice of a time unit is simple. The only relevant question would be how long this measure takes effect or would be advantageous compared to a reference scenario (that is not assumed here). If a short time period is chosen, comparability would be ensured on the one hand, and on the other hand errors would be limited by a temporal progression of reductions. For this reason, one year is assumed as the reference period here (see Figure 41 above).

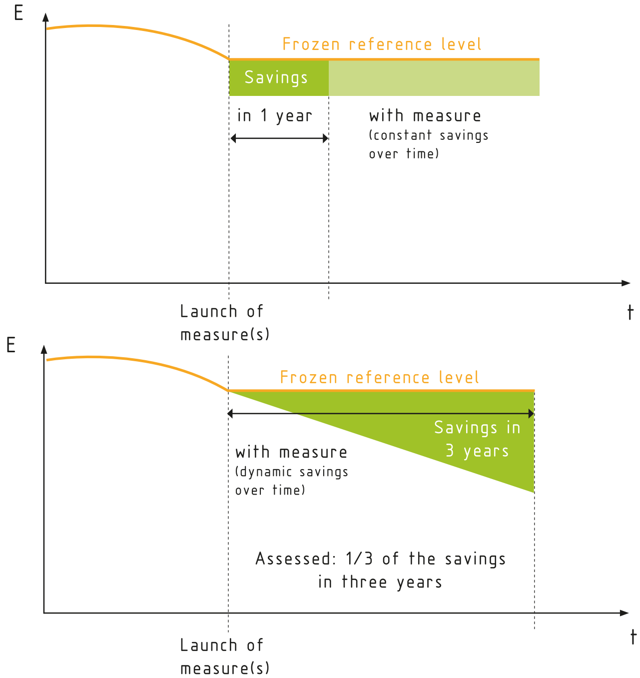


Figure 41: Temporally constant (top) and variable (bottom) emission reduction from a measure (own figure)

If a measure exhibits a dynamic reduction effect, i.e. the reduced emission quantities do not remain constant over time, an average value over a certain period can be assumed (Figure 41 below). However, choosing the correct time period would mean setting up an individual reference scenario for the measure. Instead, a suitable period is arbitrarily chosen to apply uniformly to all cases. Three years are assumed to be a suitable period for this, as this also usually covers the operational planning horizon of many companies. However, the reference value remains one year.

If a measure does not lead to a continuous emission reduction but represents a one-off saving, comparability with continuously acting measures must be established at the time of its implementation. Here, too, three years are assumed to be a suitable comparison period, i.e. the one-off saving is divided by 3 (see Figure 42).

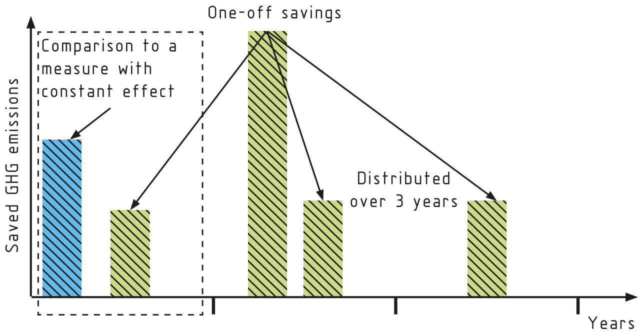


Figure 42: Consideration of one-off savings by means of distribution over 3 years (own figure)

Many material efficiency measures require investments in plants, means of transport or buildings. These investments usually cause additional emissions that have to be offset against the savings. For this purpose, a depreciation mechanism is assumed, which is also common for investments in business management. This means that the additional emissions of an investment are divided by the years of the depreciation period. To facilitate comparison, a uniform period of three years is chosen as the depreciation period. Longer depreciation periods would also be conceivable, as is customary for various investments and sectors in accordance with allowances for depreciation. However, it is recommended that three years be used as a uniform basis for the calculation procedure. If, in individual cases, the depreciation period has a (too) great an influence on the result, individual justifications should be provided when applying for funding.

4.2.3 Treatment of the end-of-life phase

Possible decision criteria for the selection of an appropriate carbon accounting approach are, among others, the applicability and the achieved control effect, which are described in detail for the various approaches in Chapter 4.1.3.

Since the applicability of the carbon accounting approach is of particular importance in the ESTEM project, the cut-off approach was chosen as the methodology for pragmatic reasons. This approach is based on the data records of common databases, which are also used, for example, in lists of the Federal Office for Economic Affairs and Export Control (BAFA), and requires data that are also collected in the context of the ESTEM calculation procedure.

During the course of this, measures taken by individual companies in their own operations or on their own products are examined. In addition, an assessment of the environmental impacts - based on existing data such as the GHG Protocol - should be possible. However, this means that a cut-off point is made as soon as the product leaves the company. Generally speaking, no or hardly any verified information is available on the subsequent life phases and this should therefore be disregarded for the time being. Moreover, the company has only a limited influence on the decisions of subsequent contributors, while it can itself take concrete actions regarding its input and its own consumption. The cut-off approach precisely reflects this demarcation and supports this input-oriented approach.

In practice, the application of the cut-off approach has various consequences for consistent carbon accounting: In the input of materials, a distinction is made between primary and secondary material. As described previously, secondary material does not contain any environmental impacts from the earlier product life, but only the environmental impacts of upstream recycling and for the provision of the material. Primary material, on the other hand, does not contain any credits for possible shares of subsequent material recycling. For example, if a product is composed of 70% primary material and 30% secondary material, the environmental impacts are calculated proportionally and added together. This means there are no credits for waste that can be recycled at the end of its life. Measures that lead to increased recycling must therefore be taken into account on the input side through a corresponding mix of primary and secondary raw materials.

The ESTEM calculation procedure takes into account the requirements of a simple and standardised calculation in the area of EoL by using the cut-off approach. This avoids double counting and is in line with a frequently used methodology of life cycle assessment, which is also used for the carbon accounting of data records in common databases. The consequence of this decision is that measures in material cycles can be credited for the group of companies that use secondary materials. This is in line with current demands in the circular economy to focus more on substitution or substitution rates. Nevertheless, it can be argued that secondary materials would not be available in the first place if companies did not take measures on operational waste or on the design of their products to ensure that waste is available for recycling and thus all those operating in material cycles should be given corresponding incentives.

In principle, two approaches are conceivable for this: On the one hand, methodological approaches such as PEF could be used. The advantage here is conformity with the life cycle assessment, especially by avoiding double counting. The main disadvantage is the lack of compatibility with existing databases and the complexity and difficulty of communicating the approach. On the other hand, it would also be conceivable in principle to deviate from the LCA methodology in the context of funding programmes, in that the substitution effects are fully counted for measures in both the supplying and the receiving companies. The resulting double counting can be interpreted as a theoretically justified incentive for the mitigation of environmental impacts such as greenhouse gas savings.[64]. However, the analysis of such incentive schemes is outside the scope of the ESTEM project and must ultimately be answered as part of policy decisions in funding programmes.

4.2.4 Influence on the use phase of products

In the ESTEM calculation procedure, the change in service life (see Chapter 4.1.4) cannot be taken into account. Retroactive effects of the use phase on the production quantity would have to be included in order to determine reduction effects. Firstly, this is very difficult to prove and/or predict. Secondly, the selected delta approach only captures changes, but not the complete state of the entire system before and after the implementation of the measures. Since the end-of-life postponement not only affects the changing energy and material flows, but also the emission inventory of the entire product system, a comparative analysis at company level is no longer suffi-

[64] Cf. Caro et al. (2013), p. 545 ff.

cient at this point. Instead, an overall inventory at product level would be needed.

The change in resource consumption (energy, auxiliary and/or operating materials) in the use phase, on the other hand, can be taken into account if corresponding data is available. For measures that lead to emission reductions in product use, the period over which these emissions are to be taken into account must be defined. This is not a problem for products used in the short term, where a reference period of one year can be assumed. For products in longer-term use, this is more difficult. It would be possible to add up the savings over the corresponding periods of use. However, reliable evidence would then have to be provided on the product usage time. For this reason, the consideration of emission reductions in the use phase of three years is assumed for long-lasting products (see Figure 43).

This specification results in a certain degree of comparability, but does not take into account the influence of measures that lead to a longer useful life of products. If the aspect of useful life is relevant for a measure, this should be presented individually in a funding application and documented in detail.

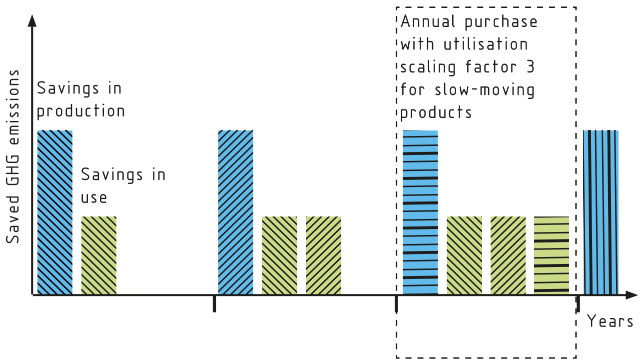


Figure 43: Consideration of savings when using long-lasting products (own figure)

4.2.5 Biogenic and fossil carbon emissions

The CO_2 emissions of biogenic origin are not included in the inventory. Only CO_2 from fossil sources and other greenhouse gases are taken into account. This is justified by the lack of public availability of corresponding values for materials and the risk of misinterpretation.

This does not mean that materials or products made from biomass do not have a carbon footprint. But this carbon footprint is made up of the fossil CO_2 emitted during the cultivation and processing of biomass, as well as other GHGs. In the course of the combustion of materials or products made from biomass, the associated CO_2 emissions are not to be taken into account. Due to this specification, the climate relevance of the long-term storage of carbon of biogenic origin cannot be mapped with the calculation procedure presented (e.g. through the long-term use of wood in buildings or in high-quality furniture).

4.2.6 Other important assumptions

A controversial issue is the use of emission factors for electric power. There are two basic options here: the use of a uniform value for the national provision of electricity (national "electricity mix"). This includes the shares of the different energy sources, i.e. fossil, renewable and other sources. All electricity consumers are then treated equally. The other possibility is to use specific supply contracts for electricity as the basis and take into account how high the respective share of renewable sources is. This would include, for example, the possibility of billing “green electricity” as climate neutral or similar.

For the calculation procedure, it is therefore suggested to always start with the national electricity mix and to use the latest emission factors, which are regularly provided by the Federal Environment Agency, for example. This is the only way to compare different material efficiency measures with each other. Otherwise, it would not be the mitigation effect of the measure itself that would be assessed, but the purchasing strategy for electricity.

The same also applies to the monetary compensation of GHG emissions. It is generally not taken into account in the calculation procedure.

4.3 The guiding questions in ESTEM

The ESTEM calculation procedure is set up in such a way that users are asked about changes in the respective activities for the various relevant system areas (see Figure 40). In most cases, these are material or energy quantities that change as a result of a material efficiency measure. A decrease in quantity is counted positively, an increase in quantity, which can also occur, negatively. An increase in quantity is therefore a negative decrease in quantity.

These quantities are then multiplied by fixed emission factors and result in the emission reductions for the respective system area. All reduction contributions from the different system areas are finally added up and lead to the overall result for the material efficiency measure under consideration. The quantity framework required for the measure is formed by the answers to the following ten guiding questions:

I. Is there a change in the quantity of materials sourced for the products?
II. Is there a change in the quantity or composition of operating materials required by the company?
III. Is there a change in the tangible capital or investment goods?
IV. Is there a change in the quantities or types of energy sources used for energy production at the site?
V. Is there a change in the direct GHG emissions resulting from a process?
VI. Is there a change in the quantity of energy sourced?
VII. Is there a change in the quantity of materials in products to be disposed of at the end of life or in the disposal process of these materials?
VIII. Is there a change in the quantity of production-specific waste generated or in the disposal of this waste?
IX. Is there a change in the consumption of operating materials during the use phase of the product?
X. Is there a change in the consumption of energy during the use phase of the product?

These guiding questions can be answered in detail and in a standardised manner in the Excel®-based ESTEM tool. The description of the tool as well as explanations on how to understand the individual questions are contained in a separate guide that builds on the methodological assumptions of this chapter and is included as part of the project.

4.4 Data origin

The standardisation of a calculation procedure for emission reduction through material efficiency measures - as well as other corresponding emission calculations in general - requires the availability of emission factors (or carbon footprints) for materials, energy carriers and processes.

While the factors for the provision and combustion of (fossil) energy sources are generally available and largely comparable[65], databases must be relied on when it comes to materials and other processes (disposal, transport). The data provided there are of very diverse origin and quality and can vary greatly for the same material. In addition, there is the need for up-to-dateness and methodological homogeneity if the data is to be used for a standardised procedure.

If the selection and use of emission factors is left to the users, this leads to an incalculable individual influence on the results of the calculation procedure. Therefore, the emission factors to be used should also be defined within the framework of a standardised calculation procedure and, preferably, be made available free of charge.

The most important emission factors have been made available in the ESTEM tool. They are protected and cannot be changed by users. It is possible to update and expand the emission factors. The following sources were used for the values:

- **The ProBas database of the Federal Environment Agency (UBA 2022):** It contains a large number of factors for materials and processes and is available publicly and free of charge. However, this data is not determined according to the same methodological procedures, is not quality assured and is not updated in large parts. There are exceptions: For example, the emission factors for traffic and transport are of good

[65] Cf. Federal Environment Agency (2016).

quality. The emission factor for the German electricity mix is also published regularly and kept up-to-date by the Federal Environment Agency. The shortcoming here is the materials. However, there is hope that the ProBas data will be improved in terms of quality, methodological homogeneity, up-to-dateness and differentiation.

- **The so-called BAFA list of the Federal Office for Economic Affairs and Export Control (BAFA 2021):** It contains a list of about 200 emission factors for “resources”, i.e. for important materials and economic goods. This list is a spin-off of updated eco-profiles that were recently created from data in the ecoinvent life cycle assessment database. This data has the advantage of being up-to-date and quality assured. The disadvantage is the limited scope. It is hoped that the list will be expanded. The emission factors for the use of energy sources are also taken from this BAFA list and originally come from the Federal Environment Agency.

- For capital goods (machinery, equipment, vehicles or buildings), emission factors from economic input-output analyses were used[66]. In this case, the emission factors refer to the monetary value of the goods and are stated in kg CO_{2e} per euro.

[66] Cf. Schmidt et al. (2021), p. 1698 ff.

5 STAKEHOLDER INVOLVEMENT IN METHOD DEVELOPMENT

The central form of stakeholder involvement was the meetings with the contracting authorities from the five participating federal states and other representatives from federal ministries, the Federal Environment Agency and interested parties. During the project, nine meetings were held with the contracting parties to fine-tune the goal and scope of the methodology.

In addition, two project workshops and a final workshop were organised to present the (preliminary) results. The first project workshop in January 2021 looked at the evaluation of existing methods and tools. The second project workshop was the stakeholder dialogue workshop to discuss the preliminary results, especially the proposed methodological approach.

5.1 Workshop for the evaluation of existing methods and tools

A workshop was organised on 26 January 2021 to present the (preliminary) results of the project. The workshop was also intended to give providers of analytical methods, databases and IT tools the opportunity to present their products. The conceptual work on assessment methods, databases and tools was thus complemented by first-hand information from the providers.

Four database providers and four tool providers were invited to give a short presentation. The selection of the company representatives to be invited was based on an evaluation grid of the databases and tools. The relevance of the products in the respective market and the innovative content of the database or tool solution were decisive in this respect. The presentations followed a predefined structure to ensure comparability of the information. In addition to the providers, the project team and the contracting authorities, other contributors, e.g. from the Federal Environment Agency (UBA), Project Management Jülich (PtJ), the Federal Ministry for Economic Affairs and Climate Action (BMWK, was BMWi)) as well as other interested parties from the participating institutions were able to take part to a limited extent.

The workshop provided a concentrated overview of the tools and databases on offer. As a result, it was found that LCA databases vary greatly in depth and breadth and that various criteria have to be considered when it comes to selecting a provider. The Carbon minds database, for example, is very specialised and is unlikely to be transferable to all sectors. Ecoinvent and GaBi, while suitable in principle, are so high in price that the purchase of licences would be disproportionate to the carbon accounting of a material efficiency project.

Hopes that a usable alternative would be available in the form of the free-of-charge ProBas database were generally dismissed. ProBas cannot be used in its present form, especially because regular data updates are not guaranteed. The creation and, above all, the regular maintenance of the databases via updates involve a great deal of effort. In this case, extensive updating and maintenance of the data would be essential.

Although the top-down approach of input-output models would ensure a broader use, the top-down approach also has disadvantages when technology-specific measures are to be assessed. Having said that, top-down approaches do make sense when evaluating companies in scope 3, where many products and inputs have to be considered.

The synopsis of the databases and an overview of the tools illustrated that the quality of the tools essentially depends on the data used from the databases. This shows the importance of the data for the determination of GHG reductions.

It is therefore proposed that the Federal Environment Agency supplement the ProBas database with annually updated data on the most important industrial materials and energy sources. The human and financial resources for this would have to be made available accordingly.

The choice of method is crucial for the choice of data, as each method has its own data requirements. The discussion of methods showed how it makes most sense to set up the methodology to be developed for the guide on the basis of existing approaches. While it is true that regular updating is necessary with regard to the data, the methodology itself should not be changed at short notice.

5.2 Stakeholder dialogue workshop to discuss the proposed methodological approach

The stakeholder workshop “Determining the GHG emissions saved from material efficiency measures” took place on 13 July 2021. In particular, the methodological approach of the ESTEM calculation procedure was presented and discussed. The discussion of the methodological and practical challenges in determining the avoided GHG emissions from material efficiency measures took place in four break-out sessions.

The following overall picture of the statements emerged from the discussions with the stakeholders.

From a company's perspective, material consumption is primarily seen as a cost factor. The link between material consumption and GHG emissions is therefore particularly evident when there is a perspective on CO_2 pricing. Here, companies want clear framework conditions in order to be able to make investments, e.g. in new technologies such as “green” steel. With a clear perspective on the development of the CO_2 price, an “internal” CO_2 price would also be helpful to anticipate cost developments. In this respect, initiatives such as EU Green Deal, EU Taxonomy, Sustainable Products Initiative and the Science Based Targets Initiative are seen as future motivation for material efficiency, whereby from the stakeholders' point of view the attention for material efficiency measures has also been heightened by current government policies. Furthermore, current material shortages are fuelling material efficiency and it is now seen as a measure of risk minimisation, which also goes back to experiences with the effects of the corona crisis.

Stakeholders see the goal of material efficiency as cost reduction, reduction of material consumption/less waste and high-quality recycling of waste. Especially in the case of metals, cutting CO_2 emissions is seen as a positive side effect. Beyond mere cost reduction, SMEs are in part highly self-motivated against the background of social responsibility. For large companies, the topic of material efficiency is seen as more important for marketing, especially with regard to attracting new employees.

In the operational area, data availability, the effort involved in data acquisition, lack of integration of data collection within the company, lack of energy management systems and lack of manpower are named as barriers to material efficiency. In addition, the supply chains for semi-finished products have an inhibiting effect, as data on the intermediate products is not available. Here, it is necessary to start in small steps with one supply chain in order to create understanding for the large efforts involved. In the area of disposal, it is also difficult to get acceptance for by-products due to the information deficit. Material exchanges would help here, as the networking between disposal chains is elementary.

The stakeholders see some synergies in the relationship between material and energy efficiency. These are primarily located in the manufacturing sector, as this is where the use of materials is highest. In contrast to energy efficiency, complex upstream chains contribute to the CO_2 emissions of materials, which is why a different mode of thinking and accounting is required here. From a stakeholder perspective, material efficiency requires an interdisciplinary approach. This requires different departments working together within companies. While energy efficiency is a topic of site management, material efficiency is one of product development. It would therefore be important to present savings through process optimisation, i.e. increasing the efficiency or quantity of materials, separately from savings through the purchase of materials that are produced with less CO_2 emissions.

With regard to the state of GHG accounting in companies, the following situation is characterised by the stakeholders. Companies are aware of the issue of GHG accounting and reporting and the range of implementation is wide. Companies usually start with the carbon accounting of individual sample products. The first steps are taken with outside help from consultants and universities. Large companies are usually more advanced than smaller ones when it comes to GHG accounting. However, the carbon accounting of materials often fails due to expensive databases and missing expertise.

The exchange of GHG data in the supply chain between customers and suppliers is not yet established in companies and is generally insufficient, with foreign parts of the upstream chain even worse. The digital product passport and its possibilities are not known to the participants. When data comes from abroad, the data quality proves to be worse than with data from within the country. Corporate inventories in scope 3 therefore pose major challenges, especially for companies with complex supply chains and a large number of inputs.

ERP systems can already map GHG data when data is collected in companies, but this practice is not yet widespread. In this respect, an automated calculation of key figures has not yet been established in practice. If customers request key figures relating to GHG, they do not ask about data quality and documentation. Key figures are accepted, regardless of how they were generated. For many companies, a corporate inventory with a top-down approach based on sectoral data from ecologically extended input-output accounting would be a great step forward, even if it would only allow a rough analysis.

With regard to data collection and data access, the following statements are made by the stakeholders: Companies, especially SMEs, are confronted with a high number of different databases, some of which represent significant cost factors for the companies. The choice of the “right” database for the company's purposes is often a challenge due to the variety and lack of expertise. Furthermore, the collection of company or primary data often results in a problem because the data often constitute only estimates or exists in different units. The experiences conveyed by the companies are confirmed by business consultants. In addition to difficulties with primary data collection, secondary data in particular is a challenge. Often there is no suitable data, especially if many semi-finished products are processed in the company. Data for special materials and processes are also very difficult to obtain.

The available databases are considered to be very heterogeneous. Using different databases will generate different results. This means that the reproducibility of the assessment results cannot be guaranteed. Even if life cycle assessments or carbon footprints already exist in companies, there is often the problem that the data used can no longer be reconstructed. In addition, the lack of up-to-dateness in databases is seen as problematic. For example, data from the mining sector in particular is considered to be very outdated, even in commercial databases. Life cycle assessments therefore only represent one possible view of a process and do not give a precise reflection of reality. Thus, data records can never be exact. Data records should therefore never provide only one value, but rather a range of variation.

A greater homogeneity of the databases would therefore be desirable. The desire was expressed for a national, publicly and freely accessible database with standard factors for the most important materials. ProBas and GEMIS are well received by the users and are considered very helpful. However, access to the data documentation and the up-to-dateness of the data records are insufficient. Here, updates and improvements are desired.

Companies would like their suppliers to provide CO_2 values directly. In practice, however, this does not happen. At the same time, customers are putting pressure on the companies and also demand CO_2 values for the products. The demand for suppliers to provide CO_2 values also comes from research and consulting.

With regard to the ESTEM calculation procedure and methodology, stakeholders expressed the following requirements, challenges and wishes.

Applicability

What is needed is a simple and quick, yet reliable assessment of measures which can be carried out not only by experts, but also by laypersons. It should be possible to carry out the method in a calculation tool. Existing tools should also be tested for their applicability. From the point of view of the representatives of the authorities, it should also be possible to map concrete funding projects. There is a great need here, which should be able to be represented individually.

Comparability

It should be possible to assess the effectiveness of a measure in comparison to other material efficiency measures in terms of GHG avoidance. Uniform calculation and allocation rules should be specified for this purpose. Accordingly, it should be possible to consider a wide range of production technologies and processes as well as the use of recycled materials. This should ultimately ensure the transferability of measures and their effects.

Data basis

The data basis should be uniform, reliable and verifiable for all users. The specific challenges of individual sectors should also be taken into account. Ideally, it will be possible to achieve this by updating and expanding the ProBas database.

Transparency and traceability as well as documentability and reproducibility

The requirements in these areas aim to ensure a comprehensible calculation procedure, which should be backed up by source references and be "visible". Traceability should be present in all steps of carbon accounting. Accordingly, the information to be provided should be uniform, as should the information on foreground and background systems.

The requirements are also accompanied by challenges that stakeholders see in the following areas: The information available in companies must be linked to the information in life cycle databases. This can be difficult in individual cases, as it is not always clear which information belongs to the background system and which to the foreground system. Dealing with allocations and recycled materials is another methodological challenge from a stakeholder perspective. Furthermore, specific data by country of origin should be used and there should generally be a uniform database. In some cases, the consideration of GHG alone can fall short of the mark. A life cycle assessment may then be necessary for the purpose of environmental evaluation. On the other hand, the life cycle approach could also be in conflict with national climate protection plans.

The wishes and comments expressed by the stakeholders were largely compiled during the method development of the ESTEM calculation procedure and ultimately also led to this method being implemented in a separate Excel® tool, contrary to what was originally planned.

6 TESTING THE ESTEM METHODOLOGY TOOL DEVELOPMENT AND PRACTICAL EXAMPLES

The following chapter will illustrate the application of the methodology for exemplary case studies. For this purpose, six case studies are presented that are assessed using the ESTEM tool. However, the assessment of case studies also serves to highlight the limitations of the calculation procedure, which is unsuitable for certain types of measures. The methodological assumptions of the ESTEM calculation procedure are documented in the final report of the project. Each case study is intended to demonstrate a possible application of the ESTEM tool. The original data basis is based on real projects implemented in companies. These have been anonymised and partly supplemented with missing data or shortened for simplification. For each case study, the initial situation and the measure are first described. Then the calculation procedure and the results are presented. Typical transport distances did not exist in any of the case studies, which is why they were not taken into account in the calculations.

6.1 Case study 1: Lightweight construction

Initial situation

The company produces solid-formed components, including steel, for the automotive and mechanical engineering industries. Significant weight savings are possible in the production of nuts. The basic structural-mechanical conditions have to be complied with when implementing measures, but components that do not directly contribute to the load-bearing capacity can be reduced.

Description of the measure

In order to obtain a lightweight nut that is optimised in terms of geometry and material, a holistic concept was developed that combines the interacting areas of material selection, manufacturing processes and design. By using micro-alloyed, bainitic steel materials, it is now possible to dispense with corresponding annealing treatments during the production of the raw material in order to achieve a sufficiently formable microstructure. In addition, the heat treatment usually required to achieve defined hardness values for the actual product, the nut, becomes obsolete.

Effect/type of measure

The main measure is the reduction of input material flows in the process itself. This is a continuous saving, which means that the savings remain constant every year. The measure theoretically also has an effect on the use and disposal phase, as the lightweight nuts are used in vehicle construction. However, the effect is extremely small due to the low weight of the nuts and is therefore disregarded in the following.

Life cycle phases affected

The affected life cycle phases are shown in Figure 44.

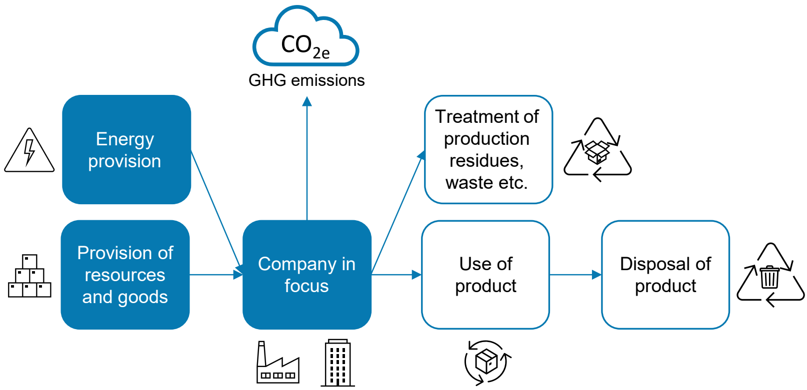


Figure 44: Affected life cycle phases in the “lightweight” case study (in blue)

Procedure for the calculation

Per year, 260 t of electrical steel (question I in the ESTEM tool), 924 t of water (question II), 118 MWh of natural gas (question IV) as well as 252 MWh of electricity (question VI) are saved. These savings are entered as positive values in the fields at the respective questions and the materials are selected in the drop-down menu. When selecting the materials, it is important to note whether they are primary or secondary materials.

Results

In total, 289 t CO_{2e} can be saved annually by implementing the measure. Reduced energy purchases save the largest share of emissions (electricity 122 t CO_{2e} / year and natural gas 24 t CO_{2e} / year). The steel savings reduce annual emissions by 143 t CO_{2e} / year. The overall results, as output by the Excel® tool, are shown in Table 9.

Table 9: Results for the "lightweight" case study

	Measures	Scope as per GHG Protocol	GHG emissions [t CO_{2e}]
I	Change in the quantity of materials sourced for the products (e.g. material substitution, biogenic instead of fossil materials, less material, use of secondary materials)	Scope 3.1/3.4	143.21
II	Change in the quantity or composition of auxiliary and operating materials required in the company (e.g. packaging, oils, paints, adhesives)	Scope 3.1/3.4	0.30
III	Change in capital or investment goods (e.g. machines, vehicles, buildings or production facilities)	Scope 3.2	0.00
IV	Change in the quantities or types of energy sources used for energy production at the site	Scope 1, incl. upstream Scope 3.3 emissions	23.72
V	Change in the direct GHG emissions resulting from the process	Scope 1	0.00
VI	Change in the quantity of energy sourced (power, heat)	Scope 2, incl. scope 3.3	122.22
VII	**Change in the quantity of materials in the finished products and thus in disposal at the end of life**	Scope 3.9/3.10/3.12	0.00
VIII	Change in the quantity or composition of auxiliary and operating materials as well as production residues and thus disposal	Scope 3.5/3.10	0.00
IX	Change in the use phase of the product (consumption of materials, auxiliary and operating materials)	Scope 3.10/3.11	0.00
X	Change in the energy **consumption in the use phase** of the product	Scope 3.9/3.10/3.11	0.00
XI	Change in the transport **service**	Scope 3.4/3.9	0.00
Total			289.45

6.2 Case study 2: Use of recycling materials

Initial situation

The company manufactures pens. It wants to develop a sustainable alternative to a felt-tip pen.

Description of the measure

To implement the measure, an increased proportion of recycled material is being used for the shell of the pen. However, the ink, the fibre refill and other materials remain the same. The felt-tip pen represents an alternative product with the same function to the standard pen. Assuming the quality of the material remains the same, it can be assumed that the process and thus the consumption of auxiliary materials and energy will remain the same. 87% of the primary material is replaced by recycled material. The recycling process takes place outside the company.

Effect/type of measure

The measure affects the provision of resources. Secondary material is being used in place of primary material. This causes lower emissions in the production of the materials. The measure can also have an impact on the use and disposal phase, as, for example, the change in the material can influence the choice of disposal route and recyclability. At the same time, the changed properties, e.g. the service life of the pen, can be influenced. In this case study, however, it is assumed that the disposal route remains the same and that there is no change in the use phase.

Life cycle phases affected

Figure 45 shows the life cycle phases involved for the example described.

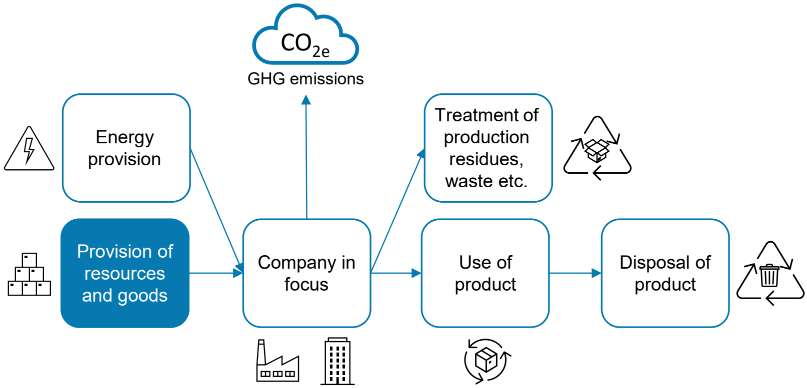


Figure 45: Affected life cycle phases in the "use of recycled materials" case study (in blue)

Procedure for the calculation

The previously documented assumptions, such as the simplifications regarding the use and disposal of the product, also apply to the following calculation. The weight of a felt-tip pen is given as 10 g. Of this, 87% is replaced by the recycled material polyethylene terephthalate (PET). Assuming that 4,687,500 pens are produced annually, 40.8 t of PP can thus be replaced. In the ESTEM tool, the reduction of the primary material PET of 40.8 t is given as a positive value and the use of the secondary material PET of 40.8 t is given as a negative value in question I.

Results

By reducing the primary material, 78 t CO_{2e}/ year can be saved, while the production of the recycled PET causes 47 t CO_{2e} / year. Thus, a total saving of 31 t CO_{2e} / year is achieved.

6.3 Case study 3: Effect on use phase

Initial situation

The company manufactures packaging machines. By improving the machines manufactured by the company, the aim is to save packaging material during the operating phase of the machines.

Description of the measure

By optimising the packaging machines, the packaging is to be produced as efficiently as possible. Material is saved by optimising the packaging design or reducing the foil thickness. This reduces the amount of material used and the amount of waste produced in the use phase. Energy efficiency measures, such as the use of servo motor-driven components instead of compressed air, can also reduce energy consumption in the use phase.

Effect/type of measure

It is a continuous measure that influences the use phase of the product.

Life cycle phases affected

For simplification and due to a lack of data, it is assumed in the calculation that the effects are limited to the use phase (see Figure 46). In practice, however, it should be checked whether other life cycle phases are also affected by the implementation of the measure, in which case they should be taken into account accordingly in the calculation.

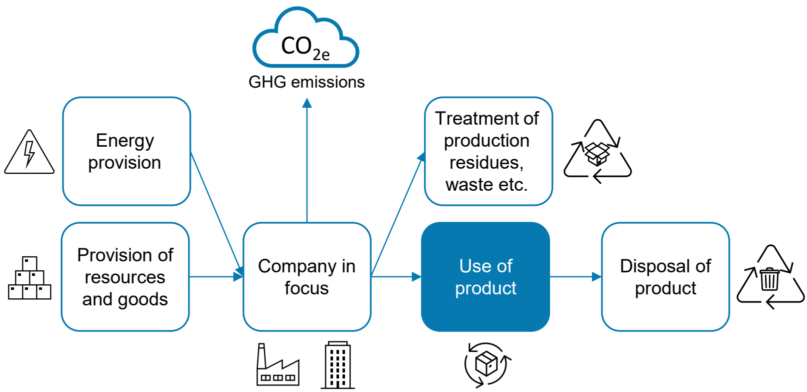


Figure 46: Affected life cycle phases in the “use phase” case study (in blue)

Procedure for the calculation

Through machine optimisation, 72,800 t of PVC as packaging material can be saved annually in the machine's use phase (question IX). While the machine is in operation, 8.05 MWh of electricity are saved annually by reducing the compressed air requirement. This is entered in question IX. Since this is a slow-moving product with a long service life, all savings are multiplied by a utilisation scaling factor of three.

Results

In total, 415,509 t CO_{2e} can be saved annually by implementing the measure. The emissions are shown in Table 10. For the sake of transparency, the results are shown once with and once without the utilisation scaling factor of three.

Table 10: Results for the "use phase" case study

Question	Measure	GHG emissions [t CO_{2e}] without utilisation scaling factor	GHG emissions [t CO_{2e}] with utilisation scaling factor of three
IX	Change in the use phase of the product (consumption of materials, auxiliary & operating materials)	138499	415497
X	Change in the energy consumption in the use phase of the product	4	12

Findings regarding the use of the ESTEM tool

As illustrated by the case study, certain effects in the use phase, such as the change in resource requirements, can be taken into account. However, measures that lead to a change in the life cycle of the product cannot be mapped with the tool, as a comparative analysis at the company level is no longer sufficient for this. In this case, a supplementary overall inventory at product level is required.

6.4 Case study 4: Reduced material use in the process

Initial situation

The company manufactures equipment carriers. The components of the carriers are cut from a sheet by laser and then further processed. At present, three components can be cut from each sheet. Due to the mainly manual and therefore not optimised and error-prone process, there is a scrap rate of approx. 35%

Description of the measure

An improved laser process that is digitally controlled is to be used. This means that several processing steps can be carried out simultaneously. Larger panels can be used, which allows for an optimised configuration of these. For optimisation purposes, different jobs that require the same material can be combined. This reduces the scrap and thus the amount of waste to about 25% of the amount before the measure. In addition, the machine's electricity and natural gas consumption are reduced. In addition, less nitrogen is used as cutting gas and the process no longer requires oxygen. Only the compressor needs more electrical energy after the measure is implemented.

Effect/type of measure

By reducing scrap, less material is needed as input. This is a continuous measure that will bring annual savings after the change.

Life cycle phases affected

The measure affects the life cycle phases shown in Figure 47.

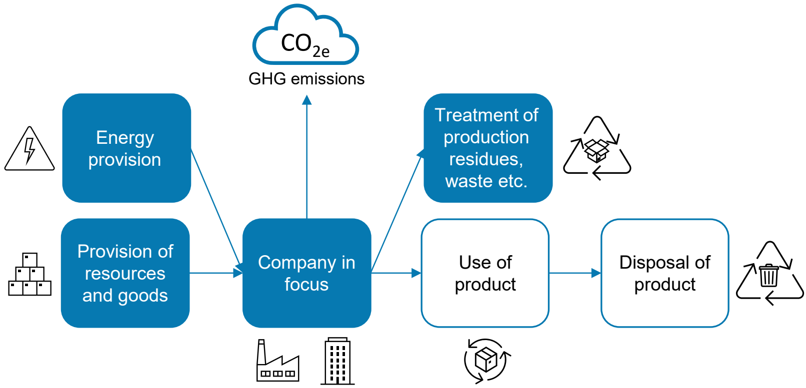


Figure 47: Affected life cycle phases in the "reduced material use in the process" case study (in blue)

Procedure for the calculation

15 t of steel are saved (question I), 3.5 t of nitrogen, 0.2 t of oxygen (question II), 0.04 MWh of natural gas (question IV) and 0.2 MWh of electricity (question VI) annually. These are entered as positive quantities in the respective questions. The evaluation of the electricity takes into account that part of the electricity is generated by the company's own solar plant.

It should also be noted that when quantifying savings, possible additional costs are taken into account and the total sum is entered into the tool. In this case, the sum of the electricity savings of the machine and the increased electricity consumption of the compressor is thus formed and noted in the corresponding field.

In addition, 15 t less steel has to be disposed of. Steel is sent to a recycling plant for disposal. According to the cut-off approach, it is therefore not possible to credit the company with emissions savings from the reduction of this production waste. Question VIII remains empty.

Results

In total, 33.8 t CO_{2e} can be saved annually by implementing the measure. The distribution of the saved emissions to the individual questions is shown in Table 11.

Table 11: Results of the "reduced material use in the process" case study

	Measures	Scope as per GHG Protocol	GHG emissions [t CO_{2e}]
I	Change in quantity of materials sourced for the products (e.g. material substitution, biogenic instead of fossil materials, less material, use of secondary materials)	Scope 3.1/3.4	32.73
II	Change in quantity or composition of auxiliary and operating materials required in the company (e.g. packaging, oils, paints, adhesives)	Scope 3.1/3.4	0.88
III	Change in capital or investment goods (e.g. machines, vehicles, buildings or production facilities)	Scope 3.2	0.00
IV	Change in the quantities or types of energy sources used for energy production at the site	Scope 1, incl. upstream Scope 3.3 emissions	0.01
V	Change in the direct GHG emissions resulting from the process	Scope 1	0.00
VI	Change in the quantity of energy sourced (power, heat)	Scope 2, incl. scope 3.3	0.10
VII	Change in the quantity of materials in the finished products and thus in disposal at the end of life	Scope 3.9/3.10/3.12	0.00
VIII	Change in the quantity or composition of auxiliary and operating materials as well as production residues and thus disposal	Scope 3.5/3.10	0.00
IX	Change in the use phase of the product (consumption of materials, auxiliary and operating materials)	Scope 3.10/3.11	0.00
X	Change in the energy **consumption in the use phase** of the product	Scope 3.9/3.10/3.11	0.00
XI	Change in the transport **service**	Scope 3.4/3.9	0.00
Total			33.72

6.5 Case study 5: Investment measure

Initial situation

Vehicle body parts are painted in the company. More than half of the total energy consumption for the production of a vehicle body is accounted for by painting. This is due to the high energy consumption during drying as well as air ventilation. In addition, the painting process produces overspray, i.e. paint that does not fall on the body parts. This has to be separated and disposed of.

Description of the measure

The investment in a new, high-precision painting facility aims to reduce overspray. This is achieved through increased precision, paint application that takes place closer to the surface to be painted and a new technique (e.g. inkjet printing). In this way, overspray can be reduced as well as the scrap that results from faulty painting.

Effect/type of measure

It is a one-time investment in a new facility, but it has a continuous impact on operations. The new facility reduces the use of paint and reduces scrap due to faulty painting. This reduces the input of materials (paint and PVC) and the production waste to be treated. In addition, the heat supply will be changed from heating oil to natural gas when the new facility is commissioned.

Life cycle phases affected

The affected life cycle phases are shown in Figure 48.

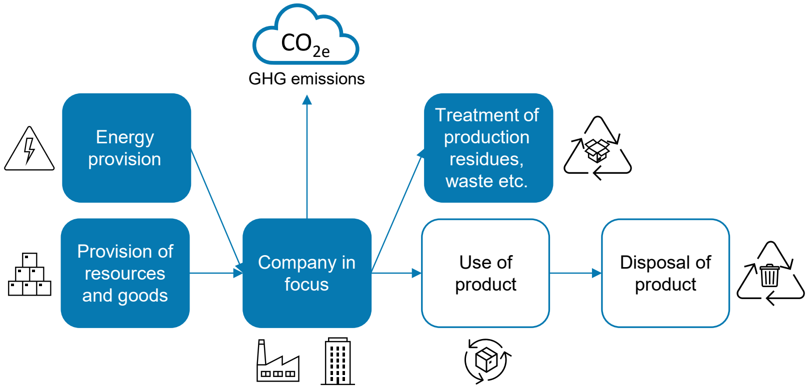


Figure 48: Affected life cycle phases in the "investment measure" case study (in blue)

Procedure for the calculation

4.3 t of PVC (question I) and 4 t of paint (question II) are saved annually. In total, the investment costs around € 2,300,000. This is entered as a negative value in question III. A depreciation period of three years is assumed for the standard case. In addition to the material savings and investments, 330 MWh of light heating oil is replaced by 205 MWh of natural gas, which is noted in question IV. Heating oil is saved and therefore entered as a positive value, while the additional natural gas is entered with a minus sign. Improved energy efficiency also results in savings of 31.8 MWh of electricity annually (question VI). In addition, savings in production waste are assumed due to the reduced amount of PVC. For this, a saved quantity of 4.3 t of landfill or household waste is entered in question VIII.

Results

The results for the standard case (three years of depreciation), as they are also presented in the ESTEM tool, are shown in Table 12.

The breakdown shows that overall negative savings are achieved due to the high CO_2 emissions caused by the construction of the facility. The measure therefore causes additional annual emissions. Without taking the investment measure into account, positive savings of around 88 t CO_{2e} would occur. In conjunction with the emissions for the acquisition of the facility, the payback period can be calculated, i.e. the theoretical depreciation period that leads to positive annual savings. This is 8.7 years.

Table 12: Results for the calculation of the "investment measure" case study for a depreciation period of three years

	Measures	Scope as per GHG Protocol	GHG emissions [t CO_{2e}]
I	Change in the quantity of materials sourced for the products (e.g. material substitution, biogenic instead of fossil materials, less material, use of secondary materials)	Scope 3.1/3.4	8.24
II	Change in the quantity or composition of auxiliary and operating materials required in the company (e.g. packaging, oils, paints, adhesives)	Scope 3.1/3.4	7.89
III	Change in capital or investment goods (e.g. machines, vehicles, buildings or production facilities)	Scope 3.2	-254.53
IV	Change in the quantities or types of energy sources used for energy production at the site	Scope 1, incl. upstream Scope 3.3 emissions	46.58
V	Change in the direct GHG emissions resulting from the process	Scope 1	0.00
VI	Change in the quantity of energy sourced (power, heat)	Scope 2, incl. scope 3.3	15.42
VII	**Change in the quantity of materials in the finished products and thus in disposal at the end of life**	Scope 3.9/3.10/3.12	0.00
VIII	Change in the quantity or composition of auxiliary and operating materials as well as production residues and thus disposal	Scope 3.5/3.10	9.44
IX	Change in the use phase of the product (consumption of materials, auxiliary and operating materials)	Scope 3.10/3.11	0.00
X	Change in the energy **consumption in the use phase** of the product	Scope 3.9/3.10/3.11	0.00
XI	Change in the transport **service**	Scope 3.4/3.9	0.00
Total			-166.96

6.6 Case study 6: Circular economy measure

Coffee dust is usually disposed of as production-specific waste. The company is planning a new pelletising plant to enable the diversion of the material flow into a high-value product, an organic fertiliser. The dust to be treated contains crushed coffee husks from the coffee bean and is separated into coarse and fine dust fractions by means of wind sifting. The fine dust fraction is sifted to remove plastic threads from the coffee bags and then homogenised in a mixer. The homogeneous dust is then pelletised and stored in an outdoor silo for removal. The pelletising plant also replaces the press container for disposal. It is planned to use these pellets as fertiliser and they can also be used as renewable fuel.

Effect/type of measure

The result of the measure is a high degree of waste avoidance at the company combined with a change in the use of resources and energy in the recycling process of the pelletising plant and the wind sifter.

Findings regarding the use of the ESTEM tool

Due to the cut-off approach in the ESTEM tool, the savings that now occur outside the company through the substitution of fertiliser are not considered. The savings would occur at another company that uses the pellets alternatively as fertiliser on the input side. Thus, the treatment of the production residues at the producing company only causes additional emissions. The positive contribution to emission reduction could only be illustrated if the system boundaries were extended.

This is a case study that is not covered by the simple ESTEM calculation process. In this case, a detailed description and justification of the measures beyond the application of the ESTEM tool would be required. Such cases are more appropriately addressed with a detailed LCA or CF analysis.

6.7 Conclusions from the case studies

The case studies are examples which cover different types of measures. Table 13 gives an overview of the examples from the guide.

Table 13: Overview of the five case studies covered by the method

Title of case study	Brief description	Impact on life cycle phases
Case study 1: Lightweight construction	Reduction of input material flows in the process itself by producing a nut with a lower weight.	Provision of energy, resources and goods; company in focus
Case study 2: Use of recycled materials	Instead of primary material, secondary material is used in the production of pens.	Provision of resources and goods
Case study 3: Effect on use phase	Manufacturers of packaging machines optimise the use phase of the manufactured machines. This reduces the consumption of resources and energy in the use phase.	Use of the product
Case study 4: Reduction of input material flows in the process itself	The optimisation of a laser process leads to a reduction in the input material. There is also less waste from scrap to be disposed of.	Provision of energy, resources and goods; company in focus, treatment of production residues, waste, etc.
Case study 5: Investment measure	Investment in new painting facility which reduces the use of paint.	Provision of energy, resources and goods; company in focus, treatment of production residues, waste, etc.

The greatest difficulty in evaluating the case studies was the unclear data or lack of data. The original data basis is based on real measures implemented in companies. These have been anonymised and partly supplemented with missing data or shortened for simplification. However, for companies carrying out the evaluation of their own project with the help of the tool, it should be easier to acquire the necessary data, because the specific questions make it possible to quickly determine which data still need to be requested or collected and in what form.

The application of the methodology to the case studies also illustrates that the provision of emission factors is indispensable for a simple and consistent assessment of measures. As described in Chapter 4.4, the tool provides a data basis for a large number of materials and energy sources. In addition, missing emission factors can be added later in the tool.

It also became apparent that the evaluation of the downstream phases (use and disposal) is significantly more complicated. This is particularly evident in the “Effect on use phase” case study. Here, many assumptions have to be made regarding the savings, as the company can only influence these to a limited extent and only has limited insight into the data of the use phase. In addition, it became clear once again during the selection and evaluation of the case studies that not all types of measures that affect the use or disposal phase can be covered by the ESTEM calculation procedure (see Chapter 4.2.3 and 4.2.4).

The evaluation of investment measures showed the high sensitivity to the assumed depreciation period. As explained in the “Investment measure”, a depreciation period of three years should be assumed for the first evaluation. In justified individual cases, this can be increased in a second evaluation. In the calculated case study, emission savings only take effect after a depreciation period of approx. eight years. The depreciation period assumed for the calculation should always be taken into account and critically questioned when interpreting the results.

Overall, the selected case studies have shown that the ESTEM methodology and tool are suitable for the consistent assessment of various material efficiency measures. The six case studies described in the guide, which cover different types of measures, can be used to help companies apply the methodology and the tool.

7 OUTLOOK

Together with the ESTEM tool, the guide and the first set of emission factors, a procedure is available that can be used in practice immediately. Thus, more has been achieved in the project than originally planned.

Nevertheless, tasks still remain for the future:

- The emission factors in the ESTEM tool have to be updated regularly. This applies in particular to the national electricity mix due to the increasing use of renewable energy sources, but also to other material or process-related factors, as they are influenced, among other things, by the changed electricity mix. We recommend an annual review and, if necessary, adjustment of the emission factors.

- The set of emission factors for materials that is available publicly and free of charge, for example within the framework of the ProBas database of the Federal Environment Agency, should be significantly expanded: to include other materials, but also other operating materials such as those used in manufacturing companies. For important materials, factors should be provided for variants from primary material as well as from secondary material. The same applies to bio-based materials.

- With regard to data provision, cooperation within the EU should generally be strengthened, e.g. with the European Commission, especially because the calculations of GHG reductions from efficiency measures are relevant in all EU member states and many upstream chains of products are located within the EU.

- An important step in terms of industrial policy would be to differentiate the material-related emission factors according to the region of origin, e.g. whether a material or intermediate product comes from Europe or Asia. This would require a considerable effort for the determination and public provision of emission factors, but would be of strategic relevance, as only in this way can global trade flows and imports be assessed in terms of their climate relevance in the future - both by the state and by individual economic stakeholders.

- Process data in the “end-of-life” and “transport” areas could be further differentiated and updated in the ESTEM tool.

- All emission factors should be adjusted to the new global warming potential values according to IPCC AR6 (2022) in the medium term. For reasons of compatibility, conversion factors for the various GHGs from IPCC AR5 (2014) are currently still used.

- Surveys should be conducted among users to evaluate the ESTEM tool. This should include asking users about the difficulties and questions encountered when entering the data in the tool and the materials or system areas for which additions are still desired. These results could be incorporated into a revised version 2.0.

- For exceptional cases not covered by the ESTEM tool, further procedures could be developed or at least illustrated by examples for users. This could include guidance on how to appropriately and comprehensibly document cases that fall outside the predefined framework.

- If the number of materials and processes is significantly expanded, the ESTEM tool as an Excel® application will reach the limits of a simple application. In this case, a new tool would have to be programmed.

8 BIBLIOGRAPHY

Allacker, K.; Mathieux, F.; Manfredi, S.; Pelletier, N.; Camillis, C. de; Ardente, F. and R. Pant (2014): Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. In: Resources, Conservation and Recycling, 88: 1 – 12.

Allacker, K.; Mathieux, F.; Pennington, D. and R. Pant (2017): The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. In: Int J Life Cycle Assess, 22(9): 1441 – 1458.

BAFA (2021): Information sheet on CO_2 factors. Federal Grant Programme for Energy and Resource Efficiency in Industry. Eschborn: BAFA. [retrieved on: 06.07.2022], available at: www.bafa.de/SharedDocs/Downloads/DE/Energie/eew_infoblatt_co2_faktoren_2021.pdf;jsessionid=BEE076F00607D83C86744ED44B6B511B.2_cid378?__blob=publicationFile&v=9

Bayerisches Landesamt für Umwelt (2021): Calculate your greenhouse gas emissions using the CO_2 calculator. Munich: LfU. [retrieved on: 06.07.2022], available at: https://www.umweltpakt.bayern.de/energie_klima/fachwissen/217/berechnung-co2-emissionen

Caro, F.; Corbett, C.J.; Tan, T. and R. Zuidwijk (2013): Double Counting in Supply Chain Carbon Footprinting, In: Manufacturing & Service Operations Management, 15(4): 545 – 558.

ecoinvent (2022): System Models. [retrieved on: 06.07.2022], available at: https://ecoinvent.org/the-ecoinvent-database/system-models/

Ekvall. T.; Björklund, A.; Sandin, G.; Jelse, K.; Lagergren, J. and M. Rydberg (2020): Modeling recycling in life cycle assessment. Final project report. Gothenburg: IVL Swedish Environmental Research Institute [retrieved on: 06.07.2022], available at: www.lifecyclecenter.se/wp-content/uploads/2020_05_Modeling-recyling-in-life-cycle-assessment-1.pdf

Estell (2021): Model of Systain Consulting GmbH. [retrieved on: 06.07.2022] available at www.systain.com/?ddownload=6426

European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010): International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg: Publications Office of the European Union.

European Commission (2013): 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Luxembourg: Publications Office of the European Union.

Eurostat (2008): Eurostat Manual of Supply, Use and Input-Output Tables. Luxembourg: European Communities [retrieved on: 06.07.2022], available at: https://ec.europa.eu/eurostat/documents/3859598/5902113/KS-RA-07-013-EN.PDF/b0b3d71e-3930-4442-94be-70b36cea9b39

Giegrich, J.; Liebich, A.; Lauwigi, C. and J. Reinhardt (2012): Indikatoren / Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion. UBA texts 01/2012. Dessau-Roßlau: Federal Environment Agency [retrieved on: 06.07.2022], available at: https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4237.pdf

IEA and OECD (2020): CO_2 Emissions from Fuel Combustion Statistics: Greenhouse Gas Emissions from Energy. Paris: IEA/OECD.

IPCC (2013): Contribution of Working Group I to the Fifth Assessment Report. Climate change 2013: The physical science basis: Final Draft Underlying Scientific-Technical Assessment. Geneva: IPCC [retrieved on: 06.07.2022], available at: https://archive.ipcc.ch/pdf/assessment-report/ar5/wg1/drafts/fgd/WGIAR5_WGI-12Doc2b_FinalDraft_Chapter08.pdf

ISO 14044:2020: Environmental management – Life cycle assessment – Requirements and guidelines [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/38498.html

ISO 14045:2012: Environmental management – Eco-efficiency assessment of product systems – Principles, requirements and guidelines [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/43262.html

ISO/TR 14069:2013: Greenhouse gases – Quantification and reporting of greenhouse gas emissions for organizations – Guidance for the application of ISO 14064-1[retrieved on: 06.07.2022], available at: https://www.iso.org/standard/43280.html

ISO/TS 14072:2014: Environmental management – Life cycle assessment – Requirements and guidelines for organizational life cycle assessment [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/61104.html

ISO 14064-1:2018: Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/66453.html

ISO 14067:2018: Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/38498.html

ISO 14080:2018: Greenhouse gas management and related activities – Framework and principles for methodologies on climate actions [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/67452.html

ISO 14064-2:2019: Greenhouse gases – Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements [retrieved on: 06.07.2022], available at: https://www.iso.org/standard/66454.html

Nuss P. and M.J. Eckelmann (2014): Life Cycle Assessment of Metals: A Scientific Synthesis. In: PLoS ONE, 9(7): e101298.

OECD (2015): OECD Inter-Country Input-Output (ICIO) Tables. Paris: OECD [retrieved on: 06.07.2022], available at://www.oecd.org/sti/ind/inter-country-input-output-tables.htm

PAS 2050:2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. London: BSI.

Pelletier, N.; Allacker, K.; Pant, R. and S. Manfredi (2014): The European Commission Organisation Environmental Footprint method: comparison with other methods, and rationales for key requirements. In: Int J LCA, 19: 387 – 404.

Schmidt, M.; Spieth, H.; Haubach, C.; Bauer, J. and M. Preiß (2019): 100 Betriebe für Ressourceneffizienz - Praxisbeispiele und Erfolgsfaktoren. 2nd volume. Heidelberg et al.: Springer.

Schmidt, M.; Nill, M. and J. Scholz (2021): Die Bedeutung der Lieferkette für den Klimafußabdruck von Unternehmen. In: Chemie Ingenieur Technik, 93(11), 1692 – 1706.

Schrijvers, D.L.; Loubet, P. and B.P. Weidema (2021): To what extent is the Circular Footprint Formula of the Product Environmental Footprint Guide consequential? In: Journal of Cleaner Production 320: 128800.

Science Based Targets Initiative (2021): SBTi Criteria and Recommendations, TWG-INF-002, Version 4.2. April 2021 [retrieved on: 06.07.2022], available at: https://sciencebasedtargets.org/resources/files/SBTi-criteria-legacy.pdf

Stadler, K. et al. (2018): EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. In: Journal of Industrial Ecology, 22(3): 502 – 515.

Federal Statistical Office of Germany (2020): Umweltökonomische Gesamtrechnungen: Methode der Berechnungen zur globalen Umweltinanspruchnahme durch Produktion, Konsum und Importe, Wiesbaden: StBA [retrieved on: 06.07.2022], available at: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/ueberblick/Publikationen/Downloads/ugr-globale-umweltinanspruchnahme-methode-5851102209004.pdf;jsessionid=01ADFC737EBF03F6D145CF5CF3F7DB32.live742?__blob=publicationFile

Federal Environment Agency (2016): CO_2-Emissionsfaktoren für fossile Brennstoffe. Climate Change 27/2016. Dessau-Roßlau: Federal Environment Agency [retrieved on: 06.07.2022], available at: www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/co2-emissionsfaktoren_fur_fossile_brennstoffe_korrektur.pdf

Federal Environment Agency (2022): ProBas – Prozessorientierte Basisdaten für Umweltmanagementsysteme. Dessau-Roßlau: Federal Environment Agency [retrieved on: 06.07.2022], available at: https://www.probas.umweltbundesamt.de/php/index.php

UNEP (2015): Guidance on Organizational Life Cycle Assessment. Paris: UNEP [retrieved on: 06.07.2022], available at: https://www.lifecycleinitiative.org/wp-content/uploads/2015/04/o-lca_24.4.15-web.pdf

VDI 4800:1:2016: Ressourceneffizienz - Methodische Grundlagen, Prinzipien und Strategien. Düsseldorf: Verein Deutscher Ingenieure

VDI Zentrum Ressourceneffizienz (2017): Ressourceneffizienz durch Industrie 4.0; Potenziale für KMU des verarbeitenden Gewerbes. Berlin: VDI Zentrum Ressourceneffizienz GmbH (VDI ZRE). [retrieved on: 06.07.2022], available at: www.ressource-deutsch-land.de/fileadmin/Redaktion/Bilder/Newsroom/Studie_Ressourceneffizienz_durch_Industrie_4.0.pdf

Weidema, B.P. (2000): Avoiding Co-Product Allocation in Life-Cycle Assessment. In Journal of Industrial Ecology, 4(3): 11 – 33.

Weidema B.P.; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O. and G. Wernet (2013): Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1(v3). St. Gallen: Ecoinvent Center.

Wolf, M.-A. et al. (2019): Circular Footprint Formula. Webinar; Environmental Footprint (EF) transition phase. European Communities [retrieved on: 06.07.2022], available at: https://ec.europa.eu/environment/eussd/pdf/Webinar%20CFF%20Circular%20Footprint%20Formula_final-shown_8Oct2019.pdf

WRI and WBCSD (without year): Quantifying the greenhouse gas emissions of products: PAS 2050 & the GHG Protocol Product Standard. A short guide to their purpose, similarities and differences [retrieved on: 06.07.2022], available at: https://ghgprotocol.org/sites/default/files/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf

WRI and WBCSD (2004): GHG Protocol – A Corporate Accounting and Reporting Standard. Revised Edition [retrieved on: 06.07.2022], available at: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

WRI and WBCSD (2005): GHG Protocol – The GHG Protocol for Project Accounting [retrieved on: 06.07.2022], available at: https://ghgprotocol.org/sites/default/files/standards/ghg_project_accounting.pdf

WRI and WBCSD (2011): GHG Protocol – Product Life Cycle Accounting and Reporting Standard [retrieved on: 06.07.2022], available at: https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf

WRI and WBCSD (2011): GHG Protocol – Corporate Value Chain (Scope 3) Accounting and Reporting Standard [retrieved on: 06.07.2022], available at: https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

Zampori, L. and Pant, R. (2019): Suggestions for updating the Product Environmental Footprint (PEF) method. JRC Technical Reports. Luxembourg: European Union [retrieved on: 06.07.2022], available at: https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf

VDI Zentrum Ressourceneffizienz
(Competence Center for Resource Efficiency)
Bülowstraße 78
10783 Berlin
Tel. +49 30-2759506-505

zre-info@vdi.de
www.resource-germany.com