Int J Life Cycle Assess (2016) 21:1473–1500
DOI 10.1007/s11367-016-1122-9

LIFE CYCLE SUSTAINABILITY ASSESSMENT

Eco-efficiency indicator framework implemented in the metallurgical industry: part 1—a comprehensive view and benchmark

Ida Rönnlund[1] · **Markus Reuter**[2,3] · **Susanna Horn**[3] · **Jatta Aho**[1] · **Maija Aho**[1] ·
Minna Päällysaho[1] · **Laura Ylimäki**[1] · **Tiina Pursula**[1]

Received: 8 July 2015 / Accepted: 20 April 2016 / Published online: 6 May 2016

Abstract

Purpose The purpose of this work was to develop an indicator framework for the environmental sustainability benchmarking of products produced by the metallurgical industry. Sustainability differentiation has become an important issue for companies throughout the value chain. Differentiation is sometimes not attainable, due to the use of average data, lack of comparative data, certain issues being overshadowed by others, and a very narrow palette of indicators dominating the current sustainability assessments. There is a need for detailed and credible analyses, which show the current status and point out where improvements can be made. The indicator framework is developed to give a comprehensive picture of eco-efficiency, to provide methods that enable relevant comparisons as well as the tools for communicating the results. In this way, the methodology presented in this study aims to make differentiation easier and thus aid companies in driving the development toward more sustainable solutions.

Methods The framework is based on the existing indicator framework Gaia Biorefiner, which is primarily intended for bio-based products. In this work, the framework was further developed for application in the metallurgical industry. The indicator framework is built by first looking at the issues, which are critical to the environment and global challenges seen today and which the activities of the metallurgical industry may have an impact on. Based on these issues, suitable indicators are chosen if they exist and built if they do not. The idea is that all indicators in a group form a whole, showing areas of innovation while refraining from aggregating and weighting, which often compromise a comprehensive and objective view. Both qualitative and quantitative indicators are included. The indicators are constructed following the criteria set by the EU and OECD for building indicators. Each indicator further has a benchmark. The rules for building the benchmark are connected to the indicators. Suitable data sources and criteria for the benchmark and the indicators are gathered from literature, publicly available databases, and commercial LCA software. The use of simulation tools for attaining more reliable data is also studied.

Results and discussion The result is a visual framework consisting of ten indicator groups with one to five indicators each, totaling up to 31 indicators. These are visualized in a sustainability indicator "flower." The flower can be further opened up to study each indicator and the reasons behind the results. The sustainability benchmark follows a methodology that is based on utilization of baseline data and sustainability criteria or limits. A simulation approach was included in the methodology to address the problem with data scarcity and data reliability. The status of the environment, current production technologies, location-specific issues, and process-specific issues all affect the result, and the aim of finding relevant comparisons that will support sustainability differentiation is answered by a scalable scoping system.

Conclusions A new framework and its concise visualization has been built for assessing the eco-efficiency of products from the metallurgical industry, in a way that aims to answer

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Responsible editor: Adisa Azapagic

Electronic supplementary material The online version of this article (doi:10.1007/s11367-016-1122-9) contains supplementary material, which is available to authorized users.

✉ Ida Rönnlund
ida.ronnlund@gaia.fi

[1] Gaia Consulting Ltd, Bulevardi 6A, Helsinki 00120, Finland

[2] Helmholtz Institute Freiberg for Resource Technology, Chemnitzer Sraße 40, 09599 Freiberg, Germany

[3] Outotec Oyj, Rauhalanpuisto 9, P.O. Box 1000, 02230 Espoo, Finland

the needs of the industry. Since there is a baseline, against which each indicator can be benchmarked, a sustainability indicator "flower" can be derived, one of the key innovations of this methodology. This approach goes beyond the usual quantification, as it is also scalable and linked to technology and its fundamental parameters. In part 2, a case study "A case study from the copper industry" tests and illustrates the methodology.

Keywords Benchmarking · Circular economy · Indicator · Metallurgy · Process and system simulation · Product environmental footprint · Resource efficiency · Sustainability

1 Introduction

Companies in the metallurgical industry and generally are competing with several assets, one being sustainability differentiation. Customers throughout the value chain, from business to business and business to customer, are seeking better and more advanced means to differentiate, as well as more detailed and credible analyses. They wish to communicate why their product is more sustainable than that of their competitor and learn which sustainability aspects need more attention and development in order to perform better. In addition, investors and stakeholders need analysis of sustainability facts, e.g., in the case of considering funding and investments. Current sustainability assessment methods are not always very well suited for these practical needs, where industry-relevant sustainability benchmarking is the focus. This is due to several facts, e.g., limited availability of other than average data, lack of comparative data, and a rather narrow palette of sustainability indicators dominating the current sustainability assessments.

The purpose of this work was to develop a comprehensive industry-relevant indicator framework for the environmental sustainability benchmarking of products produced by the metallurgical industry. This study focuses on environmental sustainability issues, while future studies will respectively analyze the other two main areas of sustainability: economic and social. While focusing on environmental sustainability issues, the main emphasis of the proposed indicator framework is in eco-efficiency. Eco-efficiency, as a term, was introduced by the Rio Earth Summit and the World Business Council of Sustainable Development in the 1990s to highlight the business-relevant aspects of sustainability: the importance of using fewer resources and causing less environmental burden per unit of produced goods and services (Schmidheiny 1992). The seven eco-efficiency guidelines introduced by DeSimone and Popof (1997) are still valid and they have guided the development of the practical indicator framework we have developed for measuring eco-efficiency in the metallurgical industry. These were reducing the material intensity of goods and services, reducing the energy intensity of goods and services, reducing toxic dispersion, enhancing material recyclability, maximizing sustainable use of renewable resources, extending product durability, and increasing the service intensity of products. Later, Derwall et al. (2005) highlighted the importance of measuring and developing eco-efficiency by performing an analysis on the effect of eco-efficiency on investment portfolio performance, showing superior performance for the eco-efficient companies. In addition, industry-relevant resource efficiency metrics and indicators and case examples are increasingly called for, e.g., in the Flagship Initiative under the Europe 2020 strategy on resource-efficient Europe (European Commission 2011). However, measuring and especially benchmarking eco-efficiency is not always straightforward, and development of industry-relevant practical frameworks is still needed.

One of the concerns raised in a review of sustainability assessment methodologies by Singh et al. (2012) is that sustainability indicators should be selected, revisited, and refined based on the appropriate communities of interest so that suitable parameters can be chosen. The issues that are important for each industry differ. In the focus industry of this work, the metallurgical industry, where limited primary resources are utilized and require resource-intensive processing, resource depletion and resource efficiency are key issues. In addition, for metallurgical products, it is very important to emphasize how to reuse, recycle, and repurpose materials efficiently as national metal recycling targets are being raised. Mineral resources are also becoming scarce, leading to increased energy requirements of mining operations due to utilization of lower grade reserves (Schlesinger et al. 2011). Although all this highlights the importance of recycled raw materials, primary raw materials are still needed as well, because there is a demand for them and recycling can only be applied to a certain extent due to techno-economic constraints. From a sustainability point of view, it is therefore important to compare the resource usage and impacts for production of primary raw material and recycled raw material, often called the geological mine and urban mine, respectively. In order to compare these very different value chains, a flexible sustainability assessment and benchmarking framework is needed. For this purpose, it is also important that the scope of the analysis is scalable.

There are several methods, tools, and frameworks available, which aim for a comprehensive view and include selected sustainability and eco-efficiency indicators following the life cycle assessment (LCA) methodologies (ISO 14040 principles). Existing sustainability assessment methods and tools to support decision-making in the process industries are currently being evaluated by the SAMT project ("Sustainability assessment methods and tools to support decision-making in the process industries") funded by the European Commission. The evaluation encompasses 51 methods and 38 tools, largely building on LCA approaches. In addition, Singh et al. (2012) have provided a recent review on sustainability indicator frameworks. The existing frameworks and the gaps that our developed framework aims to address are discussed in more detail in Section 2. With this background, it can be concluded that a lot of sustainability indicator methods and tools exist, yet they are not sufficient to cover the specific need of companies to differentiate and to build sustainable businesses.

To enable differentiation, a comprehensive sustainability picture is needed. In a simplified view, comprehensive sustainability assessment can be seen to focus on two major issues: the efficiency of the production process or use stage itself (meaning the use of resources), and the impact that the production or use has at the specific location or globally. Impacts on the environment depend on the vulnerability of the environment, which can be local or global, and the pressure put on it. In line with the LCA principles, sustainability issues, resource usage, and impacts need to be assessed at all stages of the value chain. Both resource usage and the environmental burden can be affected directly or indirectly. Indirect resource usage comes from cascading effects such as the substitution of resources in other value chains due to resource usage in the analyzed value chain. As a result, also indirect environmental impacts occur. The indicator framework developed here aims to build a comprehensive picture by including both resource use and impacts, and both in the direct system and in the broader system (Fig. 1).

Differentiation further requires a baseline (Reuter et al. 2015a, b). From an industry point of view, as described earlier, the usage of resources can be calculated, and the effluents can be measured, but evaluating what the values mean and what to compare against is difficult. Comparison could be made in a similar way as electricity, heat and water use, and waste production are monitored for private persons, and mean values have been collected for the purpose of comparing high usage and savings achieved with improved insulation, home appliances, faucets, and waste sorting. Comparing the process to other processes or to value chains of similar products makes this possible. This is the approach we have chosen to apply so as to solve the comparability problem. In order to improve comparability, system scoping must be transparent, scalable, and fully aligned with the indicator framework and the value chain in question. The developed method provides a proposed solution to this question. The fact that everything is compared to a baseline reveals truly what is techno-economically achievable and what not, hence making it possible to drive innovation where it really has an impact.

In addition, differentiation is complicated due to the use of average data in calculations and lack of data on for example waste formation, emissions, and water use. Here, simulation models provide an interesting opportunity to give more reliable and comprehensive data, building on an earlier work of Reuter et al. (2015a, b).

The eco-efficiency framework and assessment methodology developed to meet these needs of the metallurgical industry are described in this paper.

2 Discussion of other sustainability assessment methods

Environmental performance and sustainability reports for the whole plant or company have become part of the normal procedure for most companies; 93 % of the world's largest 250 companies report on their sustainability according to the Global Reporting Initiative (GRI). Some companies also report product-specific data. The most established reporting format is the GRI, with 18,000 reports recorded in their database. In Europe, another sustainability reporting format, Environmental Product Declarations, EPDs, has raised interest, for example within the construction industry. The EPD database contains 450 publicly accessible reports.

However, these approaches are quite general. In order to understand sustainability in a more comprehensive manner, including benchmarking to relevant competing products and methods with a wider scope of sustainability aspects is needed. The sustainability reports typically follow standardized LCA methodologies. The problems with LCA relate to differences in scoping, which makes benchmarking difficult, and to the difficulty of accessing reliable data. Comparison of values thereby becomes difficult, due to the absence of values to which the results can be compared. There is a strong need for increased data collection and methods for benchmarking. Although many databases currently provide LCI data, in many cases, weaknesses in data integrity and reference value scoping mismatches make benchmarking impossible without significant collection of primary data. Both EPD and GRI and the LCI databases show that systematic collecting of data is possible in principle. EPD initiatives also show that standardized methods for modeling are needed, as emphasis is placed on product-specific rules, PSR, and product category rules, PCR, which are attempts to standardize scoping and modeling in relation to specific products or product categories. The work presented here relates to the PCR methodology, looking at the specific needs for the metallurgical industry and the products produced in the sector. In addition to the problems of these methods related to data availability, integrity, and scoping, these quantitative methods lack a qualitative and risk-based approach to sustainability. Not all important sustainability aspects can be turned into numeric values.

A comprehensive review by Singh et al. (2012) lists 41 sustainability indicator frameworks in 12 categories of different indicator types: innovation, knowledge, and technology indices; development indices; market- and economy-based indices; ecosystem-based indices; composite sustainability performance indices for industries; product-based

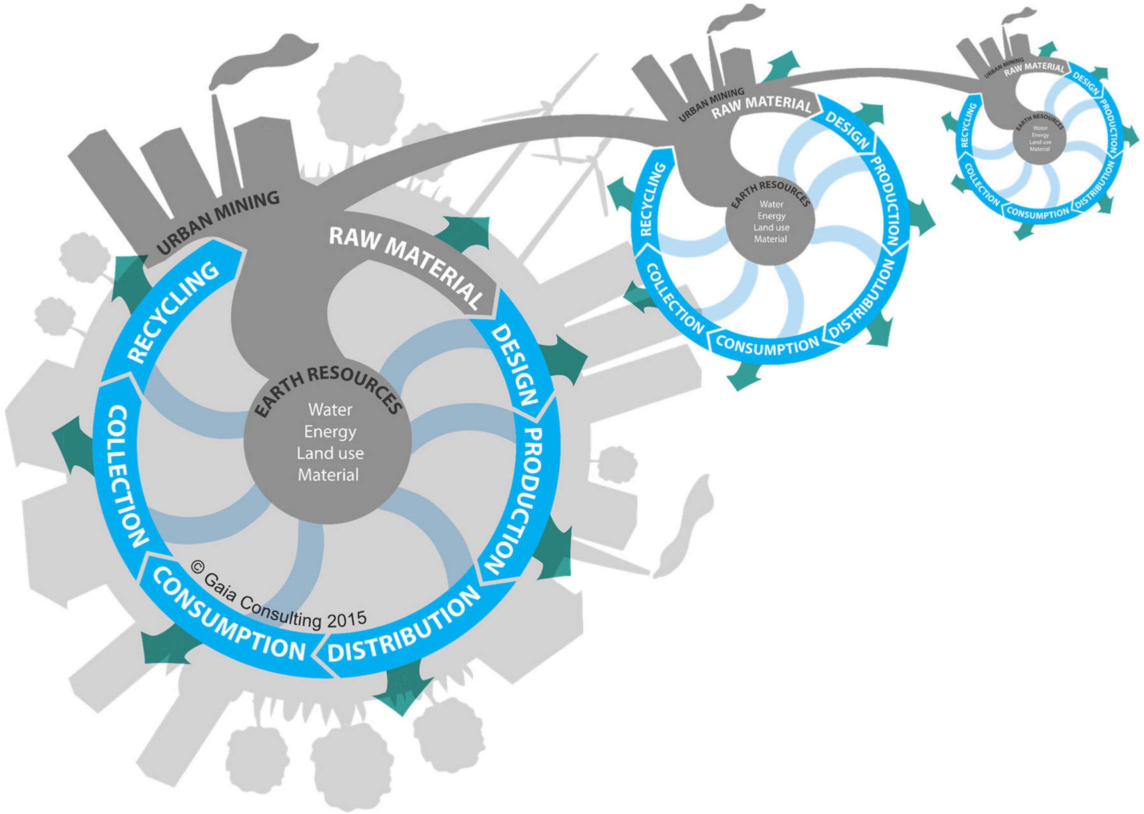


Fig. 1 The product value chain and comprehensive sustainability assessment of the metallurgical industry is focused on two major issues: resource use and impacts on the environment. Each product cycle is connected to other product cycles. They might add to the environmental burdens and depletion of resources or decrease the burdens by providing raw material, water, or energy to other cycles

sustainability index; sustainability indices for cities; environmental indices for policies, nations, and regions; environment indices for industries; social- and quality-of-life-based indices; energy-based indices; and ratings. Of these, the following three categories can be seen as relevant for processing industries. Of the indicators listed in the review, the following can also be seen to possess certain similarities to the developed framework.

Environment indices for industries Singh et al. (2012) list several environment indices for industries, three of which take a similar approach as the framework developed here. The environment assessment for cleaner production technologies made by Fizal (2007) enables quantitative analysis of the environmental impact of implemented, modernized, and modified technological processes and products, allowing comparative analyses of alternative technologies. Eco-points from the PRé Consultants tool are primarily based on a "distance to target" methodology. It evaluates the processes and products to cover all life cycle stages (Goedkoop and Spriensma 2004). The Eco-compass by Fussler and James (1996) is a simplified visual tool developed by Dow Chemical for representing the summary of life cycle assessment data, based on the indicators of eco-efficiency developed by the World Business Council for Sustainable Development (WBCSD), with some minor amendments. The three methodologies provide general indicators, but the specific industrial sectors and products require tailored indicators.

All three methodologies approach benchmarking, which points out the need for this in the industry. The approaches differ in the type of benchmark used: alternative technologies, target, and scores. Our approach aims at including the possibility for flexible benchmark, where either targets or alternative technologies can be the benchmark.

Product-based sustainability indices Singh et al. (2012) list two product-based sustainability indices. Both include social and economic aspects in addition to the environmental aspects, but neither is wide in environmental scope. The Life Cycle Index (LInX) by Khan et al. (2004) includes these three and an additional fourth aspect: technology. It is a composite index developed to support decision-making, in assessing the various design and technological considerations of processes and products. Ford of Europe's Product Sustainability Index (PSI) is a sustainability management tool for car manufacturers. PSI looks at eight indicators reflecting environmental (life cycle global warming potential, life cycle air quality potential, sustainable materials, restricted substances, drive-byexterior-noise), social (mobility capability, safety), and economic (life cycle cost of ownership) vehicle attributes. Both methodologies follow the recommendations of Singh et al. (2012), that indices should be tailored for the appropriate communities of interest. While the first methodology is directed to industry in general, it has a clear purpose of supporting decision makers. The second methodology is developed for the car industry and contains information that is interesting for the end consumer.

A similar sustainability assessment framework is the BASF Eco-Efficiency Analysis (Saling et al. 2002). With the Eco-Efficiency Analysis, selected indicators on energy consumption, emissions, toxicity potential, risk potential, and materials consumption are summarized in an environmental fingerprint. The method uses weighting and normalizing in order to compare results between value chains. However, with this method, the difficulty lies in weighting. As value chains differ a lot from each other, finding the proper weighting factors is complicated and objectivity and the transparency of the process are crucial. Nevertheless, study-specific weighting factors make it difficult to compare studies and develop a common data basis. Therefore, consistent scoping and system comparability still remain challenges for this type of approach. Further developed scoping and comparability, focus on metallurgical industry, and width of indicator set are the main differences to our approach.

Ratings Singh et al. (2012) list several rating methods, one of which focuses on environmental performance instead of economic and social. The OEKOM Environment Rating process includes the definition of relevant ecological and industry-specific assessment criteria, which is followed by giving a grade for each criterion on a scale from A+ to D−. The rating areas are weighted according to the specific industry after which the separate grades are brought together to form the overall rating. Our approach significantly differs from this as we do not apply weighting but use industry reference data instead.

Indicators and frameworks have also been developed for specific sectors or themes; for example, a set of indicators was formulated by the Institution of Chemical Engineers (IChemE) to assess the sustainability performance of the process industry (IChemE 2002). The sustainability metrics cover three dimensions, i.e., environment, economic, and social. The environmental indicators focus on resource usage and effluents, emissions and wastes, which are the core of processing industry, but, with the exception of the chemical indicators, they do not deal with the impacts on the surrounding environment. This indicator set has a wider, more generic scope, whereas we focus on metallurgical industry and detailed analysis of the environmental sustainability aspects.

One indicator framework has been developed by Azapagic (2004) specifically for the mining and metals industry; for example, indicators connected to a decrease in metal ore grade (Vieira et al. 2012) have also been in focus. The comprehensive framework for the mining and minerals industry presented in Azapagic (2004), in addition to the indicators included in the GRI reporting guidelines, also included indicators adapted to reflect the sector characteristics and new indicators connected to company compliance with environmental legislation and voluntary activities, nuisance to neighboring residents and habitat, waste, emissions, closure and rehabilitation, land use, and mineral resources. Although Azapagic's indicator framework is comprehensive, it is intended for sustainability reporting, not product group relevant sustainability benchmarking. The environmental sustainability issues presented in the framework are important also in our methodology. The indicators developed for a decrease in metal ore grade are connected to the issue of metal scarcity, which is a highly prioritized topic of the European Commission with ongoing studies on the criticality of raw materials. Mancini et al. (2015) highlight the fact that LCA is well positioned for providing information on resource-related issues of concern to business and governments such as the criticality of raw materials used in the supply chains. Issues such as criticality could be specifically addressed if highlighted during the goal and scope definition for certain product groups. If not, then the possibility is high for loss of relevant information due to, for example, cut-off criteria. Regarding the raw material criticality and recycling aspects of mining and the metals industry, Nelen et al. (2014) have developed a multidimensional indicator set to assess the benefits of WEEE material recycling, providing a good basis for further developing the recycling aspects of comprehensive sustainability indicator analysis. To summarize, earlier work on mining and metals sustainability indicator development has certain similarities with our approach and common goals, whereas the scope and approach we aim for differs.

Another relevant theme is resource efficiency, where indicators are being brought forward to respond to policies on resource efficiency. A systematized framework for resource efficiency indicators is sought by Huysman et al. (2015), as there is a need for structure and positioning of the indicators. They therefore developed a matrix that opens up the idea that there is a need to perform analyses from different perspectives to answer different needs, with the aim of supporting a meaningful application of indicators and giving a framework for the further structured development of indicators. In the matrix, indicators can be positioned according to the scale of the scope (assessment of specific processes and full supply chains, analyses at micro and macro scale) and the level of sustainability assessment (simple accounting of resource use and extraction and emissions or eco-efficiency indicators that include impact analysis). This approach is similar to our scalable scoping system, but we have implemented a similar approach specifically for the metallurgical industry and opted for a wider set of indicators.

Sustainability assessment has also been analyzed from an overall perspective by Sala et al. (2013). The outcome of their analysis is that mainstreaming LCA should be put on the agenda as a priority, that a holistic and system-wide approach is needed, that analyses should be transdisciplinary and multiscale, and that methods should be built together with stakeholders (Sala et al. 2013). Bringezu et al. (2003) also call for comprehensive approaches. They criticize material flow assessment (MFA)-based indicators, highlighting the need for the consideration of different impacts of material flows and different scales and perspectives of analysis, and distinguishing between turnover-based indicators of generic environmental pressure and impact-based indicators of specific environmental pressure. Reuter et al. (2015a) encourage the use of detailed data for sustainability analysis, as opposed to using average data for process steps, so that technological development can benefit more from sustainability analysis. Similar requests to those of Huysman et al. (2015) can be heard both on the industry level and on the national level. To conclude, current indicator frameworks lack comprehensiveness, scalability, and a connection between policy makers and companies.

As a result of the weaknesses related to the flexibility of scope and scalability, the comprehensiveness of indicators, and possibilities for benchmarking in other methods, we have aimed to develop a methodology which

- Gives a more comprehensive sustainability picture in a well-communicated manner, summarized in a concluding visualization (Fig. 2)
- Is scalable and flexible in terms of scope, i.e., indicators are scalable from technology and process efficiencies to differences between primary and secondary raw materials, so that innovation can be visualized and stimulated depending on the selected system scope (Reuter 1998)
- Provides the possibility to benchmark within the preferred scale and scope, thus providing a baseline for technology and systems to drive innovation

The first mentioned point enables easier communication of sustainability advantages and risks to policy makers and other stakeholders, while the two latter mentioned points drive the development of baselines so that technologies can be compared objectively and innovation driven from a rigorous basis.

3 Methods

The framework described here is further developed from an eco-efficiency framework developed for the bio-based industry, Gaia Biorefiner. The framework, which was initially developed together with the Finnish Forest-Based Industry organization FIBIC, has in this study been further developed together with a representative from the metallurgical industry, the mining and metal technology company Outotec. A new addition is the connection to simulation.

3.1 Methods for setting the scope for scalable system analysis

The background for a scalable system analysis builds especially on earlier publications on systems view and simulation-based analysis of metals processing and recycling systems (Reuter 1998; Reuter et al. 2013, 2015a, b; Worrel and Reuter 2014). The authors have developed the HSC Sim software used in the previous studies further to facilitate analysis while linking to LCA methodology. In developing the methodology, we have followed the LCI and LCA principles and approached system scoping from an industrial relevance point of view.

3.2 Criteria for selecting environmental sustainability indicators

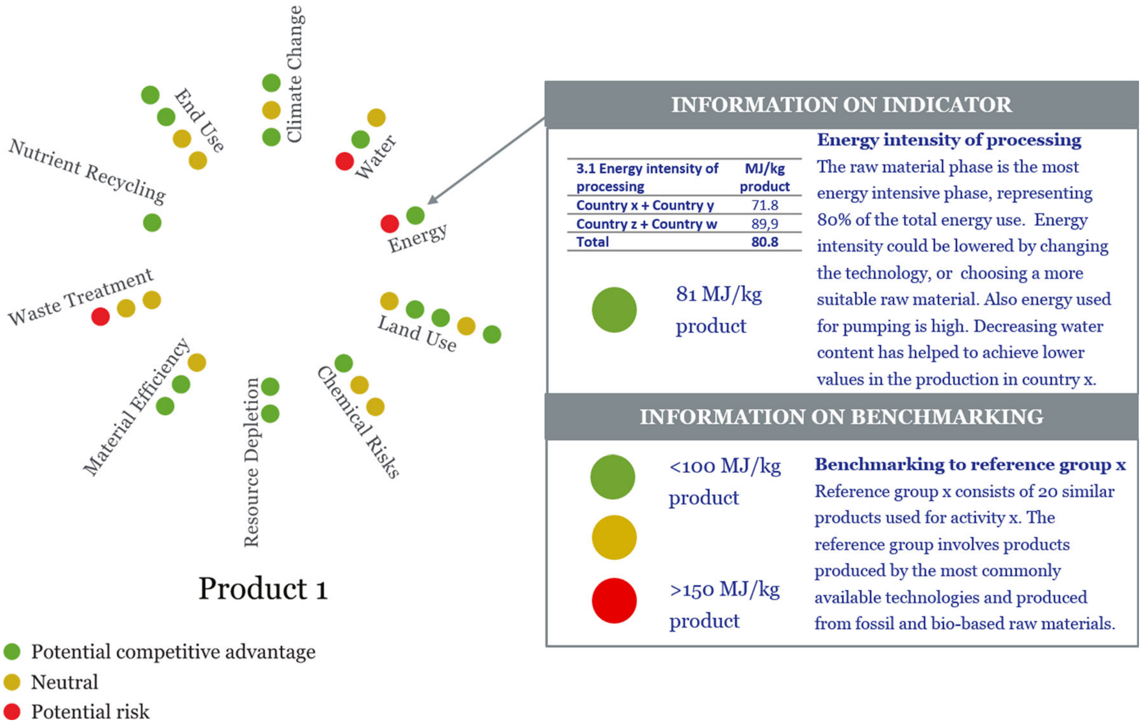
The selection and building of indicators generally follows the three basic criteria used in the OECD sustainability indicators development work (OECD 2003): policy relevance and utility for users, analytical soundness, and measurability.

> With respect to policy relevance and utility for users, an environmental indicator should:

- Provide a representative picture of environmental conditions, pressures on the environment or society's responses
- Be simple, easy to interpret, and able to show trends over time
- Be responsive to changes in the environment and related human activities
- Provide a basis for international comparisons
- Be either national in scope or applicable to regional environmental issues of national significance
- Have a threshold or reference value against which to compare it, so that users can assess the significance of the values associated with it

> With respect to analytical soundness, an environmental indicator should:

- Be theoretically well founded in technical and scientific terms
- Be based on international standards and international consensus about its validity
- Lend itself to being linked to economic models, forecasting, and information systems



INFORMATION ON INDICATOR

3.1 Energy intensity of processing	MJ/kg product
Country x + Country y	71.8
Country z + Country w	89,9
Total	80.8

81 MJ/kg product

Energy intensity of processing

The raw material phase is the most energy intensive phase, representing 80% of the total energy use. Energy intensity could be lowered by changing the technology, or choosing a more suitable raw material. Also energy used for pumping is high. Decreasing water content has helped to achieve lower values in the production in country x.

INFORMATION ON BENCHMARKING

<100 MJ/kg product

>150 MJ/kg product

Benchmarking to reference group x

Reference group x consists of 20 similar products used for activity x. The reference group involves products produced by the most commonly available technologies and produced from fossil and bio-based raw materials.

Fig. 2 Example of concluding visualization on results of sustainability indicator analysis using the Gaia Biorefiner sustainability analysis tool (www.gaia.fi/biorefiner). To the picture, a hovering textbox has been added to visualize how the summarizing flower is opened to reveal detailed information for each indicator

With respect to measurability, an environmental indicator should be:

- Readily available or made available at a reasonable cost/benefit ratio
- Adequately documented and of known quality
- Updated at regular intervals in accordance with reliable procedures

As mentioned earlier, the indicator selection further builds on the eco-efficiency perspective and the seven eco-efficiency guidelines (DeSimone and Popof 1997). These still summarize many relevant environmental sustainability aspects for the resource-intensive industries like metallurgy. In addition, in order to be relevant for the metallurgical industry, the indicators must correspond to the critical environmental issues and global challenges that can be seen today in the operating environment. This leads to a comprehensive environmental sustainability assessment. Additional relevant aspects for the metallurgical industry include the environmental risk aspect, which is highlighted from business perspective in the Global Risk Report by the World Economic Forum. Failure of climate change mitigation and adaptation, major biodiversity loss and ecosystem collapse, and water crises were all listed in top 10 risks in terms of impact in the wide stakeholder study of Global Risk Report 2016 (WEF 2016). In addition, environmental degradation, i.e., deterioration in the quality of air, soil, and water from ambient concentrations of pollutants and other activities and processes, was listed as a long-term trend affecting the risk that could contribute to amplifying global risks and/or altering the relationship between them.

Building on all these, and taking into account the specific activities along the value chains of the metallurgical industry and their impacts, a matrix of all aspects relevant for the indicator framework was compiled, and the proposed indicator framework was identified and established so that all relevant aspects were covered but no redundant indicators were included within the scope. The indicators were chosen and defined to be informative, in a way that drives development toward more sustainable solutions in an intuitive manner. Indicator-specific reasoning for selection and the respective literature references are discussed in detail in Section 4.2. Together with indicator selection and definition, the type of indicator was also defined, including benchmarking type and required reference data. This process is described in more detail in Section 3.3.

Following the abovementioned process, an indicator framework was established so that the following design criteria can be met:

- It provides a basis for technological comparison.
- It provides a basis for comparison of geographical locations of the value chain.
- It is applicable to complex systems that include multiple production locations, multiple raw materials and

processing methods, multiple energy and water sources, and multiple products and repurposing at different stages of the product life cycle.
- All of the policy and relevance criteria of OECD.

3.3 Basis for building the benchmark

The indicators define the type of benchmark that is suitable, and the benchmark aims to fulfill the policy and relevance criteria mentioned earlier of having a threshold or reference value against which to compare it, so that users can assess the significance of the values associated with it.

As described earlier, many sustainability indicators such as the usage of resources can be calculated, but evaluating what the values mean and what to compare against is difficult. Interpretation is generally highly value chain or product category specific. Therefore, comparison could be made so that value chains are compared to value chains of similar products within a product category.

It is unlikely that one product would have all the best qualities with respect to all sustainability aspects or all the average qualities. Therefore, the quantitative or qualitative results of the indicators are not compared to the values originating from one product, but each issue is looked at separately to find the specific thresholds and reference values relevant for (1) that issue (indicator) and (2) the scope of the study. This method of addressing each issue separately makes it possible to avoid generic weighting methods that often lack the necessary transparency and objectivity.

Data availability may narrow down the possibilities for reliable and meaningful benchmarking. To approach this problem, methods for data gathering are looked at.

Industries are dependent on policies, regulations, and customer demand. Together with the state of the environment and technological development, these are issues that are constantly changing. Similarly, the benchmark, to which the system is compared, must change. The benchmark therefore reflects

- The sustainability goals set by nations and various institutions
- The development and innovation of technology in the product group in question, and
- The urgency of change due to critical environmental impacts

3.4 Methods used to define the suitable type of data sources

In the first instance, data is collected from the actual processing steps that are part of the value chain. In addition, other data sources are needed for when this type of primary data is not available. For data gathering, the method uses primarily HSC Sim software for collecting primary data via process simulation (see Section 4.4), LCI databases for LCI data, as well as other complementing sources of value chain data. For LCI data, GaBi (www.thinkstep.com) and SimaPro (www.pre-sustainability.com) are used.

In addition, data is needed for the benchmarks. Generally, data for the benchmark is similar to that for the value chain being assessed. Suitable data sources were searched from commercial LCI databases, publications, and statistical databases. These are presented in connection with the results from building the indicators (Section 4.2) and forming the benchmark (Section 4.3). Simulation tools were included as an additional tool for building the benchmark and this is described in Section 4.4.

4 Results

The developed eco-efficiency indicator framework, given the name Gaia Refiner, consists of four main parts. The first part is defining the system or scope to be analyzed. Every analysis needs to have a clearly defined scope and the width of the system should reflect the purpose of the analysis. Defining the scope defines what the analysis will focus on. At the core of the framework is the second part, the indicators. The indicators define what it is relevant to measure or evaluate and how this should be performed, reflecting the selected system scope. The third part is the benchmark, which, defined by the system scope of the analysis, shows the position of the value chain with respect to others. The last part is the backbone of the analysis, the gathering of data, which ultimately defines whether the analysis can be performed. The different parts of the framework, their connections, and the use of the results from the assessments performed with the framework are shown in Fig. 3. The development and the results of the four parts of the framework are described in detail in the following.

4.1 Building a framework that allows for scalable scoping

4.1.1 Scale and focus of analysis

The design principles of system scoping were described in Section 3.1, emphasizing alignment with LCI and LCA principles together with industrially relevant flexible scoping in order to see the differences between comparable value chains in question. The first assumption is that products will be produced as long as there is a demand for them. The demand comes from the fact that the product fulfills a function. The analysis question that the sustainability assessment answers is thus how sustainable the system is for producing a product which fulfills a specific function. The comparable value chains fulfill the same purpose. The system scope always

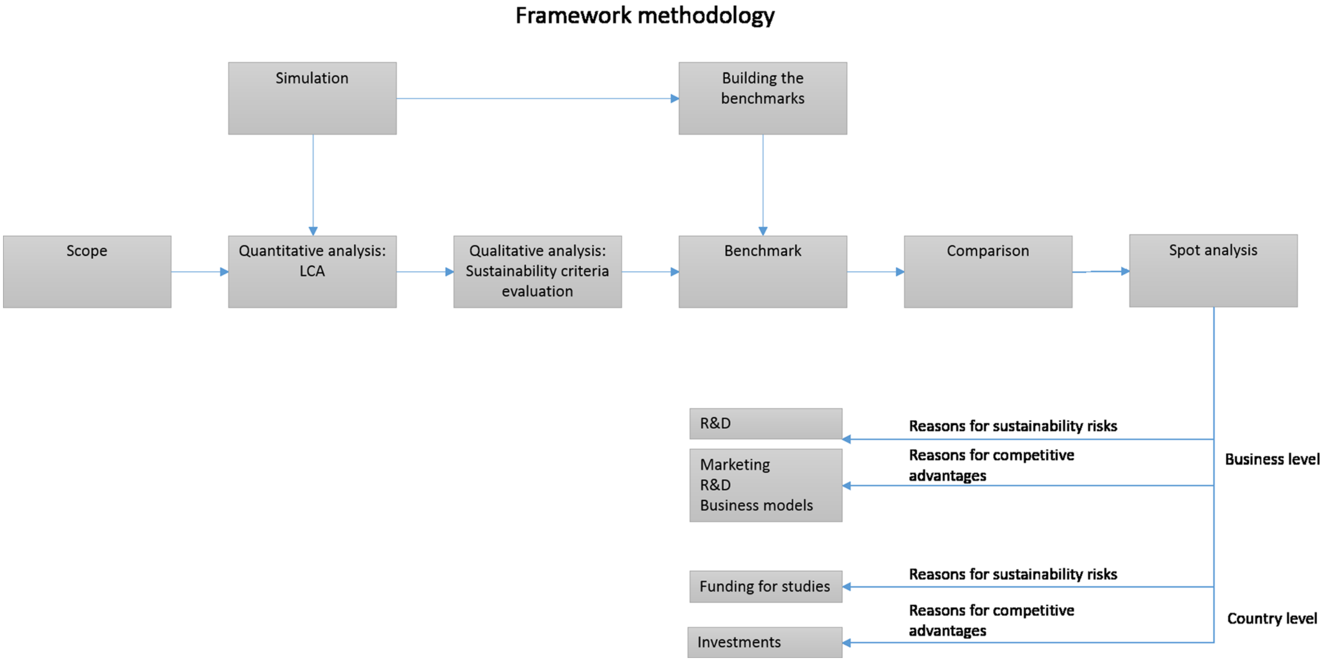


Fig. 3 Schematic picture of the developed framework and its use at different levels

includes the geographical locations, processes, and raw materials involved as well as the surrounding environment. Generally, as described below, the system scope includes the whole value chain, but in certain cases, the scope can be narrowed down to allow more focused analyses, for example, if variation in certain parts is too significant to allow seeing clear differences between the comparable value chains in question. In those cases, narrowing down of the wide system scope is an iterative process, reflecting targets of the analysis, indicators, benchmark, and available data. This is important as narrowing down, e.g., can increase accuracy of quantitative indicators in the focused scope but can lead to some system level indicators being obsolete in the specific case. In order to enable rigorous analysis, scoping is therefore aligned with all steps of the study and iteratively updated if so needed.

4.1.2 System boundaries

The general system boundary of the developed framework encompasses production phases from extraction of raw material to product's end of life. The system includes raw material production steps, pretreatment steps, processing steps, refining steps, product design steps, use phase, and end of life as presented in Fig. 4. Direct resource (energy, water, and chemicals) use, indirect resource use, direct emissions, indirect emissions, direct infrastructure, and indirect infrastructure are included for each separate step, and transportation requirements between all the steps within the system boundaries are included.

The system boundaries for some indicators may slightly differ from these general system boundaries. Any deviations from the general system boundaries will be presented case by case when the indicators are described in more detail in Section 4.2.

The developed calculation methodology follows the standards for LCA (ISO 2006a, b). All quantitative indicators are calculated per mass of main product(s) under examination and the allocation is done according guidelines in ISO 14044: 2006 (ISO 2006a). Either primary process data or secondary data from databases are used for all inputs and outputs and cut-off criteria of 1 % by mass is used in modeling. However, inputs, which are excluded from the LCI used in SimaPro modeling, are not necessarily excluded from data used to calculate all indicators. For example, all chemicals, even those that are under the cut-off criteria, should be included in the chemical risk indicators, because health and safety or environmental burdens are possible even though the chemical accounts for less than 1 % by mass of the system. Furthermore, as production value chains consist of process steps performed at multiple locations, the cut-off criteria of 5 % is used for indicators evaluating issues based on location-specific circumstances. This means that if over 5 wt% of the raw material used in the product originates from a specific location, then the circumstances connected to that location will be included in the evaluation.

4.1.3 Categorization of outputs and raw material

In the sustainability assessment, one of the most important issues is that the terms used in the assessment are clearly defined. This is specifically crucial when assigning product, co-product, and waste status to the outputs. Allocation is done

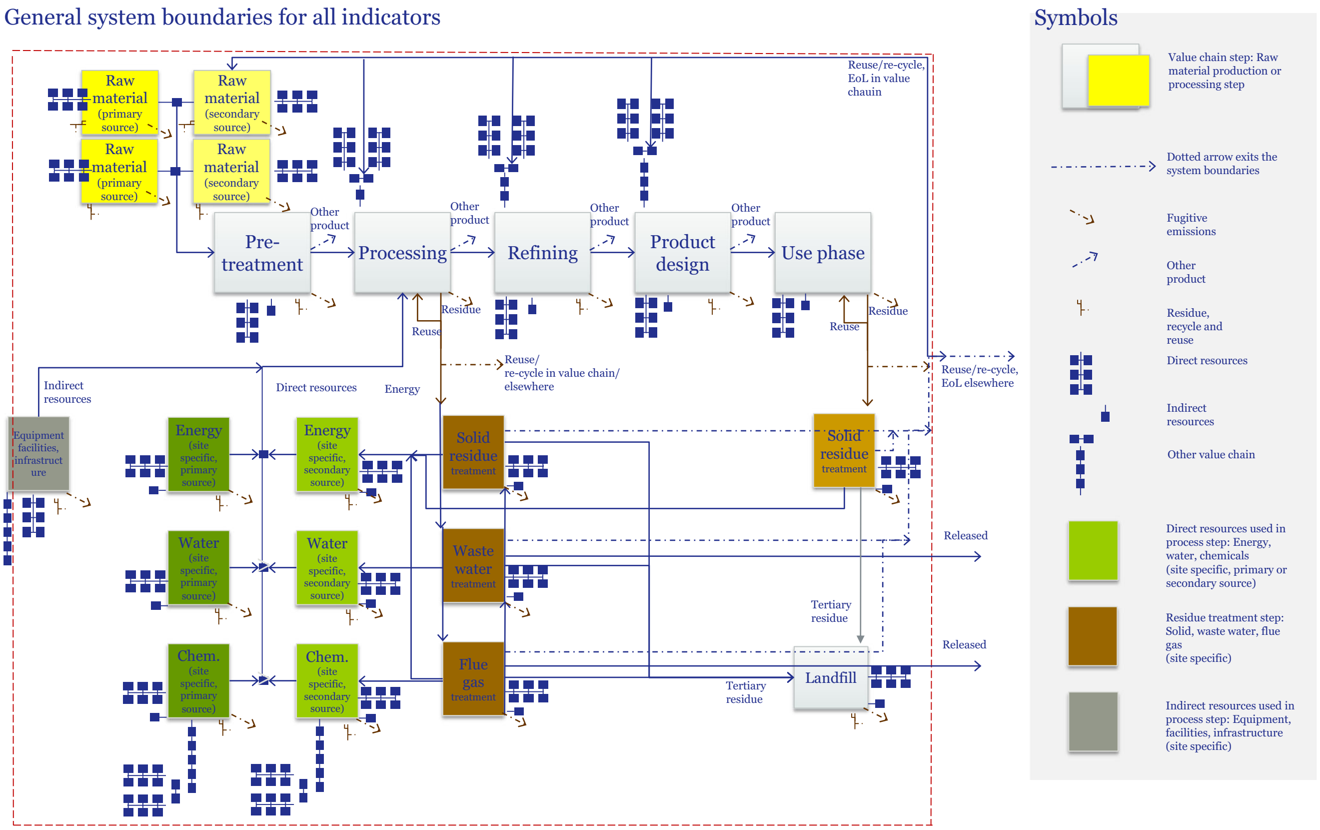


Fig. 4 General system boundaries for all indicators. Each block (indicated in *light blue*) represents a step in the main processing chain. Each step has direct resource requirements, direct effluents and emissions, and direct infrastructure requirements. This has been opened up for step 2, and for the other steps, these four issues are indicated with symbols. The production of each direct resource requires the use of other resources (indirect resources) and results in effluents and emissions (indirect effluents and emissions), all indicated with the respective symbols in the example in step 2. The effluents and emissions require treatment, from which either deposit disposal, release to air and water, or recycle occurs. The *dotted red line shows* the steps that have been included in this specific case study

based on the product/waste status of the output and it will have a major effect on the outcome of the sustainability assessment (ISO 2006a, b). Also, the rules for determining which status applies for each output need to be clearly defined to ensure consistency in all assessments. The Waste Framework Directive of the European Union (European Commission 2008) is applied for the terms connected to waste utilization and disposal. For the purpose of this work, the terms and definitions in Table S1 apply (see Electronic supplementary material).

The outputs are firstly categorized as either products or residues according to the criteria for classification as a product from the Waste Framework Directive (European Commission 2008):

- The process is modified to produce the product.
- The product has a market value.
- The product has a usage internally = replaces purchase of other products.
- The processing has a value = treatment is paid for.
- The product has a usage externally = replaces purchase of other products.

In addition, there is a need to differentiate between different types of products and different types of residues, depending on their purpose for further utilization. The possible types of products are main product and co-product and the possible types of residues are waste and raw material for another step.

- Main product: the output under inspection
- Co-product: output that meets the criteria of a product but is not under inspection
- Waste: output that does not meet the criteria of a product and is not under inspection

Similarly, raw material can be a product from a process or a waste, and the rules mentioned above are used to define whether resource usage and impacts should be allocated to the production of the raw material or not.

4.2 Defining the indicators for the framework

The Gaia Refiner framework is developed for screening the environmental sustainability of products and technologies and their entire value chains based on ten indicator groups.

Indicators can be grouped in many different ways. The approach taken here is to group the indicators according to the issue, in a way that the name is familiar to a wide variety of readers and easily comprehensible. The result is that the indicator group contains indicators, which describe the resource usage as well as the impacts from it. Thus, each group describes how much of the resource is used and how critical the usage of the resources is.

The framework is a collection of already standardized and established indicators, together with some novel ones that address issues not yet covered by the established methods. The established indicators included are those that are found in LCA software and frequently reported in company sustainability reports, the most well known being the GRI reports and EPD reports mentioned earlier. These include the environmental impact indicators global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP). The reporting of water use, energy use, and waste generation is also common, although several methods of reporting are applied, making comparison difficult.

The novel indicators, which have been developed in this work and included in the framework, are based on studies that describe environmental impacts from land use, and industrial activities, as well as sustainability development initiatives that focus on minimizing the use of resources and the generation of wastes. Some countermeasures for preventing the negative environmental impacts from resource usage are already in use, such as the sustainability criteria defined in the EU's Renewable Energy Directive (European Commission 2009b) and Fuel Quality Directive (European Commission 2009a) concerning GHG emissions, biodiversity, and land use. These criteria have been incorporated in the indicators that pertain to the respective issues.

Resource efficiency has long been a focus for industries, because of the connection to economics, but it is now also a primary focus of, for example, the EU and UN, due to the environmental and social aspects. UNIDO and UNEP support Resource Efficient and Cleaner Production (RECP) methods, defined as follows:

- Efficient use of natural resources, including materials, water, and energy
- Minimization of wastes and emissions, including those discharged to water, air, or on land
- Reduction of risks to humans and the environment from use of chemicals and disposal of chemicals used in industry

A similar view on what is needed for sustainable development is presented in the EU's growth strategy, which includes a Resource Efficiency Roadmap as part of the Resource Efficiency Flagship initiative. The roadmap offers a vision of the EU economy in 2050, where the economy is competitive and inclusive and provides a high standard of living with much lower environmental impact. All resources are sustainably managed, climate change milestones are achieved, and biodiversity and ecosystem services have been both protected and restored.

The sustainability issues mentioned in these initiatives are included in the Gaia Refiner indicator framework so that the use of key resources can be accessed from a life cycle and value chain perspective. The resulting indicator groups are presented in Fig. 5.

The aim of the assessment is to benchmark the value chain with respect to alternative value chains. The summarizing picture shown in Fig. 5 therefore only shows the result of each indicator. Each indicator can give three different results: green, indicating a possible competitive edge; red, indicating a possible alert; and yellow, being between these classes. The first part of the assessment is to analyze the value chain by calculating the values that the indicators need and listing the required criteria. In the quantitative indicators, the result is then screened against a reference group of comparable value chains and, in the qualitative indicators, against indicator-specific alert lists and sustainability criteria. The benchmarks in the qualitative indicators mainly reflect current sustainability goals and the urgency to change, due to critical environmental impacts, while the benchmarks for the quantitative indicator, such as the resource intensity indicators (water

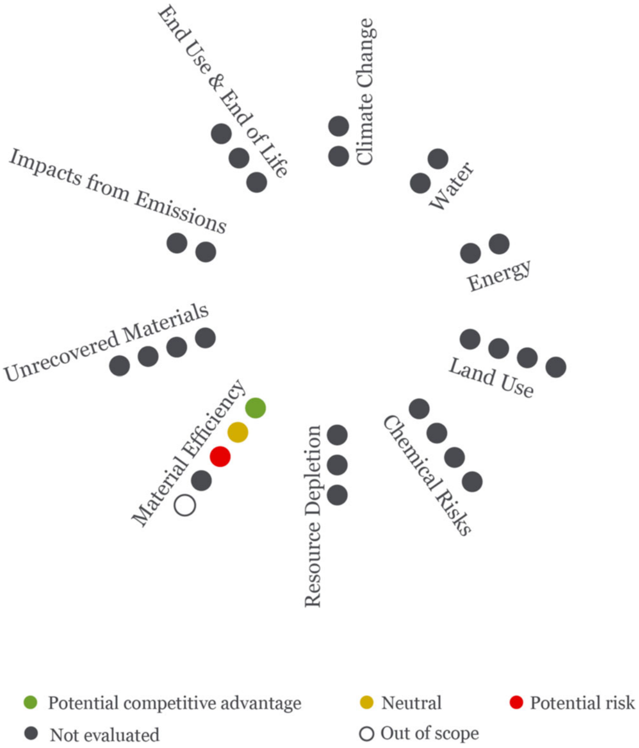


Fig. 5 The ten indicators groups of the framework. The *colored dots* seen under the material efficiency indicator group present the different results the indicators can show after benchmarking

intensity, energy intensity, land use intensity, material efficiency, and fossil intensity) are linked to the development of technology.

The indicator framework is shown in Table 1. The importance or weight of each indicator is not evaluated and indicators are not equalized or combined in any way. Instead, each issue should be addressed separately. In the following, each indicator group is described along with its respective indicators.

4.2.1 Indicator group 1: climate change

As global warming is seen as one of the major challenges of our time (IPCC 2013), global warming potential is included in the indicator framework to address the value chains contribution to greenhouse gases. The indicators are based on the existing method for evaluation of global warming potential (GWP), published by IPCC (2013). However, in the indicator group (Table 2), GHG emissions from production and GHG emissions from transport are separated and reported as two separate indicators. The measures to improve the situation are different, and by this approach, process-related and transport-related improvement potential can be detected separately.

The metallurgical industry is typically very energy intensive. Selecting more energy-efficient process technology or utilizing renewable energy sources will lower the GHG emissions from processing, but in addition, resource efficiency is a key factor contributing to reduction of GHG emissions. When less raw materials and water are used, less energy is required to produce and process (pump, heat, cool) them. Also, less transportation is needed, lowering the net GHG emissions. In metal production industry, long transportation distances are also typical as the mineral ore deposits and production sites might be located in different countries or continents.

4.2.2 Indicator group 2: water

Water intensity describes the total water withdrawal needed from municipal, groundwater, surface waters, or seas to produce the product.[1] Water is used in different operations, for the production process itself and also for cooling, heating, and washing, for example. If the water used is not incorporated into the products, the usage should be minimized. To minimize water intensity, the most water-efficient and suitable raw materials need to be chosen and all processes need to be selected so that they use as little water as possible. Recycling, especially circular closed systems for cooling water, is also an effective way to minimize water intensity. Indicator 2.1 (Table 3) covers water intensity by calculating the water use (water withdrawal) within the general system boundaries. Metallurgical processes utilize significant amounts of water. For example, flotation processes are highly water intensive and closed circuits are crucial to decrease the amount of required water. Hydrometallurgical production processes are even more water intensive.

For the sustainable use of water, in addition to water intensity, water scarcity is also important. The water scarcity indicator covers the issue of regional water availability, describing the possible imbalance between availability and demand. Water overuse is damaging the environment in many regions (UNEP 2008) and water stress has consequences for security and human well-being (Ridoutt and Pfister 2010). This is especially important issue for extraction industries such as mineral extraction, as it is a location-specific industry. Therefore, if the water scarcity level is high, it is necessary to concentrate on efficient use of water. The water scarcity indicator used by Hoekstra et al. (2012) is based on a consumption-to-availability ratio (CTA) and is calculated as the fraction between consumed (blue water footprint) and available water. Indicator 2.2 covers water scarcity within the general system boundaries.

Both the water intensity indicator and the water scarcity indicator are based on existing methodologies (Hoekstra et al. 2012). However, both indicators are included in framework as they measure different aspects of water consumption. Indicators 2.1 evaluated how efficiently water is used by the operations and the second indicator (2.2) is location specific considering the scarcity of the water resources at the specific location.

However, precise data for evaluation is not necessarily easy to find out. Data for calculation can be found from LCI databases that are included in LCA software, such as SimaPro. In addition, country-specific water scarcity maps have been developed and published by different associations, such as WWF.

4.2.3 Indicator group 3: energy

Global energy demand is constantly growing, with adverse effects on availability of natural resources, climate change and the environment, caused by energy production and use. The first indicator (Table 4) describes the energy intensity of processing, while the second indicator evaluates the sustainability of the energy sources used to meet the requirements of processing. Both of these indicators are established earlier and have been used in several initiatives and indicator frameworks, for example in the EU's resource efficiency scoreboard (European Union 2015). Within the metallurgical industry, significant amounts of energy are required in the different process steps, such as grinding and milling of ore, flotation of ore to

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[1] The indicator goes beyond the blue water footprint, which only considers the volume of surface and groundwater evaporated or incorporated into a product. The blue water footprint is the amount of water withdrawn from groundwater or surface water that does not return to the source from which it was withdrawn.

concentrate, and also in pyrometallurgical and refining processes. Therefore, it is important to minimize energy consumption by using energy-efficient process technologies and utilizing renewable energy sources that decrease the environmental impacts caused by the energy production and consumption.

Although the indicator GHG emissions from processing reflects energy use, the technological advances could be overshadowed by the source of energy. The energy indicators are included to provide more detailed information on the solutions connected to the location of production and the ones connected to the energy source.

Available data about energy consumption by the metal production industries can be found from LCI databases, but reported data are also publicly available from Eurostat and BAT reference documents published by the European Commission. The main difficulties with data are to find information for similar system boundaries so that the values are comparable with each other.

4.2.4 Indicator group 4: land use

There is an increasing pressure to use land effectively. Land provides possibilities for food and feed production, but land is required also for the production of other primary raw materials. Furthermore, it provides crucial ecosystem services and carbon sinks. Extraction of minerals causes land transformation that involves changes in local ecosystems. In addition, mineral extraction processes include various risks that might have an impact on the surrounding environment; therefore, indicators related to risk management are also included. The land use indicator group (Table 5) comprises one quantitative and three qualitative indicators.

The quantitative component measured is land use intensity (4.1). Accounting for land use intensity is especially crucial for raw materials whose production does not allow synergistic use of the land for other purposes. If synergistic use of the land area is possible, then major land use requirements become less crucial. This is indicated by a separate qualitative indicator, 4.2 Land use synergies through ecosystem services. These synergistic uses balance the quantitative land use intensity, making certain quantitatively low-efficiency sources beneficial by taking into account the synergistic benefits provided. Both indicators serve the purpose of comparing the land use requirement of different raw materials (metals, fossil, bio-based), since often very different raw materials can be used to produce an end product that ultimately serves the same purpose to its user. These indicators describe the use of resources. Indicator 4.2 is based on the methodology developed by Bukhard (2009, 2014).

The two other qualitative indicators indicate the impacts of land use. These are 4.3 Land use impact and risk mitigation of mines and 4.4 Land use impact and risk mitigation of tailing ponds, which highlight the use of sustainable practices and their relevance in protecting the land required by the mining industry. Since land use cannot be avoided (except for

Table 1 The indicator groups consist of one to five indicators each, all of which describe specific sustainability aspects within the indicator group

Indicator group	1. Climate change	2. Water	3. Energy	4. Land use	5. Chemical risks	6. Resource depletion	7. Material efficiency	8. Unrecovered materials	9. Impacts from emissions	10. End use and end of life
Indicators	1.1 GHG emissions from production	2.1 Water intensity	3.1 Energy intensity of processing	4.1 Land use intensity	5.1 Chemical intensity	6.1 Fossil intensity	7.1 Raw material suitability and utilization	8.1 Unrecovered aqueous	9.1 Eutrophication potential	10.1 Functionality
	1.2 GHG emissions from transport	2.2 Water scarcity	3.2 Share of renewables and recovered energy	4.2 Land use synergies through ecosystem services	5.2 Environmentally hazardous chemical use	6.2 Mineral availability	7.2 Main metal utilization efficiency	8.2 Unrecovered gaseous	9.2 Acidification potential	10.2 Risks related to product
				4.3. Land use impact and risk mitigation of mines	5.3 Health hazardous chemical use	6.3 Mineral substitutability	7.3 Waste prevention	8.3 Unrecovered solids		10.3 Design for recycling (DfR)
				4.4 Land use impact and risk mitigation of tailing ponds	5.4 Safety hazardous chemical use		7.4 Residue utilization and repurposing	8.4 Fugitive emissions		
							7.5 Secondary raw material/total raw material			

Table 2 Indicators in the climate change indicator group

Indicator	Description
1.1 GHG emissions from production ($kg\ CO_{2\ eq.}/kg$ product)	The indicator describes the greenhouse gases emitted from production in kilogram CO_2 equivalents per kilogram of product. The emissions are compared to emissions of other comparable products. Both energy used for processing and direct greenhouse gas emissions from processing are included for all steps of the value chain, indicating the carbon intensity of the processing chain. Benchmark type: *reference group*
1.2 GHG emissions from transport ($kg\ CO_{2\ eq.}/kg$ product)	The indicator describes the greenhouse gas emissions from transportation in kilogram CO_2 equivalents per kilogram of product. The emissions are compared to emissions of other comparable products. Raw material and intermediate product logistics are included. This indicates the carbon intensity of transportation, taking into account both transportation means and distance. Greenhouse gas emissions can be reduced by utilizing as local raw materials and production concepts as possible. However, product groups differ strongly on possibilities to do so, and therefore, the issue must be analyzed relative to the product category in question. For calculating transport to end use, the specific end user and location must be determined. Benchmark type: *reference group*

recycled materials), the impacts must be minimized, mitigated, and if necessary, compensated. Mining operations have a major impact on the environment. If risk management is poorly handled, it might cause wide environmental disasters. Indicators 4.3 and 4.4 have been developed in this study to cover these specific characteristics of land use in the metallurgical value chain. For assessment, a sustainability criteria list is formed and operations are compared against these criteria.

These indicators are not often presented together with other typical sustainability indicators, although the importance of sustainable land use increases continuously and should be taken into consideration by all industries. It should also be noted that risks related to operations and their possibility to cause negative impacts on land use more widely are not considered in existing sustainability frameworks.

Table 3 Indicators in the water indicator group

Indicator	Description
2.1 Water intensity of processing (m^3 water/kg product)	The indicator describes how much water is used in raw material production and processing in cubic meters of water per kilogram of product, compared to other comparable products. All water required for processing and cooling purposes are included, also salt water. Water, which is immediately returned and has not been altered, for example turbine water, is not included. The indicator compares the water intensity to other comparable products. Benchmark type: *reference group*
2.2 Water scarcity in production locations (WSI/kg product)	The indicator describes the scarcity of freshwater resources in the production regions of the value chain in question, indicating the general risk for water resource overuse. The approach is to look at the ratio of regional blue water footprint (based on consumption) to regional blue water availability, using the water scarcity indicator by Hoekstra et al. (2012). An exception from the water scarcity indicator by Hoekstra et al. is that water, which is immediately returned and has not been altered, for example turbine water, is not included. The benchmark is formed by combining the average water withdrawal for the value chain with the scale of stress weight from 0.01 (min) to 1 (max). Benchmark type: *sustainability limits*

Table 4 Indicators in the energy indicator group

Indicator	Description
3.1 Energy intensity of processing (MJ primary energy/kg product)	The indicator describes the energy efficiency of the value chains and products by comparing their energy consumption (MJ of energy per kg of product) to other comparable products. Energy used in the raw material procurement and processing as well as in refining the product are included. Energy efficiency of production is related to the technology chosen for production and thus this indicator guides toward using best available technologies (BAT) or better in order to minimize energy consumption of the production processes. Benchmark type: *reference group*
3.2 Share of renewables and recovered energy sources in total processing energy (%)	The indicator describes the share of renewable energy sources in processing throughout the value chain in percent of the total energy consumption. Energy used in the raw material procurement and processing as well as in refining the product is included. Benchmark type: *sustainability limits*

4.2.5 Indicator group 5: chemical risks

Chemicals are used in numerous ways during the product life cycle. The metallurgical industry utilizes chemicals in their production processes, and therefore, risks for environment and people exist. In addition to chemical consumption, some metallurgical processes produce also significant amounts of chemicals as by-products. This increases the potential risks for people and environment. Furthermore, the risks do not exist only at the production site, but also transportation and storage of chemicals comprises risks that might cause hazards outside the production facility. Minimization of chemical risks is therefore one aspect to take into account when benchmarking alternative processing technologies (Sala and Goralczyk 2013). Currently, chemical risks are included in transport and safety documents, but evaluation of risks are not connected to the overall assessment of the value chain. The use of environmentally friendly chemicals or safety measures taken for hazardous chemicals may affect resource use. Looking at resource use together with chemical risks will provide a better basis for sustainability comparison.

The indicator set, shown in Table 6, covers all three aspects separately, i.e., environment (indicator 5.2), health (indicator 5.3), and safety (indicator 5.4). The system boundaries cover only the chemicals used in in-house production, including waste treatment processes. The indicator group also includes a general evaluation of the total use of chemicals (indicator 5.1). These indicators are developed in this study as risks related to use of chemicals are typically present in metallurgical processes. Indicators are based on established hazard statements of chemicals.

4.2.6 Indicator group 6: resource depletion

Resource depletion is a globally recognized challenge and the metallurgical industry is an intensive consumer of nonrenewable resources. This group of indicators is included in the framework to cover relevant issues regarding resource depletion as well as their availability and substitutability.

Methods describing the availability of resources are included in many LCA impact methodologies; for instance, the CML LCA methodology, developed by the Center of Environmental Science of Leiden University (https://www.universiteitleiden.nl/en), includes the traditionally used, abiotic depletion potential (ADP). The method is applied in some sustainability assessments, such as EPDs. The ADP method indicates the seriousness of resource depletion and it takes under consideration existing reserves of resources and extraction rates. It however combines all resources used and converts them to the reference resource, antimony, which, although giving a good picture of the overall impact, covers the details of where improvement is needed and where improvement is possible. In this study, a wider aspect, including more aspects and avoiding combining the information into one number, was chosen to evaluate resource depletion and availability and therefore existing methodologies that concentrate mainly on physical constraints were not utilized for minerals. The CML methodology also includes a method to determine abiotic depletion potential of fossil fuels, expressed in megajoules. This approach has been applied in the indicator group, although the unit of measurement chosen is kilogram, as the indicator includes the use of fossil sources as materials.

The first indicator (Table 7), fossil intensity, measures the amount of fossil feedstock required to produce the product. This comprises the fossil fuels consumed in the production and transportation phases, in secondary energy production as well as the fossil raw material present in the raw materials. The indicator poses some duplication of information as, the use of fossil fuels is seen in the climate change and energy indicator groups, as higher greenhouse gas emissions and lower share of renewable resources, respectively. The indicator is however

Table 5 Indicators in the land use indicator group

Indicator	Description
4.1 Land use intensity (ha/t)	The indicator describes how much land is needed for primary raw material production in hectares per product tonne. The indicator result depends on the primary raw material and its production location. The lifetime of the mine is taken into account. The value is benchmarked against agricultural raw materials, raw material from forestry, and fossil raw materials. For biomass raw materials, the land area required for producing the annual biomass increment is estimated. For fossil raw materials, a comparable approach is used. Benchmark type: *reference group*
4.2 Land use synergies through ecosystem services	This indicator describes whether the land area used for primary raw material production is simultaneously beneficial for other synergistic purposes, such as providing of ecosystem services like nutrient recycling, air purification, and recreation. The sustainability criteria uses a classification method developed by Bukhard (2009, 2014), where the land type in question receives a score based on the criteria: ecological integrity, regulating services, cultural services, and provisional services. Benchmark type: *sustainability criteria*
4.3 Land use impact and risk mitigation of mines	This indicator focuses on raw material production phase, i.e., the impact of the mining is in focus. Mining has severe impacts on the surrounding land. Choosing sustainable mining practices is essential in order to minimize the adverse impacts related to land use. The indicator is evaluated based on a set of sustainability criteria formed from the International Finance Corporation (IFC) standard by the World Bank Group and other mining standards published by various organizations, such as International Council of Mining and Metals, Mining Association of Canada, and World Gold Council for land use requirements. Especially if the mine is applying the IFC Mitigation hierarchy: avoid/minimize/mitigate/compensate, it is considered sustainable, with the target of "no net loss." Benchmark type: *sustainability criteria*
4.4 Land use impact and risk mitigation of tailing ponds	This indicator covers the land requiring aspects of mine processing plant, i.e., the need for tailing ponds and their land use effects are included. Landfill policy aims to minimize landfilling of waste. Residue ponds have significant risks and thus pose limitations to use of land. The indicator is evaluated based on a set of sustainability criteria formed from the International Finance Corporation (IFC) standard by the World Bank Group and other mining standards published by various organizations, such as International Council of Mining and Metals, Mining Association of Canada, and World Gold Council from for land use requirements. Benchmark type: *sustainability criteria*

added as it includes the viewpoint whether the material used for the production of the product is of fossil origin or not and the total effect this has on the use of fossil resources. Therefore, this indicator is included to show the total effect of these issues. It does not bring new viewpoints if only products from the metallurgical industry are looked at, but if multimaterial products are included then the indicator becomes important.

The second indicator (6.2) describes the availability of mineral resources. Mineral deposits are distributed unequally in the Earth's crust and the scarcity of different minerals varies. Furthermore, declining ore grades and more troublesome locations of resources are challenges to overcome in order to utilize these resources. However, the physical constraints are not the only factors that have an impact on the availability of certain materials. Therefore, mineral availability describes not only the scarcity of the element concerned but also covers other issues that affect availability, such as the recycling rate and political stability of the producing countries. These aspects have been taken into account in relative supply risk index published by the British Geological Survey (BSG 2012), and therefore, this risk list is used as basis for the mineral availability indicator. However, there is no information how often this risk list will be updated, and therefore, it might contain outdated data in future studies.

Table 6 Indicators in the chemical risk indicator group

Indicator	Description
5.1 Chemical intensity	The indicator describes the total amount of chemicals used in the main steps of the production chain (total use of chemical in kg/kg product). Benchmark type: *reference group*
5.2 Environmentally hazardous chemical use	The indicator describes the environmentally hazardous properties of the production chemicals indicating potential risks for adverse environmental impacts. Chemical specific severity class is based on the seriousness of the hazardous properties (hazard statements) of the chemicals. The output of the indicator is the ratio of environmentally hazardous chemicals per total chemicals used, which is compared to specific sustainability limits set for the share. Benchmark type: *sustainability limits*
5.3 Health hazardous chemical use	The indicator describes the health hazardous properties of the production chemicals indicating potential risks for adverse health impacts. Chemical specific severity class is based on the seriousness of the hazardous properties (hazard statements) of the chemicals. The output of the indicator is the ratio of health hazardous chemicals per total chemicals used, which is compared to specific sustainability limits set for the share. Benchmark type: *sustainability limits*
5.4 Safety hazardous chemical use	The indicator describes the physical hazardous properties of the production chemicals indicating potential safety risks. Chemical specific severity class is based on the seriousness of the hazardous properties (hazard statements) of the chemicals. The output of the indicator is the ratio of safety hazardous chemicals per total chemicals used, which is compared to specific sustainability limits set for the share. Benchmark type: *sustainability limits*

The last indicator (6.3) of the group describes the substitutability of different materials. Especially, in emerging economies, people are dependent on the unique properties of metals and their compounds. In many applications, materials can be substituted by an alternative if necessary, as the general reason for using a certain material in an application is the cost of the material. However, in some applications, the unique properties of the material mean that there is no suitable replacement available. Therefore, the evaluation of the substitutability of different materials encompasses whether the material is substitutable or not, and how substitution impacts on the performance and price of the application. This indicator is based on substitutability scores published by the European Commission (2014a).

These indicators are developed for this particular assessment method, but both of them are based on announced sources of information (BSG 2012; European Commission 2014a).

4.2.7 Indicator group 7: material efficiency

As global resource usage rises and several resources are becoming scarce, material efficiency is a top priority. Material efficiency covers the efficient use of resources in the value chain. The more efficiently the resources can be utilized, the fewer primary resources are required in producing the product. Often material efficiency is also beneficial in minimizing adverse environmental impacts, such as waste generation. One of the European Union's strategic goals is to improve the circular economy, where one mean is the efficient utilization of residues and another the recycling of materials. Another goal is the prevention of waste formation. To reach these goals, the industries need to be able to set targets and measure the progress. The material efficiency indicators serve this purpose.

Raw material efficiency can be improved by choosing the most suitable material, choosing the most suitable method of processing, and developing methods for utilizing all fractions of the material. One measure of how efficient the utilization of material is in the process is the generation of waste. However, further treatment options of the waste also play an important role. If the generated waste can be reused after treatment, this option is better from the overall material efficiency perspective, than if the waste is in such a form that it requires much treatment or large resources to transform into something usable. The material flow in a general system is shown in Fig. 6.

Typically, the metallurgical industry produces significant amounts of unavoidable gangue material due to low ore grades. However, in various production steps, there is also a possibility to produce co-products instead of creating waste streams. This lowers the environmental impacts caused by the industry. Furthermore, minimizing the loss of valuable

Table 7 Indicators in the resource depletion indicator group

Indicator	Description
6.1 Fossil intensity (kg fossil material/kg product)	The indicator describes how much fossil resources are used as raw material, transport fuel, or energy source in the production of the product (in kg fossil material/kg product) compared to a group of comparable products. It indicates choices made in relation to raw material type, production energy sources, and production logistics. Benchmark type: *reference group*
6.2 Mineral availability	The availability of the mineral is classified by the risk list published by British Geological Survey (BGS 2012). The risk list classifies mineral resources by their scarcity, production, concentration, reserve distribution, recyclability, substitutability, and political stability of the leading global producer as well as chief reserve holder. This approach covers not only the scarcity of the minerals but also other issues that might have impacts on availability of mineral resources. Benchmark type: *sustainability criteria*
6.3 Mineral substitutability	The indicator describes substitutability of materials in different applications. If certain material cannot be substituted by another material on the application or product under consideration, it can be classified as a potential risk in the future. The indicator is based on the substitution scores for metals in different applications published by the European Commission (2014a). The outcome of this indicator describes if the material can be substituted at no or low additional cost, at high cost and/or loss of performance, or whether the material is not substitutable. Benchmark type: *sustainability criteria*

materials in different process steps decreases the amount of raw material used per product and thus lowers the environmental impacts caused by extraction. In this framework, these special characteristics of the metallurgical industry are considered in the indicator development process.

These indicators are based on mass balance and typical composition of material in the metallurgical industry. Indicators take into account both the total material consumption and the efficiency by which specific metals are extracted. Metallurgical operations also involve phase changes and changes in the composition of material; therefore, exergy is included as an indicator. This is only possible to calculate if simulation programs are used. Otherwise, the exergy losses are too complicated and time-consuming to calculate for this kind of assessment.

Indicators 7.1 and 7.2 (Table 8) cover the mass balances of raw material to products: 7.1 with an overview and 7.2 specifically looking at efficient utilization of the metals in the raw material. The two other indicators, 7.3 and 7.4, deal with material efficiency from the waste minimization perspective. Indicator 7.5 evaluates the utilization of secondary raw material, which the circular economy aspect targets.

Important issues for material efficiency calculations are as follows:

- Defining which outputs can be categorized as products
- How the mass balance should be calculated if water acts as a reactant and is included in the product
- The mass/volume of a product that should be used if the product is sellable, but contains both material suitable for the final product and unnecessary material, which will become waste when the material is further processed

4.2.8 Indicator group 8: unrecovered materials

The unrecovered materials indicators look at the discharges from the process. The indicators (Table 9) aim at describing how much is lost and to which phase, so that recovery could be improved.

Sustainability reports commonly contain information on total waste deposited to landfill, and in some cases, waste used for energy production is reported, but specific waste fractions are seldom reported in sustainability assessments. For innovation purposes and finding opportunities for utilization of waste streams, reporting the amount of generated waste streams, before waste treatment operations, could be advantageous. At the same time, this kind of information might be difficult to acquire. The metallurgical industry creates many side streams at different process phases. The side streams can be utilized by turning them into products, thus decreasing the amount of unrecovered material. Separate indicators were formed (indicators 8.1, 8.2, and 8.3) to report the waste that arises in aqueous, gaseous, and solid states, respectively, and the amount is reported before waste treatment operations.

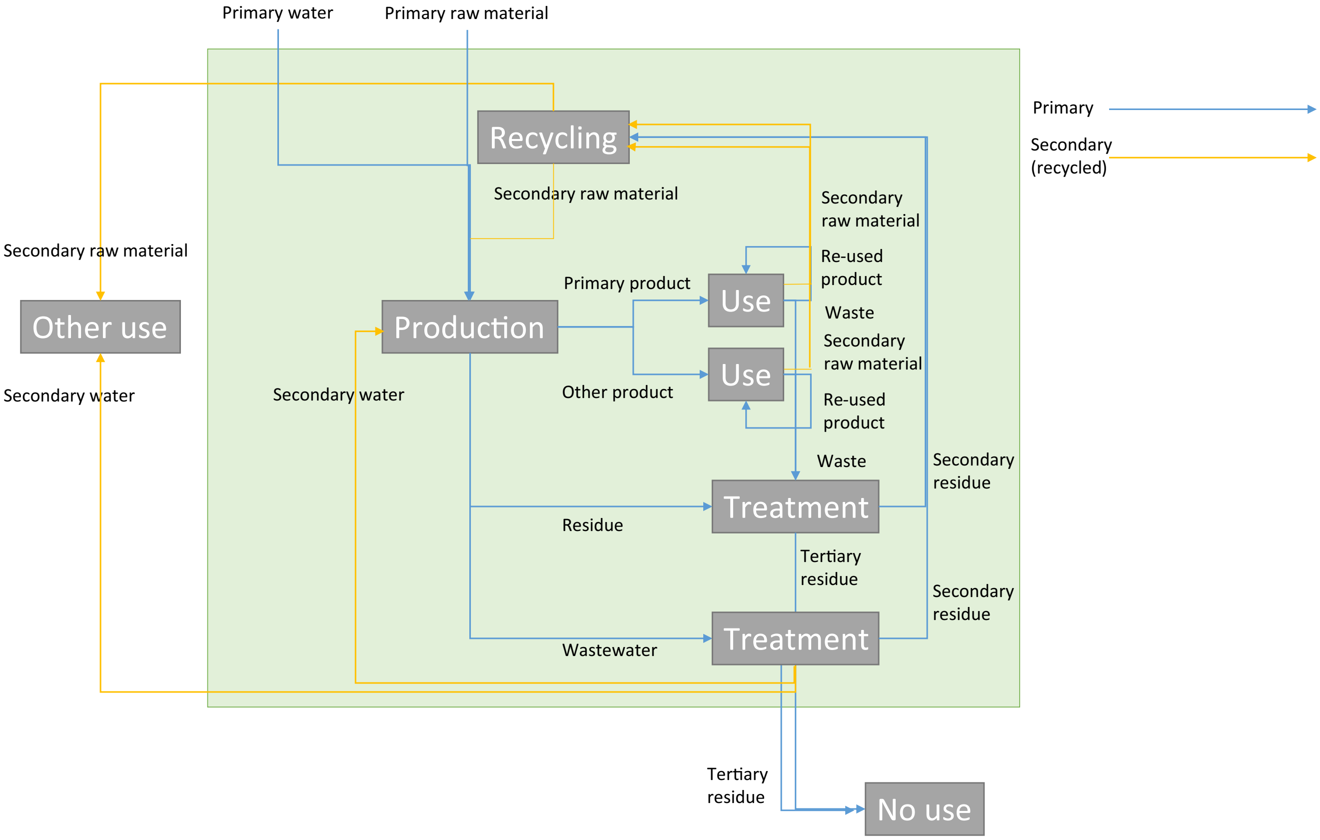


Fig. 6 The figure shows the material flow in a general system. It shows the primary, secondary, and tertiary flows as well as the meaning of the terms in this context

In addition, fugitive gas emissions are recognized as a significant source of dust emissions in the metallurgical industry. Indicator 8.4, Fugitive emissions, describes measures taken to suppress fugitive emissions. Fugitive emissions are emissions escaping collection and thus not directly measurable. Material balances could be used to approximate the loss, but the input and output values are often too uncertain for calculating the part lost from the balance. A qualitative approach is therefore used in the indicator. The indicator is based on sustainability criteria formed from lists of best practices in the metallurgical industry (European Commission 2009a, b, 2014b), and operations are compared against these criteria. The indicator thereby describes how fugitive gas emissions are prevented for example by means of process equipment or operational practices.

These indicators are specifically developed for this indicator framework. Indicator 8.4 regarding fugitive gas emissions is specifically important for the metallurgical industry, with impacts on for example air quality, health of employers, and process economics.

4.2.9 Indicator group 9: impacts from emissions

For this study, two main environmental impact assessment methods, eutrophication and acidification potentials (Table 10), were chosen as indicators. Acidification and eutrophication potentials are important indicators because the environmental burdens related to these may not only be due to the energy use during the production process but also other factors typical of mining and the metal industry, e.g., the disposal of sulfidic tailings and other emissions or pollutants to air, soil, and water may have a significant effect. In this work, existing methods for calculating eutrophication and acidification are employed. Both of the indicators cover the general system boundaries.

4.2.10 Indicator group 10: end use and end of life

The end use and end of life indicators (Table 11) cover the last part of the value chain. These indicators describe how well a product or material serves in its intended function as well as after its use phase.

Different materials can be used for the same purposes. However, the performance of the materials varies. For instance, in electronics, the material is required to have good electrical conductivity or cooking equipment should be able to conduct heat effectively. The properties of materials have an impact on how a well-chosen material delivers its function in a product (10.1). Therefore, the first indicator of the group

Table 8 Indicators in the material efficiency indicator group

Indicator	Description
7.1 Raw material suitability and utilization (%)	The indicator describes how effective the recovery process is, i.e., the recovery rate of products from total raw material inputs. In material-efficient production concepts, nearly all fractions are utilized for sellable products, indicating efficient utilization of production side streams. The indicator evaluates the ore and the processing methods, although the ore dominates the outcome. The indicator is calculated by taking the mass of products per mass of raw material and compared against reference values, which define the limits. Benchmark type: *reference group*
7.2 Main metal utilization efficiency (%)	The indicator describes the efficiency of the technology to produce products from the metals in the raw material. The indicator describes the percentage of main metals that ends up in products. It is calculated as the mass of total metal products per mass of metal in raw material and compared against reference values, which define the limits. Recovery percentage thresholds can be developed separately for all elements/ metals in ore. Benchmark type: *sustainability limits*
7.3 Waste prevention (%)	The indicator describes waste prevention, which is analyzed by looking at prevention of exergy loss. A material in a form that has little available work left will require external energy to reprocess into something else and is thus a waste. The value is compared against percentual thresholds based on theoretical calculations or similar products. Benchmark type: *reference group*
7.4 Residue utilization and repurposing (%)	Looks at the balance between repurposed material and residues. Residues can be used in the process or in another process. The value is compared against percentual thresholds defined by achievements of similar products. Benchmark type: *reference group*
7.5 Secondary raw material/ total raw material (%)	Describes how primary resources are being saved by using recycled raw material in the process itself. The value is compared against percentual thresholds defined by the current use of secondary raw material. Benchmark type: *sustainability limits*

compares the functionality and/or material properties to other comparable products or materials.

The second indicator describes the safety of a product. It gives information about the potential hazards of the materials used in a product based on material safety data sheets (MSDSs), which describes the material's capability to cause safety hazards. This indicator gives information about the stability, flammability, and possible health hazards of the material.

Table 9 Indicators in the unrecovered materials indicator group

Indicator	Description
8.1 Unrecovered aqueous (kg aq./kg product)	The indicator describes the amount of material in aqueous state, which is not recovered but treated and landfilled or emitted to water. Benchmark type: *sustainability limits*
8.2 Unrecovered gaseous (kg gas/kg product)	The indicator describes the amount of material in gaseous state, which is not recovered but treated and landfilled or emitted to air. Benchmark type: *sustainability limits*
8.3 Unrecovered solids (kg solid/kg product)	The indicator describes the amount of material in solid state, which is not recovered but treated and landfilled. Benchmark type: *sustainability limits*
8.4 Fugitive emissions	The indicator describes the measures taken to prevent fugitive emissions. The list of criteria is based on current BAT and BREFs (European Commission 2009a, b, 2014b). Benchmark type: *sustainability criteria*

Table 10 Indicators in the impacts from emissions indicator group

Indicator	Description
9.1 Freshwater eutrophication potential (kg P/kg product)	The indicator describes the impacts to eutrophication according to Recipe midpoint method (hierarchic version, European normalization) (Goedkoop et al. 2013). Benchmark type: *reference group*
9.2 Terrestrial acidification potential (kg SO_2/kg product)	The indicator describes the impacts to acidification according to Recipe midpoint method (hierarchic version, European normalization) (Goedkoop et al. 2013). Benchmark type: *reference group*

From the resource efficiency point of view, the recyclability of a product gives information about how efficiently materials can be reused. In order to recover materials effectively, the recyclability of a product has to be considered at the design phase of a product. Therefore, the design for recycling indicator describes how the issues that have an impact on recyclability are covered. The evaluation incorporates the reusability of a product, recycling infrastructure for a product, and also the possible contamination and material losses in the recycling phase. Sustainability criteria are derived from published research papers regarding the factors that have influence on the product's recyclability (Reuter et al. 2013, 2015a; Van Schaik and Reuter 2014).

These indicators are specifically developed for this indicator framework to evaluate how eco-efficiency aspects have been considered in terms of usability, safety, and recyclability of a product. Many indicator frameworks concentrate on the production processes and produced materials but do not cover sustainability issues of products. This is an especially important factor in the metallurgical industry, because for example, metals can be recycled and reused if the products have been designed in a way that enables the separation of different materials and contamination with other materials has been avoided.

Alternatively, these issues could be covered by widening the borders of the assessment and including the end use phase and end of life phase. The indicator helps to simplify the analysis in cases where this is not possible.

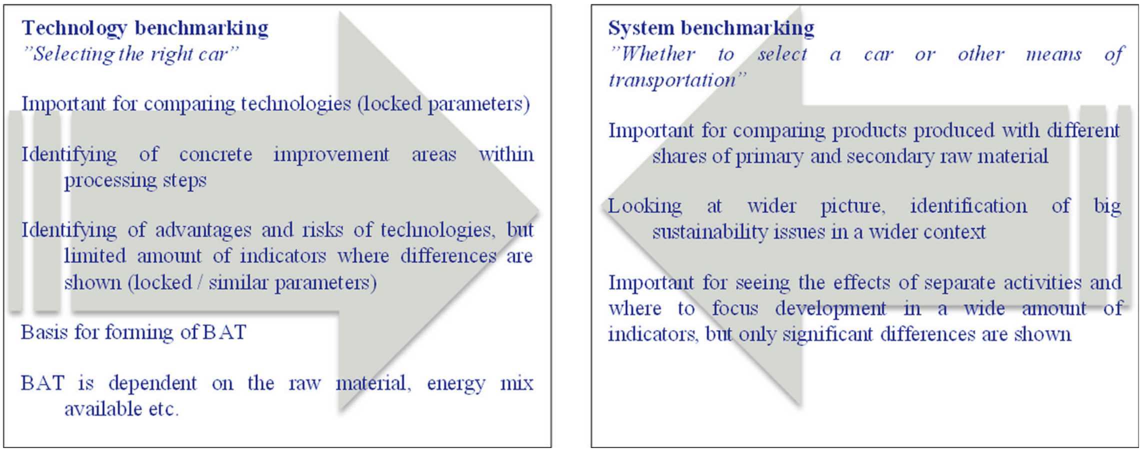
4.3 Building the benchmark for the indicators

In the framework, the benchmark is connected to the scope of the analysis. Forming a tight connection between benchmarking and the aim of the analysis makes it possible for a company to differentiate from others. As the benchmark follows the scope, the companies can choose this baseline, which allows for comparison within scopes ranging from specific narrow scopes to a system-wide scope, depending on where their sustainability advantages and risks lie.

The methodology is described here with a concrete example, comparing two alternative system scopes for benchmarking a case as shown in Fig. 7. The first system scope is called "technology benchmarking." It studies a narrower system scope with locked and normalized parameters, thereby allowing

Table 11 Indicators in the end use and end of life indicator group

Indicator	Description
10.1 Functionality	The purpose of the indicators is to compare features of different products. This indicator identifies the differences between products based on their characteristics, features, and quality. The evaluation is based on product-specific characteristics. Calculation is done by comparing the specific feature of the material to other material which might be used in the same purpose. Benchmark type: *sustainability criteria*
10.2 Risks related to product	This indicator describes the hazards that are related to the product properties and use. The evaluation is based on the classification used in material safety data sheets (MSDS), which describes whether or not the material is subjected to cause any hazards. The output of the indicator describes if there are any increased risks related to materials used in a product. Benchmark type: *sustainability criteria*
10.3 Design for recycling (DfR)	The purpose of the indicator is to evaluate the recyclability of a product. It covers issues such as reusability, existing recycling infrastructure, material losses, and contamination. This is implemented by choosing certain criteria for recyclability and how a product fulfills these requirements. Benchmark type: *sustainability criteria*



Technology benchmarking
"Selecting the right car"

Important for comparing technologies (locked parameters)

Identifying of concrete improvement areas within processing steps

Identifying of advantages and risks of technologies, but limited amount of indicators where differences are shown (locked / similar parameters)

Basis for forming of BAT

BAT is dependent on the raw material, energy mix available etc.

System benchmarking
"Whether to select a car or other means of transportation"

Important for comparing products produced with different shares of primary and secondary raw material

Looking at wider picture, identification of big sustainability issues in a wider context

Important for seeing the effects of separate activities and where to focus development in a wide amount of indicators, but only significant differences are shown

Fig. 7 The two different system scopes: technology and system benchmarking. Both aspects are relevant and thus depending on the situation, there is a need to look at the system from the narrow perspective to the wide perspective. The Gaia Refiner methodology aims at harmonizing the way of analyzing systems of different scopes and widths

higher accuracy for highlighting differences in technological processing efficiencies and identifying concrete improvement areas within the processing steps. It can also prove useful as a basis for forming BAT specifications. With this approach, however, only a limited amount of indicators is relevant, as many broader system-wide indicators become nonrelevant due to the narrower system scope and locked and normalized parameters. The second system scope is called system benchmarking. It looks at a wider system and allows the comparison of varying value chains fulfilling the same end user need. A wider amount of indicators is relevant in this scope alternative, but only significant differences are shown, as the wider system scope masks the smaller differences. These concrete examples show how selecting the system scope is crucial for carrying out an analysis and benchmark that is industrially relevant and meaningful. The usefulness of the results for various purposes directly reflects the choices made in system scoping. Therefore, flexible and scalable scoping is a key to useful analysis.

The benchmark is set differently depending on the type of indicator. The indicators included in the framework describe either intensity, output, and efficiency or qualitative issues, requiring three different types of benchmarks: *reference groups*, *sustainability limits*, and *sustainability criteria*. These three benchmark types are described in the following.

4.3.1 Reference groups

Intensity indicators would preferably be compared against a reference group of several different processes to produce a similar product. In the absence of reference values for the whole value chain, the reference values can be built up from the different technologies applicable at each process step. The type of indicators connected to this type of benchmark are GHG emissions from processing (1.1), GHG emissions from transport (1.2), water intensity (2.1), energy intensity (3.1), land use intensity (4.1), fossil intensity (6.1), freshwater eutrophication potential (9.1), and terrestrial acidification potential (9.2).

The analysis is relative to a certain product category, so that product category-specific reference groups and classification criteria can be utilized. Each product category has subcategories and each subcategory is connected to a specific reference group. Issues such as energy intensity, water intensity, fossil intensity, and raw material intensity increase with the degree of refinement and value-adding steps. By comparing products that belong to a certain product subcategory, it can be ensured that the products are benchmarked to relevant alternative products and value chains.

If the scope is made even more narrow, the reference group must follow. As an example, one of the main issues affecting the energy intensity of milling is the ore grade, i.e., the concentration of desired metal in the ore. From an environmental sustainability point of view, there are many reasons to prioritize one raw material over another. These are mainly connected to land use issues and resource depletion but also to resource efficiency. It may be much more resource-efficient to produce metal from an ore with a high concentration of the desired metal. A similar effect can be difficult to achieve with technology improvements, and thus, these achievements are easily hidden behind the parameters that affect the results more. To ensure technological development toward sustainable solutions for the metallurgical industry, a more narrow scope is needed in many cases. A narrow scope can here mean for example locking certain parameters for better comparison.

For the metallurgical industry, the product category is defined as metals and the subcategories can be narrowed down to the categorization found in the Eurostat NACE.

- Base metals
    - Iron, steel, and ferro-alloys

- Basic precious metals and nonferrous metals
  - Copper
  - Aluminum
  - Precious metals
  - Lead, zinc, and tin
  - Other nonferrous metals

Similarly, EU BREF documents can be found for nonferrous metals industries (European Commission 2014b) and iron and steel production (Remus et al. 2013). Other BREF documents relating to the metallurgical industry are ferrous metals processing industry, management of tailings, and waste rock in mining activities. Many of the techniques and individual stages of production processes are common for most of the nonferrous metals produced. Energy management, air emissions, and waste handling are similar for many metal production processes.

Looking at the type of data available, different methods for forming reference groups can be distinguished. The methods for forming the reference groups can be categorized as follows:

(A) Top-down from industry average values
(B) Bottom-up total value chain
(C) Sequential benchmarking and bottom-up sum of steps
(D) BAT according to qualitative criteria in EU BREFs and other comparable reference information

Forming the reference group "top-down from industry average values" involves using databases and literature with industry average data. The method is suitable for forming the benchmark if the system scope is wide. In these cases, the fact that industry average data includes all varieties of for example technologies, locations, and end products provides an advantage. Although national and global databases have discrepancies in the way data is reported, their advantage is that they are strictly standardized.

The next two methods are different varieties of combining data reported for process steps. The data from each process step can be collected from the literature or by using LCA software for this purpose supported by simulation models suitable for each flowsheet. The data can either be benchmarked step by step ("sequential benchmarking and bottom-up sum of steps"), which means that for example competitive advantage is formed from the optimal combination of the best processes, or by calculating all the steps together for each value chain and then forming the benchmark from the total values ("bottom-up total value chain"). The first mentioned provides an opportunity to find the best combination of process steps, while certain process steps may overshadow others in the latter alternative.

The last method involves forming the reference values by a two-step approach. The first step is to determine the processes that can be categorized as BAT, by looking at qualitative issues or performance versus limits. The second step is to gather data for such processes. This is a suitable benchmark when the scope is very specific, for example when certain environmental criteria are included in the scope. Here, the data must be very process specific and for that purpose data from the source and simulation data serve well.

Procedure for forming the reference groups:

Step 1: The end product is defined.
Step 2: The use of the end product is defined.
Step 3: The level of detail desired (based on aim of the study) is defined. This should correspond to the scope of the study.
Step 4: Available benchmarks at the desired level are searched for. The basic idea of a baseline is important here; therefore, whatever the baseline is chosen determines the evaluation.
Step 5: For each benchmark assigned to the indicator, a reliability check (number of values, variation, comparable scope) is performed.

The values are considered reliable for use as benchmarks if the following criteria are met:

- Values are based on a larger study.
- Values are based on limited but representative and reliable data.

The values are not considered sufficient for benchmarking when the following applies:

- Values are based on proxy data (for example, industry average data, or generic process assumptions).

Step 6: For each benchmark assigned to the indicator, set limits for potential advantage and potential risk (if the data for the reference group has been evaluated as reliable).

4.3.2 Sustainability limits

The indicators describing outputs and efficiency can be evaluated based on limits, for example minimum and maximum values within which an activity is considered sustainable. These are here named sustainability limits. This second type of benchmark is required for the indicators that combine several separate issues to achieve a holistic assessment. The indicators in the framework that require this type of benchmark are water scarcity (2.2), share of renewable energy (3.2), chemical risks (5.2–5.4), main metal utilization efficiency (7.2), secondary raw material/total raw material (7.5), and unrecovered aqueous (8.1), solids (8.2), and gaseous (8.3) materials.

With the exception of indicator 3.2 Share of renewable energy, and the indicators in group 5 chemical risks in production, the sustainability limits for these indicators are connected to the specific scope and product category. For the renewable energy indicator, the reason to this is that the source of energy is irrelevant to the production technologies. For the chemical risks indicators, the reason is that the chemicals should be replaceable by nonhazardous chemicals, and if not possible, then the risk must be acknowledged.

Procedure for forming the sustainability limits

Step 1: For each indicator, the relevant separate factors are first analyzed and information and data on them are collected.

Step 2: Reports on critical limits, current situation, and variation in data, as well as development targets, are used to form part of the limits.

Step 3: For each sustainability limit assigned to the indicator, a reliability check is performed on the source, study behind the said impact, statistical relevance, and comparable scope.

Step 4: For each benchmark assigned to the indicator, the limits for potential advantage and potential risk are set.

4.3.3 Sustainability criteria

The qualitative indicators are evaluated according to a set of criteria that define sustainable and nonsustainable activities. Indicators that describe qualitative issues can be very helpful in decreasing the amount of calculative work and data gathering needed in sustainability assessment. The indicators based on sustainability criteria are land use synergies through ecosystem services (4.2), land use impact and risk mitigation of mines (4.3), land use impact and risk mitigation of tailing ponds (4.4), mineral availability (6.2), mineral substitutability (6.3), fugitive emissions (8.4), product functionality (10.1), risks related to products (10.2), and design for recycling (10.3).

The sustainability criteria rely on earlier studies, often very rigorous ones, where the conclusions from the studies can be used to form risk lists or checklist for issues that, if true or false, constitute sustainability risks or advantages.

Procedure for forming the sustainability criteria

Step 1: Recent studies are gathered on the subject of the indicator and such that are connected to the scope of the study.

Step 2: The studies are evaluated for their reliability and for the relevance to the scope of the study.

Step 3: Check lists are formed based on the studies, in the case that certain criteria must be met, and risk lists are formed in the case that certain issues or activities imply risks.

Step 4: The limits and criteria that result in potential advantage and potential risk are defined.

4.4 Data sources for filling the gaps and increasing reliability

Process data, life cycle inventory databases, statistical databases, and data reported in various journals, reports, and books are always limited. It is either vaguely reported, an average of many values, or locked to certain parameters. The possibilities provided by process simulation tools are described below.

4.4.1 Process simulation tools

Process simulation tools used in process metallurgy such as ASPEN Plus by AspenTech (www.aspentech.com), HSC Chemistry (www.outotec.com), and METSIM (www.metsim.com) are well established for process simulation, process optimization, and process design. Reuter et al. (2015a, b) combined and introduced process simulation tools with environmental analysis to understand system baseline footprints specifically for the metallurgical and recycling processing industries. The use of simulation tools directly in environmental analysis opens up new possibilities, where the analysis is no longer locked to predefined process data but can be used as a tool for industries to find the most environmentally sustainable production methods and the chief culprits that are making the production and system unsustainable. Thus, sustainability analysis can become more than a stamp to compare products and market them; it is also a tool for development with the focus on sustainability. It also then permits and drives innovation in the places where it truly makes an impact.

For current sustainability analysis applications, simulation tools help in interpolating data when it is missing, decreasing uncertainties with allocation issues, capturing unknown compounds, and finding limits for specific technologies and inputs (Reuter 1998; Reuter et al. 2015a, b). In the same way as a calculation is only as good as the data behind it, a simulation is only as good as the model used in it. This is the disadvantage of the approach. The simulation requires a good model, which describes the process accurately, and while it reduces the requirements for gathering life cycle data to the inventory, it is more complex to make. The positive effect is that building a simulation model forces the company to have a deep understanding of the metallurgy, the physical phases of streams, minerals that define all streams, the temperatures and pressures, concentrations of compounds, cations and anions in the different streams, etc. while at the same time closing the mass and energy balance of all streams as well as quantifying all thermodynamic properties (including enthalpy and entropy) as well as all other physical properties (e.g., density, conductivity, etc.). The result is a true picture of each stream based on the physics and technology of the process. This permits the possibility also to simulate different flowsheet options as well as different technology combinations while keeping all boundary conditions the same. This permits the calculation of an objective baseline of the systems to be compared and thus the basis of the comparisons that are made in the methodology presented in this paper. This is the true innovation of this paper—the establishment of a comparison baseline based on the physics and technology of the system. This rigorous baseline also then reveals the weakness in environmental databases but also providing then a basis to improve the same.

The level of detail of the data required is less detailed if the system is very wide. Simulations are very useful in all cases, but when looking at wide systems of highly varying value chains, the simulation approach becomes very tedious. Also, due to data availability, simulation cannot always be applied for benchmark data, as the details of the reference processes are not always known. In wide scopes, LCI data is primarily used for the quantitative indicators. When narrower scopes or similar value chains are looked at in detail, the performing of simulations is efficient and this data source becomes very important.

4.4.2 Treatment of missing values

In cases where certain data is unavailable, the data can either be excluded based on the cut-off criteria or if the criteria does not allow for exclusion, process models can be developed by utilizing LCA software and modifying parameters or, when available, by calculating theoretical values with the help of simulation tools. If these are not reliable enough, the calculation can either be performed for a restricted case, where it clearly defines what is left out, or else the indicators that require the data must be left out of the evaluation. In the summary picture, the circle will then be colored gray.

5 Discussion

While the method in its entirety is ready for implementation, there are certain aspects that require further continuing development. Firstly, although the system scoping methodology is designed to allow flexible range of varying scopes, the practical applicability and implementation-related issues may arise when first proof of concept cases with varying scopes are analyzed. It is important to verify that indicators individually and as an entirety provide reliable results across varying scopes. Possible issues relating to, e.g., effect of background parameters masking the variation in indicators, need to be assessed.

Similarly, the practical applicability of the indicator framework in proof of concept cases shows how well the indicators can analyze and benchmark varying cases with consistent link to system scoping. Although the indicators are designed not to be redundant, by practical proof of concept cases, it can be studied whether this is realized well in real industrial cases.

Furthermore, benchmarking as such can never be truly objective, as the selection of reference levels is always at least partly based on selection of best available reference data from an available set of data. This is due to the fact that completely comprehensive, up-to-date data covering the whole scope of variation in industrial value chains can never be achieved with feasible efforts. However, although the benchmarking as a method has this inherent practical weakness, proper scoping, and target setting of analysis, together with mapping out the best available data including simulation-based data, all lead to the formation of a rigorous baseline, which still makes benchmarking a viable approach.

Partly relating to that, a major issue continues to be a need for enhanced data basis availability, including further application of simulations, that can support further improvements in the indicators and the whole method can be further developed to analyze more complex systems. Certain and more detailed issues related to system scope, indicator framework, benchmark, and data sources are further analyzed below.

5.1 System scope

Metal ore grade The indicators for material efficiency, energy efficiency, GHG emissions from production, water withdrawal, and land use intensity are all largely affected by the ore grade. If the desired outcome of the benchmarking is to show the differences of a specific technology or step in the value chain, then the ore grade is one of the parameters that needs to be locked or normalized so that its effects will not mask the parameters of interest.

System analysis In the future, as secondary raw materials and resource efficiency thinking are emphasized even more, there will be a need to analyze complex metal refinery systems using many different raw materials—both primary and secondary (Reuter et al. 2015a, b). There will also be a need to analyze urban mines utilizing complex waste streams and the circular economy, linking together value chains through waste stream utilization. The developed framework is built to be able to handle a wide variety of scopes, and the inherent scope flexibility opens up the possibility to develop the method further into the analysis of more complex systems.

5.2 Indicator framework

Chemical risk indicators When more data on chemical use in other value chains becomes available, the benchmark could be changed into a more accurate hazardous chemical intensity-based method. In this method, a three-level classification for chemical hazards could be used to obtain a wider distribution. Based on the classification, a severity value (0, 5, or 10) could be set for each chemical, and this value would be multiplied by the volume used per tonne of product. The summed result for all chemicals would then be compared to set limits for "hazardous chemical" intensity and "nonhazardous chemical" intensity. Another possibility would be to keep the indicator independent of the amounts of chemicals used, purely describing the characteristics and risks related to the chemicals in use.

Unrecovered materials indicators These now describe only the amount of waste, but future development would be needed to also include the harmfulness of the waste, so that the indicator would describe how bad the formation of waste is for the system. This can be broken down to how much waste is produced and how harmful the substances are to the environment.

5.3 Benchmark

The developed benchmarking system is applicable to a wide variety of value chains and applications due to the inherent flexibility and strong links to system scoping and indicator framework. For quantitative indicators, the availability of reliable and relevant reference data can, however, currently limit the feasibility of benchmarking. As benchmarking reflects the current status of technology development and production methods, it requires constant updating in order to provide meaningful results. However, as the method is modular, updating of benchmarking data is possible while keeping the other parts of the analysis as they are, only updating the results to reflect the evolution of the benchmark.

5.4 Data sources

The framework requires data for analyzing the value chain in focus but also for analyzing similar products for benchmarking. As mentioned earlier, the availability of data can become a large obstacle when performing sustainability analysis. The available LCI data is currently often old and limited or poorly defined. This might become an obstacle to the application of the simulation-based benchmarking methodology. In other cases, for production methods and chains that are known to the required extent, especially for analysis in targeted system scopes, simulation-based data production is again a possibility. As presented by Reuter et al. (2015a, b), simulation tools can provide both a solution for missing data and a check that the reported data is reliable.

As described earlier, the required level of accuracy differs depending on the intended application of the results from the sustainability assessment and the system scope. Initial screenings or very wide comparisons of varying value chains, where only rough estimations are needed, can be made with rough data. For more precise analysis, detailed data is needed. However, detailed data is always not readily available, due to the reluctance of companies to share it but also due to the lack of measurements and systematic gathering of primary data. Even when measurement is performed, values may differ greatly due to variations in production. We wish to point out here the need for reporting and collecting data, so that more reliable sustainability analysis can be performed. For example, the vast amount of data available on Eurostat shows that it is possible to collect the data, at least as soon as there is an obligation to do so. Database collection initiatives and standardization efforts by the EU are however driving the development in the right direction.

6 Conclusions

The eco-efficiency indicator framework developed covers ten important issues of product environmental sustainability and includes 31 indicators, each describing a specific view of the different sustainability issues. The indicators have been developed from the viewpoint of the metallurgical industry, and the suitability for the benchmarking of copper cathode production will be tested in part 2 of this study.

The approach of utilizing simulation tools in the sustainability analysis has been included, both (i) as a data source when data is not available, specifically for calculating waste stream data including its composition and mineralogy in addition to exergy flows, and (ii) as part of the methods used for defining the benchmark of systems and processes.

Novelty of the developed indicator framework There is a need to look at a broader and more comprehensive picture of environmental sustainability than that which is currently reported and analyzed. Analyses must be location specific, and mean values should be avoided whenever possible to ensure that the sustainability analysis describes the actual value chain and the points for improvements can be found. An increased focus on resource efficiency will drive development further in a more sustainable way, as this will result in savings for the company simultaneously with reduced emissions and waste. Indicators have been developed for measuring and evaluating most anything. The indicators included in the framework are for the most part already established indicators, but the novelty of the framework lies to a large extent in its system thinking: all indicators act together, so that they complement each other well, and the system is flexible for analyzing a variety of value chains and systems. Furthermore, the indicators respond to the current challenges in environmental protection, globally and locally.

Novelty of benchmarking The framework introduces benchmarking for concretizing the analysis results, enabling simple communication to customers and stakeholders, and acting as a base for strategic decisions. The benchmarking system does not use weighting and/or aggregating in order to prevent the masking of important information or trying to simplify too much. Instead, it allows a comprehensive picture to be seen and links the various sustainability aspects together in the context of an industry-relevant product category.

Novelty of scalable system assessment As the developed method links system scoping, an indicator framework, a benchmarking method, and data sources into one dynamic, flexible but consistent method, it provides the answers to several current major bottlenecks of sustainability analysis, namely limited comparability and applicability to a wide variety of systems, and limited system width in terms of the sustainability aspects under analysis. In addition, it scales back to the technology and hence helps drive innovation as it is related directly to process and reactor parameters and hence physics. Together, the scalable benchmark and the scalable indicator palette form the opportunity for producers to choose a relevant baseline that helps them to develop more sustainable solutions and to reach their markets with this message.

Request for better data sources, simulation based, and location specific when needed The limited availability of publicly available data currently poses a disadvantage to the developed method. The analysis of the quantitative indicators can be performed only by calculating the values until a sufficient amount of benchmarking data becomes available. Simulation is one answer, as missing values can be formed from the available data and the balance of the system. However, if the industry is not already simulating its processes, applying simulation to complex systems is tedious and requires comprehensive information on production methods.

Compliance with ethical standards

Funding This study was funded by Outotec Oyj and Gaia Consulting Oyj. HSC Sim is a product of Outotec Oyj and Gaia Refiner is a product of Gaia Consulting Oy.

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