Husgafvel, Roope; Pajunen, Nani; Dahl, Olli; Heiskanen, Kari; Ekroos, Ari; Virtanen, Kirsi

# Development of Environmental and Economic Sustainability Metrics for the Metal Production Industry - Experiences From University-Industry Cooperation

*Published in:*
Sustainable Business, Management, and Economics

*DOI:*
10.3390/books978-3-03842-334-8-5

Published: 01/01/2017

*Document Version*
Publisher's PDF, also known as Version of record

*Series Editor*
Manfred Max Bergman
Department of Social Sciences
University of Basel
Switzerland

*Guest Editors*
Lena Berger
Department of Social Sciences
University of Basel
Switzerland

Manfred Max Bergman
Department of Social Sciences
University of Basel
Switzerland

*Editorial Office*
MDPI AG
St. Alban-Anlage 66
Basel, Switzerland

*Publisher*
Shu-Kun Lin

*Managing Editor*
Zinette Bergman

*Production Editor*
Seline Reinhardt

**First Edition 2017**

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade

Vol. 2 ISBN 978-3-03842-335-5 (Hbk)
Vol. 2 ISBN 978-3-03842-334-8 (PDF)
Series ISBN 978-3-03842-332-4 (Hbk)
Series ISBN 978-3-03842-333-1 (PDF)

Cover photo: Matthias Burkhalter

# Development of Environmental and Economic Sustainability Metrics for the Metal Production Industry—Experiences From University-Industry Cooperation

**Roope Husgafvel, Nani Pajunen, Olli Dahl, Kari Heiskanen, Ari Ekroos and Kirsi Virtanen**

**Abstract:** Numerous sustainability assessment methods, especially environmental performance evaluation tools, have been developed to assess environmental performance of the process industry. Typically, environmental performance indicators cover only primary emissions and consumption without any recognition of secondary environmental burdens from auxiliary processes outside the plant boundaries. Therefore, the environmental impacts of the production site might be decreased whereas the overall environmental performance is not necessarily improved. The overall objective of our research project is to develop a sustainability index that comprehensively and reliably captures the environmental, economic, and social sustainability of an industrial plant. In this paper, we present this work on environmental and economic sustainability metrics for the metal production industry and two hypothetical process industry case studies on the application of the developed metrics. We develop both appropriate indicators and an example of an environmental and economic sustainability index that is also tested in two process industry case studies. Our assessment approach integrates indicators and life cycle assessment by expanding the scope of the typical environmental performance indicators. By this approach, the evaluation not only concentrates on the activities at the plant site, but also covers the emission sources that are indirectly connected to the actual production process. As a result, this approach provides comprehensive information for decision-makers on both the environmental impacts caused by plant operations and economic implications of alternative decisions. In addition, we present a discussion of according EU and Finnish legislation and their implications for both the management and assessment of plant level environmental and economic sustainability performance.

**Keywords:** sustainability metric; environmental sustainability; economic sustainability; metal production industry; sustainability index; sustainability indicator; environmental law

# 1. Introduction

## 1.1. Background

In recent years, the number of sustainability assessment methods that aim to evaluate the sustainability of companies' practices and processes has increased. In general, increasing awareness of environmental issues has led to a situation in which the production industry needs to pay more attention to the development of more sustainable products and manufacturing processes. Although the concept of sustainable development or sustainability has several definitions; the most common one is presented by the Brundtland Commission: "to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of the future generations to meet their own needs" [1] (p. 16).

Several evaluation methods exist to assess the overall sustainability and environmental impacts of companies, processes, and products. Sustainability indicators have especially gained much popularity since the United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992. One of the key outcomes of the United Nations Environmental Programme (UNEP) conference, the Agenda 21 action plan [2], encourages individual countries and organizations to develop sustainability indicators for the basis of decision-making. At the beginning, the focus was on the assessment of countries, regions, and policies; however, nowadays, sustainability evaluation has merged into the evaluation of companies themselves and their processes. Several tools and frameworks have been developed to assess the sustainability of a single company, and different approaches to assess environmental sustainability have multiplied over recent decades, including life cycle assessment (LCA) [3,4], environmental performance indicators (EPIs) [5,6], Material Flow Analysis (MFA) [7], and energy-based assessment methods, such as exergy [8] and emergy analysis [9].

Sustainability indicators have become important tools for providing information on corporate performance [10]. A considerable amount of research has been carried out in the field of sustainability assessment in general, but a uniform approach is missing to measure and compare environmental impacts. Even though the concept of sustainability is typically well understood, the methods available to measure and express progress towards sustainability have remained heterogeneous [11]. LCA is widely used to assess the environmental impact of the metal production industry [12–14].

## 1.2. Sustainability Metrics in the Process Industry Context

Despite the importance of all three dimensions—social, economic, environmental—of sustainability, sustainability performance metrics for environmental issues are the most common [15,16]. Environmental challenges have been recognized since the early 1970s and environmental issues have an impact on many decisions, both at the political and organizational levels [17]. Therefore, several tools have been developed to assess the environmental performance of the process industry. The purpose of the environmental performance tools is to provide relevant information for decision-makers. "One of the main goals in decision-making is to identify and choose the most sustainable option from among different alternatives" [18] (p. 1), meaning that decision-makers should have enough relevant information about the environmental impacts of different alternatives and about how they affect the companies' performances, as well as about their impacts on the surrounding environment, society, and economics. However, several different approaches exist to evaluate environmental performance, each with their own key characteristics and mechanics including the provision of information for different purposes.

However, it is not clear how these assessment methodologies should be applied comprehensively at the operational plant or installation level. In general, production industries are faced with the growing demands for improved environmental and social performance and at the same time they are required to sustain their economic competitiveness. Similarly, even though industrial plants create pollution, industrial activities also create wealth and well-being for the surrounding society [15]. In addition, national and international legislation set requirements for plant level operations, which need to be taken into consideration. Sometimes local regulation might even be in contradiction with global sustainability goals. Especially, measurements of environmental impacts are not straightforward, with the reduction of an emission that contributes to one environmental problem causing higher emissions contributing to another environmental problem [19]. This may apply to local and global environmental impacts as well, such that improvements in environmental performance locally might lead to increased environmental burden in the broader global context.

There is no clear definition for the difference between indicators and indices [20]. However, indices have been considered to encompass a higher level of aggregation than indicators [21–23]. Since indicators include a wide variety of data with different range of values and measuring units, it is necessary to standardize the data. By standardization, the values are converted into one comparable scale, prior to weighting and aggregation [22,23]. Weighting and aggregation of data might have a significant impact on the output: depending on the chosen method, the results might vary significantly even when using the same dataset [22]. Compressing data to form composite indicators can involve losing underlying data, thereby increasing the uncertainty [24].

Composite or summary indicators have been acknowledged as a useful tool to condense information and reduce the decision-making criteria [15,21]. Indices can provide an overview of relevant progress, but also highlight problem areas. Indices, such as the Dow Jones Sustainability Indices [25] and the Financial Times Stock Exchange FTSE4Good Index Series [26] and the Global 100 Index [27] are widely used to rate companies according to their sustainability performance. Indices are also developed for plant level evaluation; for instance, the Composite Sustainability Index for Steel Industry by using the Analytical Hierarchy Process (AHP) [21], or the Industrial Sustainability Index (ISI) [28], which is a general framework for industries. Indices can provide relevant information for decision-makers in a concise manner; however, the weighting and aggregation methods might lead to skewed or misrepresented results.

Environmental indicators have been recognized as a valuable tool providing simplified and concise information from a vast quantity of environmental data. Environmental indicators have many roles and purposes; they can be used for measuring a plant's performance over time or for comparison between plants (benchmarking), as a communication tool for internal and external use, and as a measuring stick to follow progress towards some specific environmental targets [5,6,23]. However, their most important task is to provide relevant and concise information, since good decision-making requires correct and relevant information [29]. Therefore, any set of indicators must be relevant to their intended application. In addition, indicators should be easy to understand, be measurable, target-orientated, and represent substantial subjects of the industry [5,30].

Environmental Indicators (EIs) can be divided into Environmental Performance Indicators (EPIs) and Environmental Condition Indicators (ECIs), as shown in Figure 1. EPIs consist of Management Performance Indicators (MPIs) and Operational Performance Indicators (OPIs). MPIs measure management efforts to influence companies' environmental performance whereas OPIs measure the environmental performance of operations [5,20]. In most cases, when evaluating environmental sustainability, operational performance indicators are employed and only minor importance is given to environmental condition indicators. ECIs are used to provide information on local, regional, national, or global conditions of the environment [20].

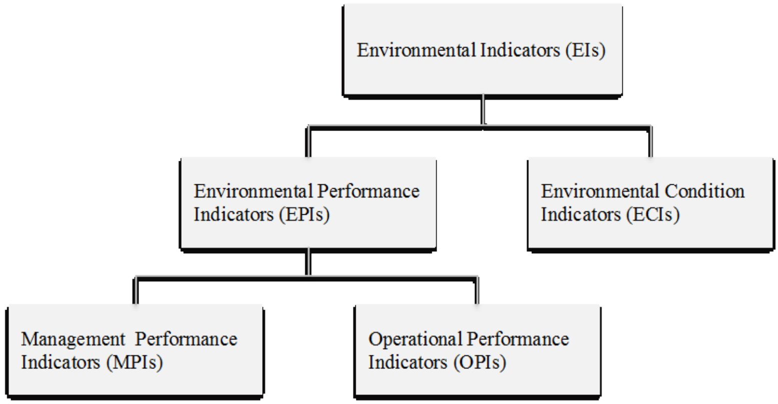


**Figure 1.** Categorization of environmental indicators [20].

Several methods that utilize environmental performance indicators have been developed to assess the sustainability of industry. Both general and sector specific Sustainable Development Indicators (SDIs) have been proposed in the literature [15,31]. SDIs should be sector specific to capture the key characteristics of specific industrial sectors [28]. Besides SDIs having been developed for individual companies and processing sites, such as SDIs for the mining and mineral industry [15], SDIs are also employed to evaluate and follow sectors' progress towards sustainability [31]. For example, the World Steel Association [32] and European Aluminum Association [33] have both developed their own sets of SDIs for sustainability assessment of their industry sectors. Even though indicators have been recognized as a valuable tool to gather and present information for different purposes, evaluation and decision-making might be difficult based on many indicators [20]. Therefore, summary indicators or indices have been recognized as a suitable technique to summarize the information provided by multiple indicators.

### *1.3. Rationale of the Study*

The general purpose of any environmental legislation is typically to directly or indirectly determine what kind of activities are allowable, including various permitting aspects that control operations. The legislator defines the appropriate level of activity that applies generally to all operators, for example, via a prohibition to use certain substances or processes altogether. In Finland, industrial activities are regulated by the Environmental Protection Act (EPA) [34], which states that an environmental permit is required for all activities that pose a threat of environmental pollution. Activities subject to a permit are detailed in the Environmental Protection Decree [35]. The objective of the EPA is to prevent the pollution of the environment and to repair and reduce the damage caused by pollution; to combat climate change and otherwise support sustainable development. According to the Decree, permits must contain necessary conditions covering the following aspects [34] (p. 19–20):

(1) emissions, emission limit values, the prevention and limitation of emissions, and the location of the site of emission;
(2) wastes and reduction of their quantity and harmfulness;
(3) action to be taken in case of a disturbance or in other exceptional situations;
(4) measures to be taken after the cessation of operations, such as remediation of the area and prevention of emissions;
(5) other measures to prevent, reduce, or assess pollution, the risk thereof, and adverse effects caused by it.

The environmental permit procedure takes account of the environmental impacts of the industrial operation as a whole [36]. Yet, it could be questioned whether the targets and environmental outcomes will be satisfactory in the bigger picture. The challenge does not necessarily relate to the environmental legislation itself but to its application in practice. For example, the requirement to use best available techniques (BAT) could be understood as allowing a rather expensive and holistic evaluation. Section 4 of the EPA mandates the use of BAT, and according to Section 43.3, permit regulations concerning emission limit values and their prevention and limitation must be based on BAT [37]. Moreover, the BAT requirement does contain a principle of proportionality, since while the requirement refers to using the most efficient and advanced methods of production possible, the required methods must also be economically (i.e., economically viable within the industry excluding individual company profitability) and technologically feasible [34]. Furthermore, Article 9(4) of the Integrated Pollution Prevention and Control (IPPC) directive refers to considering the technical characteristics of the installation concerned, its geographical location, and the local environmental conditions. However, Article 9(4) of the IPPC directive subsequently refers to ensuring a high level of protection for the environment as a whole [37]. The Industrial Emissions Directive (IED) [38] introduced many requirements on permits and the associated control of emissions. Article 13 of the IED promotes the application of BAT reference documents and the associated exchange of information. Also, according to Section 43(3) of the EPA [34], the impact of the activity on the environment and the significance of intended measures to prevent pollution of the environment must be taken fully into account. Together, these provisions clearly enable the evaluation of proportionality. An expansive reading of this provision would also allow for considering global sustainability concerns—for example via increased energy use—, even when the BAT principle must be complied with.

Environmental authorities in turn introduce more specific regulations covering plant-level activities, for example, via emission levels in an environmental permit.

Both legislation and the more specific administrative regulations define the level of environmental impact the operator is allowed to cause during its operations. The environmental impact assessment is, however, usually limited in its scope to local or regional effects, as is the scope of the legislative act regulating the activity or the competence of the environmental authority. Authorities cannot take global sustainability effects into account as this would involve exceeding their competence. Instead, authorities are required to ensure the level of local environmental protection as defined in their legislation. For example, authorities might be required to order the reduction of local particle emissions. However, the operation of filtering equipment could entail a substantial increase in energy consumption, having a significant impact on $CO_2$ emissions and introducing an additional waste residue needing special treatment, handling, and disposal. The increased energy consumption could also run counter to energy efficiency obligations the operator is also faced with. Despite this potentially contradictory situation, authorities might find themselves unable to consider global sustainability impacts or other policy areas without overstepping their competence. The competence of an authority is determined politically in the legislative process. Ideally, all legislation and competences are coordinated perfectly, and harmful cross-effects are minimized. Given the complexity in the interrelation of local and global environmental problems, it is often likely that it is difficult to accomplish a holistic approach in individual cases. A further issue relates to the sensitivity of the local receiving environment, wherein emissions into a highly sensitive watercourse, for example, may require stricter discharge limits than those that may be generally imposed elsewhere for the same type of process effluent.

## 2. Aims of the Study

The overall objective of our study was to develop a sustainability index that comprehensively and reliably captures the environmental, economic, and social sustainability of an industrial plant. This novel sustainability index is aimed at supporting informed decision-making by integrating all the relevant dimensions of sustainability through the application of a single tool. In addition, the index could be used as a communication tool for stakeholders such as environmental authorities and local communities. Our approach to plant level sustainability measurement is presented in Figure 2. However, in this paper, we concentrate on environmental and economic sustainability at the operational plant level and especially on how to measure it. The main part of the work was focused on the identification and selection of (1) environmental performance indicators (EPIs) supported by appropriate Life Cycle Assessment (LCA) methodologies and (2) economic performance indicators supported by the consideration of what plant level sustainability costs. We also present two hypothetical case studies (a particle emission collector and a wastewater treatment unit) as examples of a plant level application of the environmental sustainability index tool in practice. The development work for economic indicators is presented including a draft set of indicators and some hypothetical application considerations. The emphasis lays on the suitability of the selected approach to support decision-making processes at the plant level. Therefore, the impacts and costs of different actions should be integrated into the overall assessment. This paper, however, focuses on environmental performance aspects. We propose that the specific characteristics of the metal production industry should be addressed jointly with the relevant legal operational environment. Our purpose was to discuss the implications of the legal framework in the context of sustainability assessment, including its implications for environmental performance measurement in general. We also offer our recommendations on what environmental and economic sustainability assessment at the plant level should encompass to be able to provide relevant information for decision-makers.

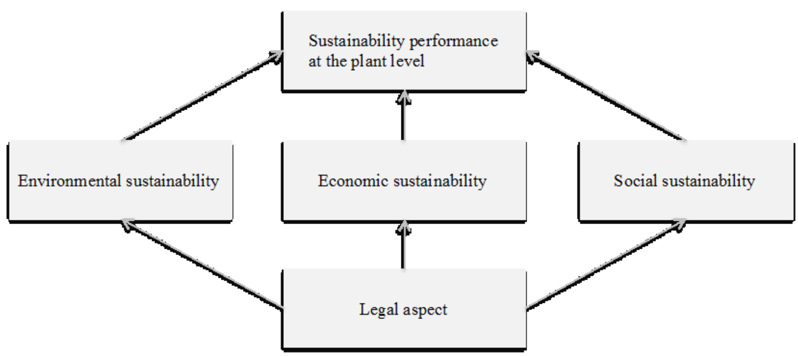


**Figure 2.** Different dimensions of sustainability assessment at the plant level.

The sustainability assessment tool covers environmental, economic, and social sustainability dimensions. However, a desired outcome should be able to adjust to different political and legal environments as well. Therefore, the legal aspect is included in each sustainability dimension to represent the extant legal requirements.

## 3. Material and Methods

The present research approach is based on both literature review and co-operation with industry partners. University-industry co-operation was arranged through workshops during the years 2012 and 2013: social indicators (28 February 2012), environmental indicators (16 March 2012), legal aspects (5 September 2012), and economic indicators (26 February 2013). This study focuses on the environmental economic parts including the associated legal aspects. By organizing these workshops, we aimed to gain a better understanding of the specific characteristics of sustainability assessment within the metal production industry and reach a common understanding of suitable indicators for the developed holistic sustainability index.

The material of the literature review covered public documentation, legislation, and the scientific literature in this field. The actual development work for the assessment method and associated details was carried out in co-operation with representatives from the participating companies. Life cycle thinking and assessment methodology [39,40] were a part of the environmental indicators' development work. Hypothetical cases of pilot testing of the developed environmental and economic indicators are also presented to demonstrate the potential and features of the chosen approach.

## 4. Development of the Environmental Sustainability Indicators

The purpose of the developed assessment method was to encompass the environmental issues relevant to the metal production industry. The scope of environmental indicators was expanded from a "gate-to-gate" approach to cover "cradle-to-gate" environmental impacts caused by raw material production and transportation. The development of appropriate indicators requires the identification of the relevant stakeholders and understanding their interests [15]. Therefore, the development work for the indicators was conducted with the co-operation of industry partners (Figure 3).

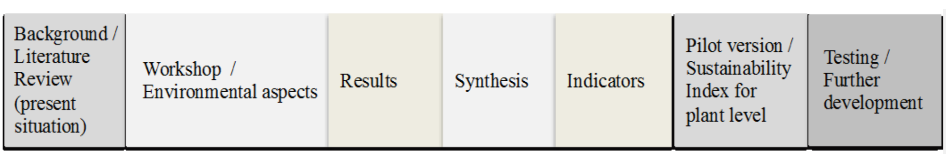


**Figure 3.** Structure of the development of the environmental indicators.

With this approach, the key characteristics and the most relevant sustainability challenges of the industry sector were identified.

### *4.1. Environmental Indicators*

The development of environmental indicators included literature review and collaboration with industry partners through discussion-based workshops, for example, on environmental indicators (16 March 2012) and legal aspects (5 September 2012), which are the focus of this section. The legal indicator development work in the context of environmental indicators addressed planning of operations, environmental permit procedures, water aspects and permits, permits and associated operational aspects of plant operations, supervision and monitoring (by authorities), and close down phase activities and responsibilities.

One of the main questions that arose during the workshops was the required level of detail for plant level assessment. This refers directly to the number of indicators. An excessive number of indicators might be too heavy and time-consuming to use, but too narrow an approach might lead to a lack of relevant information. The opinion of the industry partners was that without details the evaluation method would be without value. Therefore, we did not limit the number of indicators. However, the individual indicators were grouped as composite indicators, presenting a general overview over the environmental indicators (Table 1).

The most important environmental issues for the metal production industry are associated with air emissions, water effluents, and generation of solid wastes. In addition, depletion of non-renewable resources and primary energy demand including related $CO_2$-emissions are also significant. Therefore, selected environmental indicators reflect these key environmental issues. Furthermore, life cycle thinking has been included by broadening the scope of the evaluation to cover environmental impacts caused by raw materials production and transportation.

**Table 1.** Developed environmental sustainability indicators.

| Summary Indicators | Indicators | Provides Information on |
|---|---|---|
| Air emissions ($E_{AIR}$) | $CO_2$<br>$SO_2$<br>$NO_x$<br>Dusts<br>Metals | Contribution to global warming<br>Contribution to acidification<br>Contribution to acidification<br>Contribution to local/regional air quality<br>Contribution to human health and eco-toxicity |
| Water effluent ($E_{WATER}$) | Total effluent flow | The amount of process waters that are returned to environment |
| | Quality of discharged water, measured by water quality parameters and discharged substances, such as suspended solids, Chemical Oxygen Demand (COD) and Biological Oxygen Demand BOD, oils, nitrogen, phosphorus, heavy metals and other harmful substances | Contribution to several environmental impacts, such as eutrophication, oxygen loss, impact on organisms, etc. |
| Solid residues ($E_{SOLID}$) | Solid wastes<br>Hazardous wastes<br>Utilization rate | The quantity of solid wastes that are generated during the operations<br>Utilization rate contributes to the ability to utilize generated wastes |
| Efficiency ($E_{EFF}$) | Energy efficiency<br>Material efficiency<br>Water efficiency | Indicates the contribution to the global challenges regarding primary energy demand, consumption of non-renewable materials, and fresh water consumption |
| Production of raw materials ($E_{RAW}$) | Primary material consumption<br>Energy consumption<br>Water efficiency<br>$CO_2$-emissions | Influence of the raw materials and energy production |
| Transportation ($E_{TRANS}$) | $CO_2$<br>$SO_2$<br>$NO_x$<br>Primary energy demand | Influence of the transportation |
| Total GHG-emissions ($E_{GHG}$) | $CO_2$-eq. | Summarizes $CO_2$-eq. emissions from all the production steps from cradle to gate |
| Legal aspects ($E_{LEGAL}$) | Planning operations<br>Permit procedure<br>Water management permit<br>During operations<br>Monitoring<br>Ending operations | Indicates the level that local legislation steers the plant operations and environmental impacts |

The first three categories consist of relevant emissions contributing to air, watercourses, and land. $CO_2$, $NO_x$, $SO_2$, dust, and heavy metal emissions are common for the metal production industry sector, whereas the water quality parameters are modified for each process separately. One major environmental challenge in the metal production industry is solid waste generation. There are several sources of solid wastes: dusts, water treatment sludge, and process slags. The solid residues category covers the amount of produced solid and hazardous wastes. In addition, the utilization rate of solid residues expresses the ratio of the solid residues that can be utilized further.

The efficiency category encompasses energy, material, and fresh water consumption. Energy efficiency is determined by the amount of consumed fuels and electricity. Produced energy, such as district heat, is also included. Total non-renewable material intensity and amount of recycled material in the process are used as a measure of material efficiency. Since the metal production industry is typically a very material intensive sector, the utilization of renewable resources and recycled materials might have a remarkable effect on the virgin non-renewable material consumption. Therefore, it is an important factor to determine how much recycled and renewable materials processes can utilize. Water efficiency is simply assessed by measuring the specific fresh water consumption. This value indicates how much added make-up water is required in the process. Plants with more efficient water recycling systems and closed water-circuits naturally consume less fresh water.

The environmental impacts of raw material and energy production are included by evaluating the most relevant sustainability issues, which are (1) material consumption, (2) $CO_2$ emissions, (3) primary energy demand, and (4) fresh water consumption. The main virgin raw material in this sector is ore and the quality of ore deposits are decreasing [41]. There is potential for the reduction of energy consumption and associated greenhouse gas emissions in the metal extraction stage of the metal production life cycle. The type of reductant used is an important factor, especially in iron and steel production. In addition, utilization of biomass as a source of carbon can improve the sustainability of primary metal production [41]. In addition, emissions that arise from electricity production might have a significant role depending on the amount and origin of the purchased power.

Long distances are typical for the metal production industries' transportation, as large amounts of raw materials are transported to the processing sites. Transportation covers only a small part of the environmental impact of the production chain, but, globally, transportation plays a significant role. Transportation contributes to almost 19% of greenhouse gas emissions worldwide [41] and it is therefore an important factor in sustainability evaluation. Emissions of $CO_2$, $NO_x$, $SO_2$, and primary energy consumption are taken into consideration in the calculation. Emissions of $CO_2$ and $NO_x$ are specific for land transportation. Furthermore,

$SO_2$ emissions are included, as those are relevant emissions for marine transport, especially in Europe.

In addition, greenhouse gas emissions ($CO_2$, $N_2O$, $CH_4$) have been calculated through the whole supply chain covering raw material production, transportation, processes at the plant site, and purchased power generation. The purpose of this indicator is to reveal the main sources of greenhouse gases and the overall impact of the production route.

The legal framework and specific national legislation do not evaluate the concrete performance of industrial operations but regulate the limits within which industry can operate, and thus a review of existing legislation can shed light on how well the legislation steers the plant operations in terms of, for example, environmental performance. In summary, in this study, the legal indicators were designed to describe both the EU and the national level legal environment and control mechanisms of Finland relevant to industrial operators in Finland. The evaluation of relevant environmental legislation is important and enables the description of the minimum level of environmental protection and of the associated enforcement control mechanisms in a given country. In this manner, the legal aspect indicators provide information on the extent to which legislation and local authorities are able to address environmental sustainability issues concerning industrial operations.

### *4.2. Evaluation Method*

When condensed information is required, individual indicators need to be normalized on the same scale. To this end, this study employed the min–max method. For example, $CO_2$ signifies $CO_2$ emissions that are generated by the manufacturing process and the $CO_{2,\mathrm{Min}}$ and $CO_{2,\mathrm{Max}}$ denote the minimum and maximum $CO_2$-emissions of the specific industry sector, respectively:

$$EI_{CO_2} = \begin{cases} 0, if\ CO_2 \leq CO_{2,Min} \\ \dfrac{CO_2 - CO_{2,Min}}{CO_{2,Max} - CO_{2,Min}}, if\ CO_{2,Min} < CO_2 < CO_{2,Max} \\ 1, if\ CO_{2,Max} \leq\ CO_2, \end{cases}$$

where,

$CO_2$ = $CO_2$ emissions (kg/t product)
$CO_{2,\mathrm{Min}}$ = Minimum value (kg/t product)
$CO_{2,\mathrm{Max}}$ = Maximum value (kg/t product).

The minimum value presents the lowest emission level that is achievable with the current technology. Accordingly, the maximum value presents the highest acceptable emission level in Europe, and both the minimum and maximum values for each variable are derived from Best Available Techniques (BAT) Reference documents (BREF-documents). When necessary, the reference data is complemented from other verified sources. A similar normalization method has been applied in a previous study [28].

At this point, no separate weighting method has been employed; however, it should be noticed that each category contains a different number of indicators and therefore they unequally affect the total score. In other words, some weighting occurs unintentionally due to the different number of indicators. Although these indicators were developed especially for the metal production sector, indicators need to be modified on a case-by-case basis. In addition, the reference values (min-max-values) need to be derived separately for each industry branch depending on the BREF guidance. However, even though the scope of the environmental sustainability assessment should be expanded to cover secondary emission sources, and decision-making should cover these aspects to discover the most environmentally sustainable solution, there are other factors that influence a company's environmental performance. One example is the national legal framework that regulates industrial operations.

**5. Testing the Environmental Indicators in Potential Industrial Applications**

The developed sustainability index focuses on plant level sustainability performance. The indicator tool can be used to help the company in decision-making and self-evaluation on the operations level, for example, when buying an existing plant, building a new plant, choosing between two possible investments (which would improve total sustainability the most?), and choosing a place and country in which to locate a plant. Although our approach in this article is mainly focused on assessing the environmental impacts, industrial activities also always have social and economic implications. Our hypothetical case examples are (1) a particle emission collector (Figure 4), and (2) a wastewater treatment unit (Figure 5). These case examples are evaluated with the developed environmental sustainability index tool. The evaluation is done before and after installing the investment. The change in the sustainability state is observed in two ways; does the index tool work and how can it be improved? The first hypothetical case example, and associated data collection, was carried out in collaboration with industry partners, and the second case example is about addressing high concentrations of Chemical Oxygen Demand (COD) organic compounds in chemical pulp mill wastewater. The purpose of this case example is to evaluate the situation of wastewater treatment before and after the specific investment. The energy and material inputs and outputs change due to the investment.

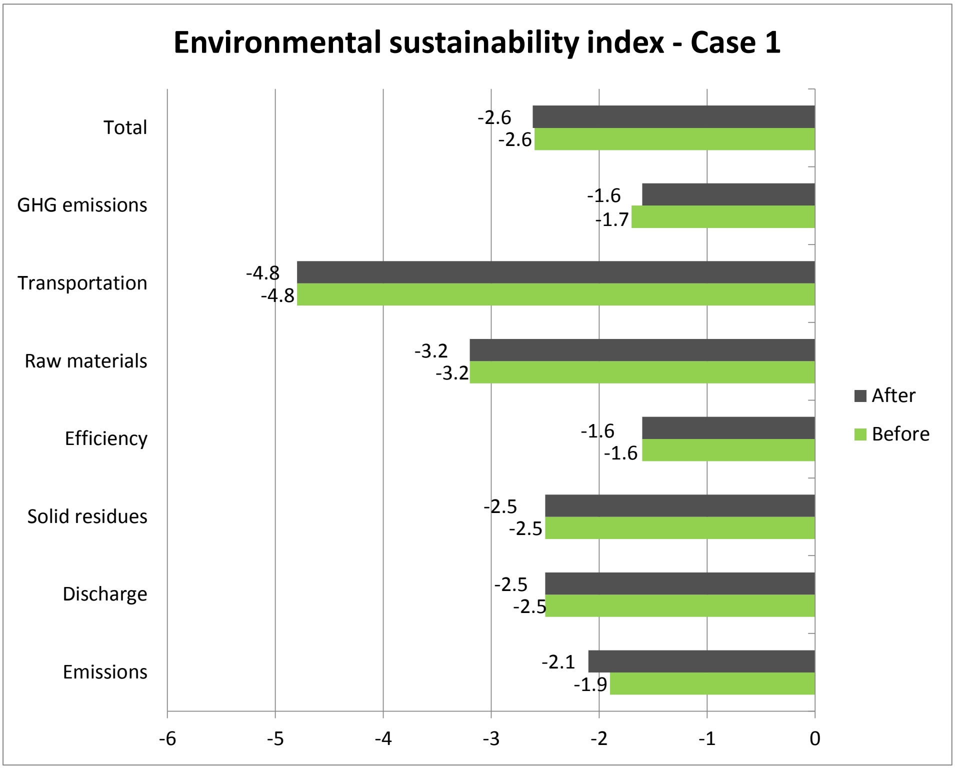


**Figure 4.** Case 1: Environmental index results for a particle emission collector before and after the investment.

Sub-indicators of the sustainability index were measured on a scale from $-5$ (best) to 5 (worst). The value 0 indicates that the given result is in the middle of the scale between the benchmark values [42]. The evaluation focused on a plant level hypothetical situation with realistic data. Because of the chosen scale, only the result of the emissions improved after investment. The case was discussed with industry partners in a workshop and they noted that in real life, the new particle emission collector worsened air quality inside the factory and thus had a negative impact on the working conditions of the employees.

The second hypothetical case example [42] is a wastewater treatment unit investment. It was required by authorities to reduce the quantity of Chemical Oxygen Demand (COD), high concentrations of organic compounds, in chemical pulp mill wastewater. The water was discharged into the surrounding waterways. Authorities demanded that the factory needed to purchase and install tertiary water treatment to reduce the amount of COD. The situation before and after this investment can be seen in Figure 5.

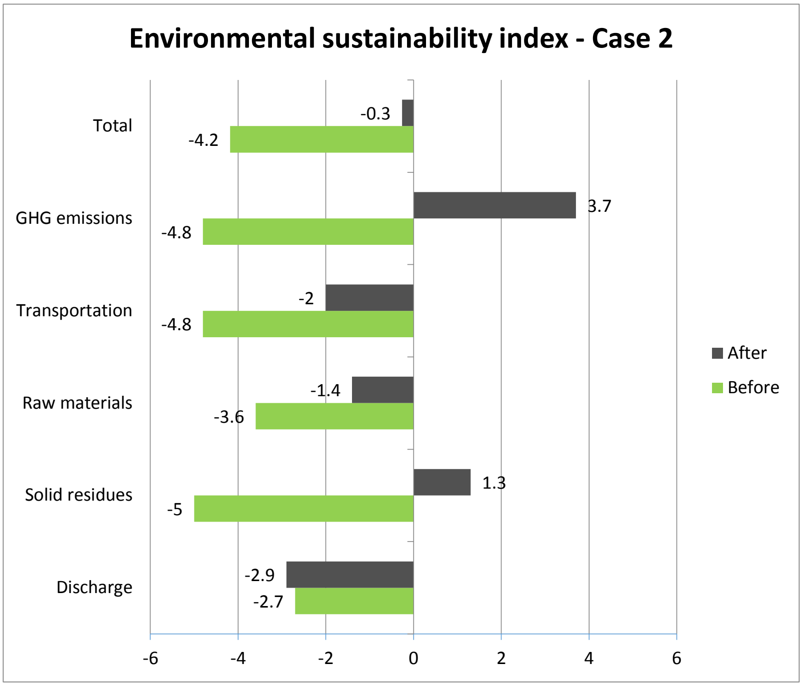


**Figure 5.** Case 2: Environmental index results for a wastewater treatment unit before and after the investment.

The tertiary water treatment reduced the amount of COD in the mill wastewater. However, tertiary treatment requires an aluminium sulphate as a water-cleaning chemical, hence the discharged sludge contains aluminium. In addition, the amount of such sludge increased due to this investment. Before the tertiary treatment investment, the sludge was disposed of in the bark boiler or recovery boiler inside the plant. After the investment, the sludge containing aluminium had to be taken to the landfill for disposal and the amount of landfilled waste increased significantly [42]. From the environmental perspective, the total influence of the investment was therefore a negative one. The sustainability index value before investment was $-3.2$ and afterwards was $-0.6$. The total environmental sustainability of the discharge cleaning unit deteriorated 2.6 units due to the investment [42].

## 6. Development of Economic Sustainability Indicators

Economic sustainability at the plant level is very much about long-term competitiveness, profitability, and meeting the demands of shareholders. Good performance makes it possible to generate societal well-being locally and to pay taxes. In addition, social and environmental responsibility and sustainability performance are very dependent on economic performance. However, companies need to pay attention to responsibility, including stakeholder communication as well as putting strong emphasis on the well-being of employees and overall environmental responsibility. The general themes that were considered to be the main drivers in this study encompass the following:

- Plant level sustainability—What does it cost? How can it be measured?
- Cross effects—Can they be anticipated? How can they be communicated? What are links with social aspects? How can environmental and economic impacts be optimized?
- Economic consequences—What are they for various options and factors that influence plant level economic sustainability?
- Investment perspective—How to best invest a given sum into sustainability most efficiently? Do investments differ in nature?
- Risks—What are the supply chain, financial, and raw material risks?
- Legal framework—What are the specificities of national, EU, and global laws (e.g., regarding taxes and emissions)?
- Social responsibility—What are its cost effects, its effects on supply chain, and its image/brand risks?
- Corporation and plant level performance and assessment—How does a company/a plant perform? How can its performance be assessed, including internal and external applications?
- Communication—How to best communicate a holistic and balanced approach to sustainability to authorities (e.g., regarding assessments and permits)?

The developed draft set of economic indicators is presented in Figure 6. The workshop discussion covered multiple topics such as corporate social responsibility, societal dimensions and benefits of paid taxes, the need for robust economic performance to ensure a basis for long-term sustainability, cross effects and associated implications, sustainability in the supply chain and associated risks, image, public relations and brand aspects, global raw materials and suppliers, characteristics of environmental investments (compared to other investments), key business performance indicators, cost categories, different levels, and code of conduct.

The estimated economic implications [42] of the above presented hypothetical case studies (Figures 4 and 5) are presented in Figures 7 and 8. Calculations are based on realistic data and market prices. These examples highlight the cross-effect perspective in Case 1 in which minor environmental performance improvements may lead to significant negative economic impacts at the company/plant level and show how costs may increase significantly due to decisions made in the environmental performance context. The legal indicators in the economic context addressed retirement pension issues (e.g., insurance), disability pension, health insurance, accident insurance, and taxation.

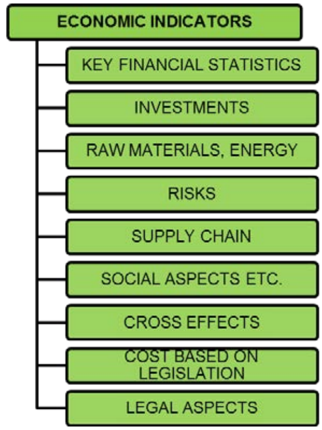


**Figure 6.** Draft set of economic indicators.

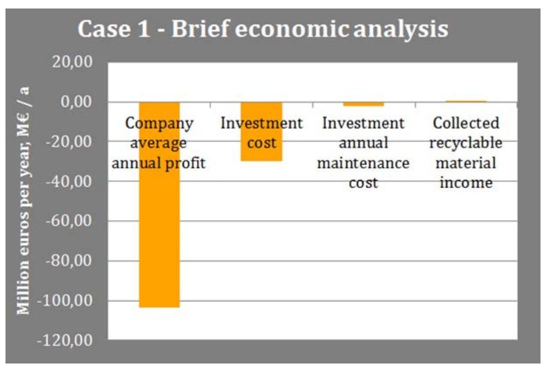


**Figure 7.** Example of the economic impacts in Case 1 (particle emission collector).

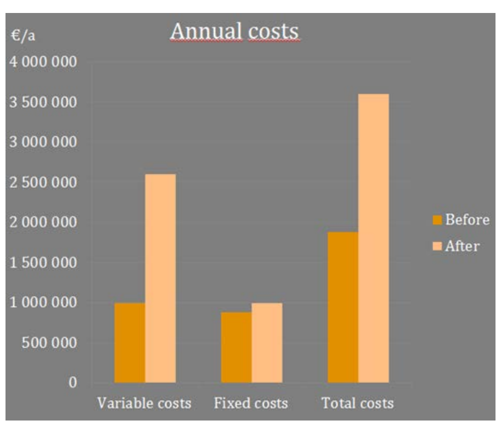


**Figure 8.** Example of the economic impacts in Case 2 (wastewater treatment unit).

## 7. Discussion

In this study, we focused on the development of an environmental sustainability index and associated indicators for plant level environmental sustainability performance assessment within the metal production industry. Our approach encompassed university-industry collaboration via workshops. Our premises included the idea that the application of sustainability metrics through indexes and indicators is a powerful tool for gathering and condensing plant level information to support informed decision-making. Our plant level approach is intended to encompass both primary and secondary emissions. Primary emissions are released from the plant activities, whereas secondary emissions arise from supportive activities, such as electricity production, which enable a manufacturing process. In accordance with life cycle thinking [6], we wanted to avoid problem/burden shifting even though full LCA studies are too laborious and costly, requiring professionals and large amounts of data for use in this context. Hence, our aim is to address the identification of cross-effects at the plant level using a comprehensive and balanced sustainability index approach. Any holistic approach requires focus on system level thinking. Our case studies highlighted the need to address cross-effects and problem/burden shifting through holistic and balanced approaches. A comprehensive sustainability index and associated indicators can be of much help in this respect.

Environmental performance and indices are usually focused on production processes without any recognition of the operations and their environmental impacts outside the plant boundaries. This kind of gate-to-gate approach risks problem shifting, indicating that the reduction of particulate emissions contributing to one environmental concern within plant boundaries might actually increase other emissions outside the boundaries contributing to another environmental problem [19]. For example, performance indicators should also cover the life cycle performance of products including, for example, resource utilization and transportation [6]. Other studies have also supported the idea of broader inclusion of relevant life cycle phases [19,43]. By broadening the scope of traditional EPIs to cover other life cycle stages as well, environmental problem shifting can be avoided. In addition, by constructing a composite index, the number of decision-making criteria can be reduced and the index can provide a comprehensive overview of environmental sustainability.

Traditional LCA could be developed towards a Life Cycle Sustainability Assessment (LCSA) that would be more similar to sustainability assessment covering all dimensions of sustainability [44]. Companies are interested in expansions of traditional LCA that include social, economic, and ecological aspects [45]. All these points speak in favour of a more comprehensive and integrated approach to the assessment of both overall and environmental sustainability. As we noted earlier, cross-effects should be addressed within the overall plant level index. Other studies have made similar suggestions about addressing dynamics and interlinkages within the assessed system [46,47]. Our previous development work on social indicators and pilot testing experiences from the process industry have also been reported [48,49]. Regarding the overall evaluation methods, there are several different approaches [50,51]. Many previous studies have also addressed the economic aspects of decisions and measures to improve environmental performance [52–54].

The integration of environmental indicators and life-cycle assessment is implemented here to expand the scope of typical environmental performance indicators. Our original idea was that all the main environmental sustainability aspects could be covered using one assessment method. However, the possible drawback of this tool, as with many other indices, is the impact of normalization, scaling, and aggregation methods. During these types of operations, the real data behind such summary indicator values are lost. Even though sustainability indicators should be able to measure progress towards sustainability, the choice of reference values has a significant impact on the results. Therefore, it is important that decision-makers are able to observe the individual indicators behind the summary indicators. The summary indicators give a good general overview of environmental performance, but the underlying reason for poor or excellent performance should also be identifiable.

When trying to identify the most environmentally sustainable option, there is the challenge of how different emissions should be compared to each other. The first example is the type of emissions; when particulate emissions from process gases are reduced by scrubbing, it does not mean that the emission in question disappears, it only indicates that the particular emission is transferred from gaseous emissions to a water effluent or solid/sludge residues. The second example is how local improvements might affect overall global sustainability goals. For example, local particulate emissions can be reduced by electrostatic filters, which naturally increase the electricity consumption, hence affecting the emissions that contribute to electricity production. Especially when fossil fuels are used, $CO_2$ emissions are increased thereby affecting the main global environmental sustainability challenge, that of global warming. In this case, there should be a technique that enables the comparison of local and global sustainability in a reasonable manner. However, no uniform weighting procedure exists to rank different emission sources.

Furthermore, local authorities cannot consider global environmental impacts as their priority, for example, in their permit considerations. This is because the aim of controlling immissions and emissions is typically on controlling environmental impacts caused at the specific plant site and in its immediate surroundings. Possible proportionality assessments should be expanded from comparing the harm caused by the emissions also to the harm caused by the operations on a significantly more extensive scale. This would include considerations of, for example, supply chain and the increased demand of materials or energy. In addition, when developing environmental performance metrics, monetary evaluation should be included if the method is employed as a decision-making tool within some company. By integrating monetary evaluation into the assessment method, the environmental impacts and costs of different actions can be evaluated.

## 8. Conclusions

In conclusion, this study suggests that environmental sustainability assessment should be expanded to cover at least the most relevant production steps beyond the conventional plant boundaries. As a result, problem/burden shifting can be avoided. It should also be noted that the application of this kind of sustainability index at the plant level always requires a case-by-case consideration of, for example, the features of the site and specific plant processes, and of the requirements for both quantitative and qualitative data. Environmental sustainability assessment at the plant level should be able to provide relevant information for decision-makers, considering the support of continuous improvement of the environmental performance of specific plant sites. The developed assessment method encompasses the main environmental issues relevant to the metal production industry at the plant level, while considering both operations beyond plant boundaries such as the environmental impacts caused by raw material production and transportation and location-specific legal aspects.

We are particularly pleased with the university-industry co-operation within this study that enabled the joint development of an appropriate set of indicators and associated methodological aspects. Joint development of the overall indices and the assessment tool was fruitful and led to many new ideas about further research and the identification of gaps that need to be bridged. For example, more research and development work is required to include monetary evaluation and social aspects into the evaluation method. Even though in this paper we concentrated on environmental and economic sustainability and associated measurements, the social and legal aspects of sustainability are at least equally important. The purpose of the plant level assessment tool is to provide information for internal use, but also to enable the assessment of environmental, social, and economic impacts on the surrounding societies and local economies, as well as of a plant's contribution to addressing global sustainability challenges. More development work is required, especially focusing on the evaluation of the cross-effects of different actions and the avoidance of problem/burden shifting. For example, our case studies clearly indicated the challenges associated with addressing the overall sustainability of dynamic and intertwined systems. The application of sustainability indicators as an evaluation tool seems to be an effective way for companies' self-evaluation of investments that are made, including the assessment of associated impacts on operations both at the plant site and beyond its boundaries. Most likely, this approach can also be used for comparison between different plant sites inside a specific company. Further research, testing, and implementation of the developed index and indicators are currently under development.

**Acknowledgments:** Research funding from Fimecc Oy, the Finnish Metals and Engineering Competence Clusters, is gratefully acknowledged.

**Author Contributions:** O.D. and K. H. conceived and designed the overall sustainability index concept with special emphasis on process industry. R.H., N.P. and K.V. performed the development and experimental work. A.E. contributed to the legal analysis. R.H. mostly wrote the paper. All authors have read and approved the final manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. United Nations (UN) Commission of Environment and Development, Our Common Future. 1987. United Nations (UN) Documents. Available online: http://www.un-documents.net/our-common-future.pdf (accessed 19 April 2017).
2. United Nations (UN) Sustainable Development. *Agenda 21*; Action Plan from the United Nations Conference on Environment & Development: Rio de Janerio, Brazil, 3–14 June 1992. United Nations (UN) Sustainable Development. Available online: https://sustainabledevelopment.un.org/outcomedocuments/agenda21 (accessed on 19 April 2017).
3. Pennington, D.W.; Potting, J.; Finnveden, G.; Lindeijer, E.; Jolliet, O.; Rydberg, T.; Rebitzer, G. Life Cycle Assessment Part 2: Current Impact Assessment Practice. *Environ. Int.* **2004**, *30*, 721–739.
4. Rebitzer, G.; Ekvall, T.; Frischknecht, D.; Hunkeler, D.; Norris, G.; Rydberg, D.; Schmidt, W.-P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *50*, 701–720.
5. Jasch, C. Environmental performance evaluation and indicators. *J. Clean. Prod.* **2000**, *8*, 79–88.
6. European Commission Joint Research Center. European Platform on Life Cycle Assessment. European Commission. Available online: http://eplca.jrc.ec.europa.eu/ (accessed on 19 April 2017).
7. Huang, C.-L.; Vause, J.; Ma, H.-W.; Yu, C.-P. Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook. *Resour. Conserv. Recycl.* **2012**, *68*, 104–116.
8. Costa, M.M.; Schaeffer, R.; Worrell, E. Exergy accounting of energy and materials flow in steel production systems. *Energy* **2001**, *26*, 363–384.
9. Hau, J.L.; Bakshi, B.R. Promise and problems of emergy analysis. *Ecol. Model.* **2004**, *178*, 215–225.

10. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodologies. *Ecol. Indic.* **2012**, *15*, 281–299.
11. Labuschagne, C.; Brent, A.C.; van Erck, R.P.G. Assessing the sustainability performance of industries. *J. Clean. Prod.* **2005**, *13*, 373–385.
12. Norgate, T.; Jahanshahi, S.; Rankin, W.J. Assessing the environmental impact of metal production processes. *J. Clean. Prod.* **2007**, *15*, 838–848.
13. Norgate, T.; Haque, N. Energy and greenhouse gas impacts of mining and mineral processing operations. *J. Clean. Prod.* **2010**, *18*, 266–274.
14. Seppälä, J.; Koskela, S.; Melanen, M.; Palperi, M. The Finnish metals industry and the environment. *Resour. Conserv. Recycl.* **2002**, *35*, 61–76.
15. Azapagic, A. Developing a framework for sustainable development indicators for the mining and minerals industry. *J. Clean. Prod.* **2004**, *12*, 639–662.
16. Van Berkel, R. Eco-efficiency in primary metals production: Context, perspectives and methods. *Resour. Conserv. Recycl.* **2007**, *51*, 511–540.
17. French, S.; Geldermann, J. The varied context of environmental decision problems and their implications for decision support. *Environ. Sci. Policy* **2005**, *8*, 378–391.
18. Azapagic, A.; Perdan, S. An integrated sustainability decision-support framework, Part 1—Problem structuring. *Int. J. Sustain. Dev. Ecol.* **2005**, *12*, 98–111.
19. Hermann, B.G.; Kroeze, C.; Jawjit, W. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *J. Clean. Prod.* **2007**, *15*, 1787–1796.
20. Perotto, E.; Canziani, R.; Marchesi, R.; Butelli, P. Environmental performance, indicators and measurement uncertainty in EMS context: A case study. *J. Clean. Prod.* **2008**, *8*, 517–530.
21. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. Development of composite sustainability performance index for steel industry. *Ecol. Indic.* **2007**, *7*, 565–588.
22. Mayer, A.L. Strengths and weaknesses of common sustainability indices for multidimensional systems. *Environ. Int.* **2008**, *34*, 277–291.
23. Olsthoorn, X.; Tyteca, D.; Wehrmeyer, W.; Wagner, M. Environmental indicators for business: A review of the literature and standardization methods. *J. Clean. Prod.* **2001**, *9*, 453–463.
24. Mitchell, G. Problems and fundamentals of sustainable development indicators. *Sustain. Dev.* **1996**, *4*, 1–11.
25. Dow Jones Sustainability Indices. 2017. Available online: http://www.sustainability-indices.com/ (accessed on 21 April 2017).
26. FTSE4Good Index Series. 2017. Available online: http://www.ftse.com/products/indices/FTSE4Good (accessed on 21 April 2017).
27. Global 100 Index. 2017. Available online: http://www.corporateknights.com/reports/global-100/ (accessed on 21 April 2017).
28. Barrera-Roldán, A.; Saldívar, A.; Ortiz, S.; Rosales, P.; Nava, M.; Aquilar, S.; Rodríquez, L.; Villaseñor, E.; Angeles, A. Industrial Sustainability Index. *Adv. Ecol. Sci.* **2003**, *18*, 337–346.

29. Seppälä, J.; Basson, L.; Norris, G.A. Decision analysis frameworks for life-cycle impact assessment. *J. Ind. Ecol.* **2002**, *5*, 45–68.
30. Böhringer, C.; Jochem, P.E.P. Measuring the immesurable—A survey of sustainability indices. *Ecol. Econ.* **2007**, *63*, 1–8.
31. Barrasso, G.; Nordheim, E. Sustainable development indicators for the mining and minerals industry. *J. Clean. Prod.* **2007**, *15*, 275–279.
32. World Steel Association. Sustainability indicators. Available online: https://www.worldsteel.org/steel-by-topic/sustainability/sustainability-indicators0.html (accessed on 19 April 2017).
33. European Aluminium Association (EAA). Sustainability Policies. Available online: http://www.european-aluminium.eu/policy-areas/sustainability/ (accessed on 19 April 2017).
34. Finlex. Environmental Protection Act 86/2000. Available online: http://www.finlex.fi/en/laki/kaannokset/2000/en20000086.pdf (accessed on 19 April 2017).
35. Finlex. Environmental Protection Decree 169/2000. Available online: http://www.finlex.fi/fi/laki/kaannokset/2000/en20000169.pdf (accessed on 19 April 2017).
36. Seppälä, M. *Ympäristösuojelulain Lupajärjestelmän Perusteista*, Defensor Legis 2003/4. 723 p. (In Finnish)
37. European Parliament; Council of the European Union. Directive 2008/1/EC concerning integrated pollution prevention and control. European Union, 2008. Available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0001:EN:NOT (accessed on 19 April 2017).
38. European Parliament; Council of the European Union. Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control). European Union, 2008. Available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32010L0075:EN:NOT (accessed on 19 April 2017).
39. International Organization for Standardization. *Environmental management—Life cycle assessment—Principles and framework*; ISO 14040; International Organization for Standardization: Geneva, Switzerland, 2006; Available online: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en (accessed on 21 April 2017).
40. International Organization for Standardization. *Environmental management—Life cycle assessment—Requirements and guidelines*; ISO 14044; International Organization for Standardization: Geneva, Switzerland, 2006; Available online: https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en (accessed on 21 April 2017).
41. Ingarao, G.; Di Lorenzo, R.; Micari, F. Sustainability issues in sheet metal forming processes: An overview. *J. Clean. Prod.* **2011**, *19*, 337–347.
42. Virtanen, K. The Use of Sustainability Indicators in Industrial Applications. Master´s Thesis, Aalto University School of Chemical Technology, Espoo, Finland, 2013.
43. Azapagic, A.; Perdan, S. Indicators of Sustainable Development for Industry: A General Framework. *Process Saf. Environ. Prot.* **2000**, *78*, 243–261.
44. Zamagni, A.; Pesonen, H.-L.; Swarr, T. From LCA to Life Cycle Sustainability Assessment: concept, practice and future directions. *Int. J. Life Cycle Assess.* **2013**, *18*, 1637–1641.

45. Nygren, J.; Antikainen, R. *Use of Life Cycle Assessment (LCA) in Global Companies*; Reports of the Finnish Environment Institute 16/2010; Finnish Environment Institute: Helsinki, Finland, 2010.
46. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainable assessment methodologies. *Ecol. Indic.* **2009**, *9*, 189–212.
47. Dahl, A.L. Achievements and gaps in indicators for sustainability. *Ecol. Indic.* **2012**, *17*, 14–19.
48. Husgafvel, R.; Pajunen, N.; Päällysaho, M.; Paavola, I.-L.; Inkinen, V.; Heiskanen, K.; Dahl, O.; Ekroos, A. Social metrics in the process industry—background, theory and development work. *Int. J. Sustain. Eng.* **2013**, *7*, 171–182.
49. Husgafvel, R.; Pajunen, N.; Virtanen, K.; Paavola, I.-L.; Päällysaho, M.; Inkinen, V.; Heiskanen, K.; Dahl, O.; Ekroos, A. Social sustainability performance indicators—experiences from process industry. *Int. J. Sustain. Eng.* **2014**, *8*, 14–25.
50. Organisation for European Economic Co-operation (OECD). *Handbook on Constructing Composite Indicators, methodology and user guide*; OECD, 2008. Available online: http://www.oecd.org/els/soc/handbookonconstructingcompositeindicatorsmethodologyanduserguide.htm (accessed on 19 April 2017).
51. Ness, B.; Urbel-Piirsalu, E.; Anderberg, S.; Olsson, L. Categorising tools for sustainability assessment. *Ecol. Econ.* **2007**, *60*, 498–508.
52. Böhringer, C.; Moslener, U.; Oberndorfer, U.; Ziegler, A. Clean and productive? Empirical evidence from the German manufacturing industry. *Res. Policy* **2012**, *41*, 442–451.
53. Clarkson, P.M.; Li, Y.; Richardson, G.D.; Vasvari, F.P. Does it really pay to be green? Determinants and consequences of proactive environmental strategies. *J. Account. Public Policy* **2011**, *30*, 122–144.
54. Horvathova, E. The impact of environmental performance on firm performance: Short-term costs and long-term benefits? *Ecol. Econ.* **2012**, *84*, 91–97.

Husgafvel, R.; Pajunen, N.; Dahl, O.; Heiskanen, K.; Ekroos A.; Virtanen, K. Development of Environmental and Economic Sustainability Metrics for the Metal Production Industry—Experiences From University-Industry Cooperation. In *Sustainable Business, Management, and Economics*; Berger, L., Bergman, M.M., Eds.; Frontiers in Sustainability Series 1; MDPI: Basel, Switzerland, 2017; Volume 2, pp. 98–122.