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Sustainable Environmental Impact Assessment Using Indicators for Sustainable Energy-Intensive Industrial Production

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Abstract: We have proposed an impact assessment methodology for determining sustainability in energy-intensive industrial production based on a comprehensive combination of economic, environmental, and social indicators for sustainable development. The goal of this study was to disclose this methodology for assessing sustainability in energy-intensive industrial production. We proved that any energy-intensive chemical, metallurgical, and energy generation processes should maximize the material output values and product value addition to ensure innovative sustainable development. We proposed indicators that determine the levels of increasing the sustainability of energy-intensive production as a whole, as well as taking into account individual technological processes. We proposed a procedure for making managerial decisions to increase the sustainability of energy-intensive outputs using the technological renewal of fixed assets and/or technological modernization of production. Our proposed methodology is based on a graphical model of the technological development's life cycle of the existing energy-intensive production process. In addition, the proposed methodology ensures resource- and energy-efficiency intensification, together with the environmental safety of the technological processes.

Keywords: criteria; indicators; energy-intensive industrial production; resource- and energy-efficiency; technological innovation; technological renewal; sustainability; economic analysis

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1. Introduction

Engineering specialists in chemical technology fields have introduced a new concept of "sustainable production" in recent years that arose from the point of view of a sustainable development concept. This new concept comprehensively considers the main activities of humanity, such as environmental responsibility (ES) or the rational use of natural resources, as well as ensuring the environmental safety of technogenic systems, economic reproduction (material values creation), and social development. The new concept represents, in particular, a complex chemical–technological system [1–4]. "Sustainable production" is an energy- and resource-efficient, ecologically safe, socially-oriented production model that is essential for producing the required high-quality products [1]. It should be noted that the modern concept of "sustainable production" differs from the traditional concept in terms of the stability of the movement of various physical systems [1,2].

Currently, most scientists and practitioners accept such opinions on the sustainable development of economic systems of any scale and level, including the industrial and economic levels [5–7]. For example, this concept was used to form the best available technologies (BAT) concept. At the same time, scientific publications have suggested using three groups of indicators to assess the sustainability of development: environmental state (ES) (or natural resource), economic, and social indicators, all of which reflect the three main components of sustainable development. However, precise vital indicators should be determined in each of these groups [2].

Unfortunately, we have admitted that the values of various indicators, even key indicators, could be contradictory. This significantly complicates or makes it impossible to choose the best option for the transition to sustainable development. In this case, various convolution methods of one or more indicators, often multiple indices, are proposed to compare development options. However, convolution is based on experts' assessments on the importance of each indicator, which adds a high proportion of subjectivity to the results of management decisions.

In recent years, several new publications have been devoted to applying the sustainable development concept in scientists' and chemical engineers' activities [8,9]. The work by [8] considers the life cycle sustainability assessment as a basis for developing a new approach to evaluating the three aspects of sustainability concerning the Vietnam energy industry. However, the authors noted that the methodology had limited practicability, thus preventing its wider use/application. Ren et al. [9] presented a decision-making methodology applicable in the early stages of the sustainable design of chemical products and processes. Ren et al. [9] proposed using indicators to evaluate design options for three aspects of sustainability, and they were computed based on an easily accessible and easy-to-calculate globally harmonized system of classification and labeling of chemicals. At the same time, the inclusion of estimates was carried out based on multi-criteria analysis methods for solutions. The proposed methodology could become a tool for rapid conceptual design for systematic decision-making at the early stages of energy-intensive product synthesis/chemical technology systems (CTS). However, firstly, it is noted that this approach could be a rapid conceptual design for systematic decision-making tool only at the early stages of energy-intensive product synthesis/CTS; it is not universal and suitable for any industrial system. Secondly, it is essential to use a certain set of baseline indicators not reflected in the financial statements of operating enterprises to implement this approach in the practical activities of engineers.

Currently, many researchers believe that the sustainable development of economic systems requires innovations at various levels [10,11]. Shumpeter [12] is considered to be the founder of the innovation theory. Shumpeter's works were the basis for the subsequent creation and development of the theory of endogenous economic growth, which reflects the direct impact of technological progress on economic growth [13–15]. Nevertheless, Foster [16], Sahal [17], Twiss [18], and Dosi [19] considered the theoretical and practical problems involved in managing the utilization of technical innovations in the 1980s of the last century. However, it is not clear how several indicators reflecting an innovation's effectiveness could be used to appraise its influence on production and an economic systems' sustainability [20].

Studying the impact on the stability of a system's life cycle is considered to be an important perspective [21]. Nonetheless, studies on such impacts are fragmentary since only one of the three sustainability aspects/indicators is studied. Conversely, life cycles vary. For example, enterprise, product (goods), and process life cycles could be considered. Many published studies have focused on life cycle environmental assessments [22,23] and evaluating goods' life cycle costs [24]. At the same time, there are few studies on the life cycles of processes, primarily, technological processes [25,26]. S-curve-related studies have been widely published [27,28]. Christensen [29] significantly contributed to these studies, especially in technology development at the individual company level [29]. However, he considered the change in various technologies' productivity depending on the time factor, which did not aid in evaluating their sustainability and the sustainability of their production and economic systems as a whole.

We have proposed a new methodology for assessing the sustainability of energy-intensive industrial production. Its disclosure was the purpose of this work.

2. Materials and Methods

Methodology of Criteria Formation

Currently, there are many definitions of sustainable development which take into account its various aspects and the scale of application (country, region, economic sector, enterprise, and technological process). In this article, we considered the main provisions of a system economic analysis for the technological renewal of production (SEATRP) that we have been developing related to one of the several categories of energy-intensive industrial production, i.e., chemical and technological production processes.

SEATRP is based on the ideas of complex systems' cyclical development, including the theory of "long waves" by the Russian scientist N.D. Kondratiev [30], and on the theory of endogenous economic growth, considering the influence of technological progress on economic systems' growth as their internal factor [31].

The problem with determining indicators that simultaneously reflect sustainability's economic, environmental, and social aspects has not yet been solved, despite several publications on the topic [21,32]. According to Machado et al. [33], further scientific research and the development of new business models in this area are required.

There are many definitions of a business model. Still, in its most general and short form, it is the enterprise management's vision and conduct of business to satisfy customers and earn profit [34,35]. Accordingly, environmental and social requirements (aspects) must be considered to develop sustainable business models in the production management process [36].

At the same time, enterprises should consider these requirements independently. Boken et al. [37] noted that maximizing efficiency for using materials and energy is one of the eight archetypes of such models. Indeed, a more efficient use of material and energy resources, i.e., a decrease in the material intensity (MI indicator) of products manufactured by enterprises, reduces "natural capital" consumption [38]. On the other hand, a decrease in material intensity ensures the transition to a circular economy through the reuse of generated waste products in energy-intensive industrial production [39]. Thus, the environmental aspects of sustainable energy-intensive production were considered. The social indicators (an enterprise's ability to meet its production team's social needs) were solved by reducing the MI indicator due to maximizing the share of value added in each unit of value of the products manufactured by the enterprise. However, to achieve this in the emerging sustainable business model, it was inherent to establish the relationship between the technological modernization of production and the possibility of reducing MI; this was the basis of the management algorithm for the innovative sustainable development of industrial production.

In the last decade, many researchers have concluded that sustainable business models should consider the interests of a broader range of stakeholders and society's general interests [40,41]. Thus, the task is to combine production development interests with the interests of the development of individual countries and the global economy as a whole. In 1997, in a report to the Club of Rome, E. Weizsacker et al. [42] showed that doubling society's wealth is possible using two times fewer resources. However, a universal criterion for the efficiency of material and energy resources usage is required to implement such a concept for production development practically. This universal criterion must be the same for all levels of the world economic system—the economies of particular countries, regions, industries, and manufacturing enterprises. This criterion was considered in our study [43]. It represented the maximization of the ratio of GDP to the value of the intermediate product necessary for its production at the country's economic level. The criterion was transformed into the maximization of the ratio of gross value addition (GVA) to the cost of material and energy resources (MC) at the level of industries and individual manufacturing enterprises.

Thus, maximizing the value of the above universal criteria at all hierarchy levels of economic systems is necessary to ensure sustainable environmental management through sustainable production development. But how could this be completed in practice? In our previous works [44,45], we substantiated the hypothesis of a proportional relationship between capital and material intensities during production based on the case studies of many large energy-intensive industrial enterprises' activities over ten years. Such dependencies are quantitatively expressed by the coefficient of the level of manufacturability of production (CLMP). The degree of renewal of the core enterprise's production active assets (i.e., machinery, equipment, and vehicles) increases the CLMP value. Quantitatively, the CLMP coefficient is the ratio of capital intensity to material intensity or the ratio of material output to capital output. We developed a matrix depicting possible directions for development based on an integrated study of material intensity, capital productivity changes (as the inverse of the value of capital intensity), and the corresponding change in the CLMP values. The matrix was based on the case studies of many industrial enterprises' activities for over fifteen years. The matrix showed that any industrial system (enterprise, industry, or industrial conglomerate) could develop technologically only in four directions, but two of the four directions had two possible development options. At the same time, changes in each or several trends were determined by the corresponding indicator in the form of changes in material consumption values, capital productivity, or the CLMP values in the opposite direction (Figure 1). The dynamics of the CLMP values showed the tempo of technological progress.

Material Intensity (MI)

<table>
<tr><td>Growth of MI
Reduction of CP
Reduction of the CLMP</td><td>IV-1</td><td rowspan="2">Growth of MI
Growth of CP
Reduction of CLMP</td><td rowspan="2">III</td></tr>
<tr><td>Growth of MI
Reduction of CP
Growth of CLMP</td><td>IV-2</td></tr>
<tr><td rowspan="2">Reduction of MI
Reduction of CP
Growth of CLMP</td><td rowspan="2">II</td><td>Reduction of MI
Growth of CP
Reduction of CLMP</td><td>I-2</td></tr>
<tr><td>Reduction of MI
Growth of CP
Growth of CLMP</td><td>I-1</td></tr>
</table>

Capital Productivity (CP)

Figure 1. Matrix and indicators of the technological development of industrial firms (indicators of the system's transition to the appropriate direction or a variant of the direction of technological development are highlighted in bold) [44]. MI—material intensity; CP—capital productivity; CLMP—coefficient of the level of manufacturability of production.

Then, we substantiated that it was necessary to increase the coefficient values to the maximum possible level in the corresponding period from the point of view of the impact of the achievements of technological progress in any production and economic system on production. We also developed a graphical model of the life cycle for the technological development of production systems (LCTDP) to determine the actions of these systems necessary for this impact. The LCTDP represented a graph of the development of the production system over time, in which each of the six stages of the cycle showed value changes (increases or decreases) for three interrelated indicators, namely, material productivity (MP), capital productivity (CP), and CLMP (Figure 2) [45].

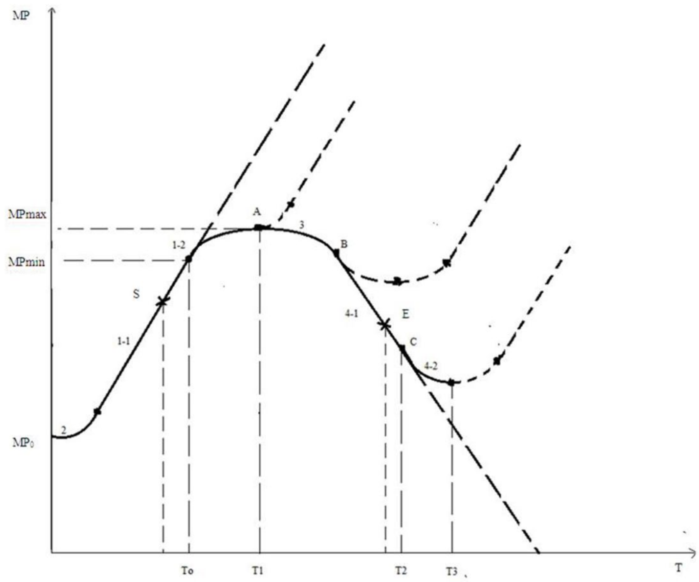

Figure 2. Life cycle graph of the technological development of production systems [45], where T is the time period. MP—material productivity; 2, 1-1, 1-2, 3, 4-1, and 4-2—life cycle stages; A—point corresponding to the maximum possible value of MP; A, B, and C—points showing the possibilities of the transition to a new technological development cycle; S—point showing the beginning of a favorable transition to a new development technology; E—point showing the necessary start of the transition to a new development technology to avoid enterprise bankruptcy; MPo—the initial level of material productivity at the enterprise during the transition to a new development technology; MPmin—the level of material productivity after which the value of the coefficient of the manufacturability level of production begins to decrease; MPmax—the maximum possible level of material productivity with the existing production technology.

Only one out of six stages was the best stage from the point of view of increasing the production resource efficiency because all three indicators increased simultaneously at this stage.

Thus, the maximum possible material use, labor, and physical capital utilization efficiency was achieved at this single technology development stage. A maximum potential profit increase could be gained from manufactured and sold products. At this stage, the technological development of production systems secures their economic stability and corresponds to the "technological stability" concept.

When there is a technological improvement, a decrease in the production MI leads to a reduction in the waste production capacity due to an increase in MP. Introducing new technology utilizes previously accumulated production waste, ensuring production's environmental sustainability. Secondly, labor productivity will significantly increase because of the maximized capital return and intensive fixed assets renewal. In addition, the enterprise and production sector's average wage growth rate will be characteristic. We can suppose that the enterprises' average wage growth rate exceeds the average industry growth rate or the country's average growth rate concurrently due to the active use of technological innovations. In this case study, part of the salary funds could be used to finance guaranteed income funds for paying the enterprises' relieved/retrenched personnel due to productivity growth. Part of this fund could also be used to support other social activities. Therefore, using part of the salary fund for the activities mentioned before will guarantee social sustainability.

Thus, economic, environmental, and social sustainability will be established simultaneously when production systems achieve technological sustainability, corresponding to the concept of "sustainable technological development".

From the LCTDP graph, it also follows that when using any production technology, an enterprise should strive to achieve the maximum possible value of the MP. In this case, the maximum reduction in material intensity will be ensured, and the maximum GVA value for each unit of the value of the goods produced by the enterprise will be achieved. According to Fige et al. [46], this state of a production system is called the achievement of an ideal sustainable value added (SVA). From the point of view of economic theory, it corresponds to the maximum possible material use, labor resources, and physical capital (fixed assets) with the use of the best production technology (BPT) for an enterprise at a specific time, i.e., it corresponds to the achievement of the limit of production capabilities.

3. Results and Discussion

3.1. Theoretical Results

The LCTDP graph shows that the maximum CLMP values will be reached at the end of stage 1-1, i.e., not until the enterprise carries out technological renewal of the active part of its fixed assets (FA). At the next stage, 1-2, the growth of the MP values will continue up to the maximum, but they are already doing so by inertia based on the use of the previously achieved potential for updating the FA. This means that it is necessary to continue timely updates to the FA by further improving the production technology to continue ensuring the technological sustainability of production. But at what point in time should it be started? From a practical point of view, it is obvious that this process must be started when the value of CLMP is at its maximum, i.e., when stage 1-1 is completed, and the transition to stage 1-2 begins when the increment in its value is equal to zero. However, the technological modernization process may be delayed with time, and the enterprise will move to other stages (3 and 4-1) where the MP will decrease. Accordingly, this point in time is determined based on the calculation of the maximum growth rate of the value of CLMP from a theoretical point of view. Of course, this will require calculating the technological development stages and the growth rate of CLMP values not once a year based on annual financial statements but quarterly or bi-annually (based on management accounting data). Ideally, such calculations should be performed at even shorter periods (up to a day or even shifts). However, this will only be possible if enterprises use cyber–physical systems to collect and transmit large data arrays, followed by processing them using Artificial Intelligence and generating averaged data for the corresponding time interval by the MP, CP, and CLMP values.

We can suppose that an enterprise in the corresponding period, which is typically at least one year, is at stage 2 of technological development. In this case, this means the beginning of mastering a new production technology when the MP is already growing but capital productivity (CP) continues to decrease due to insignificant production capacity. Accordingly, in this case, the management efforts of the enterprise are aimed at speedy access to the design capacity.

The most difficult stages for the management process are stages 3 and, especially, 4-1 for ensuring the sustainable and innovative development of production. If an energy-intensive enterprise is at stage 3 for more than one year, the effect of the MP growth due to the technological renewal of the CP has already ended. Therefore, the decline stage begins due to material resource overspending due to processing equipment wear, even if the CP continues to grow due to increased production capacity. In this case, the enterprise needs to look for options for introducing a new production technology and develop an appropriate business plan.

Suppose an enterprise has already been at the 4-1 stage of technological development for more than one year. In this case, a simultaneous decrease in the values of all three index indicators takes place, i.e., the cost of output per unit increases, which inevitably leads to a drop in total profit, and it is impossible to increase the output capacity on wornout equipment. As a result, the company loses its financial stability and rapidly moves towards a situation of financial insolvency and bankruptcy. Accordingly, the sooner the management of an enterprise realizes the inevitability of a future financial collapse, the sooner it is possible to develop and begin implementing a strategy for further production modernization on a new technological basis.

As a result, the enterprise will move to the 4-2 stage of technological development, and due to the slowdown in the rate of decrease in the MP compared to the CP, the value of the CLMP will gradually begin to increase, i.e., at the end of stage 4-1, its value will decrease to a minimum.

We can suppose that a retrospective analysis of the values of the index indicators of the sustainability of an enterprise's technological development over several years shows a downward trend in its CLMP and, especially, its MP. In this case, it is evident that the enterprise could no longer work effectively on the same technological basis. Then, it is necessary to promptly develop a strategy for further innovative development and implement the required business plans to achieve the values of the target indicators for MP, CLMP, and CP, and these values are comparable to the corresponding values at the best enterprises of the corresponding industries in the country or even in the world.

The matrix and the schedule of the housing and communal services discussed above allow us to form six levels of stability-instability for the industrial system, as well as the criteria for determining these levels (Table 1). This is very important when using the proposed methodological approach to develop criteria for assessing industrial production sustainability during the design processes, operations, and technological developments by relevant specialists.

Table 1. Criteria for assessing the level of sustainability of industrial production.

The Number of the Stage of Technological Development	Indicators of the Level of Sustainability	The Level and Dynamics of Sustainability
2	**MP increases** CP decreases CLMP increases	The increase in the level of stability
1-1	MP increases **CP increases** CLMP increases	Maximum level of stability
1-2	MP increases CP increases **CLMP decreases**	Reducing the level of stability
3	**MP decreases** CP increases CLMP decreases	Increasing the level of instability
4-1	MP decreases **CP decreases** CLMP decreases	Maximum instability level
4-2	MP decreases CP decreases **CLMP increases**	Reducing the level of instability

Changes in the values of one of the three indicators for each stage are highlighted in bold, indicating a transition to the appropriate level of stability or instability.

The value of the CLMP could be considered as a measure of the effectiveness of the open technological innovation embodied in the production processes of enterprises, which could be in the form of new machines and equipment, if only the volumes of fixed assets are used when calculating the return on capital, which is typical, for example, for Russian industrial enterprises. Accordingly, when considering the impact on the production efficiency of open "disembodied" technological innovations [47] in the form of knowledge acquired by firms, such as patents, licenses, and software, that form the basis of their intangible assets, we could calculate the overall efficiency coefficient of materialized, i.e., in the form of main productivity, and "disembodied" technological innovations instead of CP. Moreover, we can suppose that the enterprises themselves carry out research and development (R & D). In this case, they would use "closed" technological innovations, and then an integral coefficient could be calculated that takes into account the impact on the production efficiency of technological innovations of all kinds. In this case, it is possible to determine the share of influence on the effectiveness of the technological innovations and on the industrial system's stability level of each type of innovation.

In [48], we showed that the efficiency of a separate production technology or separate technological process could be determined by computing the CLMP value as the ratio of the depreciation costs from the machinery and equipment costs to the material costs used in the technology or process for the corresponding period. Such a coefficient (CLMP) measures the efficiency of open future materialized innovation. However, an enterprise's intangible assets, such as acquired knowledge, are also utilized by the enterprise for a long period and have depreciative value. In this case, the corresponding coefficient, as the ratio of the depreciation cost deduction from the intangible asset to the material cost coefficient, will indicate the enterprise's effectiveness using open future innovations in a disembodied form (i.e., acquired knowledge). We could use such an indicator to appraise innovation effectiveness in an enterprise's activity dynamics. We could also use the indicator to compare the level at which different enterprises have utilized such innovations. Moreover, increased use of firms' intellectual property signifies an increase in the technology knowledge intensity of an enterprise. This fact could currently leverage the position of an enterprise in the competition in its field. By following this approach, a quantitative assessment of the production technologies' knowledge intensity could be derived as a fraction of the coefficient mentioned above in the gross value of the coefficient of the level of manufacturability of production (CLMP). The coefficient could be determined as the ratio of the depreciation deductions from the intangible assets, machinery, and equipment costs to the material costs. At the same time, the value of such a generalized indicator could be a measure for evaluating the effectiveness of utilizing all open incoming innovations, i.e., innovations in materialized and disembodied forms. Consequently, it is possible to determine the stability and dynamics of this change for different technologies or technological processes when applying the coefficient in industrial systems.

Suffice it to say that up to 50% or more of an industrial enterprise's production costs are material costs (MC), i.e., the costs relate to raw materials, fuel, and energy. Consequently, energy costs are the main portion of material costs. Energy saving is a priority task that innovative developments introduced into production should solve. Therefore, it is desirable to have indicators whose values would exhibit their effectiveness, on the one hand, and their respective impact on the sustainability level of industrial production, on the other hand. In our opinion, such an indicator could be an indicator that is the converse of the CLMP indicator; it should be the ratio of the partial proportion of the gross material costs (only energy costs) to the depreciation costs in the total production costs and sale of products [49]. We could use this ratio to determine the depreciation costs separately for raw materials and refined materials if it is necessary to save on the costs of raw materials and refined materials. We can suppose that the enterprise reflects the division of all material costs for raw materials, fuel, and energy in the notes in the financial statements. In such a case, the indicators mentioned above could be dynamically used in an external economic analysis of the activities of the enterprise.

Enterprises could use the production cost calculation for individual components of the technological process (types of production activities) to make management decisions about introducing innovative developments and their impacts on the changes in the sustainability level. In such cases, it is possible to calculate the ratio of each element of material costs (types of raw materials, refined materials, fuel, and energy) to the depreciation costs before and after introducing the innovative developments. This ratio could be calculated in terms of the cost of material resources and in kind since all the necessary data are available in the cost calculation for this matter.

3.2. Practical Results

We used the sustainability assessment methodology presented above to appraise the sustainability levels of several dozen large energy-intensive industrial enterprises. Table 2 shows appraisal results of the ten-year (2011–2020) activities of large metallurgical enterprises in different countries, namely, PJSC "Norilsk Nickel" (Russia), PJSC "Severstal" (Russia), Boliden AB (Sweden), and Freeport-McMoRan Inc (USA). We acquired the initial data required for an appraisal from each company's annual financial statements on their websites [50–53]. Table 2 shows the calculated MP and CP values for each enterprise.

Table 2. Dynamics of the three sustainability indicators for the technological development of large energy-intensive enterprises.

Indicator	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
PJSC "Norilsk Nickel"										
MP	5.51	4.16	3.95	4.96	5.35	4.68	3.59	3.99	4.86	3.94
CPin	2.02	1.54	1.28	1.47	1.50	1.34	1.35	1.59	2.35	2.34
CLMP(in)	2.73	2.71	3.10	3.38	3.56	3.50	2.66	2.51	2.07	1.68
Life cycle stage	-	IV-1	IV-2	I-1	I-1	IV-2	III	I-2	I-2	IV-1
PJSC "Severstal"										
MP	1.44	1.51	1.53	1.65	1.85	1.73	1.62	1.62	1.45	1.60
CPin	2.62	2.05	1.84	1.83	2.02	2.07	2.37	2.53	2.42	1.97
CLMP(in)	0.55	0.74	0.83	0.90	0.92	0.84	0.68	0.64	0.60	0.81
Life cycle stage	-	II	II	II	I-1	III	III	III	IV-1	II
Boliden AB										
MP	1.74	1.74	1.76	1.85	1.86	2.27	2.27	2.23	2.35	2.20
CPin	0.91	0.81	0.64	0.64	0.68	0.57	0.66	0.63	0.54	0.59
CLMP(in)	1.92	2.14	2.73	2.88	2.75	3.95	3.46	3.53	4.33	3.74
Life cycle stage	-	II	II	II	I-1	IV-1	I-1	IV-1	II	II
McMoRan Inc										
MP	2.11	1.73	1.77	1.93	1.48	1.39	1.60	1.59	1.25	1.42
CPin	0.80	0.61	0.61	0.57	0.39	0.41	0.44	0.26	0.20	0.19
CLMP(in)	2.62	2.86	2.89	3.37	3.76	3.36	3.61	6.07	6.36	7.47
Life cycle stage	-	IV-2	I-1	II	IV-2	III	I-1	IV-2	IV-2	II

MP—material productivity; CPin—initial capital productivity value; CLMP(in)—initial CLMP.

The CP was determined in three versions, i.e., by the initial (CPin) and residual (CPres) values of the total fixed assets and by the initial cost of only machinery and equipment. In addition, the CLMP values were calculated as the ratios of MPs to CPs based on the initial costs of the total fixed assets (FA). Accordingly, the LCTDP levels were determined based on the value changes in the three indicators (increases or decreases) in any year relative to the previous year.

We divided all the figures explaining the practical use of this methodology into three groups. The first group corresponded to the MP and CP value trends, calculated in three variants for all four enterprises, as shown in Figures 3–6.

Firstly, Figures 3–6 show that the MP and CP value trends had similar directions, i.e., a proportional relationship existed between the MP and CP. Secondly, this dependence mentioned before exists for any CP calculation option.

The second group corresponded to each enterprise's graphs (Figures 7–14), representing the CLMP value dynamics computed based on the initial cost of the total fixed assets and the initial cost of machinery and equipment alone. The trends in the total values for Ktotal are described and the calculations took into account the values of not only "materialized" open technological innovations in the form of fixed assets but also "nonmaterialized" open technological innovations. The "nonmaterialized" open technology innovations (e.g., patents, licenses, and computer programs) were in the form of intangible assets (IA) and closed technological innovations were in the form of the research and development costs (R&D).

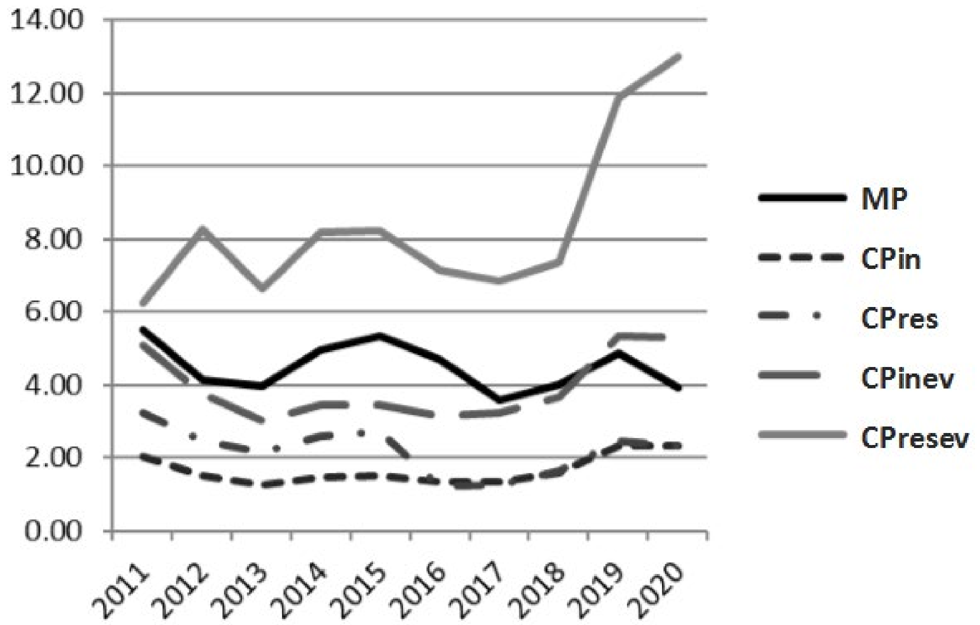

Figure 3. Material and capital productivity value dynamics for the PJSC "Norilsk Nickel". MP—material productivity; CPinev—indicator calculated based on initial CP values of machinery and equipment; CPresev—indicator calculated based only on the residual cost of the machinery and equipment.

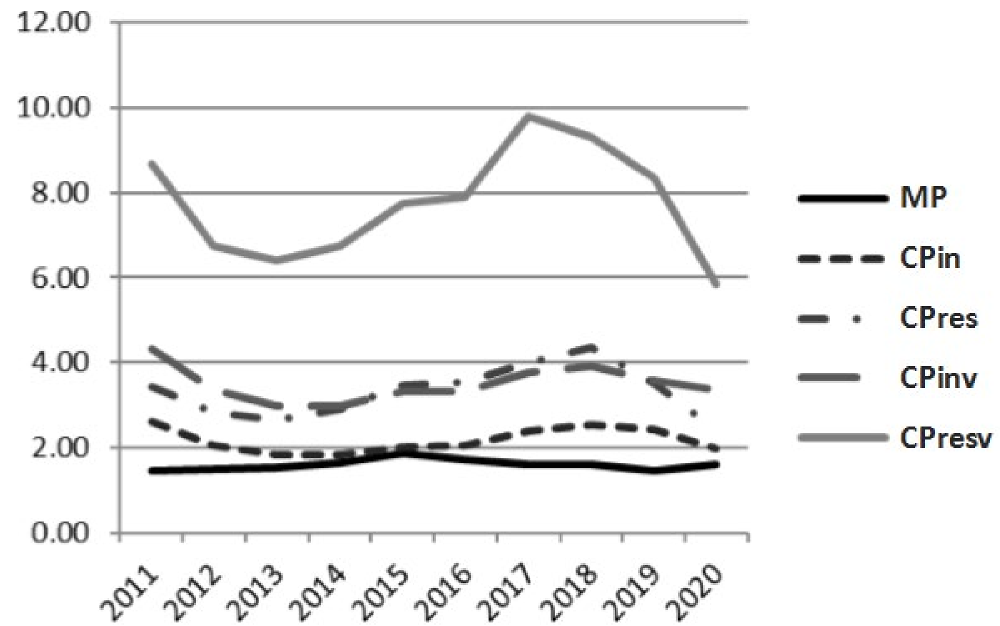

Figure 4. Material and capital productivity value dynamics for the PJSC "Severstal". MP—material productivity; CPinev—indicator calculated based on initial CP values of machinery and equipment; CPresev—indicator calculated based only on the residual cost of the machinery and equipment.

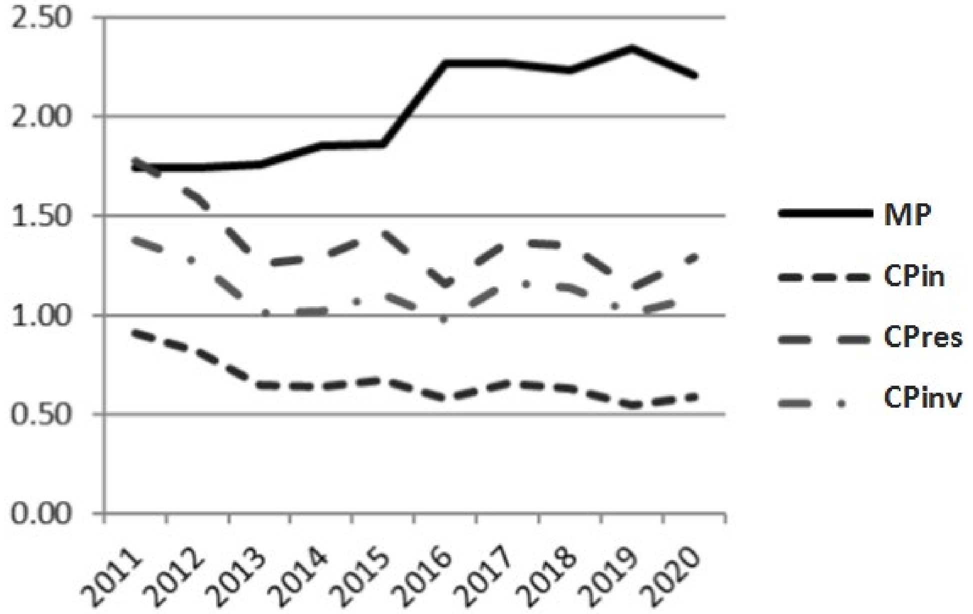

Figure 5. Material and capital productivity value dynamics for Boliden AB. MP—material productivity; CPinv—indicator calculated based on initial CP values of machinery and equipment.

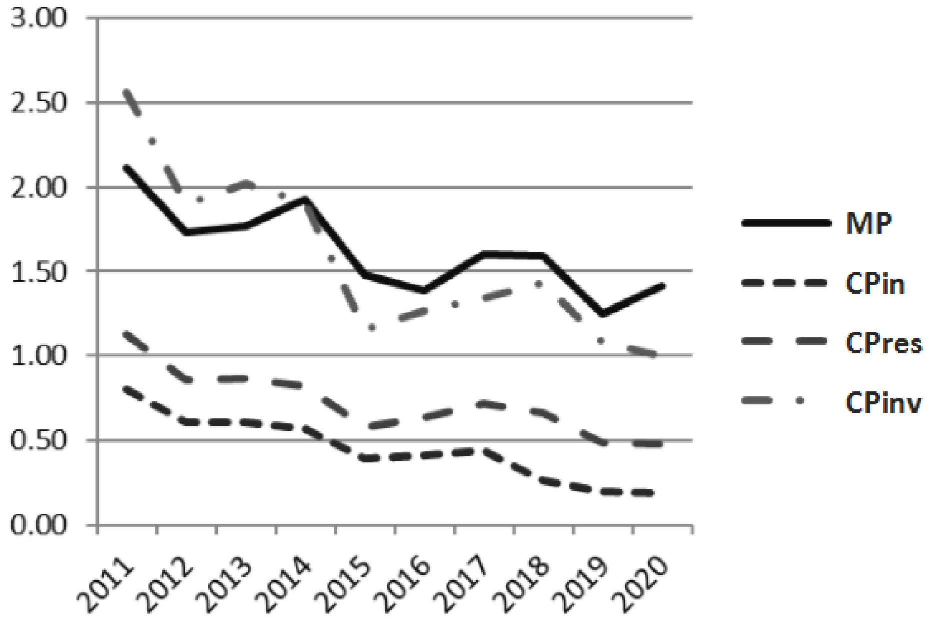

Figure 6. Material and capital productivity value dynamics for Freeport-McMoRan Inc. (Phoenix, AZ, USA) MP—material productivity; CPinv—indicator calculated based on initial CP values of machinery and equipment.

From a comparative analysis of the enterprises' graphs, we could conclude that the CLMP and Ktot values tended to increase for all the enterprises. However, this trend was more pronounced for the last two enterprises primarily due to their more active renewal of fixed assets. Secondly, CLMP_fa and CLMPv exhibited similar trends, meaning that the share of the machinery and equipment in the total fixed assets (FA) value remained constant. Thirdly, the CLMP and Ktot value changes were practically the same in the graphs. This means that the shares of intangible assets and R&D costs relative to the fixed asset costs remained insignificant. However, it was still essential to assess the impact of each of these values on the MP. Accordingly, the third group of figures (Figures 15–18) shows the changes in the coefficients of the intangible assets (K_ia) and R&D costs (K_rd) for all four enterprises.

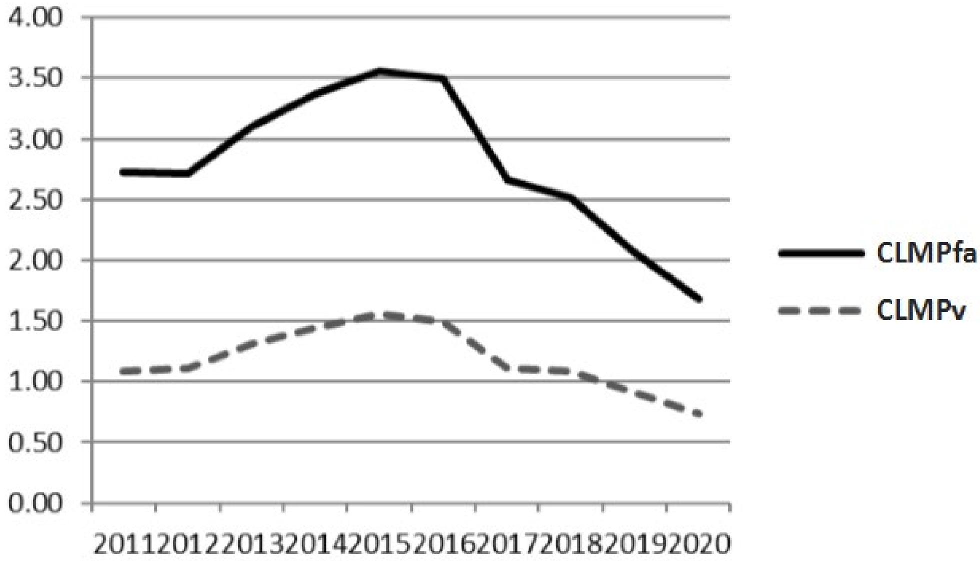

Figure 7. CLMP value dynamic for the PJSC "Norilsk Nickel". CLMPfa—CLMP based on total fixed assets; CLMPv—CLMP based on total cost of machinery and equipment.

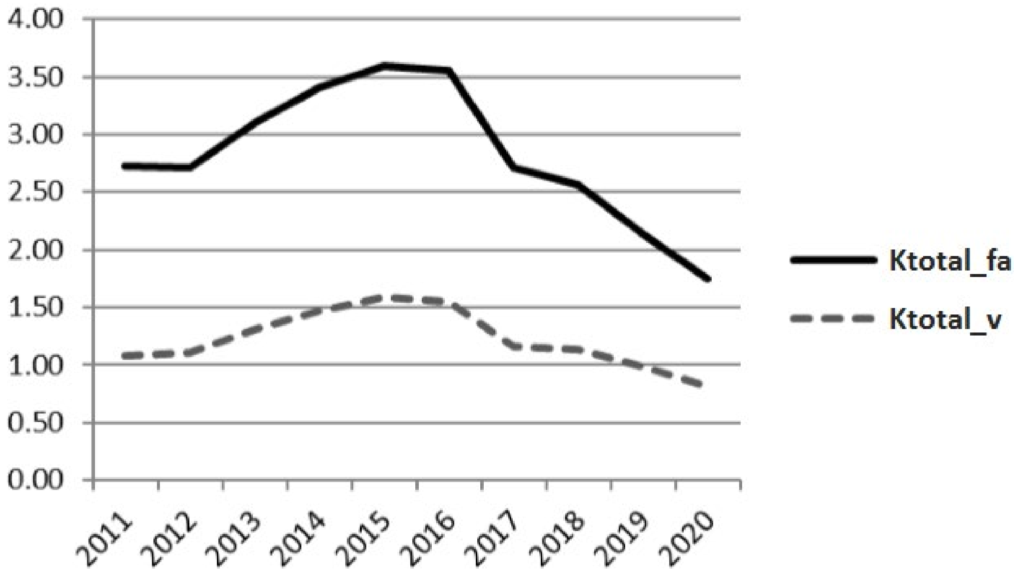

Figure 8. Ktotal value dynamics for the PJSC "Norilsk Nickel". Ktotal_fa—Ktotal for the total fixed assets; Ktotal_v—Ktotal for the total cost of machinery and equipment. Ktotal_fa and Ktotal _v were calculated based on the initial fixed assets, intangible assets, and R&D costs.

From Figure 18, it could be assumed that the downward trend in the MP values for Freeport-McMoRan Inc. was associated with a significant decrease in its R&D expenses. An increase in such expenses at Boliden AB corresponded to the rise in MP values (Figure 17). This conclusion was also confirmed by Figures 15 and 16, which show the absence of K_rd growth trends for the PJSC "Norilsk Nickel" and the PJSC "Severstal". Accordingly, there was practically no growth in the MP at these enterprises.

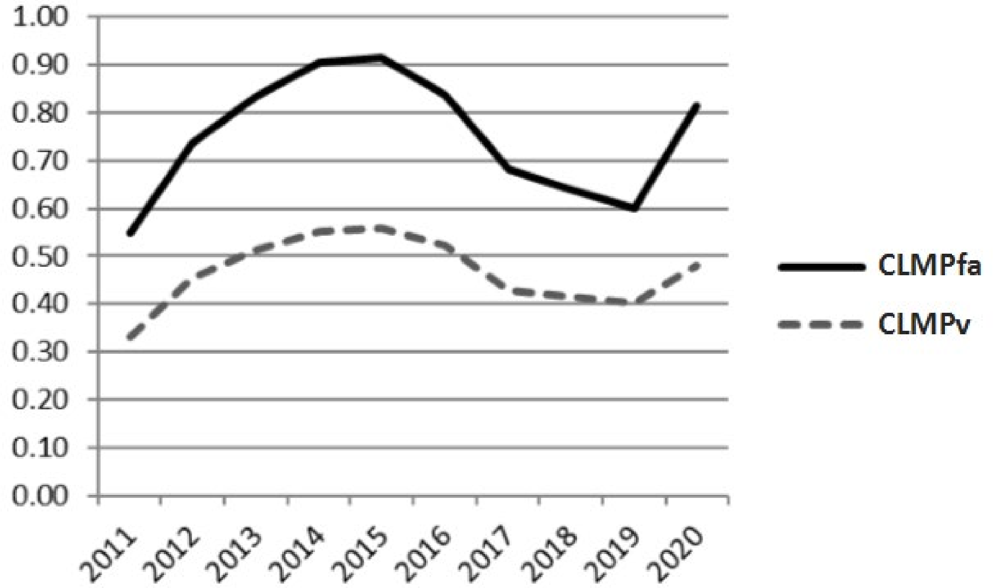

Figure 9. CLMP value dynamic for the PJSC "Severstal". CLMPfa—CLMP based on the total fixed assets; CLMPv—CLMP based on the total cost of machinery and equipment.

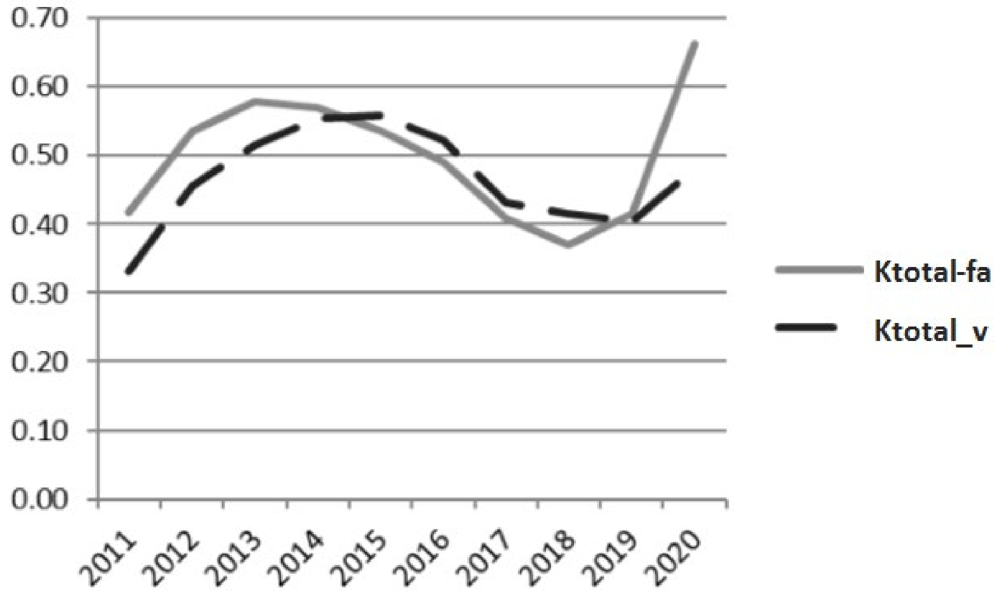

Figure 10. Ktotal value dynamics for the PJSC "Severstal". Ktotal_fa—Ktotal for the total fixed assets; Ktotal_v—Ktotal for the total cost of machinery and equipment. Ktotal_fa and Ktotal _v were calculated based on the initial fixed assets, intangible assets, and R&D costs.

The general conclusion regarding the sustainability of technological development for the four enterprises considered as case studies following the graphical model of the LCTDP and the criteria table for assessing the sustainability of industrial production was as follows: Boliden AB steadily developed over ten years since it had a prolonged period (seven years) in which its technological development stage corresponded to different levels of sustainable development (stage 1-1 for two years and stage 2 for five years). However, its technological production capacity was not fully achieved over ten years. Accordingly, the possibilities for increasing its MP and CP values were not fully used.

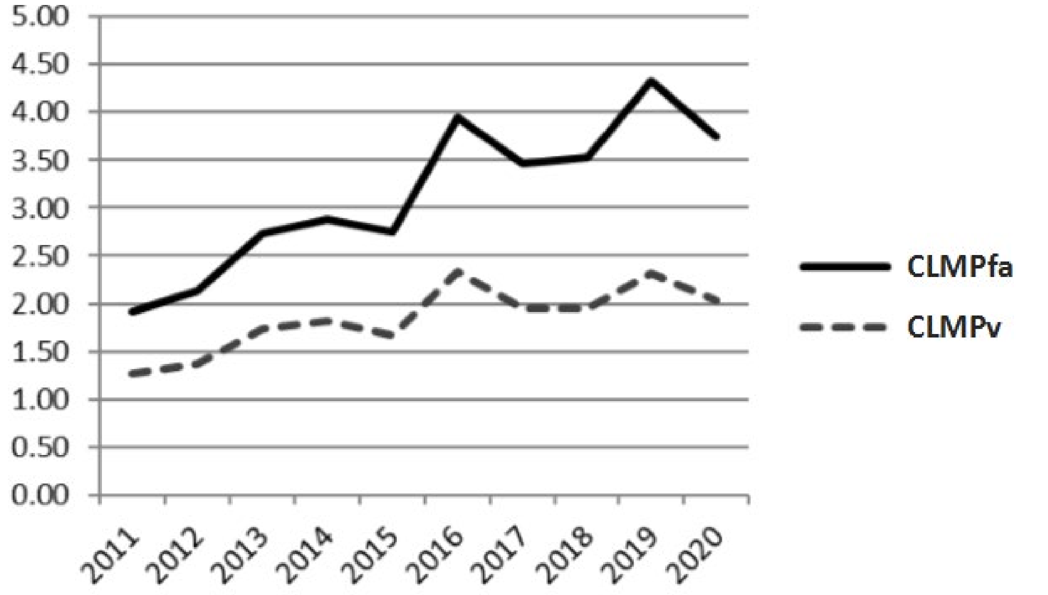

Figure 11. CLMP value dynamic for Boliden AB. CLMPfa—CLMP based on the total fixed assets; CLMPv—CLMP based on the total cost of machinery and equipment.

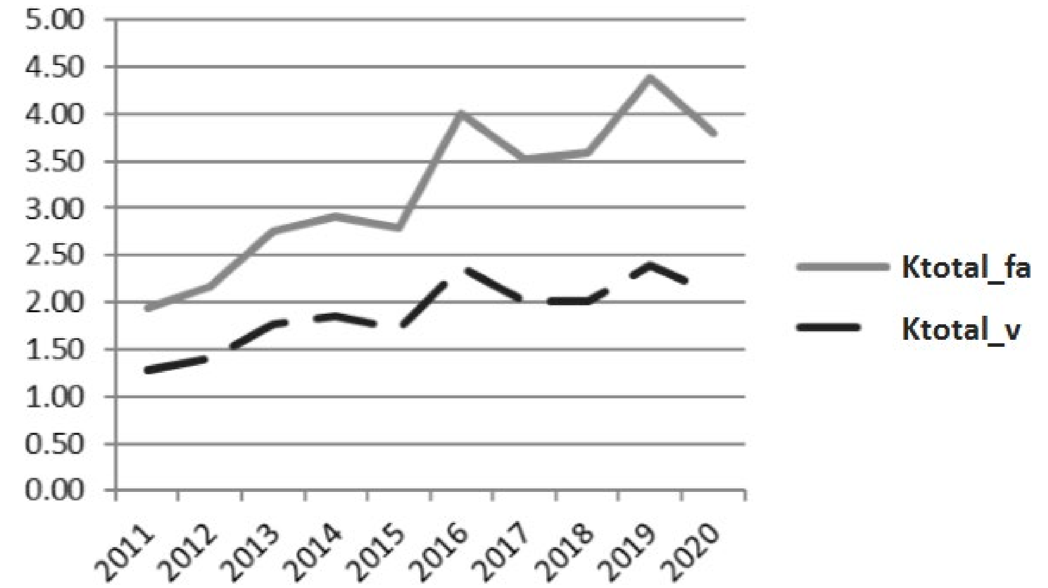

Figure 12. Ktotal value dynamics for Boliden AB. Ktotal_fa—Ktotal for the total fixed assets; Ktotal_v—Ktotal for the total cost of machinery and equipment. Ktotal_fa and Ktotal _v were calculated based on the initial fixed assets, intangible assets, and R&D costs.

Thus, the methodology presented in this paper for evaluating the sustainability of energy-intensive industrial production could be practically used to determine the sustainability level of an individual enterprise. This methodology could also be used to compare the sustainability level across several enterprises, if necessary. This methodology is sufficient for various stakeholders to use for performing an external economic analysis using an enterprise's public financial statements.

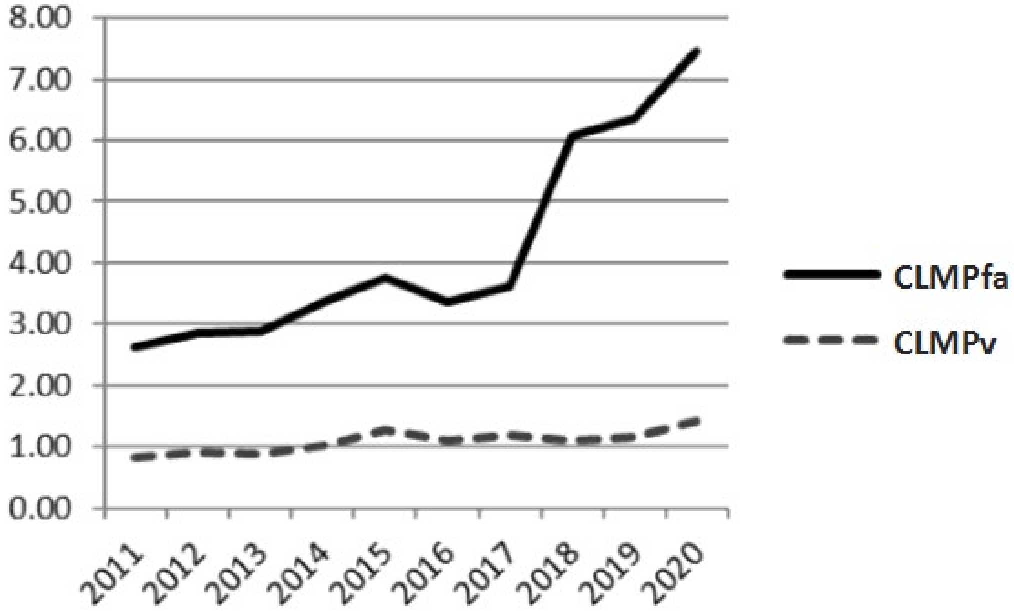

Figure 13. CLMP value dynamic for Freeport-McMoRan Inc. CLMPfa—CLMP based on the total fixed assets; CLMPv—CLMP based on the total cost of machinery and equipment.

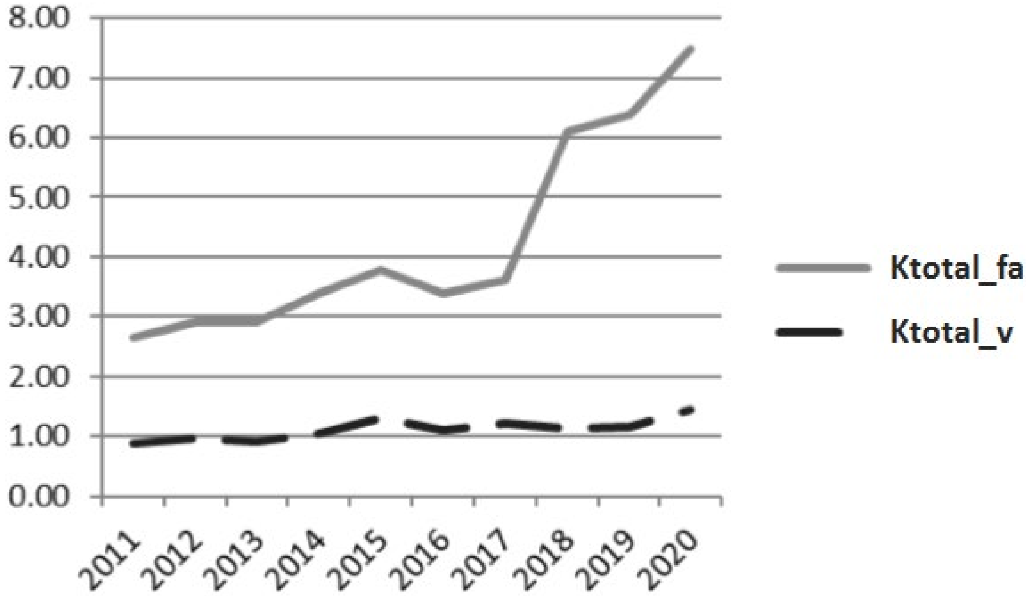

Figure 14. Ktotal value dynamics for Freeport-McMoRan Inc. Ktotal_fa—Ktotal for the total fixed assets; Ktotal_v—Ktotal for the total cost of machinery and equipment. Ktotal_fa and Ktotal _v were calculated based on the initial fixed assets, intangible assets, and R&D costs.

The limitation of this approach could be its inability to consider the price factor, i.e., the annual increase rates for the raw materials, refined materials, fuels, and energy costs. This is because constituent material and energy costs may differ from machinery and equipment costs as constituents of fixed assets. Subsequently, the computed annual CLMP values could emerge as being less than the actual values. However, trends in changes in stability level over a long period are of greater importance in an external analysis, and they will be less sensitive to the influence of the price factor. However, we can suppose that an internal analysis of a particular enterprise's activities is performed. In this case, the price factor is leveled-out since it is possible to consider the annual price changes for individual constituent materials and energy constituents, as well as for fixed assets constituents. In the future, we plan to further develop the model considered in this article to evaluate the sustainable impact on a particular technological process's environment that enables reductions in the waste quantities generated from its energy-intensive production.

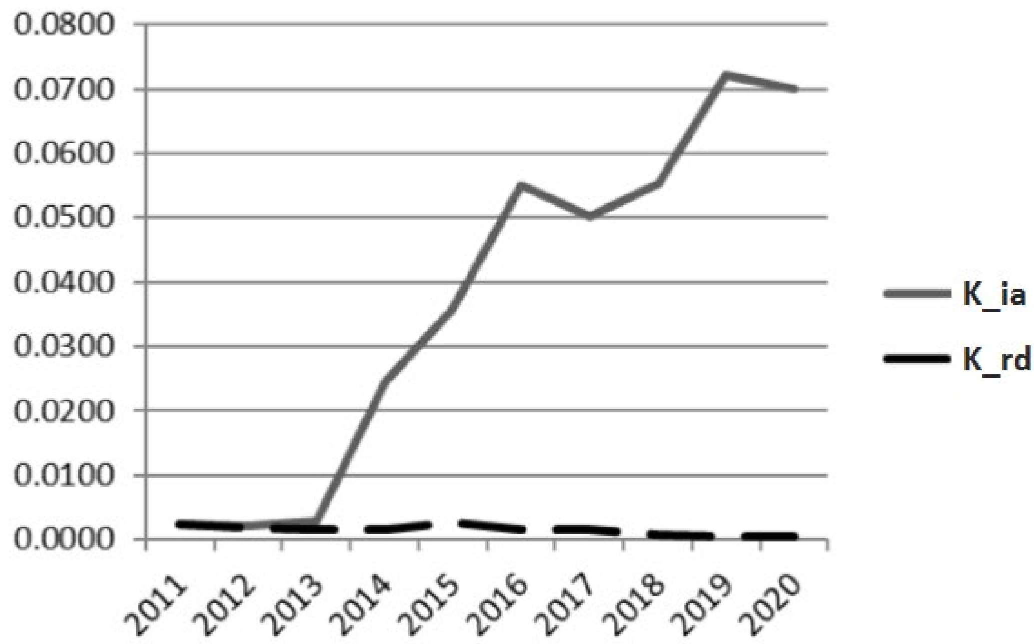

Figure 15. Coefficients of the intangible assets (K_ia) and R&D costs (K_rd) for the PJSC "Norilsk Nickel".

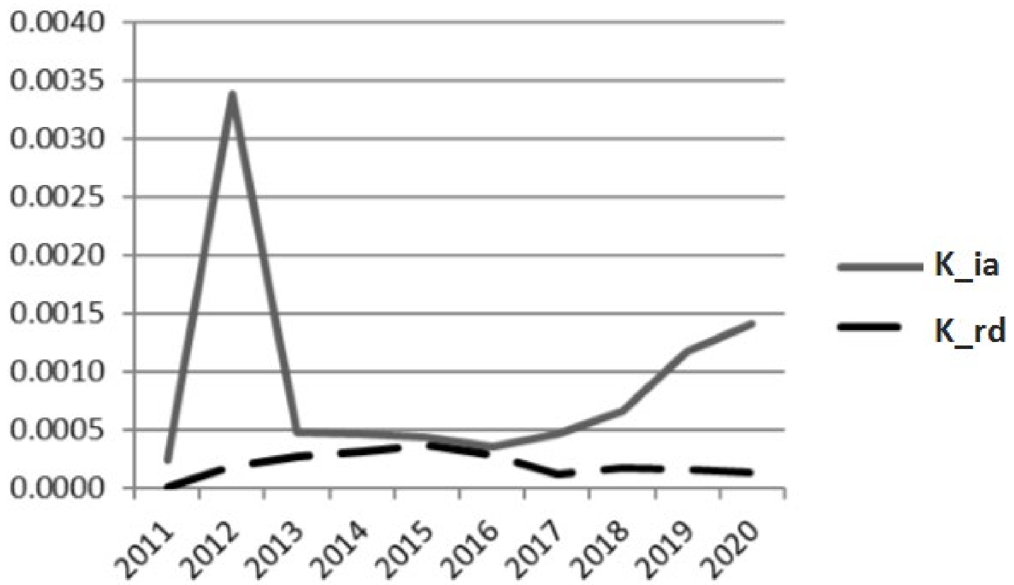

Figure 16. Coefficients of the intangible assets (K_ia) and R&D costs (K_rd) for the PJSC "Severstal".

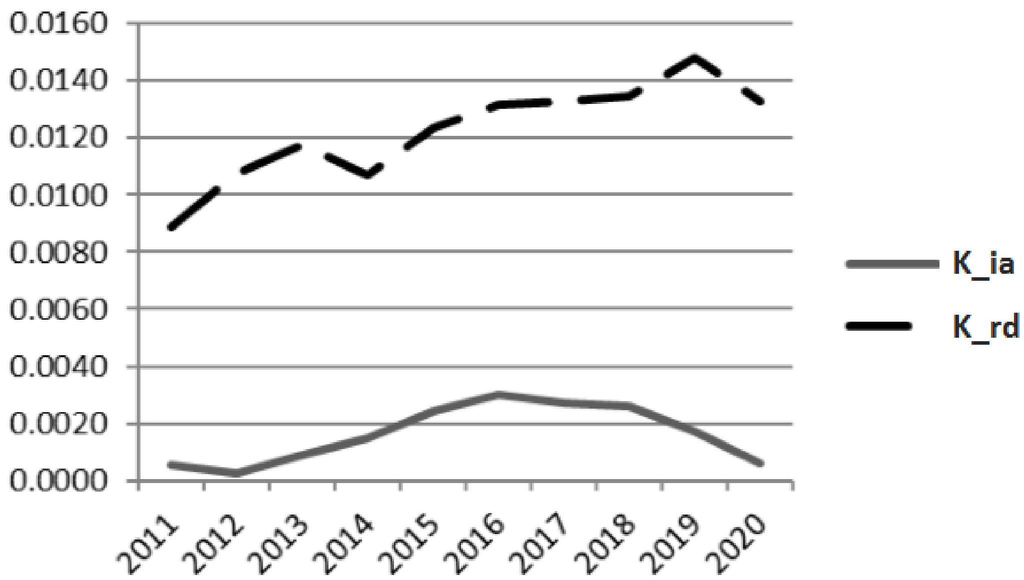

Figure 17. Coefficients of the intangible assets (K_ia) and R&D costs (K_rd) for Boliden AB.

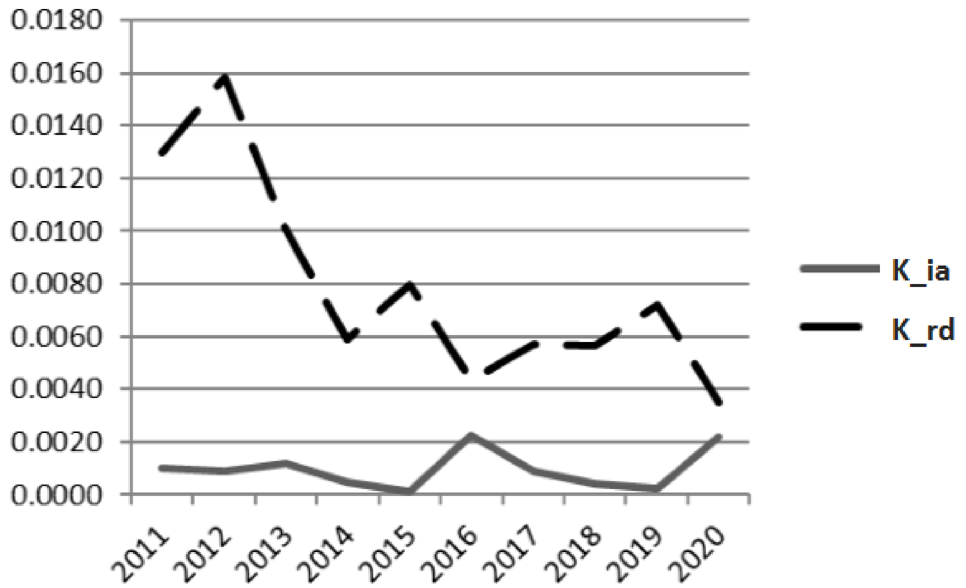

Figure 18. Coefficient of the intangible assets (K_ia) and R&D costs (K_rd) for Freeport-McMoRan Inc.

4. Conclusions

1. It was shown that resource and energy efficiencies are the main factors in the sustainable socio-economic development of industrial production.
2. A new methodology for the criteria formation for assessing the sustainability of energy-intensive industrial production was proposed based on an integrated combination of the economic, environmental (ecological), and social aspects of sustainable development.
3. It was established that in order to ensure sustainable innovative development, any energy-intensive chemical, metallurgical, and energy production processes should maximize the values of material output and value addition in the products manufactured by the enterprise.

4. The indicators were justified indicators that determined the levels of sustainability and their dynamics for the enterprise as a whole, as well as for the dynamics for the individual production technologies and individual technological processes.

Using a graphical model of the life cycle of technological development of existing production, a scientifically based procedure was proposed for making management decisions to ensure the sustainability of energy-intensive industrial production. The proposed scientifically based procedure uses the technological renewal of fixed assets and/or technological modernization, as well as ways to ensure the intensification of resource and energy efficiency, together with the environmental safety of technological processes.

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