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FROM ENERGY INTENSITY TO SUSTAINABILITY: AN ANALYSIS OF TRENDS IN THE ALUMINIUM INDUSTRY

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Abstract
The article analyses trends in the aluminium industry from the point of view of sustainable development and energy efficiency. The significant impact of industrial enterprises on the environment is discussed, particularly, the high level of greenhouse gas emissions caused by energy consumption in aluminium smelting. Possibilities of reducing the negative impact due to the use of renewable energy sources, such as hydropower, as well as the implementation of energy-efficient practices, have been identified. A taxonomic analysis was used to assess the sustainable development of aluminium enterprises due to its advantage in identifying problems and directions for production improvement. The proposed method of analysis is based on the system of factors that influence the development of the industry and correspond to the concept of sustainable development. Based on the available data of the International Aluminium Institute (IAI), the analysis was carried out using the following factors: economic (volume of production, energy intensity of primary aluminium smelting, total energy consumption of production, labour productivity, impact of energy intensity on emissions), environmental (emissions of greenhouse gases and energy consumption of aluminium smelting using different energy sources), social (million hours reported worked, lost time accident rate, restricted work/medical treatment accident rate). Approbation of the proposed methodology on the example of international statistical data makes it possible to determine the biggest gaps in ensuring the sustainable development of aluminium industry production, including the use of various energy sources. Based on the results of the analysis, it was found that none of the factors used in monitoring the activities of aluminium producers reach the reference values. In the block of economic factors, the taxonomic indicator varies between 0.18 and 0.38 (the worst efficiency is observed in terms of total production volumes). Environmental factors have taxonomic values in the range of 0.07–0.36 (the largest reserves exist in ensuring the efficiency of energy consumption using hydropower, as well as reducing greenhouse gas emissions in the process of primary aluminium production). Among the social factors, the biggest problems are labour safety and lost working hours; as a result, the taxonomic indicator for this block is in the range of 0.04 - 0.33. The obtained results indicate the need for constant improvements in the production of aluminium, which is one of the main producers of greenhouse gases due to the high energy intensity of production. The proposed approach for conducting an analysis can be improved depending on the available statistical data and the goals of the analysis. In any case, it is valuable for obtaining information on the most critical areas in supporting the sustainable development of the industry.
KEY WORDS: sustainable development, aluminium industry, energy efficiency, greenhouse gas emissions, taxonomic analysis.
JEL classification: C43, L61, O13.

Introduction

Aluminium production belongs to the sectors of the economy with a stable demand for products However, considering growing volume of production the environmental problems of the industry remain within the area of sustainable development. Despite projected efforts to reduce emissions by approximately 80%, demand for aluminium products is also expected to grow. Global demand for primary aluminium will increase by up to 40% in the coming decades, and aluminium scrap recycling will more than triple by 2050. Such forecast estimates are based on the constant development of the economy and industries that actively use aluminium in their own production, as well as active urbanization and infrastructure development (Haraldsson et al., 2021).

Industrial enterprises have a significant environmental footprint due to the large total volumes of production. This reduces their positive contribution to the economy and social stability. This sector is the dominant consumer of energy and producer of greenhouse gases. Almost 70% of emissions during aluminium production are caused by electricity consumption during smelting. This process accounts for about 4% of global electricity consumption, with up to 70% of electricity coming from fossil fuels (mainly coal) and the remaining 30% from renewable sources, mainly hydropower (WEF, 2023).

On the other hand, such data highlight the enormous potential of foundries worldwide to achieve sustainable development. Implementation of energy-efficient practices is a winning strategy for realizing sustainable energy in energy-intensive industries (Prashar, 2019). In addition, the use of sustainable development goal reporting based on sustainable energy indicators helps foundries to reduce stakeholder risks and establish their identity in the global marketplace.

Considering the importance of the aluminium industry in the economy, as well as the existing intra-industry problems of its development (primarily energy efficiency and environmental impact), an urgent scientific and applied task is to identify opportunities for improving management in this industry based on the principles of sustainable development. Considering this, the purpose of our study is to assess trends in the aluminium industry and identify current opportunities to ensure its sustainable development.

To achieve the goal, the method of taxonomic analysis was applied. Its advantages comparing to other methods of analysis of the certain processes and systems development, are in possibilities for determining gaps in the achievement of reference values.

Theoretical background

Sustainable development has a growing scientific interest, which is confirmed by the increasing number of studies devoted to various aspects in the field. Significant contribution to investigation the sustainable development issues connected with industrial development is done by G. Brundtland with her work "Our Common Future" (Brundtland, 1987), T. Jackson (2016) with the model of green economy (Jackson, 2016), J. Elkington with the concept of three pillars of sustainable of development, where sustainable development was first clearly defined in the unity of three components (economic, social, environmental) (Elkington, 1994), as well as J. Sachs, who summarized the problems in the process of complex choices faced by states when trying to simultaneously achieve three key goals: economic growth, social justice and environmental sustainability (Sachs, 2015). In addition, the researcher singled out the fourth mandatory element - managerial. Its importance was proven with the conclusions that to ensure the quality characteristics of political institutions and decisions made by the government, it is necessary to make quality state decisions, which can be of decisive importance in the implementation of specific goals and objectives of long-term development (Sachs, 2015). The findings on institutional quality importance are aligned with recent studies in the field (Mukhtarov et al., 2023).

Current research indicates the importance of sustainable development in light of ecological footprint leading to climate change (Ojaghlou & Uğurlu, 2023) and the necessity for constant development of corporate social responsibility in energy consumption (Kontautienė et al., 2024).

One of the main challenges researchers faced is finding a balance between qualitative and quantitative approaches in assessing sustainable development. The use of taxonomic analysis makes it possible to achieve this balance through the creation of synthetic indicators of the effectiveness of the evaluated measures. These indicators are called synthetic indexes or taxonomic indicators. The biggest difficulty in creating them is determining the elements that should be included and assigning them the appropriate rank (Jędrzejczak-Gas et al., 2021).

Therefore, the development of appropriate synthetic indicators remains an urgent research problem. Existing indicators need to be verified and updated considering new concepts of assessing the level of economic development, available statistical and experimental data. This will allow creating a more complete picture of the effectiveness of implemented measures in the context of sustainable development.

Examples of the application and methodology of the taxonomic analysis of economic processes, suitable for the purposes of our study, can be found in the works of Debbarma & Choi (2022) and Jędrzejczak-Gas et al. (2021). These works use complex approach to the analysis of sustainable development combining qualitative and quantitative indicators. Cheba & Bąk (2019) emphasize that one of the most common mistakes in sustainable development research is the analysis of a set of characteristics describing this development. Particularly, the problem may lie in the insufficient consideration of sustainable development factors as well as the insufficient correspondence of the selected indicators to the changes occurring in each sustainable development direction. Therefore, the stage of selecting indicators for analysis is very important.

Methodological principles and cases of using taxonomic analysis to improve the management of industries with a significant ecological footprint are well described in studies of transport activities (Czech & Lewczuk, 2016; Gružauskas & Burinskienė, 2022), wind energy (Chudy-Laskowska et al., 2020), innovative business development (Oliinyk et al., 2023) and circular economy in general (Kasztelan, 2020; Oyeranmi & Navickas, 2023). Even though the technique of taxonomic analysis is known, in its application there are still "main questions: (1) what to measure, (2) where to measure, and (3) how to measure" (Fraccascia & Giannoccaro, 2020).

One of the most ubiquitous issues in taxonomic analysis is the selection of a system of indicators suitable for further application and decision-making based on the performed analysis (Law et al., 1998). In the foundry industry, particularly, in aluminium production, the problem is the availability of initial data. At the same time, it is important to have relevant key performance indicators and information on final energy consumption for energy efficiency and greenhouse gas reduction decisions (Haraldsson et al., 2021; Saevarsdottir et al., 2021). And if at the company level this is not a problem, the analysis at the industry level is complicated by the reluctance of companies to disclose their information. However, energy efficiency research is important for the realization of the "2050 net-zero scenario", which is actively supported by scientists (Browning et al., 2023; Dafnomilis et al., 2023; Johnson et al., 2023) in the light of discussions on green deal, sustainable development goals achieving and transition to carbon-neutral society (Mishchuk et al., 2023; Olzhebayeva et al., 2023; Pinczynski et al., 2024; Zhang et al., 2024). Especially it has sense in industries that use critical materials, including aluminium (Liang et al., 2023).

Methods

To analyse the tendencies in aluminium production industry alongside with energy intensity the data of the International Aluminium Institute (IAI) were used (International Aluminium, 2024a) for the available period of 2019 – 2023. Data are analysed using traditional approach of dynamic analysis. The data are grouped according to IAI approach by the regions of world representing aluminium producers.

To find the problems of energy efficiency and sustainable development of aluminium production, we use taxonomic analysis.

Its implementation involves the following stages:

1) formation of a matrix of initial data for the research;

2) standardization of matrix values (the studied indicators);

3) division of the studied indicators into stimulators and de-stimulators;

4) formation of a standard vector for the development of each functional component of the system;

5) determination of the distance between individual variables and the reference vector;

6) calculation of the taxonomic indicator of system development.

A detailed description of the procedures for the above stages is well-described by Czech & Lewczuk (2016), Chudy-Laskowska et al. (2020), Oliinyk et al. (2023).

Standardisation of initial data is carried out according to the formula:

$$z_{ij} = \frac{x_j - x_{ij}}{s_j}, j = 1, 2, \dots, m; \quad (1)$$

where x_{ij} — is an arithmetic mean value of the j-th indicator;

s_j — standard deviation of the j-th indicator;

x_j— value of the j-th indicator for the i-th object.

m — number of indicators.

Grouping of values as stimulators and de-stimulators is the basis for building a developmental etalon - reference point with coordinates:

$$P_0 = (z_{01}, z_{02}, \dots, z_{0m}) \quad (2)$$

where $z_{0s} = \max z_{rs,}$ if $s \in I$;

$z_{0s} = \min z_{rs,}$ if $s \notin I$; $s = 1, \dots, m$);

I — set of values;

z_s — the standardized value of feature s for object r.

Construction of the distance (c_{io}) of the value of each indicator to the reference point (P_0)

$$c_{io} = \sqrt{\sum_{j=1}^{m} (Z_{ij} - Z_{oj})^2} \quad (3)$$

The calculated distances are input values used to calculate the indicator of the level of development:

$$d_i^* = 1 - \frac{c_{io}}{c_o} \quad (4)$$

where

$$c_0 = \bar{c_0} + 2 * S_0 \quad (5)$$

$$\bar{c_0} = \frac{1}{w}\sum_{i=1}^{w} c_{i0}; \quad (6)$$

$$S_0 = \sqrt[2]{\frac{1}{w}\sum_{i=1}^{w}(c_{io} - \bar{c_0})}. \quad (7)$$

The set of indicators for the taxonomic analysis was carried out according to the logic of the analysis of sustainable development, with the isolation of the "economic", "ecological", "social" blocks. At the same time, the limitations regarding the availability of statistical data regarding the aluminium industry were considered.

Data on the development of the industry for 2019 - 2022 in the world are retrieved from International Aluminium (2024a, b, c), Aluminium Stewardship Initiative (2024) (Table 1).

Table 1. Initial data for taxonomic analysis of the aluminium industry development

Indicators	Measures	Notation
Economic		
Production volume	thousand tons	X_1
Energy intensity of primary aluminium	kilowatt-hours per ton of aluminium	X_2
Total energy consumption of production	GW-hours	X_3
Labour productivity	tons per mil. of man-hours	X_4
Indicator of the influence of energy intensity on CO_2 emissions	coefficient	X_5
Ecological		
Energy consumption of primary aluminium smelting:	GW-hours	
- hydro	GW-hours	X_6
- other renewables	GW-hours	X_7
- other non-renewable	GW-hours	X_8
- coal	GW-hours	X_9
- oil	GW-hours	X_{10}
- natural gas	GW-hours	X_{11}
- nuclear	GW-hours	X_{12}
Greenhouse gas emissions, aluminium production totally	mil. tons of CO_2	X_{13}
Greenhouse gas emissions intensity, primary aluminium	tons of CO_2 per 1ton of primary aluminium	X_{14}
Social		
Hours Reported Worked	mil. of man-hours	X_{15}
Lost Time Accident Rate (per MHW)	incident/1 million man-hours worked	X_{16}
Restricted Work/Medical Treatment Accident Rate (per MHW)	incident/1 million man-hours worked	X_{17}

Sources: International Aluminium (2024a, b, c), Aluminium Stewardship Initiative (2024).

Results

The production of aluminium has a steady tendency to increase worldwide (Table 2).

As it is seen from the dynamics of aluminium production, there is a stable growth in general and in the most of regions, except for Africa, Russia and Europe (especially Western and Central where the decrease is obtained). Due to the most significant volumes of production China is analysed separately by IAI being excluded from Asia region. The Chinese leadership is obvious in this regard – more than half of the total world production belongs to Chinese producers with the most steadily increasing dynamics comparing to other countries. The total world production increased significantly too – about 7 thousand metric tonnes in 2023 comparing to 2019. Totally 335,693 thousand metric tonnes of aluminium are produced in 2019 - 2023.

Table 2. Production of primary aluminium in 2019 – 2023, thousand metric tonnes of aluminium

Region	2019	2020	2021	2022	2023
Africa	1,643	1,605	1,59	1,62	1,594
North America	3,809	3,976	3,880	3,743	3,897
South America	1,079	1,006	1,163	1,288	1,466
Asia (ex China)	4,395	4,14	4,499	4,591	4,673
Western & Central Europe	3,449	3,334	3,329	2,913	2,713
Russia & Eastern Europe	4,157	4,153	4,139	4,081	4,016
Oceania	1,916	1,912	1,888	1,843	1,884
Gulf Cooperation Council	5,654	5,833	5,889	6,074	6,217
China (Estimated)	35,795	37,337	38,837	40,43	41,666

Unreported to IAI	1,76	2,029	1,878	2,455	2,455
Total	63,657	65,325	67,092	69,038	70,581

Source: International Aluminium (2024a)

The energy intensity dynamics is given in Table 3.

Table 3. Energy intensity of primary aluminium production, in 2019 – 2022, Kilowatt hours 1000 per tonne

Region	2019	2020	2021	2022
Africa	14,527	14,567	14,499	14,463
North America	15,499	15,008	14,634	14,944
South America	15,51	17,169	16,708	15,572
Asia (ex China)	14,9	14,888	14,669	14,739
Europe	15,474	15,499	15,146	15,481
Oceania	14,501	14,515	16,513	15,027
Gulf Cooperation Council	15,126	15,129	16,513	14,833
China	13,531	13,543	13,519	13,448
World	14,255	14,243	14,209	14,103

Source: International Aluminium (2024a)

Analysing the energy intensity indicators of primary aluminium smelting, China is the most energy efficient region. This was achieved thanks to the active development of nuclear energy and alternative energy sources after 2010. In average, there is a slow dynamics of decreasing energy consumption which is achieved due to compliance with the "2050 net-zero scenario". However, the average level remains high enough.

To find possibilities to improve aluminium production in terms of energy efficiency and sustainable development, taxonomic analysis is used.

The initial data selected for analysis are standardized using formula (1). Standardization was carried out considering the maximum values of stimulators (S) and minimum values of destimulators (D) for each functional component of the system (Table 4).

Taxonomic indicators of factors calculated according to formulas (2 - 7) are shown in Table 5.

As we can see from the results, there is confirmed steady increase in the production of primary aluminium (X_1) to meet consumer demand (International Aluminium, 2024a). However, comparing these data with the environmental impact of aluminium production (according to indicators X_6 - X_{14}), the production process is mainly accompanied by an aggravation of the environmental situation, with minor exceptions according to the results of 2022.

Significant negative consequences of the growth of aluminium production are manifested in the increase in energy consumption, especially due to the use of coal and oil. This indicates the need for a more detailed study of possible ways to reduce the negative impact and the implementation of approaches that would contribute to the sustainable development of the industry.

The existing trends are not aligned with SDG7 with its focus on providing reliable and clean energy. The similar inconsistencies exist regarding the sustainable development goals indicated by aluminium producers (European Aluminium, 2019).

Table 4. Initial and standardized values of factors

Initial data					Standardized values						S/D
X	2019	2020	2021	2022	$\bar{x}_{ij}$	s_j	2019	2020	2021	2022	
X_1	63657	65325	67092	69038	66278,0	2313,6	-1,13	-0,41	0,35	1,193	S
X_2	14255	14243	14209	14103	14202,5	69,1	0,76	0,59	0,09	-1,44	S
X_3	846345	835273	843222	903980	857205,0	31529,8	-0,34	-0,7	-0,40	1,49	D
X_4	319,88	281,57	333,79	310,98	311,558	22,084	0,38	-1,36	1,01	-0,03	S
X_5	0,0012	0,0012	0,001	0,001	0,001	0,000	1,07	0,50	-0,34	-1,22	D
X_6	221294	250953	263542	310270	261515	37015,5	-1,09	-0,29	0,05	1,32	S
X_7	57003	29076	10882	38039	33750	19182,4	1,21	-0,24	-1,19	0,22	S
X_8	968	1310	1070	142	873	507,66	0,19	0,86	0,39	-1,44	D
X_9	468891	465236	479679	455337	467286	10052,3	0,16	-0,20	1,23	-1,19	D
X_{10}	309	26	37	207	145	137,31	1,20	-0,86	-0,78	0,45	D
X_{11}	90 485	82314	81812	94910	87380	6403,4	0,48	-0,79	-0,87	1,18	D
X_{12}	7395	6358	6202	5075	6258	949,6	1,20	0,11	-0,06	-1,25	S
X_{13}	1131	1133	1127	1112	1126	9,50	0,55	0,76	0,13	-1,45	S
X_{14}	16,8	16,4	15,8	15,1	16	0,74	1,05	0,51	-0,30	-1,25	D
X_{15}	199	232	201	222	213,5	16,13	-0,899	1,15	-0,78	0,53	S
X_{16}	1,3	1	1,3	1,3	1,225	0,15	0,500	-1,50	0,50	0,50	D
X_{17}	2,9	2,2	2,4	2,1	2,4	0,36	1,405	-0,56	0,00	-0,84	D

Source: authors' calculations based on International Aluminium (2024a, b, c), Aluminium Stewardship Initiative (2024).

Table 5. Taxonomic indicators

Values	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
Reference value	2,95	2,30	2,22	2,66	2,99	3,15	2,98	3,36	2,94	2,45	2,45	2,96	2,31	3,04	2,87	3,46	2,42
Distance to the reference point	0,82	0,64	0,62	0,74	0,83	0,88	0,83	0,93	0,82	0,68	0,68	0,82	0,64	0,85	0,80	0,96	0,67
Taxonomic indicator	*0,18*	*0,36*	*0,38*	*0,26*	*0,17*	*0,12*	*0,17*	*0,07*	*0,18*	*0,32*	*0,32*	*0,18*	*0,36*	*0,15*	*0,20*	*0,04*	*0,33*

Source: authors' calculations

Information on the energy intensity of processes at mining and foundry enterprises is critically important for determining energy efficiency indices used in taxonomic analysis. A positive thing is that there is a slight decrease in energy intensity in the production of primary aluminium. This indicates a gradual increase in energy efficiency and, as a result, a positive impact on both the environmental and economic sustainability of enterprises. The transition to energy sources with lower carbon emissions, such as natural gas, renewable energy sources or electricity with low CO_2 emissions, is especially relevant.

Our research, based on taxonomic analysis, confirms that hydropower and nuclear power have the greatest potential for sustainable development of the aluminium industry. They positively differ in low taxonomic indicators and surpass coal in terms of environmental characteristics.

The analysis of taxonomic indicators revealed that the smallest deviation from the reference value is observed for indicators X_{10} (0.68), X_{11} (0.32) and X_{17} (0.67), which indicates their high compliance with the standard. At the same time, the largest deviation was recorded for indicators X_{16} (0.96) and X_8 (0.93), which indicates the need for further improvements in these areas. However, it is advisable to draw generalized conclusions based on taxonomic indicators.

The taxonomic indicator is an integrated assessment that reflects the level of closeness to reference values. The greater the value of the indicator, the closer it is to the ideal. For example, X_{16} (0.04) and X_8 (0.07) show a significant deviation, indicating the need for further improvements. On the contrary, indicators X_2 (0.36), X_3 (0.38) and X_{13} (0.36) show better results compared to others.

Low taxonomic indicators indicate the presence of problems in this field, which requires a more detailed analysis of each individual criterion. This will allow a deeper understanding of the main challenges and identify priority directions for further development and improvement.

Conclusions

At the current stage, the aluminium industry plays a key role in meeting production needs that cannot currently be replaced by alternative technologies. At the same time, its further development should be based on the principles of sustainable management, which considers the economic, environmental and social components of efficiency. Our study, based on available statistical data, demonstrated the effectiveness of taxonomic analysis as a method of identifying problematic aspects in the development of aluminium production, particularly, in aspect of energy efficiency.

However, not only energy consumption and ecological factors are important. Social factors such as the risk of occupational injuries have a significant impact on industry and cannot be ignored. Occupational safety is an important element of the social responsibility of enterprises, therefore compliance with occupational health and safety rules should become a priority task. For the sustainable development of the foundry industry, it is necessary not only to improve technical processes, but also to maintain labour and environmental ethics of employees.

The obtained results emphasize the analytical value of applying the taxonomic approach to managing the sustainable development of the industry. This method allows not only to identify key problems, but also to create a basis for developing a strategy to eliminate the identified shortcomings. Among the priority measures of the sustainable development policy, it is worth highlighting the improvement of the energy efficiency of enterprises, the reduction of injuries at work, the transition to energy sources with zero emissions (or close to zero) and the introduction of innovative technologies that correspond to the concept of sustainable development. These steps will contribute to reducing the environmental burden and increasing the competitiveness of the industry.

Overall, our research confirms that an integrated approach to energy efficiency analysis, considering the environmental and social aspects of production, is essential to ensure the long-term sustainability of the aluminium industry. Further research in this direction will allow for the development of more accurate tools for assessing and managing environmental and social challenges, which will contribute to the harmonious development of the industry.

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