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Multidimensional assessment of innovation and eco-innovation performance in the manufacturing industry: A diagnostic framework approach

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ABSTRACT

This article presents a comprehensive assessment of the innovation level of a company specializing in the production of power boilers fired with pulverized coal, hard coal, liquid fuels, gas, and biomass. The assessment was conducted using a proprietary innovation diagnostic methodology, enabling a multidimensional analysis of the company's innovation and eco-innovation potential. The proposed approach integrates life cycle analysis (LCA) and technology readiness level (TRL) analysis, thereby overcoming the limitations of traditional assessment methods, which typically consider these areas separately. Integrating both perspectives enables a comprehensive characterization of the company's innovation profile, taking into account the level of technological advancement, environmental performance, and the development potential of the analyzed solutions. The analysis provided both diagnostic conclusions and recommendations supporting the strategic decision-making process regarding the company's technological development. The results identified the company's strengths and the areas requiring further improvement. The presented study is in line with the current priorities of the European Union related to industrial transformation, the development of technological innovations, the implementation of eco-innovations and the achievement of climate and environmental goals.

Keywords: innovation assessment, eco-innovation, life cycle assessment, technology readiness level.

INTRODUCTION

The European Union's primary goal is to support Europe's sustainable economic development by implementing innovative technologies, while taking into account environmental protection, resource efficiency, and the principles of social responsibility. Achieving these goals is intended to transform the EU into a modern, competitive, and resource-efficient economy. A key element of this policy is the European Green Deal strategy, which envisions a profound ecological transformation of the economic system, with the goal of achieving climate neutrality by 2050 [1]. Sustainable economic development largely depends on the effective implementation of a climate-neutral and circular economy, in which raw materials and materials remain in use for as long as possible. This concept is based on closing the life cycle of products, which are reused, regenerated, or recycled at the end of their useful life. In this context, the implementation of modern technologies, particularly low-emission technologies and those that minimize waste generation, is particularly important, as they form the foundation of a functioning circular economy. Energy-intensive sectors, such as the steel, chemical, cement, and broadly defined heavy industry, also play a significant role in this process. Although essential to the functioning of the European economy, they simultaneously require modernization and a significant reduction in greenhouse gas emissions. A significant portion of these emissions in the European Union comes from energy production and consumption across various economic sectors, further underscoring the need for energy transformation [2].

Therefore, innovation and eco-innovation are a key element in achieving the European Union's sustainable development goals. Hence, it is essential for companies to consciously and systematically implement new products as well as technologies that take environmental aspects into account. This requires continuous analysis and assessment of their innovation activities to effectively support the transformation towards a low-emission and circular economy.

Moreover, the integration of environmental aspects into innovation processes is strongly supported by global sustainability frameworks, including the 2030 Agenda for Sustainable Development, which highlights the role of sustainable industrial development and responsible production patterns [3].

Despite the growing interest in assessing innovations from a sustainability perspective, the literature still lacks the approaches that integrate the assessment of the environmental impact of a technology with the assessment of its technological maturity. Combining these two perspectives enables a more comprehensive assessment of innovations, supporting the identification of solutions that are both environmentally beneficial and ready for practical implementation. The research gap, therefore, concerns the lack of a coherent diagnostic framework that allows for the simultaneous consideration of both aspects in the innovation assessment process.

This article aimed to present an assessment of the innovation performance of a manufacturing company producing a wide range of boilers fueled by pulverized coal, hard coal, liquid fuels, gas, and biomass, with capacities from 1 MW to 250 MW. The research employed a proprietary method for diagnosing the company's innovation performance. This approach presents innovation assessment from a new perspective. It takes into account both the innovation and eco-innovation performance of the enterprise by analyzing the impact of products and technologies on the natural environment [4, 5, 6]. This approach was designed to tackle the limitations of existing tools used to assess the innovation and eco-innovation performance of companies. It offers an alternative approach to analyzing firms' innovation activities and identifies possible directions for their further sustainable development.

Interpreting the obtained results in the context of the current challenges arising from European Union policies, including climate, digital, and technological transformation, is particularly important. In this context, the analysis can serve as a practical tool supporting companies in strategic decision-making and development planning. Unlike most assessments of innovation and eco-innovation available in the literature, which focus primarily on measuring economic, environmental, or technological effects, the proposed diagnostic framework integrates these dimensions within a single analytical tool. The innovative nature of this approach also lies in considering the interdependencies between organizational, technological, and environmental factors, allowing for a more comprehensive assessment of a company's eco-innovation potential. While existing methods often analyze single indicators of environmental performance or innovation level, the proposed framework enables the simultaneous identification of an organization's strengths and weaknesses as well as the areas requiring improvement. This allows the tool to serve not only as an ex-post evaluation but also support the process of making strategic decisions related to the development of eco-innovations.

In light of the growing importance of implementing innovative and environmentally friendly solutions, the conducted analysis constitutes a significant contribution to the achievement of the development objectives established by the European Union [7].

ANALYSIS APPROACH

The analysis of the company's innovativeness presented in the next empirical chapter was conducted using the innovation status diagnosis method, which allows for a comprehensive approach to innovation. This method assesses innovation in six stages, shown in Figure 1, which present the company's innovativeness and identify the actions that support sustainable development.

The method allows assessing innovation in two functional groups: technological innovation and intellectual innovation. Technological innovation refers to new or significantly improved products, production processes, devices, or technologies used by an enterprise. Its effects are most often tangible and can be directly observed in the enterprise's operational activities. Intellectual innovation, on the other hand, concerns the creation, acquisition, and utilization of knowledge, competencies, organizational solutions, management methods, patents, know-how, and

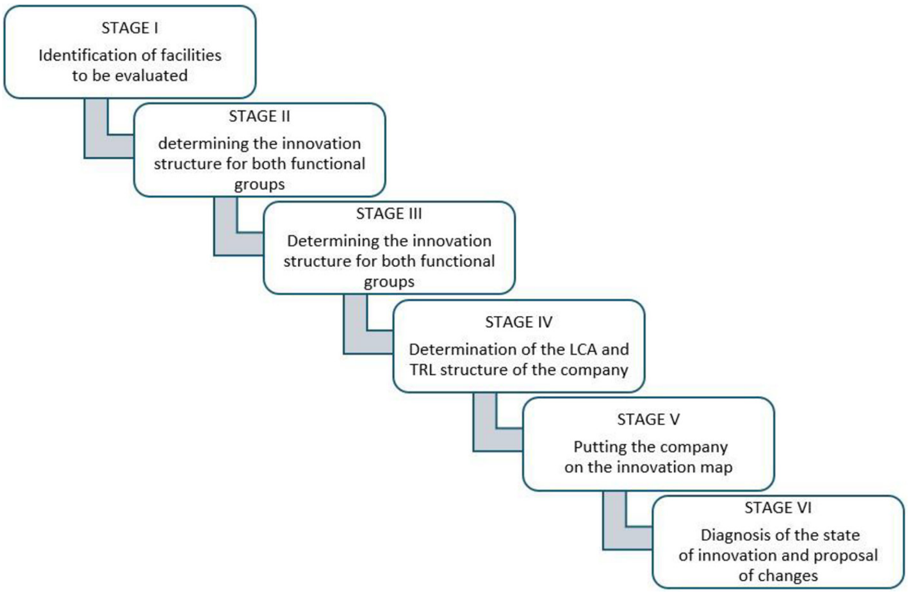


Figure 1. Stages of determining the level of innovation in companies [6]

other intangible resources supporting enterprise development. While its results do not always lead directly to the implementation of new technology, they can be a significant factor in enabling the development and commercialization of technological innovations. It is important to emphasize that there are areas of overlap between these two categories. For example, the development of a new technological solution may result from prior development of knowledge, research competencies, or intellectual property. To avoid double-counting the same innovation effects, a principle was adopted according to which innovations were classified according to their dominant result [8].

The company's innovation assessment method also utilizes a life cycle assessment (LCA) metric that takes into account environmental aspects, assessing the company's environmental impact. The company's LCA structure is determined by dividing the product and production process into the sources of environmental impacts [8, 12]. The company's assessment also utilizes a technology readiness level (TRL) metric, which considers the company's technology development level. This metric provides information on the sources of new technologies and their use within the company, as well as on the company's TRL levels of experience in product and technology development, which is helpful in formulating development directions [9, 10, 11, 15, 16]. Analyzing company innovation using the innovation status diagnosis method provides valuable information for the company, supporting strategic decision-making and planning activities aimed at increasing the company's competitiveness and innovation potential.

EMPIRICAL ANALYSIS

The analysis involved a large manufacturing company specializing in the production of various types of boilers, including those fired with pulverized coal, hard coal, liquid fuel, gas, and biomass, with capacities ranging from 1 MW to 250 MW. Boiler production is based on the company's own documentation or the documentation provided by the customer. Customers for the manufactured equipment include both domestic and foreign companies, including entities from Denmark, Finland, France, and Germany. The company additionally provides assembly services for its boilers and associated components, engineering supervision, warranty and post-warranty service, as well as diagnostics for boilers and power equipment. The company has modern machinery, advanced control and measurement equipment, a highly qualified staff, and its own research laboratory, where work on new technological solutions is conducted. Each new design solution undergoes laboratory testing before being introduced to the market. The company independently developed an innovative biomass-fired burner solution, which is protected by a utility model granted by the Patent Office. The company also collaborates with research institutions, owing to which a low-energy technology for producing corrosion- and erosion-resistant protective coatings was implemented for gas-tight wall elements and single tubes intended for power boilers. This technology extends the life of boiler components. In 2021, the company, in collaboration with the Institute for Chemical Processing of Coal, developed a market proposal for the construction of small-scale energy recovery plants from RDF (below 50,000 Mg/year), consistent with the assumptions of the European Green Deal. The company utilizes modern design and programming tools, such as 3D/2D, MES, Fluent, PDA/S, and PDMS. Both the company's technical equipment and the organization of production processes represent a high level of technological and organizational excellence. The quality and high management standards are confirmed by numerous certificates, including: Integrated Management System compliant with standards PN-EN ISO 9001, PN-EN ISO 14001, PN-EN ISO 18001, OHSAS 18001, PN-EN ISO 3834-2, PN-EN 1090-1, as well as American ASME qualifications for the production of boilers and tanks.

In the first stage of the analysis presented in Table 1, the objects subject to evaluation were identified and classified into two functional groups: technological innovation and intellectual innovation [5, 6, 13].

In Stage 2, the innovation structure indicators α_i and β_i for functional groups were determined in the examined enterprise using formulas (1) and (2) [5, 8]. The findings on the innovation structure are presented in Table 2 and Figure 2

$$\alpha_i = \frac{u_i}{\sum_{i=1}^{6} u_i} \cdot 100\% \tag{1}$$

$$\beta_i = \frac{v_i}{\sum_{i=1}^{6} v_i} \cdot 100\% \tag{2}$$

where: u_i – a numerical value representing the number of objects assigned to innovation zone i (i = 1,…,6) within the area of intellectual innovation; v_i – a numerical value representing the number of objects assigned to innovation zone i (i = 1,…,6) within the area of technological innovation.

In Stage 3, the values of the structural indicators describing intellectual innovativeness (α_0) and technological innovation (β_0) were determined using formulas (3) and (4). These indicators were used to determine the level of intellectual innovation W_{IK} and technological innovativeness W_{IT} were established in accordance with formulas (5) and (6). These indicators are calculated using the center of gravity method with weighting factors ($i \cdot \alpha i$) and ($i \cdot \beta i$), which strengthen the importance of innovative objects located at higher levels. The indicators α_0 and β_0 constitute the argument of the function (5) and (6), determining the values of the indicators: technological innovation W_{IT} and intellectual innovation W_{IK} [5, 8, 13].

$$\alpha_0 = \frac{\sum_{i=1}^{6} i \cdot (i \cdot \alpha_i)}{\sum_{i=1}^{6} (i \cdot \alpha_i)} \tag{3}$$

$$\beta_0 = \frac{\sum_{i=1}^{6} i \cdot (i \cdot \beta_i)}{\sum_{i=1}^{6} (i \cdot \beta_i)} \tag{4}$$

$$W_{IK} = W_{I,\ \mathrm{for}}\, \mu_0 = \alpha_0 \tag{5}$$

$$W_{IT} = W_{I\ \mathrm{for}}\, \mu_0 = \beta_0 \tag{6}$$

where:
$$W_I = 0.10 \cdot \mu_0 - 0.10 \text{ for } 1 \le \mu_0 < 2$$
$$W_I = 0.15 \cdot \mu_0 - 0.20 \text{ for } 2 \le \mu_0 < 3$$
$$W_I = 0{,}50 \cdot \mu_0 - 1.25 \text{ for } 3 \le \mu_0 \le 4$$
$$W_I = 0.15 \cdot \mu_0 + 0.15 \text{ for } 4 < \mu_0 \le 5$$
$$W_I = 0.10 \cdot \mu_0 + 0.40 \text{ for } 5 < \mu_0 \le 6$$

Table 1. Evaluation of enterprise innovation activities

Functional group	Scope of activity		
	Range	Assessed factors	Rate
Technological innovation	Manufactured product	Modern materials are used in production Boilers with a complex design	$\beta_{4=0.1}$ $\beta_{5=0.1}$
	Manufacturing techniques	Automated production lines, mechanized welding Modern programming tools Environmental requirements met	$\beta_{6=0,1}$ $\beta_{6=0,1}$ $\beta_{4=0,1}$
Intellectual innovation	Research and development work	In-house design office Collaboration with research centers Performing thermal, strength, and flow calculations Preparing workshop documentation	$\alpha_{5=0,1}$ $\alpha_{6=0,1}$ $\alpha_{6=0,1}$ $\alpha_{5=0,1}$
	Organization and management	Quality Management System Engagement in trade fairs	$\alpha_{4=0,1}$ $\alpha_{5=0,1}$

Table 2. Enterprise innovation structure

Parameter	Innovation zone	Structure coefficients α of intellectual innovation		Structure coefficients β technological innovation	
Conservative (non-innovative)	Definitely	α_1	0.0	β_1	0.0
	Average	α_2	0.0	β_2	0.0
	Moderately	α_3	0.0	β_3	0.0
Innovative	Definitely	α_4	0.19	β_4	0.23
	Average	α_5	0.63	β_5	0.62
	Moderately	α_6	0.19	β_6	0.15

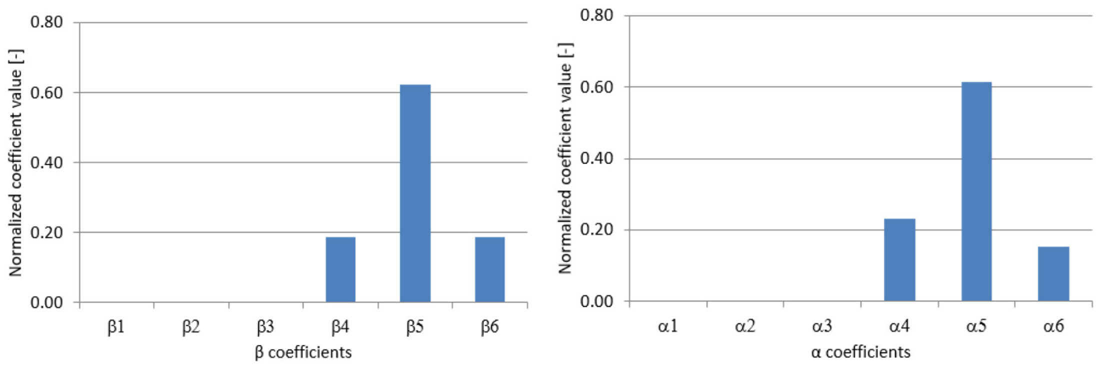


Figure 2. The firm's innovation structure within both functional categories

The following indicator values were calculated for the enterprise: $W_{IT} = 0.91$ $W_{IK} = 0.90$.

In Stage 4 of the study, the objective was to analyze the environmental impact of a manufacturing enterprise. The life cycle assessment was conducted in accordance with the updated ISO 14040 and ISO 14044 standards [17, 18]. The LCA analysis included identified products together with the related production processes. A functional unit of 1 Mg (1 ton) of finished product was adopted as the reference unit for compiling the inventory of input and output data. The next step was to define the system boundaries and conduct a comprehensive environmental inventory analysis, taking into account all input and output flows of the investigated production processes (Figure 3). As a result, an environmental balance of the enterprise was developed and presented in Figure 4. It included the consumption of raw materials, energy, and water, in addition to emissions to air, soil, and water, as well as waste generation.

The life cycle impact assessment (LCIA) was performed using SimaPro 8.1 software and the ReCiPe Midpoint (H) methodology. The ReCiPe Midpoint (H) method was chosen due to its widespread use and recognition in LCA studies. This method enables a comprehensive assessment of multiple environmental impact categories while maintaining a clear interpretation of midpoint results. Furthermore, its widespread use in eco-innovation research allows for comparison of obtained results with those presented in the literature. In this study, individual products were allocated weighting factors that reflected their share in the company's total production volume. This approach enabled the creation of a detailed and comprehensive environmental profile. The obtained results were summarized in a MAT_{LCA} matrix table, offering a structured overview of the enterprise's overall environmental impact [14].

$$M_{TRL} = [0{,}3323\ \ 0{,}0075\ \ 0{,}0075\ \ 0{,}0075$$
$$0{,}0075\ \ 0{,}4907\ \ 8{,}1798\ \ 0{,}3468$$
$$7{,}2406\ \ 0{,}2499\ \ 0{,}7748\ \ 0{,}1187$$
$$13{,}5658\ \ 16{,}4254\ \ 0{,}0335\ \ 0{,}0404$$
$$0{,}1316\ \ 2{,}4055\ \ 5{,}9952\ \ 0{,}8282]$$

The ReCiPe Midpoint (H) method was used in the study, where each column refers to a distinct environmental impact category: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity,

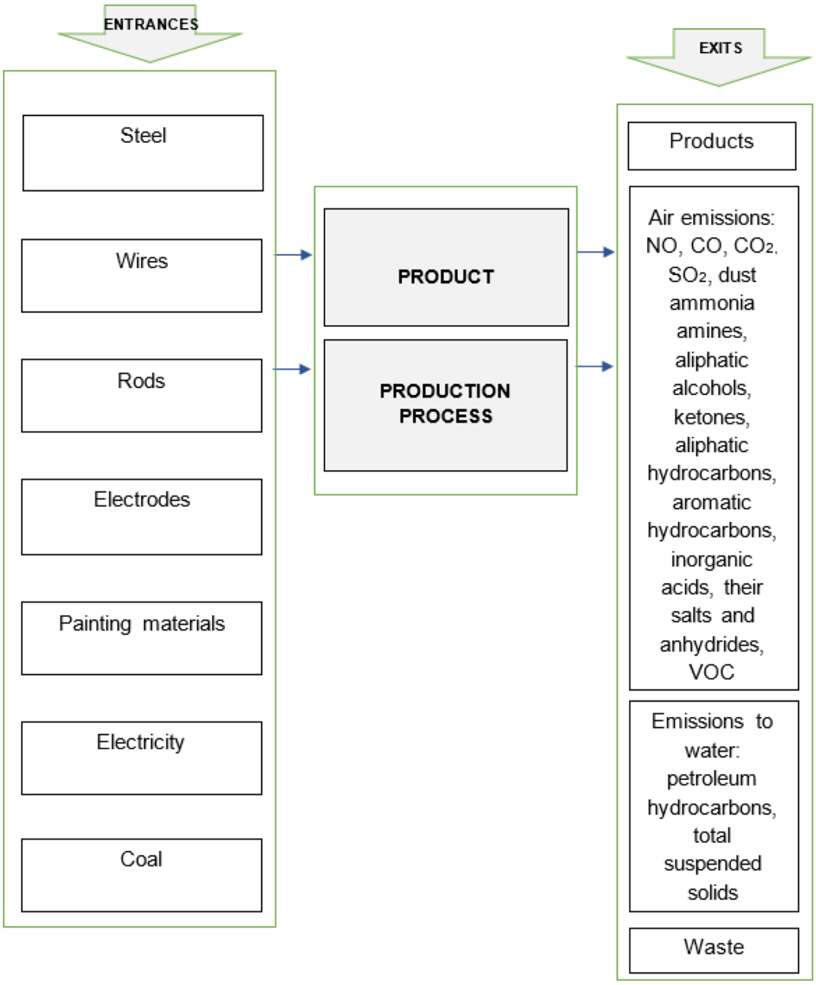


Figure 3. Overall scheme of the inventory analysis relating to the product and its production process [14]

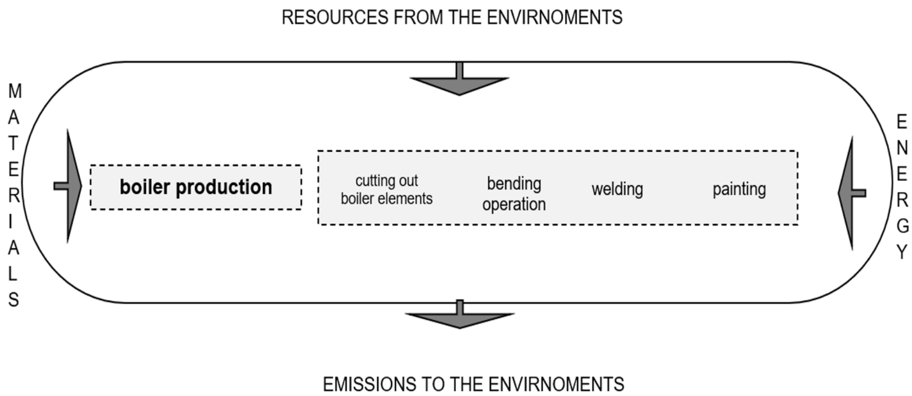


Figure 4. Scope of LCA and its fundamental unit processes

freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water consumption, mineral resource use, and fossil resource use [14]. The structure of the life cycle assessment (normalized environmental impact profile) is presented in Table 3 and Figure 5.

The LCA structure analysis identified that the strongest negative environmental impacts arise in marine ecotoxicity, freshwater ecotoxicity, freshwater eutrophication, the use of mineral resources and human toxicity (Figure 5).

The LCA analysis also shows that the materials used in the production of products are the

Table 3. Enterprise indicators classified by impact category within the ReCiPe Midpoint (H) method

Paremeter	Structure factors $\alpha_i = \sum_{i=1}^{j} \alpha_{n1}$
Climate change	0.3323
Ozone depletion	0.0075
Terrestrial acidification	0.4907
Freshwater eutrophication	8.1798
Marine eutrophication	0.3468
Human toxicity	7.2406
Photochemical oxidant formation	0.2499
Particulate matter formation	0.7748
Terrestrial ecotoxicity	0.1187
Freshwater ecotoxicity	13.5658
Marine ecotoxicity	16.4254
Ionising radiation	0.0335
Agricultural land occupation	0.0404
Urban land occupation	0.1316
Natural land transformation	2.4055
Water depletion	0.0000
Metal depletion	5.9952
Fosil depletion	0.8282

primary source of pollution in all key impact categories. Steel generates the most pollution. For example, steel is responsible for 80.6% of all impacts arising from the human toxicity impact category, 71.9% in the climate change impact category (Figure 6a, Figure 6b).

Research indicates that the energy used in the production process also constitutes a source of pollution within the enterprise. There are impact categories where energy, primarily coal used to generate thermal energy, is a significant source of negative environmental impacts. For example, coal consumption accounts for 35.5% of all impacts in the agricultural land use impact category and 39.6% in the fuel use impact category (Figure 7a. Figure 7b).

In the company, five technologies were selected for TRL evaluation, each corresponding to a row in the M_{TRL} matrix. The matrix values were assigned based on an analysis of company documentation. Classification was performed according to the definitions and criteria corresponding to the technology readiness levels (TRL). Based on this, each technology was assigned a TRL reflecting its level of advancement, which formed the basis for constructing the M_{TRL} matrix and further analyses. The a_{ki} coefficients indicate whether a given technology has reached level i within the activities carried out in the enterprise. The general form of the matrix (M_{TRL}) is presented in formula (7). The matrix (M_{TRL}) with assigned values of coefficients (a_{ki}) defining the level of technological readiness of individual analyzed technologies in the enterprise is also presented below.

$$M_{TRL} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} & a_{19} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & a_{27} & a_{28} & a_{29} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{k1} & a_{k2} & a_{k3} & a_{k4} & a_{k5} & a_{k6} & a_{k7} & a_{k8} & a_{k9} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & a_{n6} & a_{n7} & a_{n8} & a_{n9} \end{bmatrix} \tag{7}$$

$$M_{TRL} = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \\ 0 & 1 & 1 & 2 & 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \end{bmatrix}$$

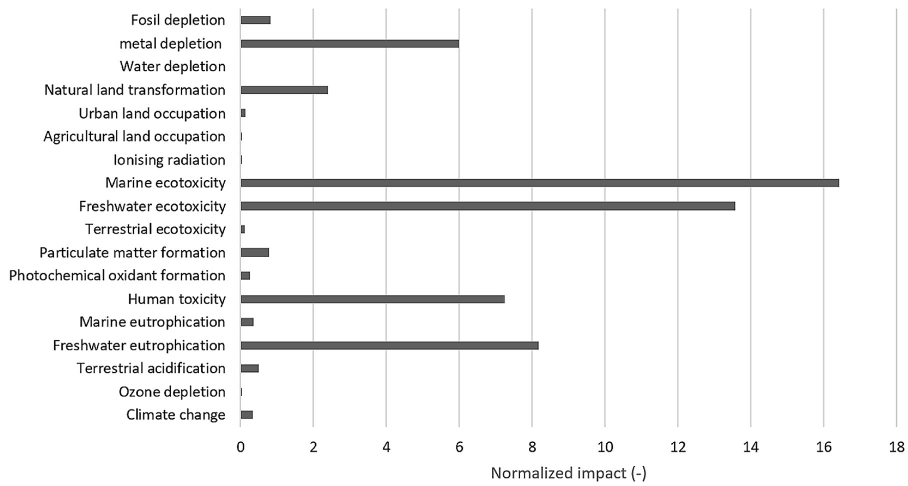
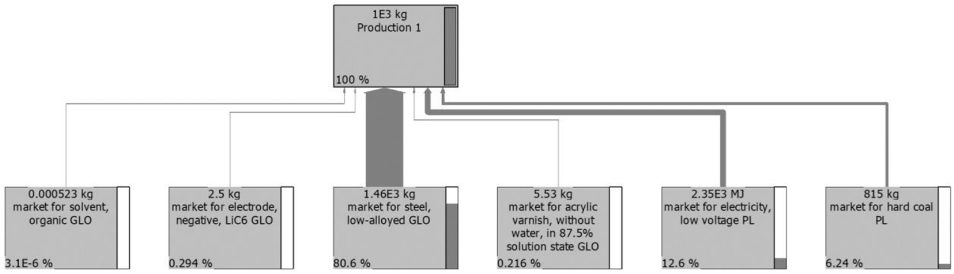
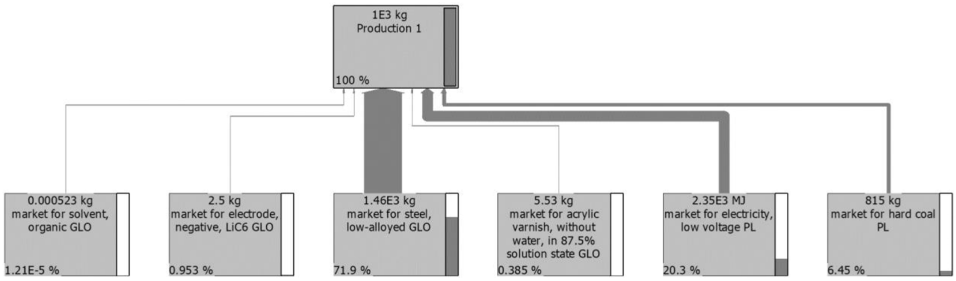


Figure 5. The LCA structure of enterprise

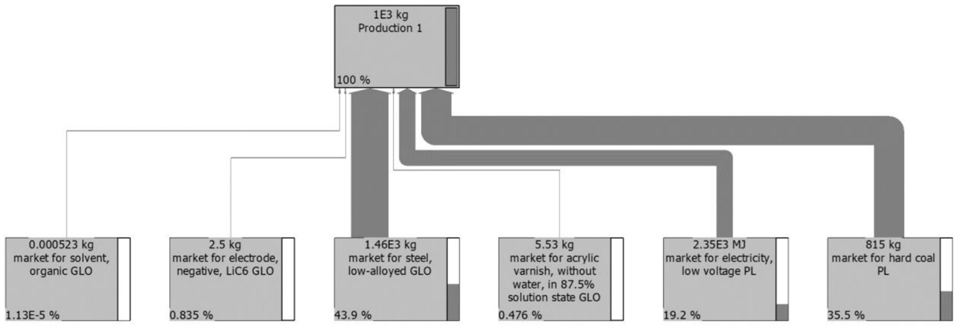


a.

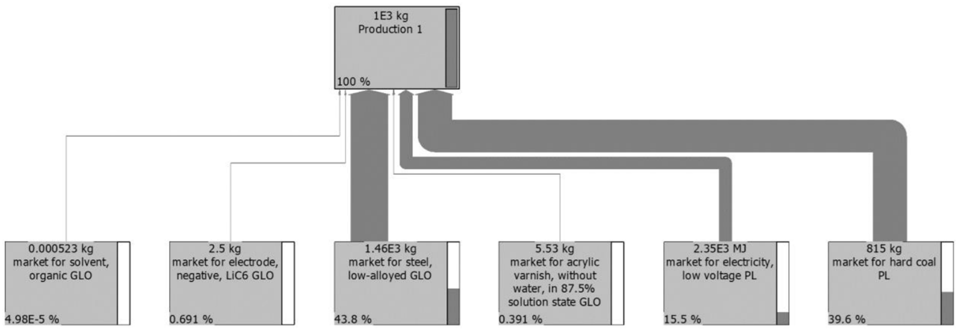


b.

Figure 6. a) Process tree of boiler production in the human toxicity impact category; b) Process tree of boiler production in the climate change impact category



a.



b.

Figure 7. a) Process tree of boiler production in the agricultural land occupation impact category; b) Process tree of boiler production in the fossil fuel use impact category

Technology 1 – Production of boiler components. Boiler components are cut on numerically controlled machines using high-end TRUMPF laser cutters. This technique ensures high precision, rapid production, and high-quality boiler components without the need for primary processing. To eliminate unnecessary welding, the company utilizes bending operations using press brakes. Boiler components are welded using modern automatic welding robots. The automated powder coating process of the external components of a boiler allows for achieving high-quality, scratch-resistant coatings and an aesthetically pleasing appearance. The work carried out at the company using this technology falls within the TRL range of 4–9, with a medium degree of complexity.

Technology 2 – Automated Welding Technology. Automated welding is performed using modern welding robots. This technology increases production efficiency and improves the quality of the joints. A significant advantage of robotic welding is the repeatability of production, which is impossible to achieve with manual welding. The work carried out at the company using this technology falls within the TRL range of 6–9, with a medium degree of complexity. Level 6 – A prototype of the technology was demonstrated under the conditions close to real-world conditions. A boiler was manufactured using automated welding of components, with appropriate weld strength parameters selected.

Technology 3 – Automated Painting Process. The automated powder coating process for boiler exterior components allows for high-quality coatings and an aesthetically pleasing appearance. The company's work with this technology falls within the TRL range of 6–9, with a medium degree of complexity.

Technology 4 – Biomass burner production technology. The work conducted at the company related to this technology falls within the TRL range of 1–9, with a high degree of complexity.

Technology 5 – A technology for producing corrosion- and erosion-resistant protective coatings on gas-tight wall elements and single tubes for power boilers. The work conducted at the company related to this technology falls within the TRL range of 2–9, with a high degree of complexity.

Technology 6 – an energy recovery installation with a thermal output of 16 MWt based on a water-fired grate boiler and a flue gas cleaning system using the semi-dry calcium-sodium method with activated carbon. In 2021, the company, in cooperation with the Institute for Chemical Processing of Coal, prepared a market offer for the construction of small-scale energy recovery installations from RDF (<50,000 Mg/year), capable of supplying the heat generated from waste. This modern installation enables the replacement of outdated boilers with water-fired grate boilers using RDF. The work carried out at the company related to this technology falls within the TRL range of 1 to 9, with a high degree of complexity.

The enterprise's technological maturity level based on the TRL assessment is presented in Table 4. The columns in Table 4 correspond to subsequent levels of the TRL scale, while the rows characterize the technologies used in the analyzed enterprise. The values in the table represent the a_{ki}, coefficients, which indicate whether a given technology has reached level i within the activities carried out in the enterprise. The TRL structure coefficients ϑ_i represent the TRL structure of the enterprise. They are dimensionless quantities and constitute the sum of the a_{ki} coefficient values for subsequent levels of the TRL scale related to the sum of all coefficients. The W_{TRL} indicator is a generalizing measure, calculated using the center of gravity method (9). It assumes values in the range <0.9>

TRL structure factor calculated according to formula 8 [5]:

$$\vartheta_i = \frac{\sum_{k=1}^{n} a_{ik}}{\sum_{i=1}^{9}\sum_{k=1}^{n} a_{ik}} \; dla \; i = 1 \ldots 9 \tag{8}$$

The TRL index was derived using the formula below (9) [5]:

$$W_{TRL} = \frac{\sum_{i=1}^{9} i \cdot \vartheta_i}{\sum_{i=1}^{9} \vartheta_i} \tag{9}$$

Table 4. The enterprise's technological maturity level based on the TRL assessment

Technology	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
1	0	0	0	1	1	1	1	1	1
2	0	0	0	0	0	1	1	1	1
3	0	0	0	0	0	1	1	1	1
4	2	2	2	2	2	2	2	2	2
5	0	1	1	2	2	2	2	2	2
6	2	2	2	2	2	2	2	2	2

Figure 8 presents the structure of technological readiness levels in the enterprise.

The innovation map in Stage V presents a graphical illustration of the W_{IK} and W_{IT} indicators [19]. In the enterprise, the indicator values are $W_{IT} = 0.91$ i $W_{IK} = 0.90$, which is illustrated in Figure 9.

The last stage of the analysis concerns the assessment of the company's innovation status and the formulation of improvement proposals. The company demonstrates a high level of innovation in terms of technological innovation and intellectual innovation. The company maintains a balanced state with a slight advantage in technological innovation. This outcome arises from innovative activities conducted within both technological and intellectual innovation groups. Maintaining this balance requires continued consistent implementation of an innovation strategy based on the synergy between both functional groups. The company should continue developing both technological solutions and intellectual competencies, as their interaction is a key factor in further innovation growth. A slight advantage in technological innovation also serves as an internal development stimulus, which can support the gradual increase in intellectual innovation through the transfer of knowledge and implementation experience to the research and design sphere. Therefore, the recommended direction of change includes intensifying the investments in the development of research and development facilities, including R&D teams and laboratory infrastructure. Expanding the collaboration with universities and research institutions is also crucial, as it can contribute to increasing the potential for generating new conceptual solutions and raising the level of intellectual innovation. At the same time, these activities will enable a more comprehensive use of existing technological resources and their further optimization.

The company's LCA analysis identified the sources of negative impacts and the direction of positive changes in the context of eco-innovation. The materials used in the company's production are the dominant source of pollution in all key environmental impact categories. There are also impact categories in which energy, i.e., coal used in the production process, is a significant source of pollution, but it is not dominant in all impact categories. Therefore, the actions aimed at reducing negative environmental impacts should first focus on implementing product eco-innovations, followed by process innovations. It is crucial to consider the specific quality requirements of the PN-EN 303-5:2012 standard, which determines the technical and operational parameters of manufactured boilers. This means that pro-environmental activities must not lead to a reduction in the quality or operational parameters of products, but should be implemented through product life cycle optimization. In this context, greater effectiveness may be achieved not so much by reducing the consumption of construction materials, such as steel, but by using them more efficiently in the final phase of a product's life, in particular in terms of recycling and waste management. An equally significant area of environmental impact is the consumption of coal in the production process, which is associated with the emission of pollutants such as carbon dioxide, sulfur dioxide, nitrogen oxides, and suspended particulate

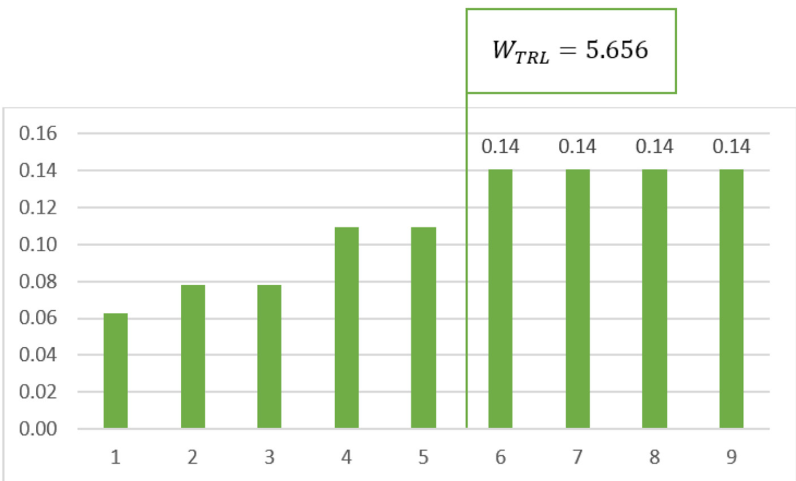


Figure 8. Structure of technological readiness levels in the enterprise

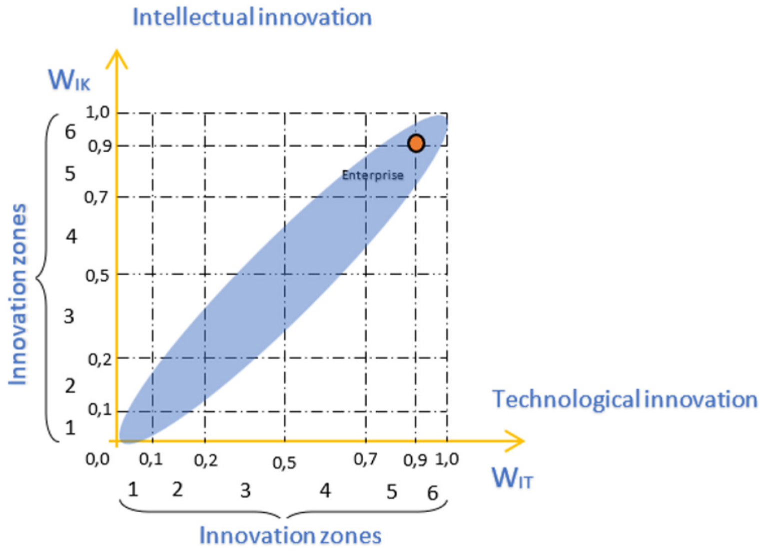


Figure 9. The enterprise shown on the innovation map

matter. One potential approach to reducing these emissions is the gradual replacement of fossil fuels with alternative sources, including the use of renewable energy sources, such as geothermal energy for electricity production and heating systems. Implementing this type of eco-innovation can provide multifaceted benefits to the company. In addition to reducing environmental pressure and the negative impact on human health, it is also possible to achieve economic benefits in the form of lower operating and production costs in the long term [20].

The company's TRL structure is uneven, with a predominance of high TRL levels, indicating that the implementation activities based on externally acquired technologies dominate. The company also has extensive research and development activities, resulting in low TRL activities. However, the value of the W_{TRL} = 5.656 indicator located in the second part of the range (W_{TRL} = >4.5) indicates a greater amount of implementation work. A significant element of the company's operations is its well-developed research and development base, which also results in the activities carried out at low TRL levels. This demonstrates the company's conceptual, design, and experimental work, focused on generating new technological solutions even before their practical implementation. The presence of activities at both low and high levels of technology readiness indicates the company's ability to conduct innovation activities comprehensively – from concept development and laboratory testing, through prototype development, to the implementation of finished solutions into operational activities. The company has the ability to independently develop new technological solutions, which, once implemented, can contribute to further growth in technological innovation, enhance competitiveness, and strengthen its market position. Furthermore, combining implementation experience with extensive research and development activities creates favorable conditions for building a sustainable competitive advantage based on knowledge and innovation. This enables not only the effective implementation of new technologies but also their further refinement and adaptation to changing market requirements, environmental standards, and customer expectations.

CONCLUSIONS

This study investigated the level of innovation at a manufacturing company specializing in the production of various types of boilers, including those fired by pulverized coal, hard coal, liquid fuel, gas, and biomass, with capacities ranging from 1 MW to 250 MW. The company operates in a sector characterized by high technological and environmental requirements, making the assessment of its innovation activity crucial both economically and ecologically. The research was conducted according to the stages outlined in the empirical part of the study. A proprietary methodology for assessing enterprise innovation was used, allowing for a multifaceted and comprehensive evaluation of the organization's innovation and eco-innovation performance. This approach allows for the integration of various analytical perspectives, providing a comprehensive understanding of the company's innovation performance. This approach takes into account not only the degree of technology implementation, but also the company's development potential, its environmental impact, and its ability to implement technologies at various levels of advancement. The obtained results provide a comprehensive characterization of the analyzed company, enabling both an assessment of its current level of innovation and identification of the areas requiring further improvement. A significant feature of the approach is its interdisciplinary nature, combining technological, environmental, and organizational aspects. This allows determining the actual effectiveness of the company's operations in the context of innovation and identifying the areas requiring optimization. The method also serves as a tool supporting the strategic decision-making process, particularly in the areas of research and development investment planning and the implementation of new technologies.

The analysis utilized the life-cycle assessment (LCA) method to determine the environmental impact of the company's operations. This method identified the main sources of environmental impacts at both the product level and individual stages of the production process. The analysis was complemented by the technology readiness level (TRL) method, which enabled the assessment of the technological advancement of the identified solutions used within the company. This method enabled identifying the development stage of individual technologies, ranging from conceptual and experimental phases to industrial implementation. This also allowed identifying sources of innovation and an assessment of the company's ability to generate and implement them. The TRL method also provided information on the organization's experience in product and technology development, enabling an assessment of its R&D potential. The collected data indicates the company's significant capabilities in conducting and expanding R&D, which constitute the foundation for further technological development and strengthening its competitive position in the market. Interpreting the obtained results in the context of current challenges arising from European Union policies, including climate, digital, and technological transformation, is particularly important. In this context, the analysis can serve as a practical tool supporting companies in strategic decision-making and the planning of development activities aimed at building a long-term, sustainable, and competitive market position.

Given the growing importance of implementing innovative technologies and products that reduce negative environmental impact, the presented study can be considered an important element supporting enterprise adaptation to the requirements of the modern economy. In particular, it aligns with the development directions set by the European Union, promoting resource efficiency, low emissions, and the development of a circular economy.

It should be noted that the validation presented in this manuscript is based on a single industrial case study, which in itself could limit the generalizability of the obtained results. However, the proposed diagnostic framework has been previously tested and applied in the analyses conducted in other enterprises, the results of which are presented in separate publications.

Despite the favorable validation results, there are certain limitations to the approach used. The effectiveness of the method depends on the availability of reliable data regarding both the environmental impacts and the technological readiness level of the solutions being assessed. Furthermore, the interpretation of the results may be partially dependent on the specific industry and organizational conditions of the company. The developed diagnostic framework has already been tested in various empirical contexts, but its full scalability requires further verification in companies of varying sizes, business profiles, and technological advancement.

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