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THE IMPACT OF PRODUCTION ECOLOGIZATION ON SUSTAINABLE DEVELOPMENT OF ENTERPRISES

ВПЛИВ ЕКОЛОГІЗАЦІЇ ВИРОБНИЦТВА НА СТАЛИЙ РОЗВИТОК ПІДПРИЄМСТВА

In the current context of global climate change and environmental challenges, increasing attention is being given to the issue of greening production processes. Therefore, one of the main tasks facing enterprises in the context of economic transformations is to maximize their contribution to such measures for sustainable development. The aim of the article is to define the features of modeling and evaluating the impact of greening production on the sustainable development of an enterprise. Within the framework of the conducted study, it has been determined that greening production is a key factor for the sustainable development of an enterprise, as it helps reduce the negative impact on the environment and increase economic efficiency. It has been proven that in order to determine the economic effectiveness of greening production, it is important to assess the cost of each of these measures, which enables the use of the Hicks-Lindahl model to simulate their impact on the overall economic result. The Hicks-Lindahl model allows for the assessment of how various environmental measures impact the sustainable development of an enterprise. Within this model, each environmental measure is treated as a separate factor, which is reflected in a multiple regression equation, where the variables interact and influence the economic outcome.

Keywords: *sustainable development parameters of an enterprise; implementation of resource-saving technologies; waste recycling; use of alternative energy sources; reduction of emissions.*

У сучасних умовах глобальних змін клімату та екологічних викликів все більше уваги приділяється екологізації виробничих процесів. Тому одним із ключових завдань підприємств у період економічних трансформацій є впровадження заходів, що сприяють сталому розвитку. Метою статті є визначення особливостей моделювання та оцінки впливу екологізації виробництва на сталий розвиток підприємства. У ході дослідження встановлено, що екологізація виробництва є ключовим чинником сталого розвитку підприємства, оскільки сприяє зниженню негативного впливу на навколишнє середовище та підвищенню його економічної ефективності. Доведено, що екологізація виробництва включає чотири основні складові: впровадження ресурсоощадних технологій, переробку відходів, використання альтернативних джерел енергії та зменшення викидів шкідливих речовин у навколишнє середовище. Звернуто увагу на той факт, що кожна з цих складових охоплює низку екологічних заходів, які безпосередньо впливають на базові параметри сталого розвитку підприємства, зокрема на зменшення витрат на енергію та сировину. Відтак, для оцінки економічної ефективності екологізації виробництва важливо визначити вартість кожного із заходів, що дає змогу за допомогою моделі Хікса–Ліндаля змоделювати їхній вплив на загальний економічний результат. Модель Хікса–Ліндаля дає змогу оцінити вплив різних екологічних заходів, зокрема впровадження ресурсоощадних технологій, переробки відходів, використання альтернативних джерел енергії та зменшення викидів, на сталий розвиток підприємства. У межах цієї моделі кожен екологічний захід розглядається як окремий фактор, що відбивається в рівнянні множинної регресії, де змінні взаємодіють і впливають на економічний результат. Рівняння множинної регресії дає змогу кількісно оцінити вплив кожного з екологічних заходів на потік доходу Хікса–Ліндаля, який є ключовим параметром для оцінки сталого

розвитку підприємства. Констатовано, що така економічна модель дає змогу обґрунтувати інвестиції в екологічні інновації та продемонструвати їхню ефективність у зниженні витрат і підвищенні економічної стабільності підприємства в довгостроковій перспективі.

Ключові слова: *параметри сталого розвитку підприємства; впровадження ресурсоощадних технологій; переробка відходів; використання альтернативних джерел енергії; зменшення викидів.*

Problem statement. There is an increasing emphasis on greening production processes in response to global climate change and environmental challenges. One of the primary tasks for enterprises during economic transformations is to enhance support for sustainable development initiatives. Sustainable development is understood as a type of progress that meets the needs of the present without harming the environment and promotes the maintenance of social balance and economic stability [2]. The implementation of environmental innovations in production processes is becoming an integral part of the development strategy for many enterprises reducing the ecological footprint and enhancing economic efficiency.

For example, renewable energy sources (such as solar panels or wind turbines) help reduce dependence on traditional energy resources and lower energy costs. Moreover, the implementation of closed-loop production technologies, which minimize waste and allow for the reuse of raw materials, reduces material procurement costs and improves the environmental condition of the surrounding area.

Analysis of research and publications. In particular, scientists such as Harafonova O., Yankova R., Khudoley V., Pishchenko O. [1], Kravchuk N. I., Kilnytska O. S., and Tarasovych L. V. [4] have actively researched the aspect of greening production in the context of sustainable development. However, despite their significant achievements, issues related to the development of universal models that allow for accurate assessment of the impact of environmental changes on the efficiency and sustainable development of enterprises remain relevant. Moreover, it remains a complex task to account for the long-term consequences of environmental changes on the surrounding ecosystem, as many interaction factors within ecosystems are intricate and unpredictable.

Such issues require further scientific research and the improvement of methodologies for modeling and assessing the impact of environmental initiatives at the production system level of enterprises. Only after this can truly effective and scalable models be created for integrating environmental aspects into the sustainable development strategies of each organizational and economic unit engaged in production or commercial activities aimed at generating profit.

Formulation of the article's objectives. The aim of the article is to identify the features of modeling and assessing the impact of greening production on the sustainable development of an enterprise.

The paper main body. Within the scope of the research, we emphasize that the greening of the production system will be viewed as the implementation of environmentally friendly technologies and practices in the activities of enterprises involved in the process of creating goods and services (which is realized through the transformation of resources into finished products [1]) with the aim of reducing the negative impact on the environment.

This process includes the following components [4–5]:

- Implementation of resource-saving technologies is interpreted by us as the introduction of innovative methods and equipment that reduce the consumption of natural resources (water, energy, raw materials) at all stages of production.
- Waste recycling refers to the reuse of materials generated from production processes for further application in other production cycles.
- The use of alternative energy sources refers to incorporating renewable energy sources to reduce greenhouse gas emissions and lessen dependence on limited fossil fuel resources.
- Reduction of harmful emissions into the environment is interpreted as the use of technologies and methods that reduce or eliminate the release of toxic and harmful substances into the atmosphere, water, and soil.

It should be noted that each of the components of greening production outlined above encompasses a set of measures that allow for the reduction of energy and raw material costs, as well as corrective base parameters for the sustainability of the enterprise's development (with the Hicks–Lindahl income flow being a possible choice as such a parameter [2]), as illustrated by the data in Table 1.

If the costs of the outlined measures can be calculated, each can be represented as an independent variable influences the impact of greening production on the enterprise's sustainable development. It can be implemented by modeling the income flow using the Hicks–Lindahl model [2].

The Hicks–Lindahl model, in the context of greening production, allows for the assessment of how different environmental investments (resource-saving technologies, waste recycling, alternative energy sources, emission reduction [3]) affect the overall outcome of sustainable development in an enterprise. Within this model, each environmental measure can be considered as a separate factor that alters the economic concept used to evaluate the value of environmental goods or services and economic activity.

It should be emphasized that the cost of each environmental measure, as an independent variable, should be reflected in the multiple regression equation, where these variables interact and influence various aspects of the enterprise's economic outcome.

The multiple regression equation used to model the impact of greening production on the sustainable development of the enterprise may, for example, look as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + ... + \beta_n X_n + \varepsilon, \quad (1)$$

Where Y — dependent variable representing the overall economic result (expressed as the Hicks–Lindahl income flow);

$X_1, X_2, ..., X_n$ — independent variables representing different environmental measures, such as the cost of resource-saving technologies, waste recycling, the use of alternative energy sources, and emission reduction;

β_0 – constant (initial level of the result without environmental investments);

$\beta_1, \beta_2, ..., \beta_n$ — coefficients that determine the weight of each environmental measure about the overall economic result;

ε — random error accounting for other factors that may influence the result.

Table 1

A set of measures for greening production.

Components of greening production	A set of measures that allow for the adjustment of the basic parameters of the enterprise's sustainable development.
Implementation of resource-saving technologies	Automation of processes, optimization of production lines, and implementation of technologies that reduce energy consumption and minimize waste.
Waste recycling	Sorting, cleaning, disposal, and recycling of materials (such as metals, plastics, and organic waste) significantly reduces the amount of waste sent to landfills and minimizes the need for new resources.
Use of alternative energy sources	The implementation of renewable energy sources, such as solar, wind, biomass, or geothermal energy, instead of traditional fossil fuels.
Reduction of harmful emissions into the environment	The installation of filters, the use of less harmful chemicals, and the modernization of production processes to reduce energy consumption and the formation of pollutants.

*Each of the measures should be economically evaluated through parameters such as the costs of implementing technologies, economic benefits from their application, resource savings, reduced energy costs, decreased fines for pollution, and other factors.

Source: compiled based on [1; 4–6]

In such a regression model, each environmental measure (for example, waste recycling or the implementation of alternative energy sources [3]) can be assessed considering its existing impact on the Hicks–Lindahl income flow present in the enterprise.

It will allow for the prior calculation of the benefits of implementing environmental investments and their impact on sustainable development, considering:

- Theoretical analysis of the relationship between results and the set of factors that have a significant impact on them. In identifying all core factors and evaluating their impact, various theoretical approaches and models can be employed.
- A quantitative evaluation of the relationship between various factors and their outcomes. It should be noted that scientifically grounded solutions to such tasks are carried out using multifactorial analysis of variance, as this involves studying the impact of a combination of factors on the result.

The specifics of identifying the impact of greening production on sustainable development can be demonstrated through the example of Eno Mebli Ltd, which specializes in woodworking and furniture manufacturing, with its headquarters located in the city of Mukachevo, Zakarpattia region. Specifically, the management of Eno Mebli Ltd decided in 2025 to expand a range of environmental initiatives that have been implemented since 2019 (as shown in Table 2) to reduce the negative impact of its production processes on the local community's environment, which, in turn, is expected to improve its sustainable development.

In particular, it is planned to implement new filtration systems to reduce harmful emissions, increase the volume of material recycling, and make additional investments in resource-saving technologies.

It should be noted that in the outlined model, as the result, we will consider not the entire economic flow, but only those aspects directly related to the evaluation of the value of environmental goods and services. In other words, in our case, for Eno Mebli Ltd, this will concern only the costs and benefits arising from the implementation of environmental investments, such as the installation of air filtration systems and other environmental measures.

Table 2

Assessment of the impact of greening production on the sustainable development of the enterprise for the years 2019–2024, million UAH

Period	Input data for impact assessment				The vector of regression coefficient estimates
	Hicks–Lindahl income flow (У) ****	Optimization of production lines (X1)*	Deepening of material recycling (X2)**	Installation of filters (X3)**	
2019	22.3	1.6	0.8	0.95	9,4571 8,3365 -0,977 1,5047
2020	24.8	1.67	0.79	0.88	
2021	22.1	1.44	0.31	0.72	
2022	20.6	1.22	0.76	0.96	
2023	25	1.7	0.43	1.1	
2024	28,3	2.1	0.8	1.4	

*This refers to the implementation of resource-saving technologies on the hardware production line.

** This refers to increasing the volume of wood chip recycling into materials for the production of composite panels or other products.

*** This refers to filtration systems that can help reduce the emissions of substances such as formaldehyde, which are harmful to health.

**** The performance indicator is formed through economic benefits related to: reduced energy and raw material costs, reduced environmental fines, and increased competitiveness through enhanced environmental responsibility.

Source: compiled based on data from business entities.

As a result of the calculations based on the data presented in Table 2, the multiple regression equation obtained is:

$$Y = 9.4571 + 8.3365X_1 - 0.977X_2 + 1.5047X_3, \quad (2)$$

Thus, the possible economic interpretation of the impact of greening production on the sustainable development of the enterprise can be presented as follows:

- An increase in costs for optimizing production lines (X_1) by 1 million UAH leads to an increase in the Hicks–Lindahl income flow (Y) by an average of 8.337 million UAH. This measure creates economies of scale, allowing the enterprise to obtain benefits that exceed the costs. It can be explained by improved efficiency, reduced costs, increased productivity, and enhanced competitiveness reflected in the Hicks–Lindahl income flow.
- An increase in costs for deepening material recycling (X_2) by 1 million UAH leads to a decrease in the Hicks–Lindahl income flow (Y) by an average of 0.977 million UAH. It may be the result of high short-term costs for recycling infrastructure, low efficiency in the use of secondary materials, or a temporary decrease in the effectiveness of other production processes. Therefore, although recycling can bring economic benefits in the long term, in the short term, these costs may reduce the income flow.
- An increase in costs for the installation of filters (X_3) by 1 million UAH leads to an increase in the Hicks–Lindahl income flow (Y) by an average of 1.505 million UAH. This effect is driven by:
  - the reduction of environmental fines and operational costs;
  - the improvement in reputation and employee health.

Investments in environmental technologies generate benefits that outweigh the costs of their implementation, resulting in a significant increase in the income flow.

These adjustments help make the text more concise and logically coherent while preserving its content.

In your study, the model has high statistical significance, with a coefficient of determination of 94.29%, indicating the ability to explain the variation in the enterprise's income flow caused by ecological investments. It allows for the conclusion that there is a significant positive impact of greening on the sustainable development of the enterprise, further confirming the effectiveness of the measures taken.

Therefore, the greening of production not only contributes to environmental conservation but can also become an important tool for improving the financial performance of the enterprise, ensuring its sustainable development and competitiveness in the market [2].

Conclusions. The study determined that the greening of production is a key factor for the sustainable development of an enterprise, as it helps reduce the negative environmental impact and improve economic efficiency. The following conclusions were made:

1. Four main components of production greening can be identified: the implementation of resource-saving technologies, waste recycling, the use of alternative energy sources, and the reduction of harmful emissions into the environment. Each of these components includes a range of environmental measures that directly affect the key parameters of enterprise sustainable development, particularly in reducing energy and raw material costs. Therefore, to determine the economic efficiency of production greening, it's important to assess the cost of each of these measures, which enables modeling their impact on the overall economic outcome through the Hicks-Lindahl model.
2. The Hicks-Lindahl model allows for the evaluation of how various environmental measures (such as the implementation of resource-saving technologies, waste recycling, use of alternative energy sources, and reduction of emissions) impact the sustainable development of an enterprise. Within this model, each environmental measure is considered a separate factor reflected in a multiple regression equation where the variables interact and influence the economic outcome.

3. The multiple regression equation provides the ability to quantitatively assess the impact of each environmental measure on the Hicks-Lindahl income flow, which is a key parameter for evaluating the sustainable development of the enterprise. This economic model allows for justifying investments in environmental innovations and demonstrating their effectiveness in reducing costs and improving the economic stability of the enterprise in the long term.

The prospects for further research include the development of more detailed models to assess the impact of specific environmental innovations on the financial performance of enterprises, as well as studying the long-term effects of production greening in the context of climate change and regulatory requirements.

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