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ASSESSMENT OF THE EFFICIENCY OF MODERN TECHNOLOGIES FOR REDUCING GREENHOUSE GAS EMISSIONS IN INDUSTRIAL ENTERPRISES OF UKRAINE

The object of this research is the problem of greenhouse gas (GHG) emissions, which are one of the main factors of global climate change, which necessitates the creation and implementation of innovative technologies for their reduction. Greenhouse gas emissions have been found to significantly affect ecological and socio-economic systems, creating a number of challenges, such as increased risk of natural disasters, deterioration of public health and increased mortality. This causes significant economic, environmental and social losses. Leading approaches to reducing GHG emissions are analyzed, including carbon capture and storage (CCS), use of renewable energy sources (RES), energy efficiency developments, and biotechnologies for waste reuse. The advantages and limitations of these technologies are studied, as well as their potential for adaptation to the conditions of industrial enterprises of Ukraine. The importance of CCS for reducing emissions at large industrial facilities, such as power plants and cement plants. is assessed, and the important role of RES in reducing dependence on fossil fuels is determined fuel and increasing energy efficiency. The expediency of applying a comprehensive approach to the implementation of these technologies, which covers the improvement of the regulatory and legal framework, the attraction of investments in environmental protection projects, the implementation of international experience and the creation of climate funds to finance the most effective solutions, is substantiated. A new computational mathematical model is proposed, which takes into account the factors of saving resources, reducing costs for environmental protection and obtaining profits from trading carbon quotas. A three-level mechanism for the implementation of measures to reduce GHG emissions is proposed, which includes the development of regional emission reduction strategies, the implementation of programs at the local level, and the creation of centers of environmental and climate culture to coordinate actions between stakeholders. The prospects for the application of innovative technologies in Ukrainian industry as an effective tool for achieving climate goals, reducing the negative impact on ecosystems, and increasing the competitiveness of enterprises have been assessed.

Keywords: *industrial enterprise, greenhouse gases, innovative technologies, capture and storage technologies, energy system.*

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1. Introduction

The issue of reducing greenhouse gas emissions is becoming increasingly urgent in the light of global climate change, and Ukraine, which is a party to international climate agreements such as the Paris Agreement, has an obligation to reduce emissions. Since the industrial sector is one of the largest sources of greenhouse gases in the country, the introduction of modern technologies for their reduction is critically important. Because it is the effectiveness of such technologies that determines the success in achieving climate goals, maintaining the ecological balance and strengthening the competitiveness of enterprises.

However, many Ukrainian industrial enterprises use outdated approaches to managing energy resources and environmental processes, which reduces their efficiency. The implementation of innovative solutions is often complicated by a lack of funding, an imperfect regulatory environment and the absence of clear criteria for assessing the effectiveness of such measures. In this regard, studies that assess the effectiveness of emission reduction technologies are urgently needed to identify optimal solutions and form long-term strategies for decarbonizing industry.

Studies [1, 2] focus on the integration of innovative technologies, such as carbon capture and storage (CCS), the use of renewable energy sources and the optimization of industrial processes. The authors analyze the economic

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and environmental aspects of these approaches, their application in various industries, and also emphasize the importance of state support and international cooperation to accelerate technological transition. Methodological approaches to assessing the effectiveness of environmental technologies are considered in works [3, 4], which offer multi-criteria assessment methods that take into account technical, economic and social indicators. Particular attention is paid to the development of integrated indices that allow assessing the impact of technologies on the overall level of emissions and the effectiveness of their implementation in specific economic conditions. Scientific publications [5, 6], analyze in detail the current state of the industrial sector of Ukraine, its impact on the climate and the main barriers to the implementation of modern emission reduction technologies [7]. The studies highlight the problems of outdated equipment, limited financial resources, low level of awareness of enterprises about available technologies and the need to improve the regulatory environment.

Works devoted to the adaptation of international experience to Ukrainian realities, such as studies [8], which offer examples of successful implementation of technologies in countries with similar economic conditions. Attention is paid to partnerships between the public and private sectors, the use of international investments and grants, as well as the importance of forming effective mechanisms for stimulating enterprises to reduce emissions. In the latest scientific developments described in the works of the European Commission for Climate Research (Greenhouse Gas Protocol) [9], attention is focused on promising technologies, such as green hydrogen, innovative materials for energy saving and digitalization of emission management processes.

Analysis of scientific sources demonstrates significant interest in the topic of assessing the effectiveness of technologies for reducing greenhouse gas emissions, while at the same time identifying a number of gaps. In particular, in the issues of adapting international experience to local conditions, detailed analysis of barriers to implementation and development of integrated approaches to assessing effectiveness.

Despite the availability of research on the implementation of emission reduction technologies, a number of key issues remain unresolved, namely:

1) insufficient analysis of barriers to the implementation of new technologies, when the current conditions of the regulatory, financial and technological environment require detailed study to form effective mechanisms for supporting enterprises;

2) the limited number of recommendations for enterprises in different industries within the framework of the implementation of emission reduction technologies varies significantly depending on the specifics of industrial processes, which requires an industry-specific approach to analysis.

The aim of research is to assess the feasibility and determine the level of effectiveness of the implementation of modern technologies aimed at reducing greenhouse gas emissions at industrial enterprises in Ukraine, taking into account their environmental, technical and economic impact.

2. Materials and Methods

The proposed methodology is aimed at integrating economic, technical and environmental aspects, which allows for a comprehensive and balanced approach to assessing the effectiveness of implementing technologies aimed at reducing greenhouse gas emissions. One of the key elements of the methodology is the development of a multi-criteria assessment system that takes into account such parameters as economic feasibility, the level of environmental impact and social consequences of the use of innovative technologies. The proposed approach creates an opportunity to adapt the developed methods to the specifics of individual industries in Ukraine, ensuring their effectiveness and practicality in different conditions.

3. Results and Discussions

Greenhouse gas (GHG) emissions have become a determining factor in climate change, which encourages the development and implementation of innovative technologies aimed at reducing them. In this context, the study of modern technologies that allow minimizing the impact of industrial processes on the environment is of exceptional relevance [10]. Greenhouse gas emissions significantly affect all the main elements of the "environment-society" system, creating various problems that cause significant direct and indirect economic, environmental and social losses, the main ones of which are presented in Table 1.

Table 1

Environmental, economic and social losses from greenhouse gas emissions by industrial enterprises in Ukraine [11, 12]

Environmental subsystem	Socio-economic subsystem
– Environmental and economic damage from the impact of greenhouse gases, which are both traditional atmospheric pollutants. This is manifested in ecological and socio-economic systems. – Environmental damage from a decrease in the regenerative capabilities of the natural environment. This leads to the destabilization of the ecological balance in ecosystems and their ability to resist anthropogenic pollution. The probability of extinction of at least 10 % of terrestrial species with an increase in the average global temperature by 1 °C and 20–50 % of terrestrial species with an increase in the average global temperature by 3 °C	– Environmental and economic losses from an increase in the number and scale of natural disasters. – Economic losses from changes in economic conditions that may hinder the development of industries. – Economic and social losses from the spread of abnormal diseases. Increased mortality with an increase in average surface temperature, as well as with an increase in the concentration of pollutants in the air caused by an increase in temperature

The magnitude of the probable damage of those consequences that are subject to economic assessment reaches 7.5 % of global GDP, and material losses from extreme and dangerous natural phenomena of a weather and climate nature in Ukraine on average per year amount to at least 0.5 % of GDP. At the same time, in some territories this figure may be 4–5 % of GDP [7, 12]. It was also found that a fairly high level of connection between the magnitude of greenhouse gas emissions and the levels of various risks to the health of the population from the impact of priority air pollutants. It has also been proven that reducing greenhouse gas emissions leads to a decrease in mortality of the population by an average of 30 additional cases per year per 100 thousand population, during the transition to advanced coal combustion technologies [13].

Modern technologies for reducing GHG emissions can be divided into several main groups:

1. *Carbon capture and storage (CCS) technologies*, which involve capturing carbon dioxide generated during industrial processes and storing it in geological formations. CCS is one

of the most promising technologies capable of reducing emissions from large industrial enterprises, such as power plants, cement and chemical plants. CCS projects are related to the capture and storage of carbon dioxide in geological formations and aquifers. Underground reservoirs can be used for long-term storage of carbon dioxide – depleted and operating oil and gas fields, salt formations, and undeveloped coal seams. The latter option provides additional opportunities for the accumulation and use of adsorbed methane. Thus, this physical process allows achieving two goals: to convert greenhouse CO_2 into a solid state and to release a clean energy resource CH_4 in the process of coal seam degassing.

Further focus on traditional energy sources will ensure the demand for environmental technologies, including CCS technologies. CCS projects are characterized by high capital and operating costs, which is the main barrier to their large-scale implementation. However, in the case of CCUS projects, additional volumes of oil, methane, liquid mineral resources obtained as a result of the implementation of such projects make it possible to partially or fully compensate for the costs of capturing and transporting CO_2, and in some cases, to obtain a commercial effect. A threat to the development of CCS technologies in Ukraine is environmental legislation, which is characterized by rather low fines for the negative impact of companies on the environment. The legislation is stable, which stimulates big business to actively implement environmental technologies. At the same time, the development of alternative energy, the introduction of modern technologies for land reclamation, the use of industrial waste, the utilization of associated petroleum gas, etc., also hinder the development of CCS technologies, since the budget allocated by companies for environmental projects is quite limited [14].

2. *Renewable energy sources (RES)*. The use of solar, wind and geothermal energy significantly reduces dependence on fossil fuels, which are the main source of GHGs. The introduction of RES in industry should effectively contribute to both the greening of production and the reduction of energy costs in the long term (Fig. 1).

Fig. 1. Solar energy mini-complex for supplying individual workshops (production areas) of an industrial enterprise [15]

The use of renewable energy sources provides the following key effects:

1) replacing fossil fuels with renewable sources allows for a significant reduction in emissions of carbon dioxide, methane and other greenhouse gases generated during the combustion of traditional energy sources;

2) increasing energy efficiency: RES allows for a reduction in energy losses during its production and transportation, contributing to the optimization of resource use;

3) using own renewable energy capacities reduces dependence on fluctuations in fossil fuel prices and ensures the stability of energy supply;

4) enterprises that implement RES improve their reputation as socially responsible, which has a positive effect on partnerships and public relations [16].

3. *Group of energy-efficient technologies*. Innovations in the field of reducing energy consumption, such as improved thermal insulation systems, modernized equipment and digital monitoring technologies, contribute to reducing emissions through the rational use of resources. One of the most promising areas of energy efficiency is the use of improved thermal insulation systems, which can significantly reduce heat losses in buildings and industrial facilities [17]. Innovative insulation materials, such as aerogels or multilayer membranes, not only provide a high level of thermal protection, but also have a minimal impact on the environment during production and disposal. By implementing such solutions, industrial enterprises can significantly reduce heating and air conditioning costs, which, in turn, contributes to reducing energy consumption and, accordingly, reducing carbon dioxide emissions. Another manifestation of energy-efficient technologies is the modernization of equipment, which involves replacing outdated mechanisms with more modern, more efficient and environmentally friendly analogues. Modernized equipment can help reduce harmful emissions and increase productivity, which makes it attractive from both an economic and environmental point of view [18].

4. *Biotechnology and waste recycling*. The use of biogas obtained from organic waste allows replacing fossil fuels, reducing both the volume of waste and GHG emissions. Biotechnology, which is based on the use of biological processes for waste processing, in particular fermentation, composting and anaerobic digestion, has a wide range of applications. One of the most promising areas is the production of biogas by anaerobic digestion of organic waste, such as food residues, agricultural waste or biological waste from industrial enterprises. The biogas obtained in this process can be used as a source of renewable energy, replacing fossil fuels. This allows not only to reduce greenhouse gas emissions, but also to create economically profitable energy supply models for industrial enterprises [19, 20] (Fig. 2).

Waste recycling also finds its application in the creation of new materials that can replace traditional resource-intensive products. For example, organic waste, wood residues, can be processed into bioplastics or biomaterials that are environmentally safe and subject to complete biological degradation. Such a practice helps reduce dependence on fossil materials, in particular oil, which is the main raw material for the production of conventional plastic products, and contributes to the creation of closed resource use cycles. Bioremediation is a process in which microorganisms or plants are used to remove harmful substances, such as heavy metals or toxic organic compounds. The above technology is especially important for industrial enterprises that generate significant amounts of waste that require special treatment, because biological methods are much cheaper and environmentally safer than traditional chemical or physical approaches [21].

The selection of measures that contribute to the reduction of greenhouse gas emissions is carried out in accordance with the developed economic and mathematical model, the objective function of which is the additional income of industrial enterprises as a result of the implementation of innovative technologies:

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$$D_{add} = \sum_{t=1}^{T}\sum_{i=1}^{I}\left[\begin{matrix} D_{ec} + D_{en} + D_c + D_{met} - \\ (B_i + qD_{erj}) + H_l \end{matrix}\right] a_t \to \max, \quad (1)$$

where D_{add} – the amount of discounted income of the enterprise from the implementation of the measure, taking into account the reduction of environmental costs and the cost of environmental resources, c. u.; D_{ec} – the income generated as a result of reducing environmental costs while reducing the negative impact of the enterprise in the time period, c. u.; D_{en} – the income generated as a result of reducing the use of energy resources in the t-th time period, c. u.; D_c – the income from the sale of reduced emissions on the carbon market in the t-th time period, c. u.; D_{met} – the income from methane utilization for a coal mining enterprise in the t-th period of time, c. u.; B_i – costs of implementing the i-th measure in the t-th period of time, c. u.; I – number of measures being implemented; qD_{erj} – cost of environmental resources included in the production activities of the enterprise in the form of income for donor regions and taxes for recipient regions, c. u.; q – proportionality coefficient that takes into account the share of the cost of environmental resources included in the production activities of an industrial enterprise; H_l – tax benefits for enterprises implementing innovative technologies characterized by a progressiveness coefficient $K_p > 1$, c. u.; T – calculation period of time, year; a_t – discount coefficient, fractions of units.

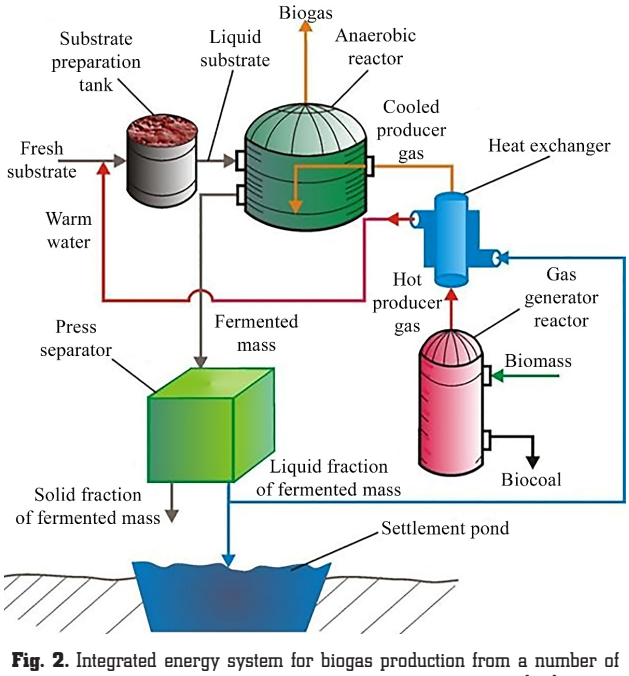

Fig. 2. Integrated energy system for biogas production from a number of bioconversion crops based on an industrial enterprise [20]

The following objective restrictions must be taken into account in the economic and mathematical model: the costs of implementing measures must not be less than the minimum required budget funds. This will stimulate the attraction of extra-budgetary investments. Also, these expenses should not exceed the total amount of funds coming from various sources of financing:

$$B_{bud} \le B_{I,t} \le \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} I_{i,t,j}, \quad (2)$$

where $I_{i,t,j}$ – the amount of funds coming from the j-th source of financing of the i-th option of measures to reduce emissions in the t-th period of time, in USD; J – the number of sources of financing; B_{bud} – the minimum necessary budget funds that allow stimulating the attraction of extra-budgetary investments in this area.

The implementation of measures to reduce greenhouse gas emissions should contribute to improving the quality of the environment:

$$U_2 \le U_1, \quad (3)$$

where U_1 and U_2 are the ecological and economic damage, respectively, before and after the implementation of measures, in USD.

Practical significance. Based on the proposed methodological approach to assessing measures that contribute to reducing greenhouse gas emissions, it is possible to develop a strategy for reducing emissions of these gases by industrial enterprises of Ukraine.

Prospects for further research. This already involves studying the interests of the subjects of the process of reducing greenhouse gas emissions, and the list of stakeholders of this process includes regional authorities, industrial enterprises, non-governmental organizations, and the population [22]. Systematization of areas of activity to reduce greenhouse gas emissions and a description of the interests of the subjects of this process are presented in Table 2.

The first level of implementation of the mechanism involves the development of a strategic goal of regional reduction of greenhouse gas emissions by industrial enterprises of Ukraine, coordination of its phased achievement. As well as the development of regional programs for reducing greenhouse gas emissions, energy conservation and increasing energy efficiency. The authorities ensure the harmonization of regional legislation taking into account the climate factor, the creation of a data bank of innovative technologies, promotes the introduction of innovative technologies and renewable energy sources. And also creates conditions for the development of an institutional framework for trading in GHG emission quotas and the introduction of market mechanisms for attracting investment resources to the industry. To stimulate the development and implementation of the most effective projects aimed at reducing greenhouse gases, a regional climate fund is being created [23].

The second level of implementation of the mechanism involves conducting an inventory of greenhouse gas emissions by industrial enterprises of Ukraine, assessing the potential for reduction by industrial enterprises. The management of the enterprise develops a list of measures that contribute to the reduction of greenhouse gas emissions and carries out verification according to the criterion of the economic and mathematical model [24]. The third level of implementation of the mechanism involves the creation of a center for ecological and climate culture and information. This center serves as a link between the population, non-governmental organizations, authorities and business, ensuring the dissemination of reliable information about the problem under study and methods for mitigating anthropogenic impact on the climate system.

Table 2

Proposals for ensuring the participation of stakeholders in order to reduce greenhouse gas emissions by industrial enterprises of Ukraine

Subjects	Characteristics of interests	Directions of implementation and use
Regional authorities	1. Timely achievement of obligations to reduce greenhouse gas emissions and energy conservation. 2. Minimization of costs of achieving the stated goals. 3. Attracting investments for the implementation of innovative technologies that reduce greenhouse gas emissions and increase the energy efficiency of the enterprise	1. Development and implementation of sectoral target programs. 2. Improvement of the legislative and regulatory framework taking into account the climate factor. 3. Development and implementation of economic mechanisms for stimulating innovative activity, which increases energy efficiency. 4. Use of renewable energy sources. Introduction of market mechanisms for attracting investment resources. 5. Creation of a climate fund, which stimulates the development and implementation of the most effective projects invested in reducing greenhouse gases
Industry	1. Maximization of profits. 2. Optimization of taxation. 3. Increasing competitiveness. 4. Creating a favorable image	1. Implementing of new technologies. 2. Expansion of the range and improvement of the quality of manufactured products. 3. Reduction of the cost of products. 4. Use of low-carbon fuels
Non-governmental institutions	1. Informing the public about the problems associated with climate change. 2. Ensuring control over the activities of industrial enterprises and the introduction of new technologies. 3. Ensuring interaction of stakeholders: government – business – population	1. Creation of independent media and a center for ecological and climate culture and information. 2. Compilation of climate ratings of enterprises. Dissemination of experience in innovative technologies. 3. Holding conferences, meetings, round tables with the participation of all stakeholders
Population	1. Meeting the needs for a high-quality environment. 2. Obtaining complete and objective information about the state of the industry. 3. Exercising the right to public control over the activities of government bodies and enterprises	1. Formation of effective demand for low-carbon products. 2. Fulfillment of energy saving requirements in everyday life and at the workplace. 3. Creation of independent public organizations that ensure control and dissemination of reliable information. 4. Holding public events

4. Conclusions

Modern technologies aimed at reducing greenhouse gas emissions are studied, including carbon capture and storage technologies, the use of renewable energy sources, the use of energy-efficient innovations and the introduction of biotechnology for waste reuse. The study makes it possible to analyze the advantages and disadvantages of each of the presented technologies, in particular their impact on the economy, ecology and the social sphere. And also, to identify key obstacles to their widespread implementation, such as high financial costs, imperfect legal framework and the presence of technical restrictions. The possibilities of reducing greenhouse gas emissions through the use of these technologies at industrial enterprises of Ukraine are assessed. And their contribution to reducing environmental damage and increasing the level of energy efficiency of domestic enterprises is also determined.

It is proved that to achieve effective reduction of greenhouse gas emissions, an integrated approach is necessary, which includes technical modernization of enterprises, adaptation of best international practices, improvement of environmental legislation and stimulation of investments in environmental projects. A model is developed that allows assessing the effectiveness of measures to reduce greenhouse gas emissions, taking into account such factors as resource saving, reduction of environmental costs and obtaining profits on the carbon quota trading market. A three-level mechanism for implementing measures aimed at reducing greenhouse gas emissions is proposed, which involves improving the legislative framework, implementing programs, creating climate funds, and organizing centers of ecological and climate culture for effective coordination of actions between stakeholders.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship or other, which could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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