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TAKING INTO ACCOUNT ENVIRONMENTAL CONSTRAINTS ON EMISSIONS IN ECONOMIC MODELS LONG-TERM FORECASTING OF ENERGY CONSUMPTION (REVIEW OF PUBLICATIONS)

Abstract. *An overview of existing methodological approaches for long-term forecasting of energy consumption at various hierarchical levels of economic structure (in individual sections, sections, groups, classes, and industries or services) is provided for the development of mathematical dependencies for accounting for restrictions on emissions of greenhouse gas and air pollutants in further work. These approaches will complement the system of mathematical models for long-term forecasting of energy consumption in the country's economy, which were previously used at General Energy Institute of National Academy of Sciences of Ukraine. It is proposed to use mutually agreed mathematical models of three types to study the long-term development and functioning of energy consumption: models of the life cycle of the main technological facilities at the enterprise level, simulation models of the formation of transit flows of energy resources through the territory of Ukraine and optimization models for predicting the development of a certain section (industry) of the economy, which are generally applied in the energy supply system in the country. Also, for energy-intensive sections of the economy as electricity consumers, it is necessary to take into account: the manufacturer of products that has a reference indicator of emissions, with or without interchangeability of electricity and fuel, calculates direct emissions from production plus indirect emissions from consumed electricity. In other cases, they are calculated on the basis of a reference indicator of emissions for fuel or technological processes, and (or) adjusted for the ratio of direct emissions to the sum of direct and indirect emissions.*
Keywords: fuel and energy resources, modeling, forecasting, electricity consumption, greenhouse gases.

1. Introduction

Environmental problems of our time exacerbate the general economic crisis in the country. This occurs under the influence of long-term factors of environmental pollution and worsens during military operations. Increasing the rate of fossil fuel use increases the processes of warming the environment on the planet. Average temperature records published daily are a reflection of how human activity affects the environment and what irreversible results we will get already approximately after 2030. Limiting the amount of fossil fuel burning is vital in combination with the simultaneous development of the economy on the basis of energy conservation, energy efficiency, and the implementation of measures to prevent climate change, which is primarily related to the reduction of greenhouse gas (GHG) emissions. The window of time to prevent dangerous climate change is rapidly shrinking, and getting rid of fossil fuel dependence is one way to solve this problem.

The main official document that provides estimates of actual GHG emissions is the National Inventory of Anthropogenic Emissions from Sources and Absorption by Sinks of Greenhouse Gases in Ukraine, which is annually developed, published, and provided to the Conference of the Parties to the United Nations Framework Convention on Climate Change.

2. The main part

The purpose of the article is to review the existing methodological approaches in individual sections (sections, groups, classes) and productions (when providing services) for the development of further work on mathematical dependencies regarding taking into account restrictions on emissions of greenhouse gases and pollutants into the atmosphere, which will complement the system of mathematical models of long-term forecasting energy consumption in the country's economy, which were developed at General Energy Institute of National Academy of Sciences of Ukraine.

Analysis of the latest research and publications in which the solution to this problem was initiated. One of the important publications that take environmental factors into account in long-term forecasting is the TIMES Model-Ukraine [1]. It was developed according to the methodological recommendations of international organizations regarding the calculation of energy and environmental forecasts. In particular, the recommendations of the Secretariat of the UN Framework Convention on Climate Change regarding the development of national communications. As part of the project, the TIMES-Ukraine model was improved thanks to the joint efforts of experts from the Institute of Economics and Forecasting of National Academy of Sciences of Ukraine and the Technical University of Denmark. This model is important for our research due to the possibility of assessing the potential of energy saving at different levels of economic construction, identifying the share of renewable energy sources, attracting new types of energy and fuel, and prioritizing investments based on cost optimization. It forecasts the dynamics of greenhouse gas emissions, identifies possible threats to the country's energy supply and determines measures to prevent them, and assesses the impact of energy, economic, ecological, climate, industrial, agricultural, transport, innovation, and other policies on the development of energy, study the advantages and risks of integration processes and international obligations in the energy, environmental, climate and other spheres. The TIMES-Ukraine model is largely based on national statistical classifiers, including KVED-2005 and KVED-2010, which are aligned with NACE, CPA, and CN (UN classifications), which were significantly updated after the last calibration of the model in 2012. Inclusion to the data model for 2013–2015, which is based on new revisions of statistical classifiers, in most cases required revision of the data processing algorithm.

In the TIMES-Ukraine model, the main areas of economic development were laid: agriculture, food and pharmaceutical industry, and technology and services (primarily, information technologies, research, education, and health care) will accelerate their development by the end of 2010–2020. Attention was paid to the technological renewal of energy-intensive sections and industries, primarily ferrous metallurgy, as one of the main export-oriented sections for currency replenishment of the economy.

Within the framework of this project, four main scenarios were developed ("No action", "Baseline", "National strategies", and "Low-carbon society") and a set of sensitivity scenarios developed as variations of the base scenario Energy efficiency.

The energy efficiency policy, which was laid down in this model, includes measures aimed at improving the efficiency of the use of energy resources and the implementation of energy saving, which is accompanied by an increase in the quality of the provision of energy services. To achieve the goals, the following (main) measures are presented, which have not lost their relevance today: thermal insulation of buildings; cogeneration introduction at new and existing power plants; increasing the efficiency of the use of fossil fuels in the production of heat (that is, through reconstruction and replacement of technology); advanced energy efficiency technologies in industry; new agricultural technologies to reduce fossil fuel consumption [1].

The scenario of reducing greenhouse gas emissions in the economy, which is currently the most important in our research, takes into account: a significant decrease in the energy intensity of the economy, a significant increase in the share of renewable energy sources in the UPP and the generation structure (this statement is false since it is not clear how the electricity deficit and frequency fluctuations will be covered beyond the normative indicators), achieving 47% share of NPPs in the generation structure in 2035, the introduction of Unit No. 3 of the Khmelnytsky NPP in 2025 (will not happen), European environmental requirements for TPPs, introduction of new balancing capacities. It also emphasized the need for a new high-quality generation forecasting system at wind and solar power plants, the existence of a "green" tariff until

2030 in accordance with the current legislation, the goals of other national strategies and plans (industrial development, transport, etc.), a reduction of greenhouse gas emissions by 80% from the level of 1990.

In general, TIMES-Ukraine is a linear optimization model of the energy system that belongs to the class of MARKAL/TIMES models. It provides a technological representation of the energy system (bottom-up) to assess energy dynamics in the long term. The structure of the TIMES-Ukraine model corresponds to the methodological approach of the State Statistics Service of Ukraine (aligned with the methodology of Eurostat and the IEA) for energy statistics. The model developers used economic and energy statistics for the years 2005–2012, and the model was fully calibrated for the years 2005, 2009, and 2012 (except for the process parameterization, other model parameters were properly estimated to reflect the energy balance; any of the calibrated years can be used as the base year for calculations). Later, the model database was supplemented with data for 2013–2015, which made it possible to revise the parameters of energy technologies. In addition, some key inputs such as energy production, international trade, power plant, and boiler production figures have also been included for 2016–2018 [1].

The sources of information embedded in this model are also taken into account in other economic and mathematical models. These are statistical observations of the State Statistics Service of Ukraine; data from the Ministry of Energy of Ukraine, the Ministry of Economy of Ukraine, the Ministry of Environmental Protection and Natural Resources of Ukraine, the Ministry of Internal Affairs of Ukraine, the Ministry of Development of Communities, Territories, and Infrastructure of Ukraine, the State Agency for Energy Efficiency and Energy Saving, energy generating companies and supplier companies, etc.; - data from IEA (in particular ETP, E-TechDS), DIW Berlin, IAEA, OECD, DEA and others (used to determine promising energy technologies and their technical and economic characteristics); data from industry associations and public unions (Bioenergy Association of Ukraine, Ukrainian Wind Energy Association, Ukrainian Renewable Energy Association and others) and companies (Energoatom, Ukrenergo, DTEK, Naftogaz, etc.).

The study continues with the following indicators as the structure of demand in the end-use sectors (which corresponds to the structure of models of other European countries); long-term indicators of macroeconomic development, based on data from the National Bank of Ukraine, the Ministry of Economy of Ukraine, including the Consensus forecast of the country's economic development, data from leading rating agencies, the IMF, the World Bank, leading economists, energy experts, and others, price forecasts for the main energy resources (based on World Bank data); forecast of the demographic situation in Ukraine (according to the Institute of Demography and Social Research of the National Academy of Sciences of Ukraine and the Department of Economic and Social Affairs of the United Nations); GHG emission coefficients (based on data from the National Cadastres on anthropogenic emissions from sources and absorption by sinks of greenhouse gases in Ukraine).

Unfortunately, there is no access to the model codes, and since 2015, the volume of statistical observations has significantly decreased (11-MTP and its modifications no longer exist on the website of the State Statistics Service). Therefore, this model, despite some announced updates for 2016–2018, cannot be used now. However, many of the theoretical and methodological approaches outlined in it are widely used by specialists in modeling and forecasting the state of Ukraine's energy sector, taking into account the recommendations of the Secretariat of the UN Framework Convention on Climate Change regarding the development of national messages. Namely: assessment of the optimal technological structure of the energy system based on the criterion of minimizing the total discounted value of the system, analysis of the structure of energy, material, and financial flows in the system taking into account trade in resources, assessment of possible investment prioritization measures based on cost optimization, forecasting of the dynamics of greenhouse gas emissions, identification of threats the country's energy supply and determination of measures to prevent them, assessment of the impact of energy, economic, environmental, climate, industrial, agricultural, transport, innovation, and other policies on the development of energy, research of advantages and risks of integration processes and international obligations in energy, environmental, climate and other areas [1].

The next important publication that examines the impact of greenhouse gas emissions into the atmosphere in the mining industry as a section of the national economy, namely coal mines, is the work of

V. Makarov, M. Perov "Assessment of the prospectiveness of operating coal mining enterprises". The authors propose to introduce the "Integral Indicator of Perspective". This indicator includes volume factor, technological factor, financial and economic factor, safety factor, social factor, and environmental factors. The authors note that "a factor that should be taken into account when determining the integral coefficient of the attractiveness of mines in the conditions of Ukraine's accession to the EU is the coefficient of environmental acceptability K6. The basis for calculating the environmental acceptability factor is the value of specific methane emissions during coal mining:

$$K_6 = \frac{Q_i^{\min}}{Q_i},$$

where Q_i is the specific emissions of methane per 1 ton of production at the *i*-th mine, m^3/t; $Q_i^{\min}$ – minimum methane emissions per 1 ton of production from a sample of mines, UAH.

It is proposed to determine the prospects of mines in Ukraine by the dimensionless integral coefficient of prospects Ri according to the formula:

$$R_i = \sum_{j=1}^{m} \left(K_{i,j} \cdot a_j \right),$$

where *m* is the number of factors of functioning of coal mining enterprises; $K_{i,j}$ is the *j*-th factor of *i*-th mine; a_j is a dimensionless coefficient of the importance of the *j*-th single factor of the functioning of coal mining enterprises, which reflects the degree of importance of this factor from the standpoint of its influence on the technical and economic level of the mine. The following values of dimensionless coefficients of significance are used for calculations: a_1 = 0,20; a_2 = 0,22; a_3 = 0,18; a_4 = 0,10; a_5 = 0,14; a_6 = 0,16 [2].

The difficulty of applying this model for our study is to determine dimensionless coefficients of significance for other sections of the industry, as well as sections, groups, and classes in the mining industry itself.

Another publication investigating the impact of environmental restrictions is "Mathematical model of the optimal structure of coal production for thermal power plants of Ukraine with taking into account environmental constraints", authors: Makortetsky M.M., Perov M.O., Novitsky I.Yu. [3]. Here, a mathematical model for optimizing the provision of domestic TPPs with coal products with general thermophysical properties at the minimum price and costs associated with the tax on emissions of harmful substances into the atmosphere from burning coal and the costs of installing gas cleaning equipment is proposed and tested. The model allows calculations of the supply of coal products of the required type based on forecast quality indicators at world market prices, taking into account environmental restrictions. It describes the factors that are calculated by coefficients, developed mathematical dependencies, and the range of applicability of these dependencies. This model, with some modification, can be used to calculate the emissions of coal-fired power plants of the gas group in our further study of energy consumption of Section D "Supply of electricity, gas, steam, and air conditioning" and power plants (units) of sections (sections, groups, classes) of extractive and processing industry.

M.I. Kaplin, V.M. Makarov, and T.R. Bilan consider in the work "The balance-optimization model of the Ukrainian power sector and fuel industries mutually coordinated operation in the view of European environmental legislation ", a mathematical model expressed by a system of equations, which provides a general presentation of the product-production relations of the extractive industries and thermal energy, with details to a separate mining enterprise and power plant. Its practical implementation is possible only in the presence of detailed initial information on costs and releases of individual manufacturers. This model, like the previous one, can also be used to calculate greenhouse gas emissions of power plants (block plants) operating on coal in the industrial sector of the economy [4].

V.M. Makarov, M.I. Kaplin, and M.O. Perov in another article "Consideration of environmental constraints in modeling the development of coal industry" developed a model for optimizing the technological development of coal mining taking into account the capture and utilization of mine methane in the form of a mixed-integer linear programming problem. The objective function of the model is the cumulative forecast production of all mines, and the optimization variables are binary variables of the intensity of use of options for modernization of individual sections – mine pits, as well as binary variables of the intensity of use of degassing equipment designed for the capture and utilization of mine methane [5].

The next important article for forecasting the consumption of energy resources for the long term is "Modeling of country energy supply by structure of product energy balance data in the format of the International Energy Agency ", authors: Mykola Kaplin, Tetiana Bilan, Ihor Novytsky. They proposed the structure of the production type model according to L.V. Kantorovych using the expanded nomenclature of the product energy balance of Ukraine, as well as the IEA energy balance indicators for Ukraine, which made it possible to determine mutually agreed and balanced volumes of production and supply of energy carriers using the minimum volume of open information sources regulated by the current legislation of the country [6]. The methodology outlined in this article has already been used earlier for the "Consumption" part of the General Energy Institute of NAS of Ukraine [7].

T.P. Nechaieva considers the reduction of greenhouse gas emissions in the work "Assessment of the expediency of introducing advanced nuclear reactors with regard for requirements to the reliability and ecological compatibility of the operation of Ukrainian UPS" [8]. She believes that with the increase in CO2 emissions fees, which is expected in the future with the introduction of a long-term strategy of low-carbon development and the carbon market, the implementation of nuclear technologies has significant economic advantages, compared to organic fuel technologies. In particular, the cost of coal and gas technologies when they are used in variable modes of operation increases significantly with an increase in carbon emissions fees at constant cost of small light water modular reactors used in the same maneuverable modes of operation. Our study will take into account the reduction of coal consumption at power stations of section D and block stations of sections B and C (industry) with a simultaneous increase in electricity production at modular nuclear reactors and a significant reduction in greenhouse gas emissions.

In the article N.V. Parasyuk, M.V. Lebid researched "Prospects of implementing the internal system of quota trade for greenhouse gas emission in Ukraine" [9]. The authors envisage four key strategies in the production of heat and electricity: increasing the spread of renewable energy sources; expanding the use of combined production of heat and electricity; transitioning to low-carbon fuel; increasing energy efficiency in the economy. To this end, they propose 1) Creation of a legal basis for the national emissions trading system (ETS); 2) Collection of reliable and accurate data at the level of enterprises/installations; 3) Determination of the method of allocation of quotas for greenhouse gas (GHG) emissions. Problematic issues of development of control indicators (benchmarking) include the differentiation of indicators by fuel types and production technologies, for example: – electric power industry: coal/gas; – metallurgy: March/oxygen converter technology; – cement: wet/dry method; – economic impact: quota distribution method (according to changes in production volumes or fixed). 4) Creation of a national registry of installations and a trading platform. Types of activities that are planned for inclusion in the STV system are energy, iron and steel production, coke, ferroalloys, cement and limestone production, and oil refining. Preliminarily to STV in the energy sector, it is planned to include installations with a capacity of >20 MW: 44 CHPPs, boiler rooms at industrial enterprises, 14 TPPs, 72 compressor stations of JSC "Ukrtransgaz" and ~1,000 municipal boiler rooms. It is also advisable to include these studies in the assessment of measures, volumes, and sources of emissions in sections B, C, and D of the national economy.

Parasyuk N.V., Nechaieva T.P., and Lebid M.V. in the article "Evaluations of benchmarks for greenhouse gas emission in engineering under the emissions trading system of Ukraine" defined the Rules for taking into account electricity flows in the calculation of benchmarks and allocation of quotas. The greenhouse gas (GHG) emissions trading system considers electricity producers and electricity consumers separately. Separately for electricity consumers: at the manufacturer of products that has a reference indicator, with interchangeability of electricity and fuel, direct emissions from the production of products plus indirect emissions from consumed electricity are calculated. In this case, the quota is calculated on the basis of the benchmark for this type of product with an adjustment for the ratio of direct emissions to the sum of direct and indirect emissions. In the case when the producer of products has a reference indicator, but without interchangeability of electricity and fuel, direct emissions from the production of products are also calculated, and the quota is determined on the basis of the reference indicator for this type of product. A producer of products that do not have a benchmark, but the installation is located in the ETS, the benchmark is not calculated, and the quota is calculated based on the benchmark for fuels or processes. Currently, no reference indicator is calculated for the production of products outside the STV, and no quota is provided [10].

Leshchenko I.Ch. the work "A system of mathematical models for studying the prospects of functioning and development of gas industry under current conditions" examines the life cycle models (LSC) used in the extraction, transportation, and storage of gas (section D). This is the MZH of a technological pair – "workshop - linear section", MZH of underground gas storage, and MZH of a typical gas deposit. A simulation model of the formation of transit flows through the country's GTS and an optimization model for forecasting the operation and development of the gas industry are applied. They form the Database of technological objects of the gas industry and gas markets. In general, a new methodical approach is proposed for the study of the long-term development and functioning of the country's gas supply system, which differs from the existing ones by the use of mutually agreed mathematical models of three types – models of the life cycle of the main technological objects of gas extraction, transportation and storage in a deterministic-stochastic formulation, a simulation model the formation of transit flows through the GTS of Ukraine and the optimization model for forecasting the development of the gas industry. In the updated optimization model for the study of the long-term development and functioning of the gas industry, it is proposed to use a combination of criteria – minimizing the cost of services for providing the country with natural gas, taking into account the fact that part of the costs depends on the volume of activity of the technological facilities of the industry, and the other – on their installed capacity, and minimizing the cost of gas for domestic consumers. By introducing additional restrictions that were not used before, the updated model takes into account the conditions of incomplete loading of the gas transportation system, reverse gas supplies, the possible construction of a regasification terminal, changes in the structure of the GTS, and the extraction of unconventional gases in Ukraine. The expediency of implementing the optimization model in the MathProg modeling language, which allows for sufficiently transparently describing the logic of the mathematical model, directly using binary variables, which is quite problematic in other optimizers, has also been confirmed. It has been practically proven that the use of the GLPK optimizer allows solving large-dimensional problems with binary variables, which include the task of forecasting the functioning and development of the gas industry, within acceptable time frames [11].

The authors of the article "Overall estimation of the potential of GHG reduction in Ukraine's oil and gas industry by 2040" Leshchenko I.Ch., and Yeger D.O. considers all the infrastructure necessary for the exploration and development of deposits, extraction of hydrocarbons, preparation for transportation, processing, delivery to the market, and the final consumer in accordance with the Guidelines for National Greenhouse Gas Inventories developed by the Intergovernmental Panel on Climate Change (IPCC) when determining GHG emissions in the oil and gas industry. The main GHGs produced in the oil and gas industry are carbon dioxide and methane. The analysis of the state of greenhouse gas emissions in the oil and gas industry of Ukraine according to the data of the National Cadastre of anthropogenic emissions from sources and absorption by sinks of greenhouse gases in Ukraine showed that the industry is a large source of methane leaks, which in 2017 accounted for 44% of the total emissions of this greenhouse gas across the country Carbon dioxide emissions from the industry make a small contribution to the country's total emissions of this greenhouse gas and in 2017 amounted to only 3%. Small-scale projects are often sufficient to reduce methane leaks in gas distribution networks, but a significant barrier to their implementation is the lack of motivation of gas distribution companies in carrying out such measures. Reduction of GHG emissions in the consumption of natural gas by the residential and commercial sectors can be achieved by installing modern burners, including household appliances, with "smart" starters; "smart" detectors for closing shut-off and regulating valves in the event of a leak; quality gas meters for all consumers. JSC "Naftogaz of Ukraine" presented a new strategy, which provides for support of basic gas production of JSC "Ukrgazvydobuvannya", development of existing infrastructure and work with the most efficient wells;

limiting drilling by choosing only the best wells, where the company will be sure of a return on investment; implementation of digitization at deposits and updating of the IT infrastructure of the mining system to optimize costs; increase in production of liquid hydrocarbons; involvement of global industry companies in cooperation on depleted large fields and fields with deposits of unconventional gas. It has been established that the main priority for the industry is the reduction of methane emissions from natural gas activities, which is typical for the gas industries of other countries [12].

"Assessment of the greenhouse gases emissions reduction by the coal sector of Ukraine to meet international climate agreements", author Iryna Leshchenko. This publication is important for analyzing the dependence of fuel (electricity) consumption in the mining industry, as one of the significant sources of emissions of greenhouse gases and pollutants in the economy of Ukraine. In 2022, Ukraine, as a Party to the Paris Agreement, submitted the "Updated Nationally Determined Contribution of Ukraine to the Paris Agreement", which sets the goal of reducing greenhouse gas emissions to 35% by 2030 compared to 1990. Ukraine at the 26th Conference Parties on climate change joined the initiative to reduce global methane emissions to this initiative and undertook to reduce methane emissions by 30% from the level of 2020 to 2030. In order to assess the country's ability to achieve its commitments to reduce greenhouse gas emissions gases in general and methane in particular, the article develops forecasts for the functioning of the coal sector both in Ukraine and in the temporarily occupied territories as of December 1, 2021. When developing the scenario of decarbonization of the economy, the commitment that Ukraine took at the 26th Conference of the Parties to stop the construction of new coal-fired power plants and abandon the use of coal fuel by 2035 was also taken into account [13].

For the coal sector until 2040, three scenarios of the development of the coal sector were formed: basic, moderate development, and decarbonization. A characteristic feature of the base scenario is the existing technological state preservation of the coal sector. During the implementation of the scenario of moderate development in the sector, changes are taking place, which are the most expedient and realistic in the existing conditions of Ukraine's development. A characteristic feature of the decarbonization scenario is the introduction of a greater volume of measures aimed at reducing GHG emissions in economic sectors. In particular, this scenario considers the fulfillment of Ukraine's commitment, taken at SOR-26, to end the use of energy produced from coal by 2035, which will require additional investments from 10 to 26.9 billion dollars USA [13]. These scenarios will form the basis of the development of relevant scenarios for the consumption of PER for the economy of Ukraine in the post-war period.

In order to study the conditions for fulfilling obligations to reduce greenhouse gas emissions in accordance with the updated nationally determined contribution of Ukraine to the Paris Agreement and the obligations assumed by Ukraine by joining the Global Methane Pledge, the article develops forecasts of GHG emissions in the equivalent of carbon dioxide and methane emissions from the coal sector until 2040. It was determined that GHG emissions in the coal sector will not exceed the value determined in accordance with the updated nationally determined contribution for all considered scenarios until 2030 [13], [16].

In the article B.A. Kostyukovskyi "The modelling of Power System of Ukraine development for assessment of nationally determined contribution of Ukraine to the Paris Agreement", notes: one of the important tasks in forecasting the development of the unified electric power system (UPS) of Ukraine is the assessment of the volume of greenhouse gas (GHG) emissions in the future under different scenarios of its development. The author points out that "... the correctness of the justification of the Second Nationally Determined Contribution (NDC2) is of great importance, because by adopting overly ambitious goals, Ukraine may face a number of challenges in the future, in particular: - overly limited volumes of GHG emissions that Ukraine can annually achieve may become a factor that will restrain the development of the domestic economy; - lack of financial opportunities to ensure the implementation of the policy of decarbonization of the economy and the implementation of relevant measures, which must be presented in the National Integrated Energy and Climate Plan (NPEC). Failure to take appropriate measures will be a violation of Ukraine's international obligations" [14].

"In the conditions of Ukraine, such a path, i.e., high payments for GHG emissions against the background of the implementation at the expense of auctions of significant new capacities of WPPs and

SPPs, will of course lead to the decarbonization of the economy, but not at the expense of the implementation of decarbonization measures, but at the expense of further stagnation of the Ukrainian economy." The Ministry of Environment declares the possibility and expediency of adopting very ambitious goals – reducing GHG emissions by 65% compared to the level of 1990. The urgent task is to ensure the correctness of GHG emissions forecasts, which, first of all, concerns key categories, in particular the production of thermal and electrical energy at TPPs and thermal power plants, operating on fossil fuels. As a tool, the model and software of the BACS-RVE complex were used, which is currently supported by the NGO "Bureau of Comprehensive Analysis and Forecasts" and was used in the preparation of the Report on the Assessment of Compliance (Sufficiency) of Generating Capacities, which is being developed in compliance with Article 19 of the Law of Ukraine on the Electricity Market NEC "Ukrenergo". Unlike the TIMES-Ukraine model, the BACS-RVE complex provides a detailed consideration of regulatory factors, balance sheet reliability requirements, and the specifics of market regulation of activities in the power industry [14].

The authors B.A. Kostyukovskyi, O.O. Ruban-Maksimets in the article "Improvement of methods for formation of prognostic balance of fuel for TPP of generating companies for formation of prognostic balance of electricity of the UES of Ukraine" proposed an approach to improving the development of the forecast balance of electricity (PBE) due to the introduction into practice of its development of a specialized optimization mathematical model for calculating the necessary general changes in fuel stocks at the TPP. The developed model takes into account the operating modes of the TPP, the need to meet the requirements for limiting pollutant emissions into the air according to the National Emission Reduction Plan (NEPSP), restrictions on the possibility of fuel supply, etc. The model proposed in the article is used for short-term forecasting of the volumes required for fuel combustion, taking into account the presence of restrictions on emissions of pollutants into the air with the determined possibilities of electricity production at different groups of power units, the possibility of general fuel supply for all TPPs, a more reliable forecast of electricity production at individual TPPs provided PBE according to retrospective data. The improvement of the PBE formation method can be based on the developed mathematical model for optimizing the coverage of monthly electricity balances by separate groups of TPP power units with similar technical and economic indicators [15].

However, the specified methodical approaches to the formation of PBE can be used in the formation of long-term balances both from the side of production and from the side of consumption, since the production of electricity and thermal energy partly takes place not only at large power plants but also at power plants of enterprises of sections of the economy (block-stations).

Important publications for taking into account environmental restrictions on emissions of greenhouse gases and pollutants in the context of long-term forecasting of energy consumption are the works of M.M. Kulyk, which were recently published by Springer Publishing House and a collective monograph by Naukova Dumka Publishing House [17]–[18]. Also, the work of N.Yu. Maistrenko is taken into account [19].

3. Conclusions

The article considers various economic and mathematical models that take into account the impact of emissions of greenhouse gases and pollutants into the environment during the functioning of the main energy-intensive sections of the economy: extractive industry (extraction of coal, oil, and gas), processing industry (including oil refining), electricity supply, oil, gas and air conditioning (in it: production of electricity at power plants). It is proposed to use mutually agreed mathematical models of three types for the study of long-term development and functioning of energy consumption: models of the life cycle of the main technological objects at the enterprise level, simulation models of the formation of transit flows of energy resources on the territory of Ukraine, and optimization models for forecasting the development of a certain section (industry) of the economy, which in general in the form applied in the energy supply system in the country.

Also, for energy-intensive economy sections as consumers of electricity, it is necessary to take into account: the manufacturer of products that has a reference indicator of emissions, with interchangeability of electricity and fuel or without such interchangeability, direct emissions from the production of products plus indirect emissions from consumed electricity are calculated. In other cases, they are calculated on the basis of a reference indicator of emissions for fuel or technological processes, and (or) with an adjustment for the ratio of direct emissions to the sum of direct and indirect emissions.

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ВРАХУВАННЯ ЕКОЛОГІЧНИХ ОБМЕЖЕНЬ НА ВИКИДИ В ЕКОНОМІЧНИХ МОДЕЛЯХ ДОВГОСТРОКОВОГО ПРОГНОЗУВАННЯ ЕНЕРГОСПОЖИВАННЯ (ОГЛЯД)

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Анотація. *Огляд існуючих методичних підходів для довгострокового прогнозування енергоспоживання на різних ієрархічних рівнях побудови економіки (в окремих секціях, розділах, групах, класах та виробництвах або наданні послуг) надано для розроблення в подальшій роботі математичних залежностей щодо врахування обмежень на викиди парникових газів та забруднюючих речовин в атмосферу. Ці підходи доповнять систему математичних моделей довгострокового прогнозування енергоспоживання в економіці країни, які раніше застосовувались в Інституті загальної енергетики НАН України. Запропоновано використати взаємоузгоджені математичні моделі трьох типів для дослідження довгострокового розвитку та функціонування енергоспоживання: моделі життєвого циклу основних технологічних об'єктів на рівні підприємства, імітаційні моделі формування транзитних потоків енергоресурсів територією України та оптимізаційні моделі прогнозування розвитку певної секції (галузі) економіки, які в загальному вигляді застосовані в системі постачання енергоресурсів в країні. Також для енергоємних секцій економіки як споживачів електроенергії необхідно врахувати: у виробника продукції, яка має контрольний показник викидів, з взаємозамінністю електроенергії та палива або без такої взаємозамінності, розраховуються прямі викиди від виробництва продукції плюс непрямі викиди від спожитої електроенергії. В інших випадках вони обчислюються на основі контрольного показника викидів для палива або технологічних процесів та (або) з коригуванням на відношення прямих викидів до суми прямих і непрямих викидів.*

Ключові слова: паливно-енергетичні ресурси, моделювання, прогнозування, споживання електроенергії, парникові гази.

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