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GEOINFORMATION ANALYSIS OF THE PROSPECTS FOR THE DEVELOPMENT OF RENEWABLE ENERGY SOURCES IN UKRAINE, TAKING INTO ACCOUNT THE REMOTENESS OF ELECTRICITY CONSUMERS

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The article explores the prospects for the development of renewable energy sources (RES) in Ukraine, taking into account the territorial remoteness of electricity consumers. The main goal of the work is to determine the most appropriate regions for the implementation of RES, taking into account geographical features and energy consumption needs. The study analyzed spatial data on available RES resources, assessed the impact of the location of energy facilities on their efficiency, and modeled ways to optimize energy transmission to consumers.

The work uses methods of geoinformation analysis and cartographic modeling. The results reveal the most promising regions for the location of renewable energy facilities, emphasize the role of remoteness in the formation of energy losses, and offer practical solutions for reducing electricity transportation costs.

The study provides valuable recommendations for strategic planning of renewable energy development, in particular for government agencies, investors, and energy professionals.

Keywords: *geoinformation analysis, renewable energy sources, remote consumers, energy planning, GIS, energy infrastructure, economic efficiency, sustainable development.*

ГЕОІНФОРМАЦІЙНИЙ АНАЛІЗ ПЕРСПЕКТИВ РОЗВИТКУ ВІДНОВЛЮВАЛЬНИХ ДЖЕРЕЛ ЕНЕРГІЇ В УКРАЇНІ З УРАХУВАННЯМ ВІДДАЛЕНОСТІ СПОЖИВАЧІВ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ

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У статті досліджено перспективи розвитку відновлюваних джерел енергії (ВДЕ) в Україні з урахуванням територіальної віддаленості споживачів електричної енергії. Основна мета роботи полягає у визначенні найбільш доцільних регіонів для впровадження ВДЕ з урахуванням географічних особливостей та потреб енергоспоживання. В рамках дослідження проведено аналіз просторових даних про наявність у ресурсах ВДЕ, оцінено вплив розміщення енергетичних об'єктів на їх ефективність та модельовано шляхи оптимізації передачі енергії споживачів.

У роботі застосовані методи геоінформаційного аналізу та картографічного моделювання. Отримані результати виявляють найбільш перспективні регіони для розміщення об'єктів ВДЕ, відзначають роль віддаленості у формуванні енергетичних втрат та пропонують практичні рішення для зменшення витрат на транспортування електроенергії.

Дослідження надає цінні рекомендації для стратегічного планування розвитку ВДЕ, зокрема для урядових органів, інвесторів та фахівців у галузі енергетики.

Ключові слова: *геоінформаційний аналіз, відновлювані джерела енергії, віддалені споживачі, енергетичне планування, GIS, енергетична інфраструктура, економічна ефективність, сталий розвиток.*

List of abbreviations and symbols used:

RES - renewable energy sources

GIS - geographic information systems

PV – Photovoltaic

WT – WindTurbine

Introduction. Sustainable development and ensuring energy security remain key challenges for Ukraine in the context of the global climate crisis, dependence on conventional energy resources, and the need to integrate into the European energy space. Renewable energy sources (RES) are an important component of clean energy, which contributes to reducing greenhouse gas emissions, increasing energy independence, and ensuring a sustainable energy supply.

In world research, considerable attention is paid to the issues of implementing RES, especially using geographic information systems (GIS) for modeling the location of generation facilities, assessing resource potential and optimizing energy costs (U. Shahzad, A. Qazi, NL Panwar). In Ukraine, there is also a growing interest in the development of RES, as evidenced by the works (Kudrya S.O., Budko V.I., Velichko V.V., Zhovmir M.M. Telizhenko O. M.), which analyze the technical, economic and environmental aspects of this area. However, the issue of the influence of the spatial location of energy facilities and the remoteness of consumers on the efficiency of RES still requires more detailed study [1-4].

Previous studies have highlighted the need for an integrated planning approach to ensure sustainable development when scaling up renewable energy sources (RES). The focus has been on analysing the trade-offs between the deployment of RES and the maintenance of key ecosystem services such as biodiversity, water regulation and carbon sequestration. However, insufficient attention has been paid to regional specificities, including political and social constraints that significantly affect the implementation of these initiatives. One key challenge has been the limited use of spatial analysis tools, which has made it difficult to identify areas where RES expansion could pose threats to ecosystems. Although GIS technologies have begun to be used to identify such trade-offs, their integration into the overall planning concept has remained incomplete.

Previous studies have also addressed the importance of aligning policy strategies with public expectations, and have laid the foundation for future work aimed at developing integrated solutions. Such approaches should combine spatial analysis, environmental priorities, and regional political realities, ensuring an optimal balance between energy and environmental interests [5–8].

As we can see, previous research in the field of renewable energy focused on improving methods for assessing the potential of projects, taking into account aspects such as environmental conditions, technical viability and social factors. However, traditional approaches to assessment were often limited by static models that could not dynamically respond to variable factors affecting the performance of projects. This made it difficult for investors and planners to make informed decisions, as they lacked up-to-date and adapted information to optimize projects. One of the main problems was the use of geographic information systems (GIS), which until now were static and did not allow for the creation of interactive models for analyzing different project development options. This became an obstacle to effectively assessing the potential of wind and solar power plants, where geographical location has a significant impact on performance. In addition, previous research did not always take into account the need to involve all stakeholders in the project assessment process. The lack of convenient and interactive tools for interaction between investors, government agencies and planners complicated decision-making and delayed project implementation. Thus, previous approaches were not flexible enough for modern requirements for renewable energy, which led to the need to develop innovative solutions. Modern dynamic web-based GIS tools are able to integrate various data in real time and allow for more informed and adaptive decisions in the process of planning and implementing projects in the field of renewable energy [9-12].

In addition, as can be seen from previous studies in the field of renewable energy, the main focus was on assessing the potential for energy production from renewable sources, but the issue of effective self-consumption of this energy at the level of individual households and small enterprises was not sufficiently taken into account. Many approaches focused on a general analysis of energy production potential, without considering the possibility and need to optimize energy consumption directly at the local level. Typically, studies focused on the optimal location of solar and wind power plants or on the integration of renewable energy sources into existing power grids, without taking into account the specific needs of individual consumers. One of the main problems was the lack of methods for in-depth assessment of the ability of renewable energy to self-consume in specific territories, taking into account local conditions and infrastructure. Geographic information systems (GIS) used previously often did not allow for the taking into account of important aspects, such as variations in energy consumption during the day or the characteristics of consumer groups. Previous work also lacked attention to the relationship between energy production and consumption at the local level. Since the main analysis methods focused on energy networks or general indicators, they could not take into account individual consumer needs.

These limitations have highlighted the need to develop new methods for assessing the self-consumption capacity of renewable energy, taking into account local conditions, seasonal fluctuations in consumption, and other factors. The implementation of new GIS-based approaches allows for more accurate modeling of energy consumption and effective planning at the level of individual consumers [13-17].

Early research in renewable energy focused primarily on identifying the potential of solar and wind power, but often did not consider the full range of factors needed to optimize energy systems. Most work was limited to analyzing available natural resources without considering economic aspects such as infrastructure development costs and integrating renewable energy sources into existing power grids.

It is worth noting that, in previous studies, early approaches also did not always combine the assessment of natural resources with the economic characteristics of projects, which limited the possibilities for creating comprehensive planning models for 100% renewable electricity. Most of these models offered only theoretical data on resources, without linking them to real economic conditions, which made it challenging to apply them for strategic planning at the state level.

Thus, previous studies indicate the need to develop more comprehensive approaches that integrate the assessment of natural resources, economic aspects and opportunities to achieve 100% renewable energy, especially in countries with special conditions such as Bolivia. The implementation of geographic information systems (GIS) allows combining these aspects and creating accurate models that take into account both natural resources and economic, social and technical factors, helping to effectively plan energy systems [18-20].

Research in the field of renewable energy management has mostly focused on assessing the potential of different renewable energy sources, such as solar, wind or hydropower. However, relatively little attention has been paid to an integrated approach to selecting optimal locations for biomass plants, combining environmental, economic and social aspects. Most studies have been limited to analyzing individual characteristics of biomass resources or studying only individual geographical regions, without including a comprehensive approach that takes into account all key factors.

Much of the previous work focused on single indicators, such as feedstock availability or productivity, without considering the importance of selecting locations for biomass facilities with environmental, social and economic requirements in mind. This means that site assessments often did not take into account factors such as environmental impact, infrastructure accessibility or socio-economic conditions, which are critical for the effective operation of such facilities.

These limitations indicate the need for new approaches to assessing potential locations for biomass plants, which include not only resources, but also environmental, social and infrastructure aspects. The use of geographic information systems (GIS) can significantly improve the process by combining data on natural resources, the environment and socio-economic conditions. Such a comprehensive approach provides an accurate and objective assessment for selecting optimal locations for biomass facilities that meet the requirements of environmental sustainability and economic benefit.

Thus, previous studies highlight the need for a comprehensive assessment of locations for biomass plants, which takes into account not only resource availability but also important environmental and social factors. The use of GIS technologies is a key tool for effective planning and management of renewable energy sources, helping to ensure the sustainable development of biomass projects [21-23].

A review of previous studies shows a high interest in the application of geographic information systems (GIS) for the development of renewable energy sources (RES) in different countries. However, despite significant advances in the use of GIS for the assessment of natural resources of solar and wind energy, as well as for the selection of locations for biomass plants, there is still insufficient research on how to integrate these data into a general model of energy system development that takes into account the specifics of specific regions. This especially applies to the factor of remoteness of electricity consumers, which is important for determining the economic feasibility of such projects.

Previous studies, such as the assessment of solar and wind resources for Bolivia or methods for managing renewable energy sources in biomass plants, indicate the potential of GIS to improve the management of energy projects. However, they do not always take into account the issue of remoteness of consumers, which is an important aspect for assessing the efficiency and accessibility of energy projects, especially for remote regions. For Ukraine, which has large territories with different levels of infrastructure development, this problem is even more relevant.

Research mostly focuses on the analysis of natural resources, without sufficiently considering social and economic factors that significantly affect the planning of energy projects. Ukraine has significant potential for the development of renewable energy, but the difficult infrastructure situation and the large gap between the central and remote regions of the country require a new approach to assessing the opportunities for the development of renewable energy, which takes into account not only natural resources, but also infrastructural and economic aspects.

Therefore, our study is an extremely important, relevant and necessary step – as can be seen from the analysis of previous studies. This will allow to expand existing research and offer a comprehensive approach that includes all key factors: natural resources and geographical features of the country. The use of GIS in this context will allow to effectively develop RES, taking into account the needs of remote consumers, and contribute to the sustainable development of the energy system of Ukraine.

The purpose of this study is to determine the territories most suitable for the location of renewable energy facilities, taking into account the geographical remoteness of electricity consumers.

Research objectives cover spatial data analysis, assessment of the impact of logistical factors on energy efficiency, and development of recommendations for optimizing the location of generation facilities. The theoretical basis of the work is the methods of geoinformation analysis, spatial modeling, and economic evaluation.

This article is aimed at solving an important scientific and practical problem – developing approaches to the effective use of renewable energy in Ukraine by taking into account territorial specifics and logistical aspects. The results of the study will contribute to improving the country's energy strategy, increasing economic efficiency and sustainable development of the energy sector.

Relevance of the research topic. Ukraine has favorable natural conditions for the development of renewable energy. Large areas, climatic diversity and availability of resources create the prerequisites for the use of solar, wind, biomass and water energy. In addition, international obligations, such as the implementation of the goals of the Paris Climate Agreement, stimulate Ukraine to reduce greenhouse gas emissions and increase the share of green energy in the overall balance.

At the same time, for the effective implementation of RES, a systematic approach is needed that takes into account geographical, environmental and economic factors. Here, GIS is of particular importance, allowing for a comprehensive assessment and modeling of the energy potential of alternative territories.

Setting the task. The study is aimed at optimizing the location of generation facilities to minimize transportation costs, reduce energy losses, and increase the efficiency of using RES resources.

To achieve the goal, the following tasks have been set:

- perform an analysis of spatial data that reflects the potential of renewable energy sources (RES) in different regions of the country;
- develop an algorithm for determining the correction of RES potential values taking into account the remoteness of electricity consumers;
- determine the energy losses of RES generation depending on the distance between generation facilities and consumption centers on the economic and technical efficiency of RES application.
- provide practical recommendations for integrating renewable energy into the national energy system in order to minimize energy costs and losses.

To accomplish the objectives set in the study, the following methods were used:

- geoinformation analysis for collecting, processing and visualizing spatial data related to the resource potential of renewable energy sources and centers of electricity consumption.
- spatial modeling to identify losses and determine optimal options for placing generation facilities.
- comparative analysis to generalize international experience and its adaptation to Ukrainian realities.

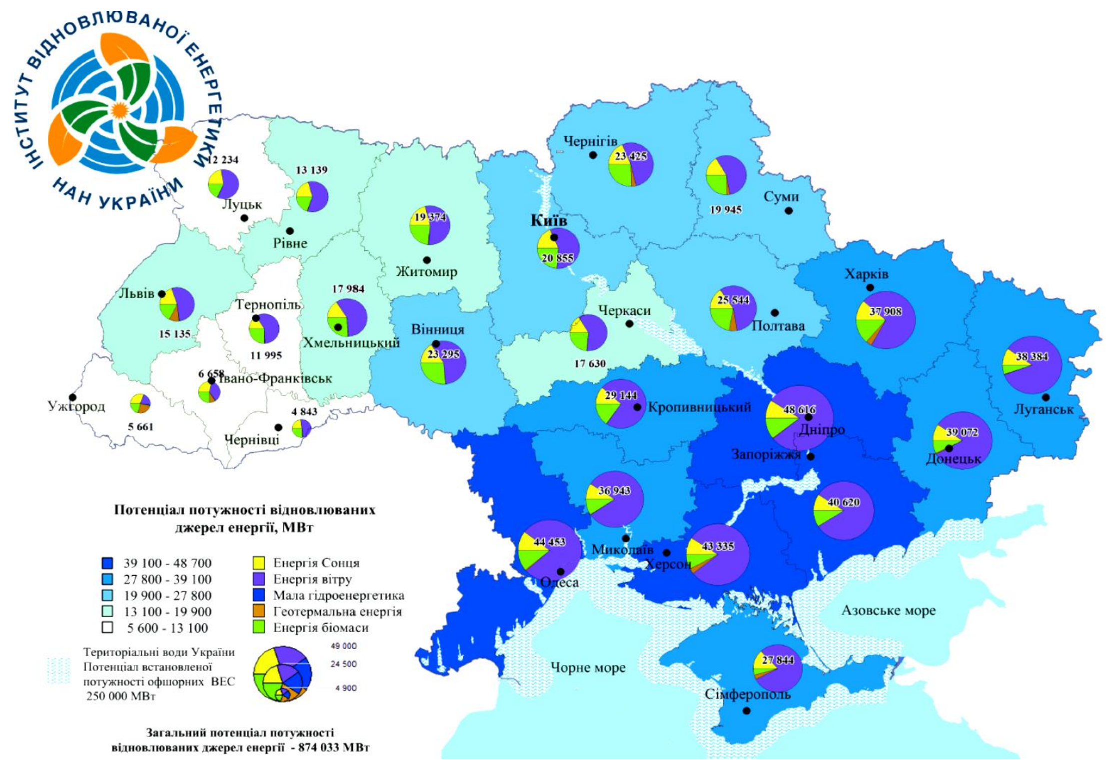
The research results are aimed at:

- justification of effective approaches to the development of renewable energy sources in Ukraine.
- rational use of energy resources.
- improvement of energy infrastructure.
- reducing overall costs when generating electricity using renewable energy.

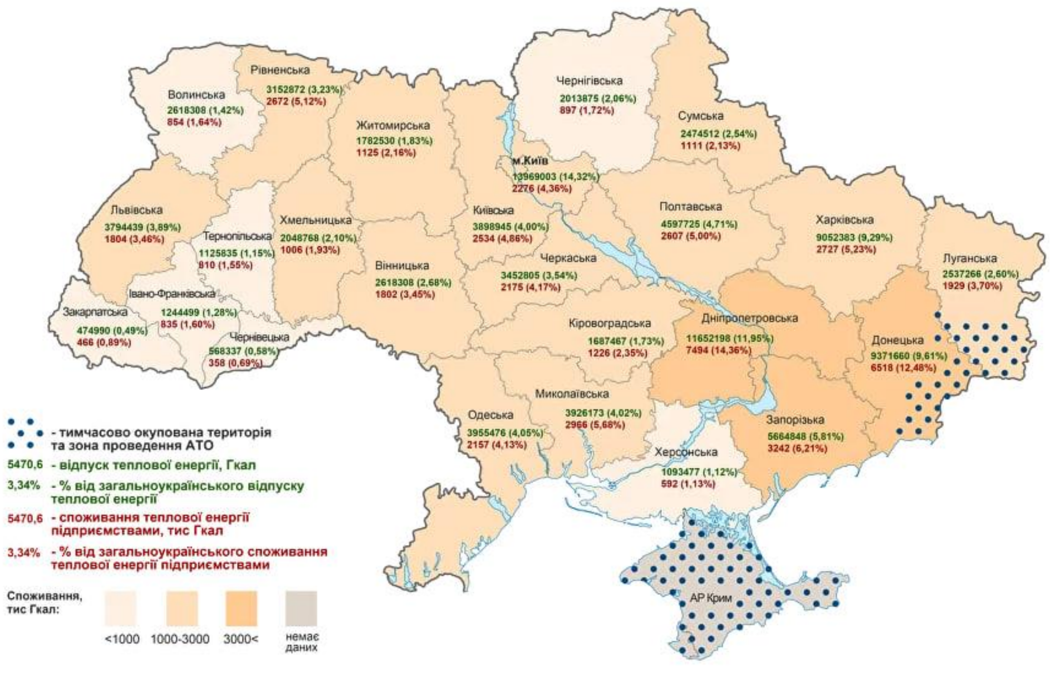
Presentation of the main material. As part of the study of the prospects for the development of renewable energy sources (RES) in Ukraine, taking into account the remoteness of electricity consumers, a comprehensive approach was applied, which included the development of mathematical models, analysis of natural resources, technical limitations and economic aspects of the implementation of RES. The main goal of the study was to create a model that would allow optimizing the placement of energy installations and assessing their efficiency, taking into account the geographical location and needs of consumers.

When using geoinformation technologies, researchers encounter significant difficulties in using well-known GIS software packages (ArcGIS, QGIS, GRASS, OpenOrienteering-Mappe, etc.). The main reasons are the overcomplexity of the interface, the need to master the mathematical apparatus and programming associated with various cartographic systems, high cost, lack of data necessary for analysis, etc. At the same time, a number of powerful mathematical platforms, in particular MATLAB Online and MATHCAD, are presented openly and allow analyzing graphic data (maps) and performing the necessary calculations. Also, the advantage of these application software packages for numerical analysis is their ability to integrate large data sets, mathematical analysis of data sets and visualization of results, which is necessary for solving problems related to the optimization of energy capacities and the analysis of economic efficiency.

Initially, data were collected on natural resources for different regions of Ukraine (solar and wind energy potential, climatic conditions), as well as on the existing energy infrastructure, including the distance to energy consumers [2]. Among the graphical data representing the potential for electricity generation through the use of RES and energy consumption of the power system, the data presented in Fig. 1 were selected.



a



b

Fig. 1. Distribution maps of RES generation (a) and electricity consumption (b) in Ukraine [2]

When creating these maps, researchers usually do not indicate the system of map projection. Therefore, for research, the maps were scaled to a uniform scale, taking into account the largest dimensions of the country: 1316 km from west to east and 893 km from north to south. The territory was divided into squares with sides of 10 km. The resulting files were recognized in a 4-bit system, which allowed to create, depending on the map, division of the territory into 6 and 4 zones, respectively, according to the map data. The converted maps, taking into account the above, allowed for the creation of data arrays reflecting the distribution of RES generation and electricity consumption in Ukraine, presented in Fig. 2. As can be seen from the figures, areas with greater generation potential are located far from areas with relatively high electricity consumption. These circumstances will lead to significant losses of electricity during its transmission.

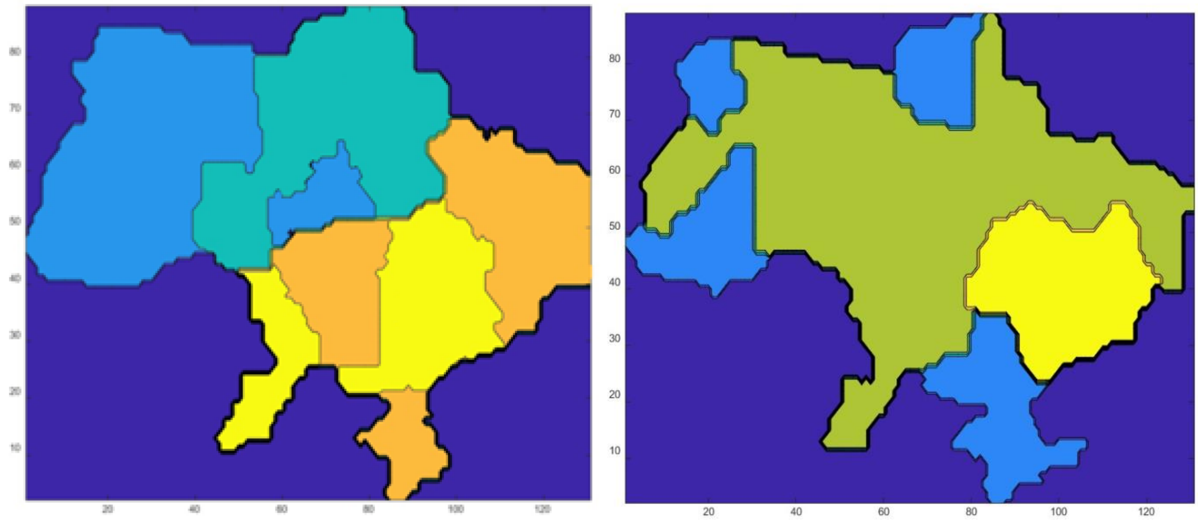


Fig. 2. Distribution maps of RES generation (a) and electricity consumption (b) in Ukraine after recognition and data array creation

Obtaining the distribution of renewable energy generation and electricity consumption in Ukraine allows us to determine possible energy losses during transmission. To determine the share of energy transmitted from one region of Ukraine to another $WT_{j,i}^{k,n}$, the following dependence is proposed

$$WT_{j,i}^{k,n} = W_{j,i}^{R} \frac{W_{k,n}^{C}}{\sum P^{c}} \tag{1}$$

where $W_{j,i}^{R}$ - RES generation potential of the district with coordinates j,i, corresponding to the division of maps into squares with a side of 10 km; $W_{k,n}^{C}$ - power consumption of the area with coordinates k,n; P^{c} - the total capacity of the country's power system.

The above dependence is based on the assumption of a direct proportional dependence of the share of consumption of the country's regions on total capacity of the country's power system:

$$\frac{\sum_{k=1}^{k=89}\sum_{n=1}^{n=131} W_{k,n}^{C}}{P^{c}} = 1 \tag{2}$$

Scheme for calculating losses during energy transmission from the generation area j,i to the consumption area k,n shown in Fig. 3.

To determine the calculation of RES potential losses when transferring energy from the generation area to the consumption area, we will use the methodological recommendations for determining technological costs of electric energy in transformers and power transmission lines. Methodological recommendations are used to determine technological electricity costs in elements of electrical networks (transformers, transmission lines, reactors) when calculating the consumption, transmission, supply and production of electricity in accordance with regulatory documents, if the measurement points do not coincide with the balance sheet boundary; take into account losses due to electromagnetic processes, climatic influences and insulation, and are recommended for use by energy transmission and supply organizations, design institutions, producers and consumers of electricity, except for interstate and specialized networks[26].

According to the above methodological recommendations, the loss of active $\Delta W^{(P)}$ or reactive electricity $\Delta W^{(Q)}$ in electrical networks for the calculation period are determined separately for each element of the electrical network (power transmission line, reactor, transformer or autotransformer, etc.) based on the flows of active or reactive electricity at the metering points located on the connected network element in accordance with the generalized formulas:

$$\Delta W^{(P)} = a \cdot I^{2} \cdot R \cdot k_{f}^{2} \cdot T^{p} + P_{y.n} \cdot T_{н} \tag{3}$$

a - coefficient depending on the type of network (three-phase, single-phase); I - average effective value of the current in the network element; R - active resistance of the network element; k_{f}^{2} - average effective value of the current in the network element; $P_{y.n}$ - conditionally constant losses of active energy in the network element, which depend on the voltage and do not depend on the current strength;

$Q_{y.n}$ - conditionally constant reactive energy losses in a network element, which depend on voltage and do not depend on current strength;

$$\Delta W^{(Q)} = a \cdot I^{2} \cdot X \cdot k_{f}^{2} \cdot T^{p} + Q_{y.n} \cdot T_{н} \tag{4}$$

X - reactance of the network element;

The use of the dependence is significantly limited by the need to determine the reactive and active resistances of network elements, which depend on a number of structural elements of the power line. At the same time, the use of economic current density $i\ A/mm^2$ enables the determination of power losses under the conditions of choosing the average voltage and the material of the power line conductors

$$\Delta WT = I^2 R = \left(\frac{P}{U}\right)^2 \rho \frac{LUi}{P} = \rho \frac{P}{U} Li \qquad (5)$$

where ρ - resistivity; P - power ($WT_{j,i}^{k,n}$); L - transportation distance.

The shortest path for transmitting electrical energy is proposed for the selected stage of development of the algorithm for determining losses.

$$L = \Delta l \sqrt{\left(i-n\right)^2 + (j-k)^2} \qquad (6)$$

Δl - map breakdown step.

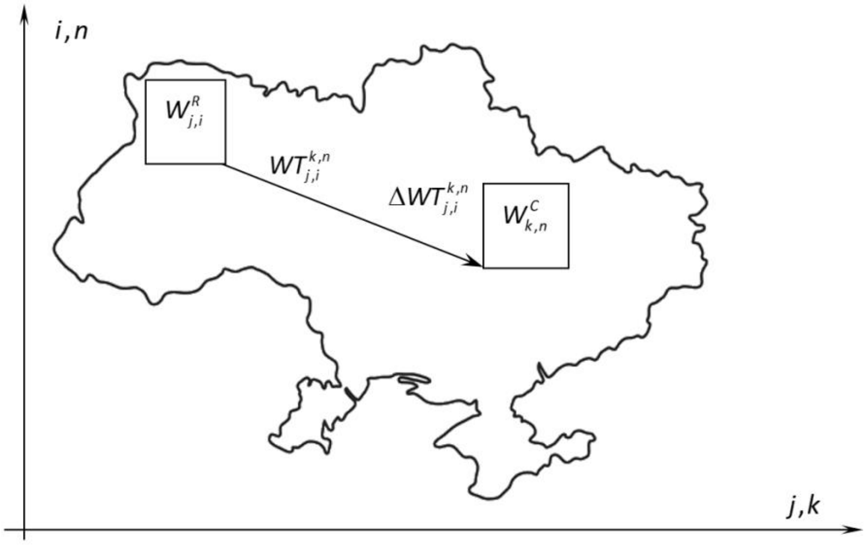


Fig. 3. Scheme for calculating RES potential losses when transferring energy from the generation area to the consumption area

The algorithm for determining losses will consider the density and direction of Ukraine's power supply networks by recognizing power line maps. The results of power losses for individual regions are shown in Fig. 4.

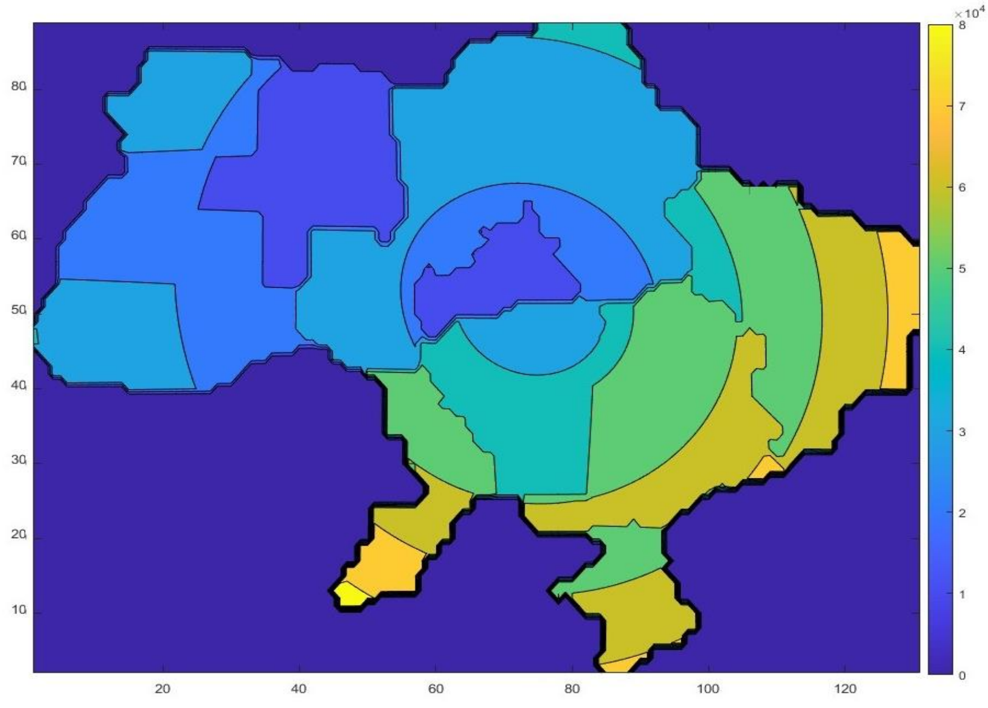


Fig. 4. Maps of distribution of losses predicted during the transmission of renewable energy, taking into account the remoteness of consumers

Analysis of the distribution map of absolute losses predicted during the transmission of renewable energy, taking into account the remoteness of consumers, indicates a significant impact of the location of renewable energy sources and their remoteness. It is quite natural that the lowest total losses during the transmission of electricity are characteristic of the central regions of Ukraine. The highest absolute losses during the transmission of electricity should be expected in the eastern and southern regions. The most promising areas for the development of renewable energy generation should be considered areas with average losses and close to the regions with the highest consumption, Dnipropetrovsk and the northern part of Odessa regions.

Using the MATHCAD software product, a model was created to assess the optimal locations for RES deployment, taking into account natural conditions and distance to consumers. The model included an assessment of the potential of various energy sources and their combinations to select the most effective development options.

Using MATLAB, optimization calculations were performed to determine the most advantageous location for renewable energy sources, taking into account economic aspects such as infrastructure costs and accessibility for consumers.

After the modeling was completed, the results were analyzed to identify the most promising regions for the development of renewable energy. It was assessed which renewable energy technologies are the most effective depending on the specifics of the region and the distance to energy consumers.

Thanks to the use of MATHCAD and MATLAB, it was possible to develop mathematical models for the optimal placement of renewable energy sources in Ukraine, taking into account the distance to consumers and natural resources. This allowed for an accurate assessment of the potential of renewable energy in different regions, as well as to assess their economic efficiency.

Therefore, using MATHCAD and MATLAB instead of traditional GIS programs has become an effective solution that allows for detailed modeling without significant financial costs. This approach allows for highly accurate calculations and offers practical recommendations for the development of renewable energy in Ukraine [26-30].

We have built an algorithm for calculating losses and analyzed the potential and level of losses in the transmission of electricity by renewable energy sources. We have also considered the Law of Ukraine on Methodological Recommendations for Determining Technological Consumption of Electric Energy in Transformers and Power Transmission Lines, paying special attention to paragraph 7 of the law. We have analyzed and developed the following conclusions. [26].

Analysis of the calculations shows that reactive power losses account for almost 70% of active losses.

Conclusions

As a result of the research, a comprehensive methodology was developed for assessing the prospects for the development of renewable energy sources (RES) in Ukraine, taking into account the remoteness of electricity consumers. An approach was applied that combines mathematical modeling, analysis of the geographical distribution of resources, technical limitations, and feasibility of implementing RES.

Based on geoinformation technologies, a spatial analysis of the potential for electricity generation from renewable energy sources and its consumption was carried out, which allowed identifying regions with the greatest losses in energy transmission. An algorithm for estimating power losses in electricity transportation based on cartographic data was proposed, which takes into account the distance between the zones of generation and consumption, as well as the features of the power grid infrastructure.

The results of the study showed that the largest losses of electricity during its transmission are predicted in the eastern and southern regions of Ukraine due to the significant distance of consumers from the main sources of RES generation. The most promising for the development of RES are areas with moderate losses, located near regions with high levels of consumption.

The developed methodology can be used for further planning of the country's energy infrastructure, optimizing the location of generating capacities, and minimizing electricity losses during its transportation.

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