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RENEWABLE ENERGY SOURCES AND HYDROPOWER

Geoinformation Systems for Renewable Energy (Review)

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Abstract—A brief review of geoinformation systems (GIS) intended for collection, storage, integration, analysis, and graphical interpretation of spatial and temporal data on various technologies for the application of renewable energy sources (RES) to make substantiated decisions on the development of RES based energy (here in after referred to as renewable energy) is presented. The development of the geoinformation system "Renewable Energy Sources of Russia" (GIS "RES of Russia") commenced in 2010 and was performed by specialists from the Faculty of Geography of Lomonosov Moscow State University and JIHT RAS. It is focused on the spatial mapping of solar and wind energy resources for the territory of Russia. The initial data for the assessment of these resources are formed mainly on the basis of satellite measurements, mathematical modeling and verification of the results against ground-based meteorological observations. The geographic information system also contains data on operating and designed renewable energy facilities and scientific, educational, and commercial organizations engaged in this area. As the geoinformation system has been developing, it has been supplemented with information on the distribution of geothermal energy resources and the energy of small rivers over the territory of Russia as well as with estimates of the specific capacity of solar and wind energy installations, the gross and technical potential of crop, livestock, horticulture, and viticulture waste. The paper briefly describes the methods and approaches employed for the development of GIS, including those for improvement of resource data spatial resolution and calculation of renewable energy sources technical potential considering hi-tech advancements. Lines for further development and improvement of the domestic geoinformation system are formulated.

Keywords: geoinformation system, renewable energy, resources, gross and technical potential, capacity of installation, energy-generating facilities

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Geoinformation systems are automatic computer systems for collection, storage, integration, analysis, and graphic interpretation of spatial and temporal data and associated information about the presented facilities. The development of the first GISs commenced in the 1960s and, as computer technologies, they found application in science and technology. GIS technologies are actively engaged recently in the field of renewable energy (RE).

Geoinformation products on renewable energy, which are available in the public domain, can be divided by their territory coverage into local, regional, national and global scale. Analysis of the current state and directions of development of GIS for renewable energy in the world has a major practical importance, including the elaboration and improvement of domestic products in this field. GIS-technologies are applied in development procedures for solving various RE problems among which the following have major practical interest:

1. Assessment of renewable energy resources in large areas with different spatial details;

2. Optimization of the equipment list, capacity, and location of autonomous and grid-connected power facilities and power plants considering physiographical and environmental restrictions, load modes, and grid infrastructure;

3. A comprehensive analysis of various types of renewable energy sources in a given territory and optimization of hybrid energy supply systems considering the current energy generation, characteristics of consumers, and potential restrictions on the application of RES-based power units.

The aim of this work is to analyze the major lines of development of modern GIS products in the field of renewable energy and application of such technologies to solve urgent scientific and engineering problems. A brief description is presented of the GIS Renewable Energy Sources of Russia [1], developed by the RES Research Laboratory (Faculty of Geography, Lomonosov Moscow State University) together with specialists from the Joint Institute for High Temperatures (Russian Academy of Sciences), and of lines of its further development and modernization.

STATE OF THE ART REVIEW OF GIS PRODUCTS FOR THE RENEWABLE ENERGY

The first atlases (including interactive ones) and national scale GIS products were undoubtedly developed in countries where renewable energy was actively progressed at the end of the 20th century: the United States, Germany, France, Denmark, etc. By far the obvious leader in the elaboration of such GIS products is the National Renewable Energy Laboratory (NREL) of the US Department of Energy. The content and form of data presentation in these GIS reflects the modern trends and demands in the renewable energy. The GIS NREL provides resource assessment of all RES types for the United States territory and some regions of the world, including: the potential capacity of typical power unis, information on the location of existing energy facilities, some important characteristics of the territories, including grid and land infrastructure, protected natural areas (PNA), limiting factors including water bodies, swamps and karsts. Regional modules in the GIS NREL have the widest list of cartographic layers. Most of the national and global GIS products developed to date in the field of renewable energy have more or less a similar structure and a list of maps (interactive or static). A number of GISs not only report data and maps on RES resources but also contain simple calculators enabling the user to obtain rough estimates of the solar and wind installations performance.

It is worth to note the latest NREL's developments on the presentation of the wind and solar energy potential in GIS in the form of "energy curves." They are constructed on the basis of a step-by-step and detailed analysis of natural resources and technical potential (potential specific capacity of RES-base power plants), applicable restrictions, and the levelized cost of energy (LCOE) for a specific territory. The result of multifactor cartographic analysis is presented in the form of LCOE versus installed capacity curves for a specific territory. This simulation method, on the one hand, allows for not overloading the end user with information and, on the other hand, it is not transparent and requires understanding of the simulation procedure. NREL proposes to employ its developments in the form of ready-to-use software tools (such as the Cost of Energy Mapping Tool [2]) and provides examples of application of these tools for the countries of Southeast Asia.

In 2013, the International Renewable Energy Agency (IRENA) initiated the development of the Global Atlas for Renewable Energy [3]. One of the main objectives of the project is to obtain, based on Google Maps, regional interactive maps of the resource characteristics of wind, solar, geothermal, tidal and biomass energy considering the factors limiting their application. At the same time, the spatial data grid attains 100 m (for wind energy) in some regions. The infrastructural characteristics of the territories are presented, including RES-based and conventional power plants, electrical grids, substations, regional boundaries, meteorological stations monitoring applicable characteristics, and PNA. The list of cartographic layers includes brief comments about the spatial resolution, data sources, and associated resources and the user receives a digital value of the resource upon selecting a specific geographic point. In 2020–2021, the project expanded into individual global atlases for different types of renewable energy.

The Global Solar Atlas and the Global Wind Atlas with a spatial data resolution of 3 × 3 and 4 × 4 km, respectively, are in open access on the internet. Information for the Global Solar Atlas and procedures for assessing energy potentials are provided by Solargis [4], one of information data suppliers and cartographic and software products for assessing solar energy resources. For interactive cartographic layers in the Global Wind Atlas, the weather data of reanalysis performed by the ERA5 tool developed by the European Center for Medium-Range Weather Forecasts [5] are employed. The reanalysis (or restoration) of meteorological fields is the model fields of meteorological parameters at the nodes of a regular spatial grid covering the entire surface of the Earth with a time coverage up to the middle of the 20th century and earlier. Reanalyses are generated by the world's leading meteorological centers on the basis of complete sets of observational data obtained from various platforms (ground-based observations, satellite monitoring, etc.) and available at the time of calculation. As a topographic basis, the atlases include open vector sets of cartographic materials Open Street Map (OSM) [6], Bing maps (from Microsoft Corporation), and space images from Earthstar Geographics SIO. The interactive component of the maps is supported by the Leaflet Java library [7].

Individual countries and regions are actively developing and supporting their own national GIS products in the field of renewable energy. Most of these products are focused primarily on resource assessment, but many projects only present information on existing renewable energy facilities and average long-term ground-based monitoring data on resource characteristics (solar radiation, wind speed, river flowrates at long-term metering stations, etc.). The scale in the displayed information sometimes reaches individual buildings, which enables us to assess the performance indicators of small (operating as a power island or in parallel with a grid) wind or solar power plants. This feature results from the fact that these products are intended for public deployment (commercial and free), and they can often be assigned to calculators containing spatially integrated data on RES resources rather than to cartographic items.

The construction of GISs for bioenergy is typical for countries that have gained experience in implementing large projects in this field. Information systems of this type give characteristics of waste sources, including industrial and agricultural enterprises, and municipal solid waste landfills. Interactive map layers are usually differentiated by waste types. Attribute tables contain information about the types, amount, quality, and cost of waste distributed over time ranges (seasons, months, etc.). The tools in this type of GIS are suitable for economic, logistical, and environmental assessments (see, for example, GIS for bioenergy of Ireland [8]). Among the applicable lines of studies is tools development for geoinformation simulation of bioenergy facilities performance. An example is the "Bioenergy Simulator" [9], developed within the scope of the above-mentioned project IRENA Global Atlas of RES Resources. For the user-selected territory, the tool can determine the potential generation of heat, electricity, or the production of various fuel types depending on the specified type of resource (waste or specially grown crops) and the technology of its processing. This model takes into consideration the geographical and climatic features of the territory.

It is important to consider those research directions in the field of renewable energy that provide, on the one hand, further development of methods for spatial analysis of the characteristics of renewable energy sources, and, on the other hand, application of the developed GISs for a wide range of renewable energy problems. The following directions, which are often logically related, can be outlined:

1. Assessments of resources and energy potentials of various types of RES performed at a detailed regional level, using GIS tools, taking into consideration the characteristics of modern technologies and the availability of resources, which depend on the physicogeographical and infrastructural features of the area [10, 11]. The most difficult is the assessment of the availability of forest complex waste due to the need to take into account many physicogeographical, technical, and economic factors. Thus, in [12], the energy potential of woody biomass in the Italian Alps is estimated taking into account the technical and logistical potential of its use.

2. Development of comprehensive GISs that present both RES resources and the spatial distribution of various factors which limit their employment. For example, [13] and [14] describe geoinformation systems that present the spatial distribution of geothermal resources and restrictions on the use of geothermal power plants and heat pumps in Spain and Ecuador, respectively. A GIS covering the territory of Chile is outlined in [15]. It has been elaborated to take into account the agricultural restrictions on the construction of hydro- and photovoltaic power plants.

3. The best locations definition for renewable energy power plants on the basis of GIS resources. This direction is especially important for the energy utilization of organic waste, for which transportation is one of the substantial cost items [16–18]. This direction also includes activities for a comprehensive assessment of resources and potential capacity of power plants using various RESs considering the applicable limits and restrictions (such as land use, PNA, electric grid, and road infrastructure) in order to design hybrid power plants operating as a power island in a given area [19–21].

4. The energy supply options analysis with specified reliability to consumers when the territorial distribution and power of operating power plants and energy consumers, as well as RES resources presented in GIS cartographic layers, are known [22, 23].

5. Development on the basis of GIS tools of decision support systems for spatial planning of RES-based power plants [24]. At the same time, multicriteria decision making (MCDM) systems are being developed to support decision making on the basis of fuzzy logic should comprehensive initial data be unavailable [25, 26]. Thus, the analysis of expert opinions [27] laid down the significance of ten criteria that were subsequently used to implement an analytical hierarchical process in order to determine the suitability of land for solar power plants. The analysis of the territorial distribution of lands having appropriate values of these criteria was carried out using GIS tools. A similar approach for Ecuador is described in [28], where MCDM is also applied in combination with GIS tools. In this direction, studies are presented not only for the most widely used wind and solar photovoltaic stations but also for solar heat supply systems for large consumers, including those outside centralized networks [29, 30]. The results of these works are usually presented as interactive maps with a proper interface enabling one to determine not only the suitability of territories for placing stations but also potential energy production and cost indicators of projects depending on technical characteristics of equipment.

6. Investigation of new niches for consumption of energy from renewable sources (production of "green" hydrogen, development of electric vehicles, etc.). For example, a GIS-based electricity supply-demand model was used in [31] to check whether all charging stations for electric vehicles in Australia can be powered with 100% renewable electricity. The required installed capacity and the cost of energy were determined. Optimal site selection for hydrogen production by electrolysis using excessive power of solar power plants was performed in [32, 33] on the basis a GIS giving the spatial distribution of water resources, solar energy, and road infrastructure.

Almost all of the above-mentioned lines of development, in fact, are aimed at solving one complex problem: planning the development of RES-based energy production. Thus, GIS tools are widely used not only for the assessment of RES resources but also for more detailed planning of the development of renewable energy, including features of its interaction with consumers, centralized grids, electric transport, and hydrogen systems. Displaying information tied-in to a specific geographical point or area and provisions for the simultaneous application of several cartographic layers offer adequate assessment of various restrictions on the location of renewable energy facilities and ensure properly justified decision-making. Cartographic information is often supplemented by analytical tools, such as systems for estimating the specific capacity of plants and installations with detailing in time and the levelized cost of energy.

GIS "RENEWABLE ENERGY SOURCES OF RUSSIA": STRUCTURE AND FUNCTIONS

The development of environmentally friendly renewable energy in both regions of centralized and autonomous energy supply to consumers seems to be among of the priority lines for implementing the Strategy for Scientific and Technological Development [34] and the Energy Strategy of Russia [35]. At the same time, an urgent problem is to elaborate a domestic platform containing initial data and calculation procedures for assessing the potential performance of renewable energy facilities, taking into consideration the resource potential and factors limiting their location, including infrastructural and environmental factors. Activities in this area in Russia commenced in 2010–2012 at Lomonosov Moscow State University and the Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS). The initial stage included collection, generalization, and presentation in the form of databases of satellite information on solar and wind energy resources followed by its verification against ground-based measurements [36]. The results of this stage of activities were reported in the Atlas of Solar Energy Resources in the Territory of Russia and the Atlas of Renewable Energy in the Territory of Russia [37, 38]. Due to active development of web technologies and geoinformation mapping, it has become possible to represent resources and gross and technical potentials of solar and wind energy in the format of a geoinformation system [39].

Nowadays the geographic information system "RES of Russia" operates on the basis of the freely distributed Word Press management system, and interactive maps have been built by means of Java Script API based on the Yandex. Maps system using the author's plug-in. Interactive maps include two large thematic blocks: maps of renewable energy facilities and maps of RES resources (Fig. 1).

The block of renewable energy facilities in Russia contains spatial data on solar power plants (SPPs), including solar-diesel power plants (SDPPs), wind power plants (WPPs), including wind-diesel power plants (WDPPs), solar water heating plants, small hydroelectric power plants, geothermal and tidal power plants, biomass-fired power plants, and boiler houses, as well as on organizations in the field of renewable energy (scientific and commercial). Information sources include open thematic databases of specialized associations (Russian Wind Industry Association, Russian Biofuel Association, Russian Hydropower Association, etc.), interactive maps with the principle of free editing Wiki Mapia [40], OSM vector databases [6], and other open sources. The maps provide information about a facility (its capacity, status, year of commissioning, address, and reference to the source of information), enable the user to perform search by the name of a facility, filter facilities by type, and also display the total capacity of the facilities presented on the map.

The RES resource block includes interactive maps of solar and wind energy resources; of the capacity of photovoltaic modules (PMs) and wind power plants (WPPs), and an interactive map of explored geothermal fields with their characteristics for the territories of Kamchatka, the Kuril Islands, and the North Caucasus. Maps of solar and wind resources display information in the format of polygons on a degree grid with provisions for selecting both the type of displayed parameter and its secondary characteristic (averaging period for solar radiation and height for wind energy characteristics). The data sources include the databases Prediction of Worldwide Energy Resources (POWER) from NASA [41], databases of the NASA project "The Clouds and the Earth's Radiant Energy System" (CERES) [42], and ERA5 of the European Center for Medium-Range Weather Forecasting [5]. Examples of components of the GIS RES of Russia are shown in Figs. 2–5.

Verification of the data presented in the above-listed sources is critical for substantiating the accuracy of resource assessments and calculation of capacity for solar and wind power plants. That is why a detailed comparison of satellite data, reanalyses, and ground-based observations becomes an urgent topic of scientific research. For example, the results of verification of satellite observations (CAMS-RAD, NSRDB, SARAH-2, SARAH-E, CERES-SYN1deg, Solcast) and reanalyses (ERA5 and MERRA-2) on the total solar radiation on a horizontal surface based on data from the global network of ground-based meteorological stations (Baseline Solar Radiation Network) are reported in [43]. As to the scope of the engaged information sources (six satellite observation programs, two reanalyses, and 57 ground-based weather stations), as well as the duration of the compared series (27-year sequences of hourly data), this study is exceptional. According to the obtained results, the commercial satellite database Solcast demonstrated the minimum rms deviation from ground-based measurements, and reanalyses are poorer in accuracy than satellite observations.

Since the global network of ground-based weather stations used for verification in the works of foreign authors does not include the territory of Russia (with the exception of individual stations in the Arctic zone), the problem of comparing various sources of

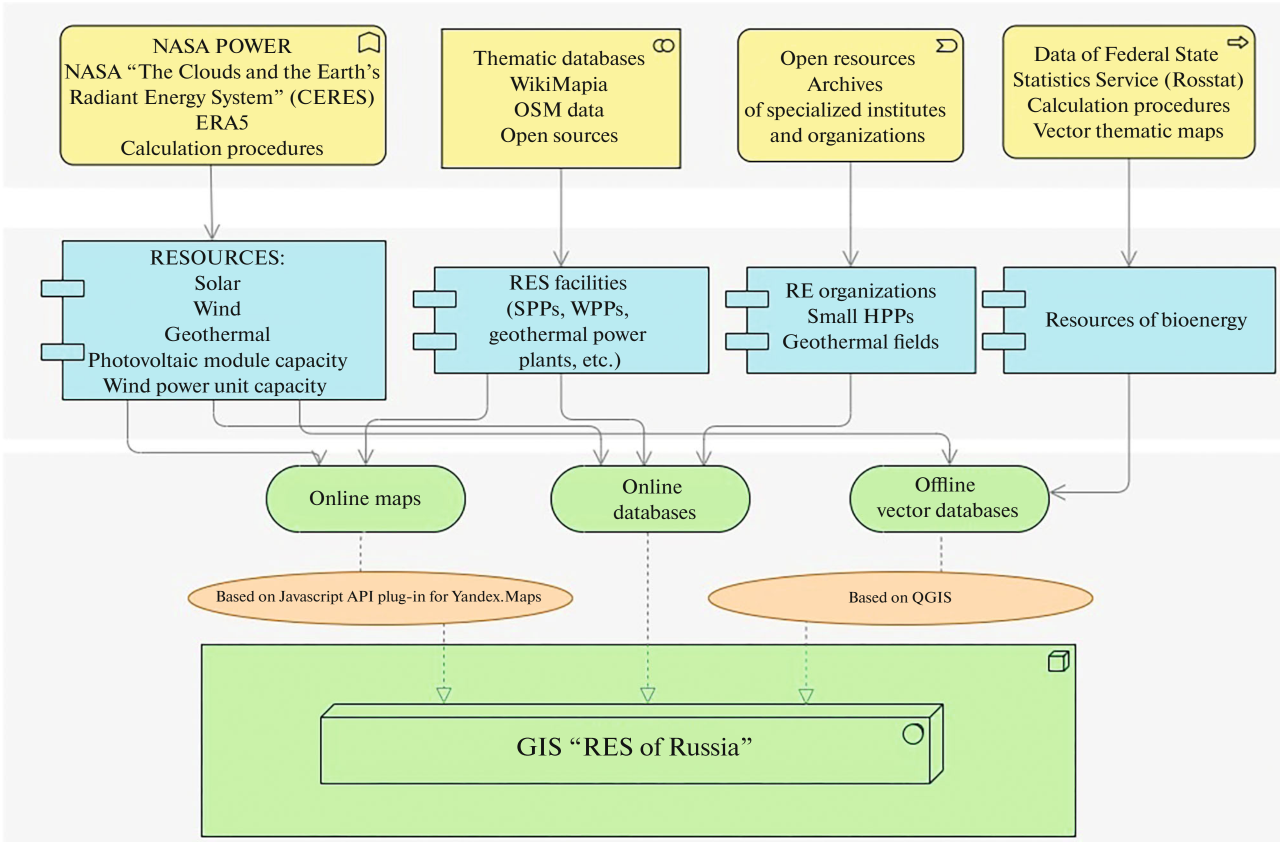

Fig. 1. Structure of GIS "RES of Russia."

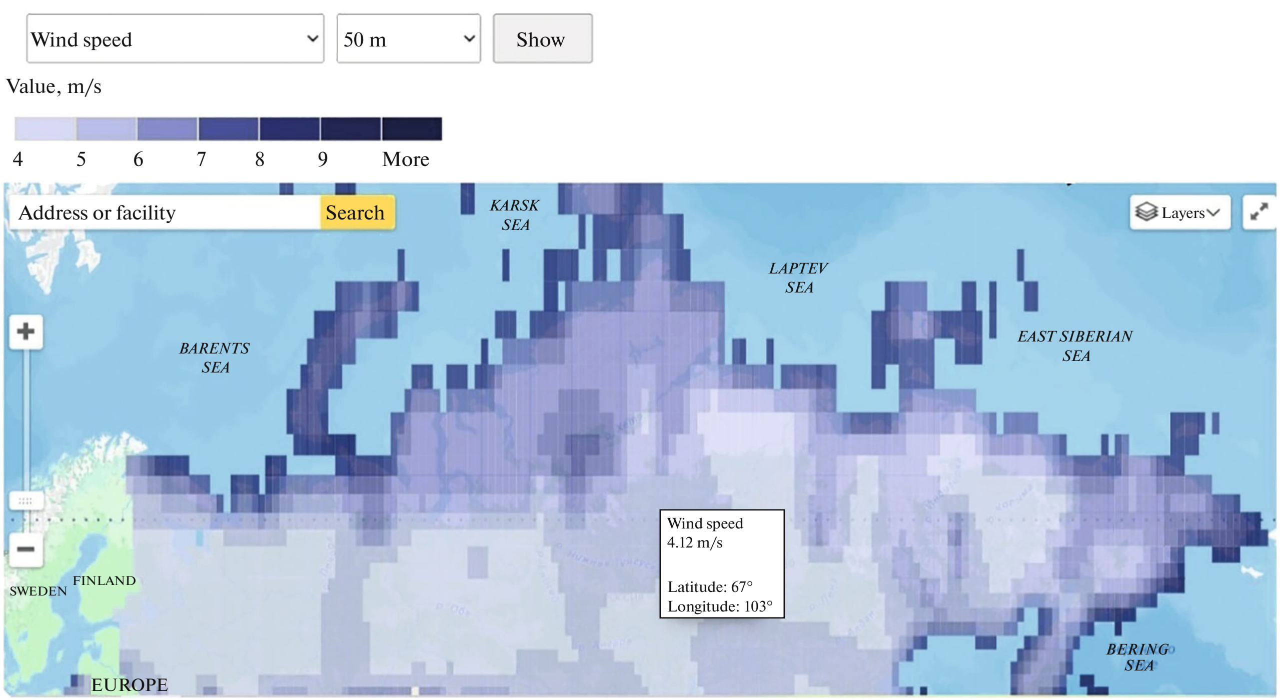

Fig. 2. Fragment of an interactive map of wind energy resources: annual average wind speed at a height of 50 m.

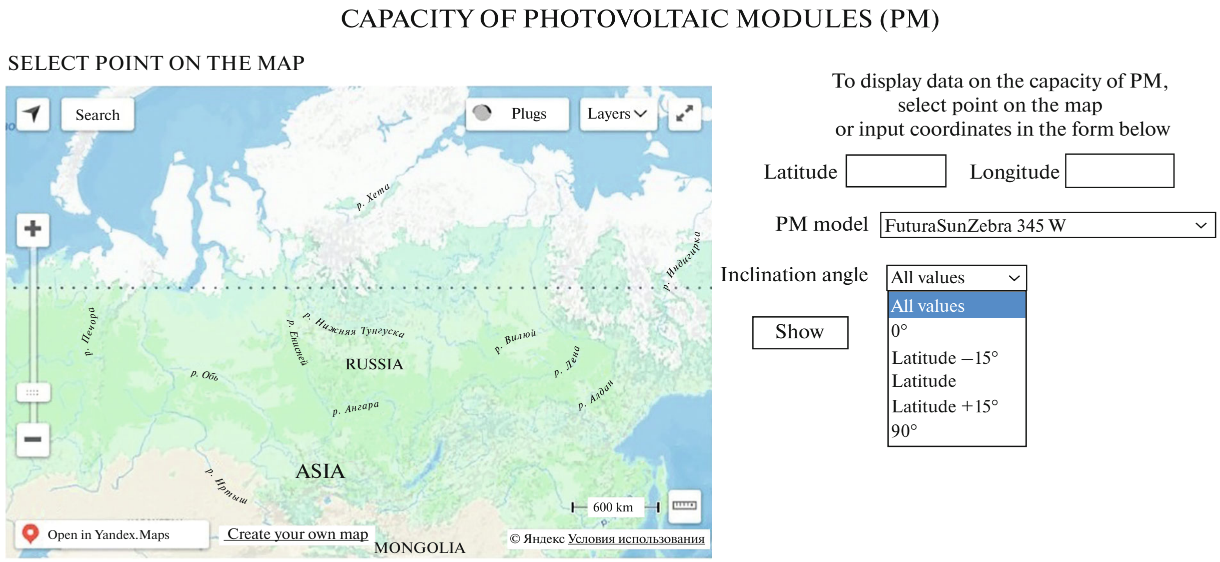

Fig. 3. Fragment of interactive database on the capacity of PMs in Russia.

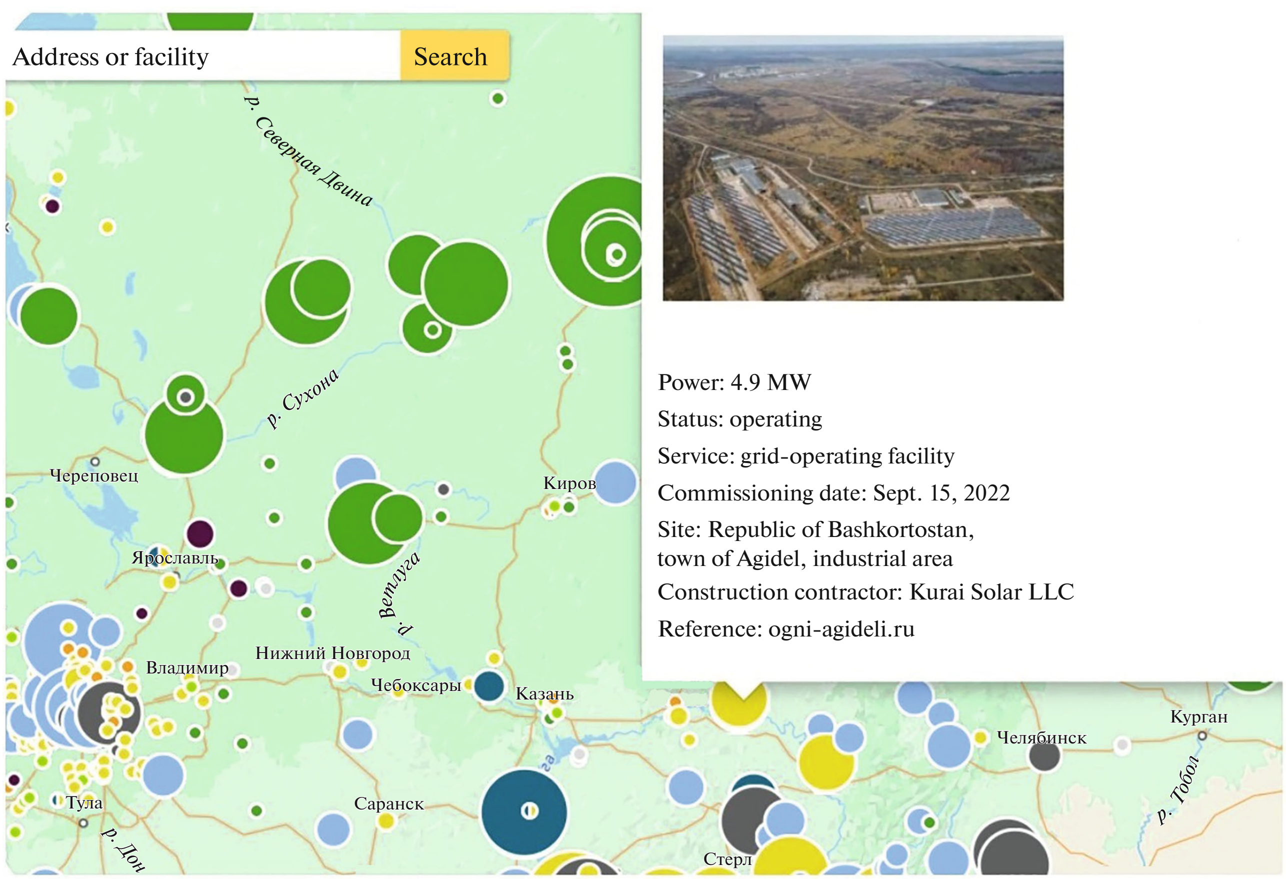

Fig. 4. Fragment of an interactive map of RES-based facilities.

information remains urgent for domestic researches in this subject area. The authors of [44, 45] previously verified and confirmed the suitability of NASA POWER for assessing the capacity of photovoltaic stations for both substantiating data sources for the GIS "RES of Russia" and assessing the accuracy of calculation of the capacity of solar power plants on the territory of Russia.

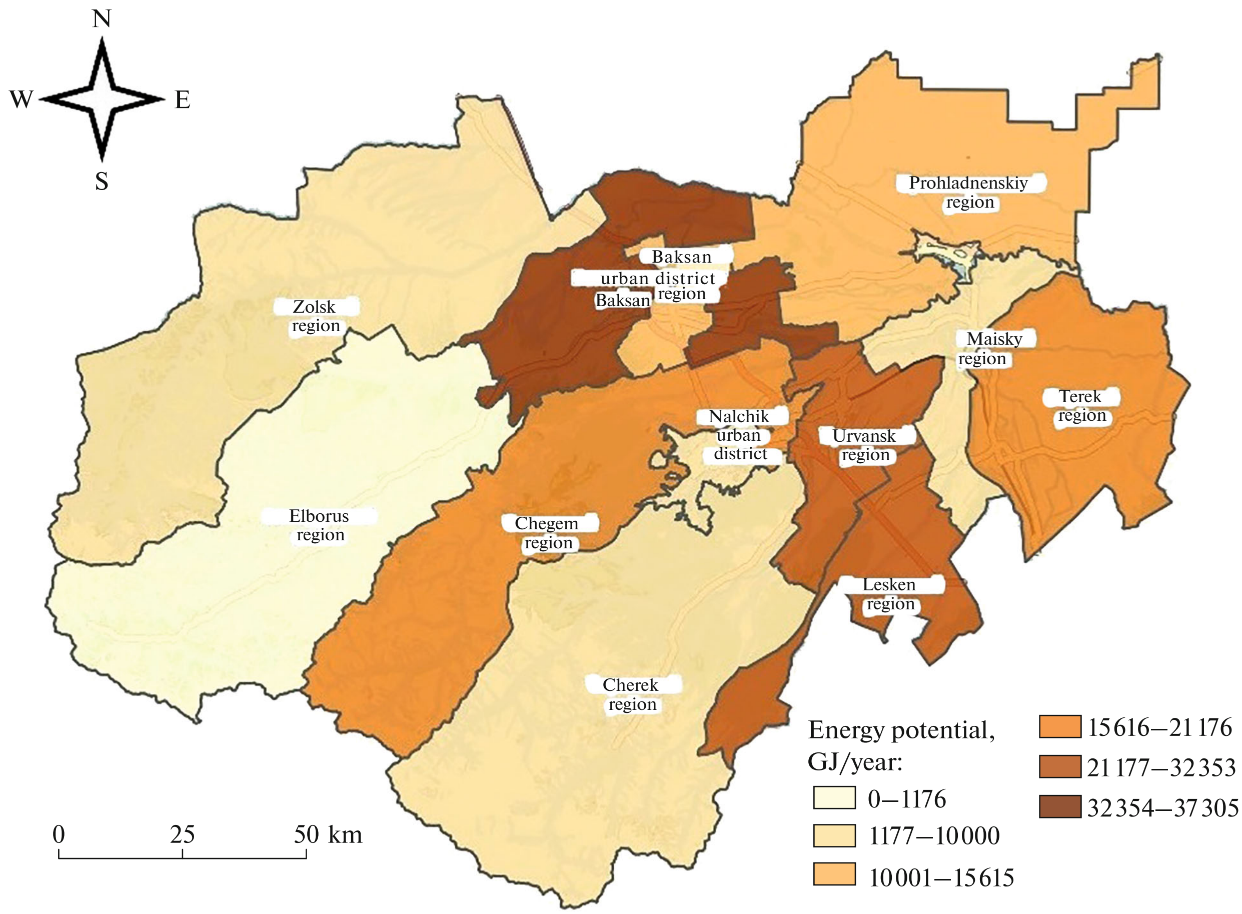

Fig. 5. Example of static regional off-line bioenergy resources map (spatial distribution of gross potential for the production of thermal energy using gardening wood waste as fuel, the Republic of Kabardino-Balkaria).

A wide range of studies devoted to the verification of various sources of information on wind energy resources have been conducted by specialists from the National Research University Moscow Power Engineering Institute (MPEI). Thus, criteria and procedures for verifying climate data were proposed in [46, 47]. To do this, it is recommended to rank various information sources according to five ranges. The reliability of satellite databases (NASA POWER) and reanalyses (ERA 5) was assessed for both the regions of Russia, which are promising for the development of wind energy (shelf zones of the northern seas, the Kamchatka Peninsula, etc.), and the territories of the countries of Southeast Asia [48]. The issues of improving the reliability of the assessment of wind energy resources and selecting of an adequate information base are also examined in [49] where a procedure is proposed for a three-level assessment of wind energy resources in remote underpopulated areas with a low concentration of sources of reliable natural and climatic information. The procedure was successfully employed for the regions of Russia, in particular for the territory of the Arctic zone, in designing wind energy systems [50].

Databases on the capacity and performance of solar and wind installations included in the GIS "RES of Russia" provide assessments for a user-selected model and its additional characteristics (if necessary), whose geographical coordinates were inputted by the user on the map or in a corresponding window. There are provisions for presentation of information detailed by time, including average, median, maximum, and minimum daily indicators for each month and overall year. The data are presented as specific values of output per 1 kW of installed capacity. The calculations were performed using the hourly sequences of the appearance of solar radiation and wind velocity at the height of a wind power unit for a period of 20 years (2001–2020).

Photovoltaic modules and wind generators were selected for performance calculation depending on the current state of available technologies in Russia and abroad. At present, the solar power industry has completed the change-over to photovoltaic modules based on half-cells made of single-crystal silicon, which, due to lower currents through a single half-cell of a larger area (156 × 156 mm^2 silicon wafers are replaced with 166 × 166, 182 × 182, or 210 × 210 mm^2 ones) and

Table 1. Characteristics of wind power units used for calculation of the specific capacity in GIS "RES of Russia"

Type of wind power unit	Manufacturer	Power, kW	Average mast height, m
SG 3.4-132 Siemens-Gamesa	"Siemens Gas Turbine Technologies" LLC (SGTT)	3400	154
V126 Vestas	Rosnano-Fortum	3400	100
L100 Lagerwey	NovaWind	2500	100
KWT300 KOMAI HALTEC	KomaiHaltec	300	42

optimization of contact structures, provide lower ohmic and optical losses. At the same time, the PERC technologies (elements with passivated emitter and rear contact) remains the basic technology due to its relative simplicity and low sensitivity to the quality of the original wafers [51]. Such modules, mainly made in China, are available in Russia from a number of distributors. At the same time, production of improved high-tech silicon modules based on heterojunction technology (HJT) manufactured by the Hevel company, has been localized in Russia [51]. They are widely used in the projects of large network photovoltaic stations and are also available from distributors. Finally, interdigitated back contacts (IBC) technology remains among the leaders in achieving high efficiency. Progress has been made recently in improving the manufacturability and reducing the cost of such elements and modules [52]. In Russia, CJSC Telecom-STV assembles high-efficient modules from foreign-produced elements by CJSC Telecom-STV, but their passports do not contain all characteristics required for simulation of the module performance. Hence, a foreign analogue (Futura Sun) is integrated into the GIS.

When choosing wind generators, preference was given to systems whose production is localized in Russia [53], but they can only be used in the construction of large wind power plants. For smaller systems operating basically as part of wind-diesel power plants, Komai Haltec 300 units (Japan) were considered, which were used in the implementation of some similar projects in the Far East. For wind power plants with a capacity up to 100 kW, series Ghrepower FD16 wind turbines, manufactured in China and developed with the participation of Russian specialists for the conditions of the Russian Arctic [54], seemed the most promising. Therefore, the selected systems have already been used throughout the country and cover a wide range of capacities [55].

The performance of photovoltaic modules was calculated considering their efficiency depending on environmental conditions and transmitted power. The temperature of a photovoltaic module (PM) was estimated for each hour using the applicable meteorological and actinometric data as well as its passport characteristics. The calculations were performed for three types of PM: Hevel HVL-395/HJT (with a peak output of 395 W), Ja Solar Half Cell PERC 72 cells JAM72S30 (540), and Futura Sun Zebra 345 W (345).

The specific capacity of WPPs was calculated on the basis of hourly data on wind speeds and passport curves of power output for wind generators. In the case when the height of the wind turbine mast did not coincide with the heights of the reanalysis (10 and 100 m), the wind speeds were recalculated to a given height under the assumption of an exponential dependence. Calculations were performed for four types of wind power units (see Table 1).

Besides maps, the GIS "RES of Russia" contains the following interactive databases:

1. "Small Hydroelectric Power Plants of Russia" with a detailed description of the facilities in .pdf format (according to data from relevant organizations);

2. "Design, Research, and Commercial Organizations in the Renewable Energy Field" with provisions for selection by the territorial of the Russian Federation or by type of organization (according to the data from open sources).

The GIS also contains the "Bioenergy" block, which includes static maps of the gross and technical potential of biomass waste in Russia (such as waste water sludge, municipal solid waste, or various types of crop waste). Methodically, this section of the GIS is based on the "Handbook of Renewable Energy Resources in Russia and Local Fuels" [56], which belongs to the most demanded publications on renewable energy in Russia. At present, this section of the GIS is being updated by integration of interactive maps into it, which make is possible to go from the national scale to the scale of Russian districts with the distribution of potentials by municipalities. Vector databases and thematic maps of the gross and technical potential of crop, livestock, horticulture, and viticulture waste for the regions of the south of Russia (by municipalities) were prepared in an offline format using the QGIS open source software [57].

CONCLUSIONS

(1) The study of geographic information systems in the field of renewable energy, developed in scientific centers around the world since the 1980s, demonstrates impressive progress in the development of this tool and its great importance for the assessment and spatial analysis of renewable energy resources. Geoinformation systems are finding ever increasing application not only as a method for presentation of information but also as a decision-making tool for optimizing

the capacity and a list of equipment of power generating stations, taking into consideration the physical and geographical conditions of the site, road and grid infrastructure, the type and power demand of consumers, and environmental restrictions.

(2) In Russia, activities aimed at elaboration of web-atlases of renewable energy sources and a geographic information system commenced at the beginning of 2010. At present, the GIS "RES of Russia" in the format of interactive maps presents assessments of the country's renewable energy resource base. The system can estimate resources, gross and technical potentials of solar and wind energy at sites with inputted coordinates, provides data on geothermal resources of the Kamchatka Peninsula, the Kuril Islands and the North Caucasus, contains databases on facilities and projects in Russia, which employ all types of RES, as well as on scientific, educational and commercial organizations whose activities cover the field of renewable energy.

(3) The progress of technologies, an increase in the amount of installed capacities of RES facilities in the Russian Federation, and the introduction of support measures, including those in the field of microgeneration, dictate the need and feasibility of a deep modernization of the GIS "RES of Russia" to improve its practical importance. As a result, databases of long-term average annual specific capacity of modern solar and wind power units with a spatial resolution of 1° × 1° were elaborated within the scope of this system for the entire territory of the country. The data on the assessment of resources and potentials of bioenergy for the territory of Russia are being updated considering the dynamics of agricultural production, which is the largest source of organic waste. Developments are performed aimed at presenting data in an interactive format with provisions for navigation from the level of national overview maps to regional maps of Russian constituent entities with detailing up to municipalities. The most difficult problem is to construct a decision-making support system in the field of renewable energy, for which regional modules should be developed with detailed data on infrastructure (networks, substations, generating facilities, energy consumption) and calculators for the balance of generation and consumption of energy from RESs.

(4) The development of the GIS "RES of Russia" seems to be an important component of the successful implementation of the Strategy for Scientific and Technological Development, the Energy Strategy of Russia, and requires the involvement of a wide range of interested specialists, organizations, and government departments in the implementation of the project.

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