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GEOGRAPHICAL PRECONDITIONS FOR THE DEVELOPMENT OF WIND ENERGY OF ICELAND

ABSTRACT

Among the sustainable development goals set by the United Nations, one notable is "the production and consumption of low-cost and clean electricity". One of the worldwide leaders in this field is Iceland, which in an effort to gain energy independence has reached a share of 99 % of the country's total electricity production from renewable energy sources. At the same time, the share of wind energy resources is only 0.05 %, although the island territory has exceptional wind energy potential. It was not until 2018, that the government approved the realization of a large-scale project of establishing a network of wind farms as a part of a plan to lay a high-voltage cable along the bottom of the Atlantic Ocean to export electricity to Europe. However, a comprehensive geographical analysis of promising areas for the location of wind farms has yet to be carried out. In addition, when assessing territories across the world, the parameters usually taken into account are meteorological and economic only. Environmental factors and the degree of impact on nature are often disregarded. Thus, the aim of this work is the assessment of the territory of Iceland for the optimal placement of wind farms based on a set of indicators, including meteorological, geological and geomorphological, socio-economic and environmental parameters. The absence of such a comprehensive analysis for the territories of Iceland determines the relevance of the study.

The study resulted in a map, which shows that 10 % of the territory of Iceland is extremely favorable for construction of the network of wind power stations. This will help the government to ensure the economic benefits of selling energy to the UK and continental Europe without harming the environment. What is even more important, the method used to assess the potential of the island's territories by various environmental parameters (quantitative and qualitative) can be applied not only to Iceland but also to any region of the world.

KEYWORDS: sustainable development, wind energy, Iceland, geoecology, fuzzy clustering method

INTRODUCTION

Rapid climate change, depletion of natural resources, especially fuel and energy resources, aspiration of many countries to gain energy independence and pursue the transition towards sustainable development have allowed us to formulate the main contemporary tasks of the green economy, among which the United Nations names the production and consumption of low-cost and clean electricity.

Today, renewable energy sources are increasing their energy structure share in developed and developing countries. The growth is due to constant decline in prices for renewable energy technologies, increased demand for electricity in many countries and targeted federal support mechanisms [*Berezkin, Sinyugin,* 2018]. Modern renewable energy sources provide 9 % of the total global electricity demand[2]. The environmental policies of numerous countries are aimed

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[2] Renewable Energy Policy Network for the 21st Century. Renewables 2017 global status report. Paris, 2018. 325 p.

towards the development of solar, wind, geothermal and wave energy. The use of wind energy occupies an important place in this series.

In the near future, Iceland has the potential to become a strong “player” on the wind energy market. The country’s energy production to this day has the following structure: 71.03 % — hydro-energy, 28.91 % — geothermal energy, 0.04 % — wind energy. However, in 2018, the government approved the realization of a large-scale project to create wind farms in order to meet the increasing energy consumption needs in the country (due to relatively rapid increase in both population and tourist flow), as well as to lay a high-voltage cable along the bottom of the Atlantic Ocean to export electricity to Europe[1].

The development of wind energy in Iceland requires a comprehensive geographic analysis of favorable wind farm locations. The aspects considered should not be limited to meteorological and socio-economic. In a region focused on nature tourism, it is important to maintain the integrity of natural landscapes and their aesthetic appeal. It is also necessary to take into account the specifics of the location of the region in a seismically active zone. Considering the ecophilic nature of Icelandic society, it is important to address the occurrence of Red List species, the proximity of the key ornithological territories, etc. A comprehensive geoecological assessment is required.

In the process of research, the author came across many interesting works on the topic of assessing the potential for the development of wind energy in various regions of the world. However, not all authors took into account the natural aspect, nor applied the integrated approach.

In the monograph “Theoretical Framework of Alternative and Renewable Energy” [*Elistratov, Kuznetsov*, 2003] there is a section devoted to the selection of favorable for the construction of wind power stations territories, however, all attention is paid exclusively to meteorological features. In an article written by specialists from the Uzbekistan Technical University [*Zhamolov et al.*, 2019], the situation is similar. In the work of scientists from the Hong Kong Polytechnic University [*Zhou et al.*, 2006], the attention was paid to the assessment of territories by wind energy potential, Weibull distribution coefficient, and other physical parameters of the state of the atmosphere.

Nevertheless, there are certainly considerable projects that take into account geo-environmental aspects. Usually, they are implemented in developed countries. For example, a work of scientists from the Korea Institute of Energy Research focused on assessing the potential of wind resources is relying on the ecological value of territories [*Kim et al.*, 2013]. The ecological value of the regions of South Korea was determined by their correspondence with one of 57 types of specially protected natural territories (ecological landscape conservation regions), as well as the presence of habitats of rare and endangered species, potential damage in case of emergencies, proximity to settlements and infrastructure, etc. Regarding the complexity of the approach, our work is consistent with the approach of Korean scientists, but the number of parameters taken into account is lower. Experts at Columbia University in the United States had a similar approach in their analysis of New York State territories [*Van Haaren, Fthenakis*, 2011]. They regarded, for example, the state program “E-Powering America’s Land Initiative”, a program that aims to clean and use potentially contaminated land and mine sites. However, they limited themselves to a small number of parameters. Scientists at the University of Nebraska-Lincoln [*Miller, Lee*, 2014] analyzed the situation in the Northeast Nebraska region through a series of layering and synthesis operations in GIS packages.

A brief literature review shows that the issue of installing new wind power stations is worldwide relevant.

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[1] Askja Energy: https://askjaenergy.com/2017/11/21/icelandic-wind-power-becoming-highly-interesting (accessed 14.01.2020)

Wind characteristics and wind power potential of Iceland

Iceland is a volcanic island located in the central part of the North Atlantic Ocean. Today, there are about 100 volcanoes on the territory of 103 125 km², 31 of which are active. 13 500 km² are occupied by glaciers — this is almost 13 % of the country's territory. Iceland has a subarctic marine climate [*Alisov, Poltoraus*, 1974]. The island is located in the center of a low atmospheric pressure region (the Icelandic minimum), which stimulates the intense atmospheric circulation: cyclonic activity, frequent cloud cover, rain and, of course, strong winds.

Long-term data retrieved by the Global Wind Atlas[1] show high average annual wind speeds, 5 m/sec. and above for most of the territories. In comparison, the average annual wind speed in Moscow is 2.3 m/sec., and indicators above 5 m/sec. are typical, for example, for the shores of the Arctic and Pacific Oceans.

The wind reaches its highest speeds on the coasts and in the midlands. The largest number of days with strong winds was recorded there. The highest speeds are observed on the south coast [*Einarsson*, 1984].

For a comparative analysis of the wind energy resources of Iceland, we compare them with similar indicators in continental Europe. The largest specific wind capacity among European countries is found on the western and northern coasts of Ireland, in Scotland and in the north-west of Denmark. The annual average indicators at an altitude of 50 m are: more than 250 W/m^2 on the plains, more than 700 W/m^2 on the coasts and more than 1800 W/m^2 across mountain ranges and on the hills [*Troen, Petersen*, 1989].

Iceland's wind and energy resources are quite comparable to those possessed by the European wind energy leaders. For example, the West Fjords region, where specific capacity often reaches 2000 W/m^2, has the largest amount of wind energy resources; more than 80 % of Iceland's territory has a potential above 1000 W/m^2, more than 95 % — at least 500 W/m^2 [*Nawri et al.*, 2014].

This means that the island's wind energy resources make the country potentially competitive not only on the domestic but also on the foreign market.

Current state of wind energy in Iceland

Wind power production in Iceland emerged recently — the first test wind turbines were built in 2012–2014. The first two turbines with a total capacity of 1.8 MW were installed near the Burfell hydroelectric station in the Southern Region under the National Power Company of Iceland project. Then, in 2014, the private company Biokraft launched two wind turbines with a total capacity of 1.2 MW in the area much closer to the coast.

Both projects were designed as pilot versions of large-scale wind energy development programs. National Power Company of Iceland is working on a wind farm with a total capacity of 200 MW. The farm will be about 40 km^2 in area, where 67 turbines will be installed on the sandy-lava plain near Burfell[2]. Biokraft is developing a 13-turbine Vindaborg project with a total capacity of 45 MW[3].

In January 2018, the Minister of Environment and Natural Resources Gudmundur Gudbrandsson on behalf of the government appealed to municipalities to pay attention to wind energy and proclaimed this direction a new priority for the country. One of the main reasons is that new geothermal and hydroelectric stations require large expenditures and have a greater impact on the environment. As mentioned above, due to high population growth rate and rising tourist flow, Iceland is in need of an increase in electricity production. Still, one of the main catalysts of the development might be the export of electricity to the UK and continental Europe.

[1] Global Wind Atlas: https://globalwindatlas.info (accessed 24.01.2019)
[2] Burfell wind farm: https://burfellwindfarm.landsvirkjun.com (accessed 28.03.2019)
[3] Biokraft: http://biokraft.is/vindaborg (accessed 28.03.2019)

According to studies at the Massachusetts Institute of Technology, Icelandic wind farms can produce electricity at an estimated cost of 35 $ per 1 MWh or even less. That is not only much cheaper than generating energy from hydro- and geothermal stations in the country, but it is cheaper than all of the similar European projects. For example, the Danish station Vattenfall's Kriegers Flak, which has become Europe's record holder for the lowest projected cost of energy, plans to reach 40 $ per MWh in the long term and 53 $ in the short term. All of this gives Iceland the status of a potential energy donor of the Old World. By 2025, a high-voltage direct current transmission line (HVDC) is to be put into operation, which will connect the UK and Iceland with an underwater cable of 1 000 MW[1]. The national energy company announced that it plans to export 5 800 GWh/year, so it will be necessary to increase the amount of electricity generated in the country by 30 % since today it produces about 18 500 GWh/year.

All of the above indicates the inevitable significant growth of the Icelandic wind energy sector, especially in connection with an increase in prices of the construction of geothermal and hydroelectric power stations and their larger impact on the surrounding ecosystems.

MATERIALS AND METHODS OF RESEARCHES

The selection of optimal areas for wind farm placement is determined by many natural and socio-economic factors. The combined analysis of both types of factors can be carried out by mathematical modeling using the fuzzy clustering method [*Tikunov*, 1997].

A) To conduct the assessment, the territory of Iceland was divided into polygons sized 20 km by 20 km (fig. 1), a total of 346. The use of a regular square grid is explained by the fact that the data used are both socioeconomic, which is gathered within certain administrative boundaries, and physico-geographical, which is linked to natural contours. To unify a variety of data and increase ease of handling of such units (taking into account a large number of parameters and the need for their further mathematical processing) quadratic fragmentation of the study area was used. This method is often used to solve a variety of spatial problems (EMEP grid, for example).

A spacing of 20 km was chosen as the most optimal scale for analyzing the territory of the country as a whole. The reasoning is that a smaller scale implies a less accurate and objective portrayal, and a larger one is appropriate for a more detailed study of individual regions of the state (there was no such task during the study).

B) The modeling database was developed according to the following groups of parameters: meteorological, environmental, socio-economic, geological, and geomorphological.

1. Meteorological parameters are decisive since they directly affect the efficiency of wind farms. It depends on these figures whether the selected territory will have the potential for the development of the industry or not. Considered parameters included wind power potential (according to Global Wind Atlas data), seasonal variability of wind speed, and frequency of calmness (in months). The last two parameters were calculated using the interpolation of monthly average wind speeds data from the Icelandic Meteorological Office website[2]: from 35 operating meteorological stations for the period between 2008 and 2018 and from 6 closed stations in the internal regions for the period between 1980 and 2000. It seems possible to use data from 20 to 30 years ago since these regions belong to the uninhabited area of Iceland, where were not recorded any sharp climatic changes.

2. Environmental parameters are extremely important, especially in such an "ecophilic" society as Icelandic. To preserve the unique nature of the island, the construction of any industrial facility should be carried out in accordance with the environmental situation. The following indicators were taken into account: presence or absence of specially protected natural

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[1] Askja Energy: https://askjaenergy.com/2018/04/17/icelink-in-operation-by-2025 (accessed 20.01.2019)

[2] Icelandic Meteorological Office: https://en.vedur.is/climatology/data (accessed 20.01.2019)

areas, endangered Red List species and natural habitats of birds within the studied range, as well as land cover characteristics. Data on protected areas, bird habitats, and key ornithological territories were taken from the maps made by the Icelandic Institute of Natural History[1]. The distribution ranges and the number of endangered species of animals and plants were obtained from the Red List[2] (the International Union for Conservation of Nature project). Information on the prevailing land cover patterns was taken from the Copernicus Land Monitoring Service (CORINE Land Cover 2018 project[3]).

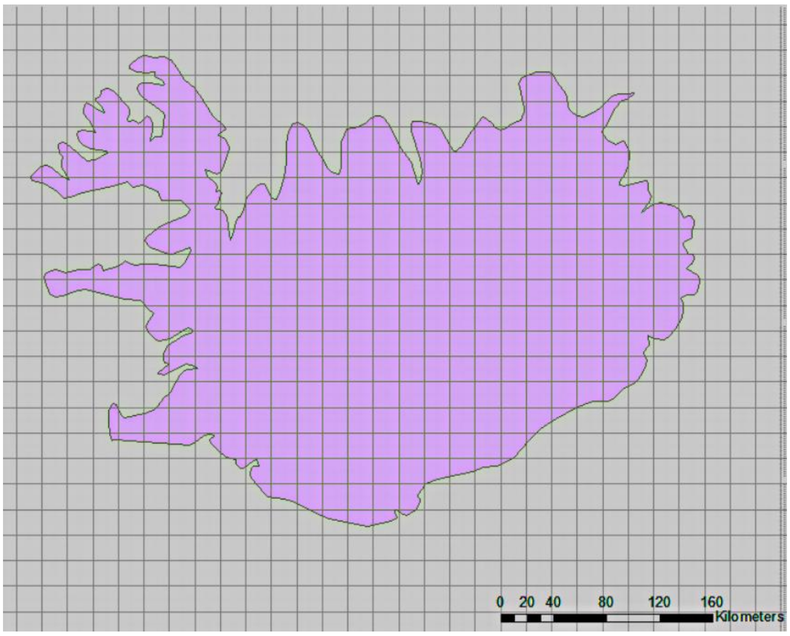

Fig. 1. Regular square grid as a result of a division of the territory into polygons sized 20x20 km (by author)

3. Socio-economic parameters: the presence of roads, power lines, tourist sites, settlements, in other words, the presence of consumer and infrastructure. Information on the road network is taken from the corresponding map of the National Land Survey of Iceland[4]; power lines are shown on the map by the National Energy Authority[5], and the main tourist sites are on the tourist map by GIF map[6]. Google Maps was used to find settlements with a population of more than 200 people.

4. A separate group of factors under consideration is the geological and geomorphological features of the terrain, which can affect the wind speed, flow turbulence, and the profitability of construction of wind farms in connection with the possible activation of dangerous processes. Data on active volcanic systems were taken from the Catalogue of Icelandic Volcanoes[7]; average relative heights were calculated using the ArcGIS software based

[1] Icelandic Institute of Natural History: http://vistgerdakort.ni.is (accessed 14.02.2019)
[2] IUCN Red List of Threatened Species: https://www.iucnredlist.org/search/map (accessed 14.02.2019)
[3] Copernicus Land Monitoring Service: https://land.copernicus.eu/news/corine-land-cover-now-updated-for-the-2018-reference-year (accessed 17.02.2019)
[4] National Land Survey of Iceland: https://atlas.lmi.is/LmiData/index.php?id=269478228222 (accessed 17.02.2019)
[5] National Energy Authority: https://nea.is/hydro-power/electric-power/transmission (accessed 17.02.2019)
[6] GIF map: https://www.gif-map.com/maps-of-europe/maps-of-iceland (accessed 18.02.2019)
[7] Catalogue of Icelandic Volcanoes: http://icelandicvolcanos.is (accessed 13.02.2019)

on the digital elevation model from the National Land Survey of Iceland; a map of the distribution of geothermal stations was compiled according to the data of the National Energy Authority.

The characteristics made it possible to form a database for subsequent modeling.

C) In order to determine the areas with the greatest potential for wind energy production the methodology of creating assessment maps was used. The methodology of such an assessment was developed by V.S. Tikunov [1997].

The first step was the normalization of indicators of the data matrix; it allows you to compare different-quality information. All of the data, both quantitative and qualitative, were brought to a single format and expertly evaluated using the point system (on a scale from 1 to 5) according to the degree of favorability for the development of wind energy of this territory (1 — least favorable, 5 — most favorable). The resulting database which included the assessment of each factor and the necessary explanations, as well as subsequent calculations, turned out to be over-detailed, therefore, could not be placed in this article, but can be provided by the author upon request.

Next, a synthetic indicator was created. The indicator reflects the total values of the estimated characteristics and signifies the deviation from their prime values. Then, the ranking of territorial units was held, mainly by integrating deviations from the prime indicators of the synthetic coefficient through Euclidean distances (as a measure of the proximity of the synthetic indicator to the prime value). The final stage was the expert identification of the number of clusters of territorial units based on a synthetic coefficient in accordance with the objective characteristics of the object of study.

RESULTS OF RESEARCHES AND THEIR DISCUSSION

As a result, the focus polygons were divided into 5 clusters according to the synthetic coefficient values and weight of individual parameters and limiting factors. The clusters were formally labeled as follows: (1) most favorable, (2) optimal, (3) suitable, (4) not suitable, (5) least favorable (fig. 2).

The following correction transformed clusters into 2 groups: “suitable for windmill placement”, and “not suitable for windmill placement” (fig. 3).

The results achieved were unexpected. The most densely populated and touristically attractive areas in the south and south-west of the island near Reykjavik were ranked as the most unsuitable for the windmill placement, based on a combination of environmental and socio-economic factors. The most suitable for windmill placement regions are located in the hinterland. These regions are predominantly concentrated in areas with less rainfall which are more protected from the damaging effects of cyclones and winds. The protected areas, as well as bird nesting and feeding places, are located far from there. The most suitable regions also are situated far from tourist sites, and usually, represent vast wastelands or rocky ledges. At the same time, the average altitude is 250 m above sea level and more, which provides for high wind speeds and essentially power potential. The most favorable areas are confined to the eastern and southeastern regions of the Western Fjords (the central part of Iceland between the three main glaciers and Lake Thingvallavatn) and near the border of the North-Eastern and Eastern regions.

The least favorable for windmill placement areas include 310 polygons out of 346 — this amounts to 90 % of the island’s territory. Almost the entire western half of Iceland and vast areas in the hinterland confined to glaciers are not suitable for the development of wind energy. However, even the remaining 10 % of suitable land could be used in order to build economically viable and environmentally friendly wind farms. These territories have the potential to provide cheap energy not only to Iceland itself but also to continental Europe and the UK.

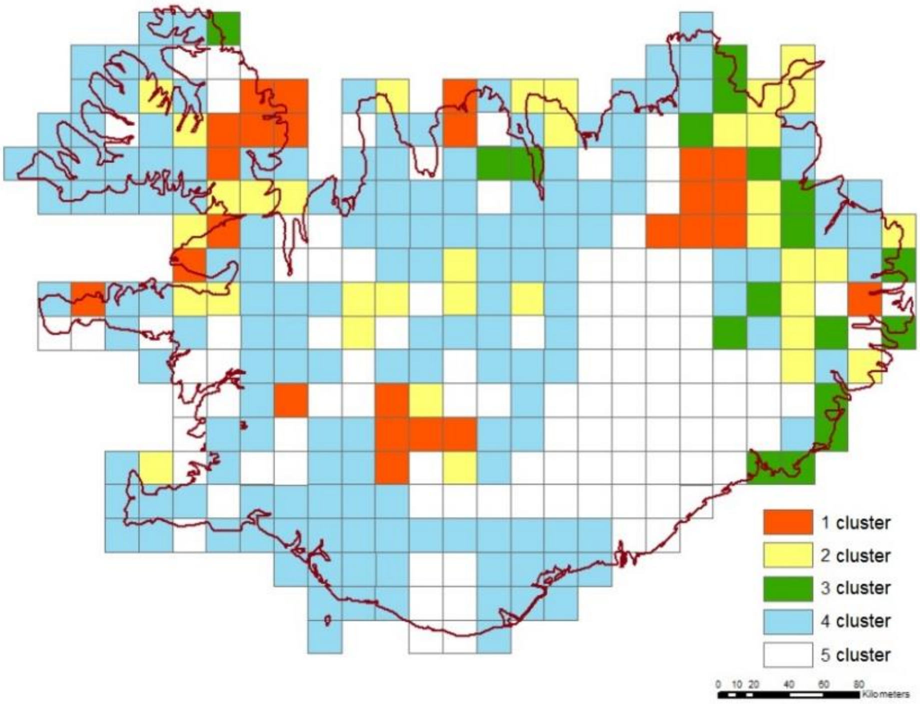

Fig. 2. Assessment of territory of Iceland according to the degree of suitability for the development of wind energy using the fuzzy clustering method (by author)

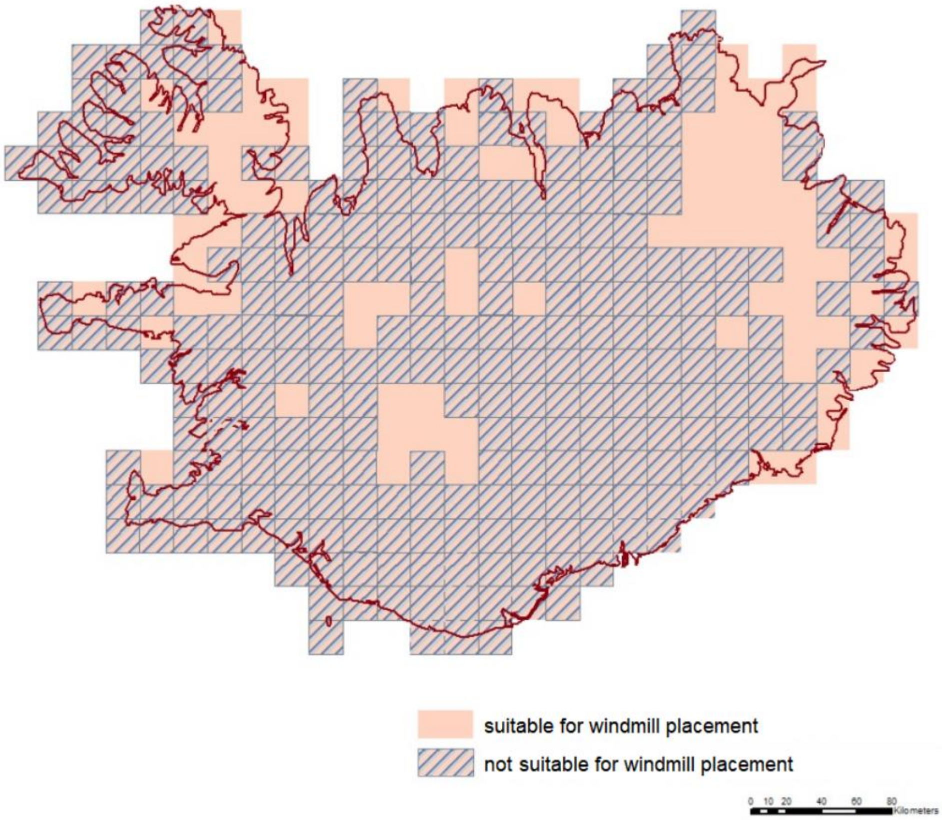

Fig. 3. Assessment of territory of Iceland according to the degree of suitability for the development of wind energy (final schematic map, by author)

CONCLUSIONS

The exploitation of renewable energy sources is growing every year all over the world. Europe is actively diversifying its energy structure, reducing its energy dependence and solving environmental problems associated with the development of traditional energy. Iceland is one of the leaders in this area, as 99 % of the heat and electricity it provides itself is renewable. However, until recently, only hydro- and geothermal stations were involved in the production of electricity, which have a great negative impact on the natural environment. In this context, the use of wind turbines seems to be the best solution for a country that lacks sunny days, but is rich in wind resources, especially if it is planning to supply European countries with relatively cheap energy.

The study allowed us to establish the following:

- approximately 10 % of the territory of Iceland has the potential for windmill placement, from physico-geographical, socio-economic and environmental points of view;
- the most favorable for wind farms placement areas are confined to the south of the Western Fjords, in the easternmost part of the coast of the Gulf of Breidafjordur, on the shore of the Eastern Fjords, in the central part of Iceland between the three main glaciers and Lake Thingvallavatn and near the border of the North-Eastern and Eastern regions;
- the development of wind energy could not only fully satisfy the increasing energy demand in the country, but also provide economic benefits from the sale of excess energy to European countries;
- the evaluation methods used to estimate the diverse parameters that affect the efficiency of windmill placement are applicable not only to Iceland but also to any country in the world or in any particular region.

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