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Master’s thesis in Geoinformatics for Urbanised Society (30 ECTS)

A GIS-based multi-criteria evaluation of the wind energy potential of Kherson and Zaporizhzhia oblasts of Ukraine

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Abstract (Annotation)

The aim of the thesis is to determine regulations for wind farm siting in Ukraine and to create a suitability map of the most perspective region in terms of wind conditions. These regions are Zaporizhzhia and Kherson oblasts (counties) of Ukraine.

Legislation analysis was conducted for wind energy regulations in Ukraine. Analysis of foreign legislation was done in the aspects where the correspondent Ukrainian legislation doesn't exist yet (e.g. about bird reserves). Otherwise, standards of international researchers were used.

I made analysis of works of other researchers to define factors and distances for suitability map. The most important and commonly used factors are: settlements, road network, nature protection areas, bird reserves, power lines, railways, slope degree, airports, water bodies, wind speed and land use.

Data is taken from different sources (open data, international, governmental), depending on quality. Methods used in my research are GIS analysis, multi-criteria decision-making (MCDM) and analytical hierarchy process (AHP). I chose the most important factors using MCDM method and graded them according to their importance using AHP method.

Unsuitable areas excluded and maps for each criteria were made. As final result, two maps were created: Equal Weights map and map with factors graded by AHP. Percentage of suitable areas were calculated and the analysis of the most influential factors after analysis was made.

Key words: wind farm siting, wind farm suitability, wind energy regulations, multi-criteria decision making, analytical hierarchy process analysis.

CERCS code: P510 - Physical geography, geomorphology, pedology, cartography, climatology.

Abstrakt (Annotatsioon)

Uurimistöö eesmärk on varasemate rahvusvaheliste uuringute eeskujul töötada välja reeglistik tuulikuparkide asukoha valikuks Ukrainas ning koostada selle alusel tuuletingimuste poolest kõige sobivamate piirkondade *Zaporižžja* ja Hersoni oblasti kohta sobivuskaart.

Tuuleenergia kasutussobivuse määratlemiseks oli tarvis läbi viia Ukraina seadusandluse analüüs. Valdkondades, kus vastavaid Ukraina õigusakte veel ei eksisteeri (nt linnukaitsealade osas) analüüsiti ja rakendati välisriikide seadusandluse alusel loodud reeglistikku. Seadusandlusega reguleerimata juhtudel kasutati reeglistiku loomisel rahvusvahelisi teadusuuringute tulemusi.

Teadusartiklite põhjal loodud andmebaasi alusel analüüsisin teiste riikide näiteid, et määrata tuuleenergia kasutamist enam mõjutavad tegurid ja vajalikud vahemaad või kaalud sobivuskaardi loomiseks. Kõige tähtsamad ja enamkasutatud tegurid on asustus, teedevõrk, looduskaitsealad (eriti linnukaitsealad), kõrgepingeelektriliinid, raudteed, nõlvakalle kraadides, lennujaamad, veekogud, tuule kiirus ja maakasutus.

Sõltuvalt andmete kvaliteedist on kasutatud erinevaid allikaid (avaandmed, rahvusvahelised ja riiklikud andmekogud). Meetoditena kasutasin oma uurimistöös mitmekriteeriumilist otsustamist (MCDM) ja analüütilise hierarhia protsessi (AHP) GIS-analüüsil. Kõige tähtsamad tegurid tuvastasin MCDM-meetodi abil ning seejärel sorteerisin neid olulisuse alusel AHP-meetodiga.

Tuuleenergia arendamiseks sobimatud alad jäeti välja ning iga kriteeriumi alusel koostati eraldi kaardikihid. Kihtide kombineerimisel sündisid lõpptulemusena kaks kaarti: võrdsete kaalude (*Equal Weights*) sobivuskaart ja sobivuskaart, mille loomisel kasutatud tegurid järjestati AHP alusel. *Zaporižžja* ja Hersoni oblasti kohta leiti tuuleenergia arendamiseks sobivate alade protsent, täiendavalt analüüsiti piirangute põhjustajatena kõige olulisemaid tegureid ja nende osakaalu.

Võtmesõnad: tuulikuparkide asukoha valik, tuulikuparkide rajamise sobivusanalüüs, planeerimisreeglistik tuuleenergia kasutuselevõtuks, mitmekriteeriumiline otsustamine, analüütilise hierarhia protsess.

CERCS kood: P510 – füüsiline geograafia, geomorfoloogia, pedoloogia, kartograafia, klimatoloogia (physical geography, geomorphology, pedology, cartography, climatology)

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List of abbreviations

MW – megawatt
kV - kilovolt
GWA – Global Wind Atlas
EIA – environmental impact assessment

Introduction

Wind energy (along with solar) is a most perspective type of renewable energy in today’s world. It has a second largest installed capacity in EU (after natural gas) and the pace of its growth is higher than of any other source of power generation in Europe (WindEurope 2018). By the end of 2018, the total of 591,549 MW of wind power were installed in the world, with growth rate of 9,6% annually. (GWEA 2019)

Installing new renewable energy capacities can make power system of Ukraine more sustainable and less dependent on external supply of resources. Ukraine has a big territory and good wind conditions in many regions, but the best conditions are in the South and in the East. Development of wind power is one of the key priorities in the energy policy of Ukrainian government.

Developing of renewable energy can reduce the dependence of Ukrainian energy system on the import of coal and other fossil fuels. And using less coal in energy production will cause less harm to environment. Today about 93% of electricity in Ukraine used to be produced from non-renewable sources and about 44% is produced from carbon-intensive sources. (Chmeruk 2018)

Ukraine has much lower wind power capacity installed than European countries of approximately same size and population (Spain, France, Poland). Ukraine has bigger territory than these countries (though approximately same population), and it means that Ukraine has a big unused potential. I think that topic of wind energy is very actual for Ukraine nowadays. That is why I decided to do my thesis on this topic.

First aim of the thesis is to find spatial regulations for wind farm siting in Ukraine. Second aim is to create a suitability map of the most perspective region in terms of wind conditions. This region is Zaporizhzhia and Kherson oblasts (counties) of Ukraine.

Ukraine’s territory is divided to 24 counties (or regions), which in Ukrainian are called “oblasts” (singular – oblast). I analyze two of such “oblasts”. I use term “oblast” further throughout all my work, because, as for me, it is a most precise definition of the administrative unit I use. This unit is used internationally. Though the terms “county” and “region” would be good for definition of the unit as well.

I chose Kherson and Zaporizhzhia oblasts as study area, because they have best wind conditions, and therefore the yield of energy from wind parks, constructed there, will be the highest. Infrastructure and other nature conditions also are making it suitable.

Legislation for wind turbines in Ukraine is not complete yet, and the methodology, which I am working out, can be helpful for other researchers, who will study this topic in Ukraine (and not only). Finding the necessary rules and regulations is one of the aims of my thesis.

Result of the thesis is a suitability map of counties, with areas marked in different colors, depending on suitability extent. Places not suitable for wind farms are excluded from the map and are marked accordingly.

Methods used in my research are GIS analysis, multi-criteria decision-making (MCDM) and analytical hierarchy process (AHP). I chose the most important factors using MCDM method and graded them according to their importance using AHP method. QGIS and ArcGIS were used for processing of spatial data, areas were calculated in Excel.

While studying the legislation, it was be analyzed where current legislation is sufficient and where it has to be improved. Thesis may be also useful what are the data sources available for spatial analysis in this field in Ukraine. As proper quality governmental data for such an analysis doesn't exist yet.

I describe tools for processing of the data and explore some common rules for better wind energy planning. As well as write about some theory from sphere of wind energy.

Novelty of my research is in comparison of two neighboring counties with different conditions and types of land use. As a rule, papers on this topic include only one county or part of the territory in analysis, without references to conditions in surrounding places. I consider two oblasts (counties) which have different settlement and population structures. And which are, at the same time, the most suitable for wind energy in relation to whole Ukraine. After comparison, the aim is to determine which one has bigger suitability percentage and total area. In the end two suitability maps are created and factors affecting wind farm suitability in study area are analyzed.

Based on spatial analysis, I make calculations and conclusions, which give answers to my research questions.

Research questions:

1. Which percentage of territory is suitable for wind power development in two oblasts? Which oblast has bigger percentage of land available to install wind turbines?
2. What percentage of suitable land has high suitability (over 80%) according to equal weights and AHP scenarios and high wind speed (over 9 m/s)?
3. What are the most important factors affecting the suitability of sites for wind turbines in the region? Are road and power lines networks dense enough to support the development of wind energy in study area?

1. Theoretical overview

1.1. Wind energy in Ukraine and factors

Ukraine had an aim to increase the share of renewable energy in a final consumption to 11% by 2020 (Cabinet of Ministers of Ukraine 2014). But by end of 2019, the share of renewable energy in Ukraine is approximately 9%, while share in consumption is 3,7% (Hrytsyshyna 2019, NKREKP 2019). Wind energy has only 1,1% of share in total. Next goal in new Ukraine's Energy Strategy (2017) is 25% of renewables by 2035. Plan is ambitious and previous one was not fulfilled yet.

Ukraine has smaller share of wind energy than many European countries. Big potential for new wind power remains unused. Though there is progress as well. By end of 2019 Ukraine has 1170 MW of installed wind power capacity, In comparison, in 2018 it had only 533 MW. Our country is currently leading among ex-USSR countries in capacity. New plants are built every year. In 2018 new law was adopted, which is making the construction of wind farms easier (Cabinet of Ministers of Ukraine 2018). But still, if to compare to countries of same population, it is low capacity (e.g. 25,704 MW wind capacity in Spain).

There is a big amount of unpopulated land available in Ukraine. Density of population in study area is one of the lowest in the country. But the site for wind plant installation should be chosen very carefully. I analyzed many works of other researchers on the topics of wind farm siting and wind farm suitability. And selected for my research the factors they consider as most important and which they use most frequently.

One of the most crucial factors is a wind speed. But even in case if the meteorological conditions are perfect, not every location is suitable for a wind farm. According to some researchers, first of all, the impact on environment should be taken into account. Wind farms can’t be built in the nature protection areas, and in some cases, in areas next to them. Other researchers think that there are other factors (settlements or infrastructure), which are more important. Wind farms have to be distant from the urban, rural and any other populated areas, and to not disturb and be safe for people living nearby. The proximity to transmission lines is important, and the closer lines are, the better it is. Buffer zones from roads, railways, settlements and airports should be taken into account for safety reasons. I define buffer zones and distances based on legislation and common practices. Land use and land cover (if it’s agricultural site, forest or cultural heritage area) may not allow to place wind turbines. But it doesn’t necessarily exclude these sites from possible construction.

In order to make a geospatial analysis I use information and layers about natural protected areas, analyze information about existing transmission lines and power stations, airports, roads, highways, settlements boundaries, railroads, water bodies and about other possible restrictions for land use. Another important characteristic is slope gradient.

Wind turbines have to be situated on safe distances from living areas because of noise they create, flickering effect and because of safety (to prevent damage from fall of wind turbine or particles of ice from it). Noise and flickering may have negative effect on human health. Distance from bird and nature reserves is calculated for the same, noise, reason. Also, the functioning of turbine shouldn’t be dangerous for life of birds. Roads, railways and power lines should be on safe distance in case if turbine falls down.

Researchers include different factors as key ones. For example, Baban and Parry (2001) define four groups of factors, depending on their importance. As first-grade factors they define slopes, roads and urban centers, as second-grade agricultural lands, railways, woodlands and rivers. Höfer et al. (2016), made a survey among industry specialists to define criteria. I studied the criteria in papers of researchers to define my own factors. I divided factors into four categories, by their type: economic, social, environmental, technical. (Table 1)

Table 1. Factors of my research

Factor	Group of factors
Settlements: - big (urban) - small (rural)	Social
Road network	Economic and technical
Nature protection areas	Environmental
Bird reserves	Environmental
Power lines	Technical and economic
Railways	Technical
Slope	Technical
Airports	Techno-social
Water bodies: - rivers, lakes, wetlands	Techno-environmental
Wind speed	Economic
Land use	Socio-technical

Three factors are excluded from final map without grading for more or less suitable: water bodies, land use and nature protection areas. All the other factors are graded according to suitability extent, and have some parts excluded as well (e.g. settlements).

1.2. Overview of previous research

During process of writing my thesis I found 72 papers of researchers on this topic, analyzed 38 of them and defined 22 most relevant and helpful for my research. I also created a comparison table for this papers (Table 2). I also studied above 20 official documents regulating wind turbine placement.

The GIS based approach to study wind energy potential sites was used in a number of studies in different countries before. Miller and Li (2014) studied the wind energy potentials in Nebraska. The paper didn't go deep into analysis, but it defined the main criteria for analysis: wind speed, population density, land use, distance to the roads, slope gradient and distance to transmission lines. The sources of data for which layer were defined, as well as structure (vector, raster), type of the spatial data (point, polyline, polygon) and reasons for selection described. Regions were divided by a suitability score for each of the criteria, from unsuitable to high. The study also defines existing and potential wind energy capacity. Deriving from the numbers and qualities for each suitability score for each criteria, the criteria for my work was defined separately.

Good example of this type of suitability analysis is work by Höfer et al. (2016) in Aachen region of Germany. It contained all the methods I used in my thesis (GIS, MCDM and AHP) and included references to German legislation.

Similar study was made by Wang et al. (2014). Paper studied the potential sites in Fukushima Prefecture. The analysis was needed because of the Daiichi nuclear disaster in 2012. New sources of energy are needed in the region to replace the energy, which was produced by nuclear power plant.

Latinopoulos and Kechagia (2015) defined constraints criteria (buffer zones) for their analysis of one of the regions in Greece. Combined land use and wind conditions analysis was made by a number of different researchers, where they include all the conditions in one comprehensive map. Also the environmental and economic separate analysis were made in this paper, with choosing the best sites for each of two criteria.

Concerning the research already done in Ukraine, I found one paper of Ukrainian researchers "Assessment of regional wind energy resources" (Sobchenko and Khomenko 2015). Though, the analysis doesn't contain precise information about possible location sites and don't include GIS component. The research is more concentrated on the wind speed statistics in certain locations. It can be a source for defining a best region for wind conditions, but it doesn't present the information about suitable locations. The topic was studied by Volkovaia et al. (2015), and Makarovskiy et al. (2013), but papers contain more general information about wind conditions, without detailed GIS analysis. The analysis of wind conditions in Western counties of Ukraine was made by Moskalchuk and Prykhodko (2017). It doesn't contain multi-criteria land use analysis, but contains example of calculation and projection of wind speed on 30, 50, 70 and 100 m height, based on meteorological data. Paper of Velychko (2003) contains wind maps of Ukraine for months of all seasons of the year. Many environmental assessments were made for different farms in Ukraine (Bota 2018, Luczak and Dembinska 2017, Ukrecoconsult 2018, Ukraine Power Resources 2019). Though, they don't contain references to legislation which they used during planning.

1.2.1. Similar research in Ukraine

There is a plenty researches done in other countries about wind-farm site selection, which include information about regulations and suitability maps. Though, no such research was made on Ukraine's territory. Reason for that could be a lack of institutional regulations, lack of data or lack of interest in such research.
Similar study was made by International Renewable Energy Agency (IRENA) in Ukraine. They created a map of investment opportunities, with assessment of wind power potential based on six factors: wind speed, grid distance, population density, topography, land cover and protected areas. Map has suitability assessment with scale of 0-100% (Figure 1).

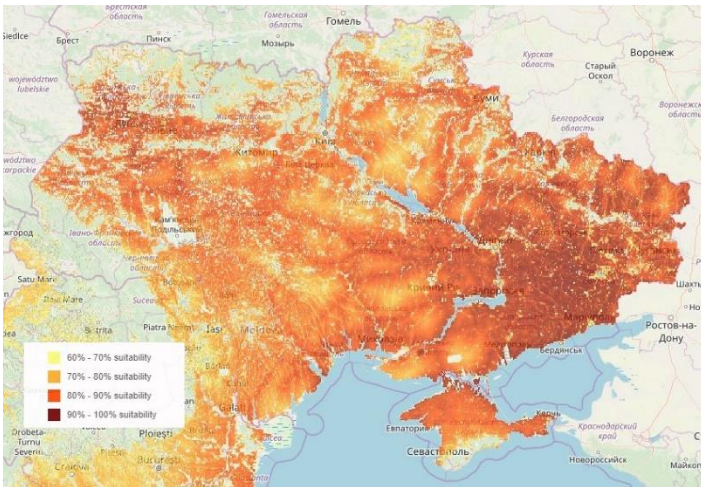


Figure 1. Investment opportunities map in South-Eastern Europe (source: IRENA)

However, this study is very basic and approximate. First, the resolution is low. Second, many crucial factors (roads, railways, slope degree, settlements, water bodies) are not taken into account. Third, not suitable zones were just excluded, without creating any safety buffers.. Despite this, we can see from map that suitability of Kherson and especially, Zaporizhzhia, oblast region, is remarkably high.

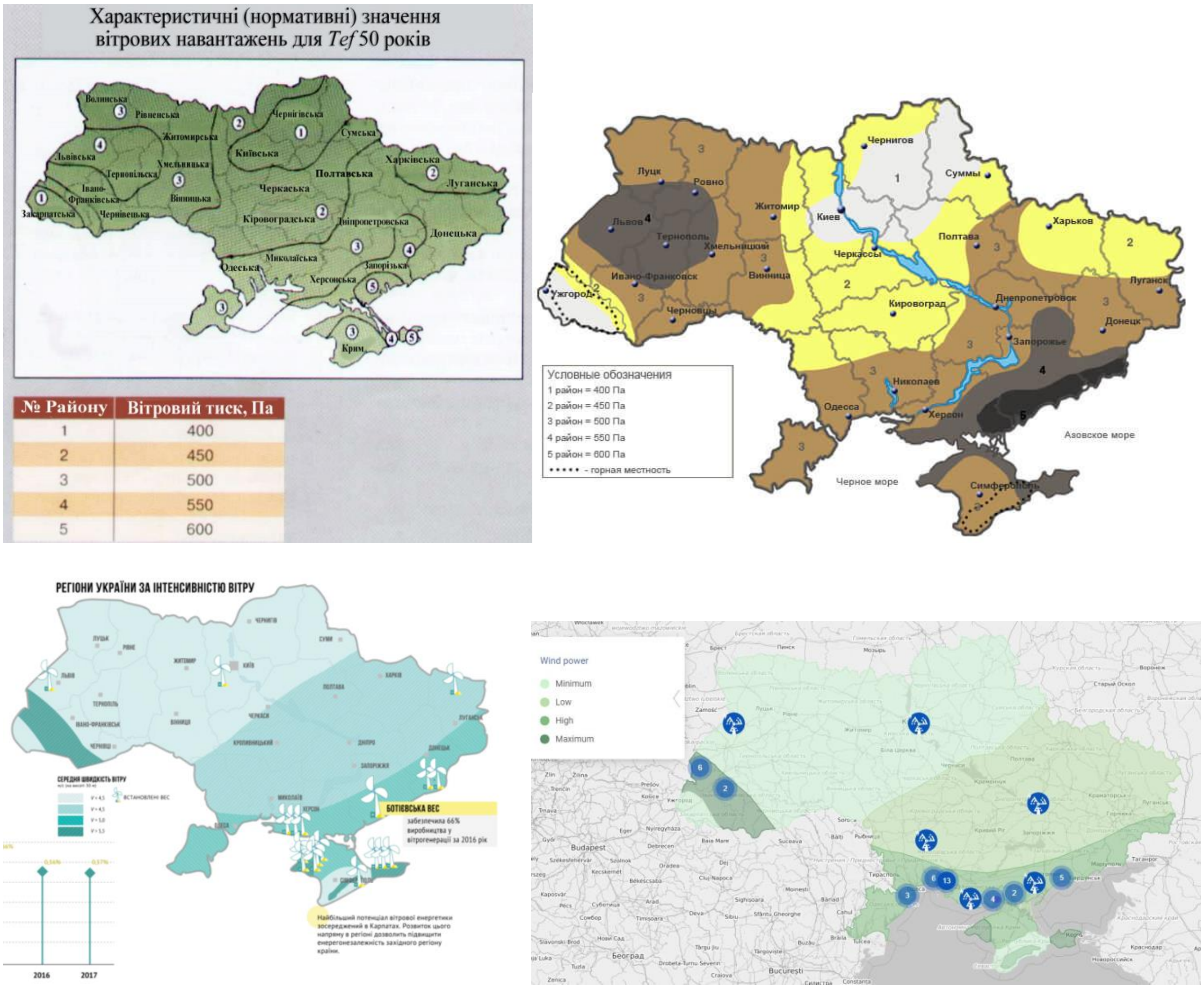
1.3. Study area

I chose Ukraine, because no research was done on topic of wind farm suitability, in any region of our country. Studies made by now about topic of GIS and wind energy are very basic and mostly just overview a theory of wind farm planning (Volkovaia 2015, Velychko 2003, Moskalchuk and Prykhodko 2017, Molodan 2013 and others). Legislation which would regulate the turbines placement is not complete. Though Ukraine is not the alone in it. Same situation was, for example, in Poland, as it is described in a work of Sliz-Szkliniarz and Vogt (2011).

1.3.1. Choice of study area

As study area I chose a part of Ukraine, which has best wind conditions, in order to maximize the economical feasibility of wind energy production. Based on the analyzed papers I concluded that it is better to concentrate on county level (oblasts in Ukraine), not on the whole territory. In this case, research is more detailed and quality is higher.

I found next maps showing the best wind conditions in Ukraine. (Figures 2,3,4,5)



Figures 2,3,4,5. Wind potential of Ukraine (sources: wikipedia.org, stalex.ua, nachasi.com, ua.energy)

According to these maps, the biggest wind pressure is in the zone which corresponds to the location of Kherson and Zaporizhzhia oblasts, especially in localities close to the coast. (Figures 2,3,4,5) That is why I chose these two oblasts for my analysis. Wind conditions are also very good in Carpathian region of Ukraine, but high slope degree, high elevation, land cover and infrastructure in mountain areas don't allow to build many wind parks there. The conditions in Kherson and Zaporizhzhia oblasts are opposite: low elevation, steppe area, low slope degree and dense enough road network. Good wind conditions are also in Donetsk oblast, but construction there is not that feasible.

1.3.2. Description of study area

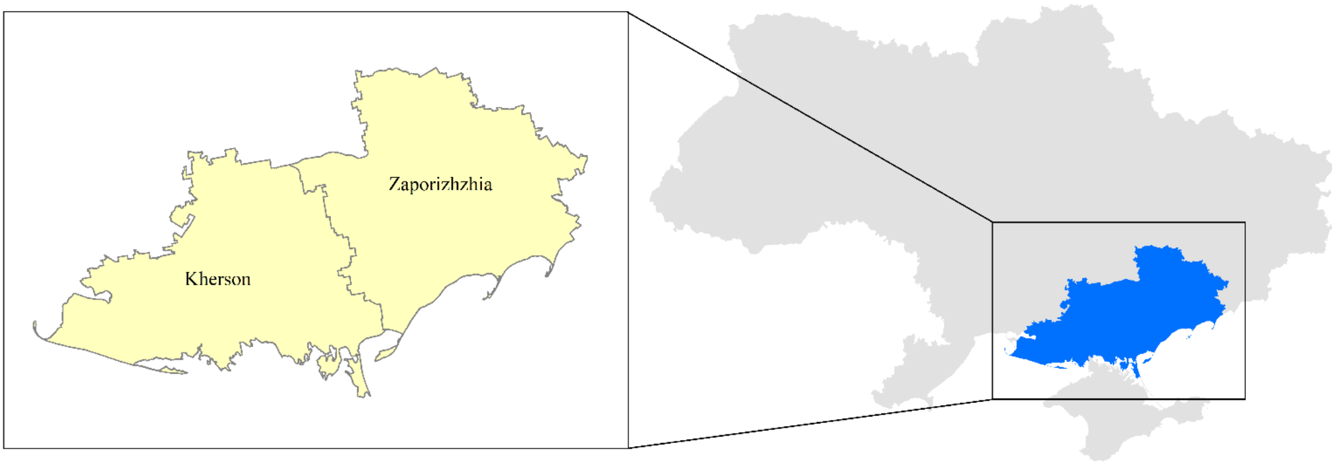


Figure 6. Study area. Kherson and Zaporizhzhia oblasts on a map of Ukraine

Kherson and Zaporizhzhia oblasts are located in South-Eastern Ukraine near the sea coast of Black and Azov seas (Figure 6). Both oblasts have low elevation. Highest point in Kherson oblast is 101 meters. In Zaporizhzhia elevation is a bit higher – highest point is 327 meters above the sea level. Together these two oblasts constitute 9,2% of territory of Ukraine. Their total area is 55,64 km^2, which is e.g. bigger than a territory of Estonia (45,23 km^2).

Population of these oblasts is 2,743 million people. But settling type is different. Zaporizhzhia has bigger population, and a bit smaller territory. Kherson oblast has a second lowest density amoung oblasts in Ukraine. Percent of rural population is bigger in Kherson (Table 2). (Ukrstat 2019)

Table 2. Comparison of counties

	Kherson oblast	**Zaporizhzhia oblast**
Population (mil. people)	1,038	1,705
Area (km^2)	28,46	27,18
Density	36,08/km2	61,97/km2
Rural population %	38,7%	22,6%

Zaporizhizhia oblast is more urbanized and industrialized. Kherson's settlements occupy bigger territory, as most of them are rural. It may mean that distances between settlements in Zaporizhzhia oblast are bigger and therefore bigger amount of unoccupied land is available for placing wind turbines. But as a population density of Zaporizhzhia oblast is higher, the effect may be an opposite. It is one of my research questions: to find out which oblast has bigger territory, suitable for wind farms.

Kherson oblast contains a biggest desert in Europe – Oleshky Sands. Oblast also contains big amount of nature reserves, most famous of which is Askania-Nova. Kherson and Zaporizhzhia oblasts contain approximately half of the existing wind power stations in Ukraine. Currently, these two oblasts are leaders in Ukraine by amount of installed wind turbines.

Oblasts occupy a minor part of the territory, but there is a huge area potentially suitable for the wind turbine development, especially near the sea coast. Land there is used for many other purposes, like recreation, settlement and agriculture. The region is flat and the elevation is not an obstacle. In addition, the percent of forests in the area is very low, as it is steppe region. The land cover in study area is different from the other parts of Ukraine.

2. Results - Factors

I created guidelines for wind turbine construction, by finding out what are the most necessary restrictions for wind plant placement in Ukraine, with some regard to international rules and practices. Wherever it is possible, I use Ukrainian regulations. Where it is not, I used legislation of other countries and common practices to create distance buffers and hierarchy scales. I am analyzing different sources to define the optimal and most commonly used regulations.

I made a table (Table 3) with most commonly used factors and distances indicated in other papers:

Table 3. Factors in works of other researchers

Country	Germany	Greece	UK	Denmark	Greece	Ecuador	USA
Author	Hofer	Tegou	Baban	Hansen	Latinopoulos	Villacreses	Miller
Place	Aachen	Lesvos		Northern Jutland	Kozani		Nebraska
Year	2016	2010	2001	2005	2015	2017	2014
Distances from (m)							
Natural reserves	0		1000		1000	250	
Water bodies	50		400	150		4000	
Big settlements	550	1000	2000	500	1000	3000	
Small settlements	550	500		500	500		
Separate houses	400		500				
Airports				5000-7500	3000	2500	
Bird habitat	300 (1200)						
Roads and highways	0 - 20	100-10000	100-10000	150-300	150, 5000		100-10000
Wind speed (m/s)	>6	>4	>5		>4,5	>3	>5,6
Slope (%)	<30%	<25%	<10%		<25%	<15%	<40%
Power lines	100-9000		10000	200			100-20000
Railways	100	100	100				

Table 3 continuation.

Country	Thailand	England	Japan	Poland	USA	Turkey	Turkey	Turkey	Japan
Author	Bennui	Watson	Wang	Sliz-Szkliniarz	Gorsevski	Değirmenci	Atici	Aydin	Derdouri
Place		South England	Fukushima		Ohio			Western Turkey	Fukushima
Year	2007	2016	2014	2011	2013	2018	2015	2010	2018
Distances from (m)									
Natural reserves		1000	1000	500			2000	1000, 250	300
Water bodies	200		500	200			3000	400	50
Big settlements	2500		2000			1000	2000	2000	
Small settlements	1000		500					1000	
Separate houses		500							
Airports	3000		2500	3000		3000	5000	3000-6000	200
Bird habitat				1000					
Roads	500			100	1000-10000		500		20
Wind speed (m/s)			>6		>5,6				<6
Slope (%)	<15%	<10° (%)	<20%				<10%		<30%
Power lines				200	1000-20000		200		100
Railways				100			500		100

Table 3 continuation.

Country	Cyprus	Greece	Vietnam	Taiwan	USA	USA
Author	Georgiou	Bili	Nguyen	Yue, Wang	Carlino	Van Haaren
Place	Larnaca	Andros		Chigu	Massac husets	New York
Year	2012	2018	2007	2006	2013	2011
Distances from (m)						
Natural reserves	300	1000	500	250, 500		
Water bodies	150	400	400			3000
Big settlements	850	1000	2000	500		2000
Small settlements		500		250		1000
Separate houses						
Airports	4000	2500	2500			
Bird habitat	500			500		
Roads	150 - 5000	130 (1,5⌀)	100	0		500
Wind speed (m/s)	<5	<6		<4	<6	
Slope (%)	<10%				<30%	<10%
Power lines	100-5000	130 (1,5d)				
Railways			100			

Analysis of bigger amount of papers lead to more precise definition of buffers in cases where national legislation doesn't regulate distances. I gathered as many papers on this topic, as possible.

Settlements

Distances from wind energy objects in Ukraine are not regulated by any specific law. The only law regulating them is UkrNDNC (2017), defining 700 m safety zone from wind turbines to other objects. There are regulations, defining safety distances, for roads, nature reserves, water bodies, power lines and railways.

The only existing Ukrainian official regulation "Wind farms. Evaluation of environmental impact of wind farms" by UkrNDNC (2017) defines the minimum buffer zone of 700 m for wind farms of more than 20 MW and turbines of more than 100 kW (today's wind turbines have bigger capacity than 100 kW, so it applies to all stations existing in the area). This distance I take as a basis. From person in UWEA (Ukrainian Wind Energy Association) I found out that 1000 m distance is taken as a standard nowadays. Therefore I created a first suitability buffer for 700-1000 m from the settlements of all types/

According to EBRD Recommendations (Environmental and Social Suitability Criteria for Projects in the Field terrestrial wind power, 2015) from paper of Ukraine Power Resources (2019) the minimum distance from living houses should be 700 m. They also suggest setting the minimum distance of 800 meters to any other object.

Papers of most of the researchers (Tegou et al. 2010, Latinopoulos and Kechagia 2015, Bennui et al. 2007, Höfer et al. 2016, Baban and Parry 2001, Wang et al. 2014) and regulations of EU countries differentiate the required distances, depending if it's rural, urban area, or separate houses. Urban areas need bigger buffer zones than rural ones. Researchers suggest even smaller zones for separate housing.

Distance to small settlements (rural, villages) varies from 500 m (Höfer et al. 2016, Tegou et al. 2010, Hansen (2005), Latinopoulos and Kechagia 2015, Wang et al. 2014, Andros) to 1000 m (van Haaren and Fthenakis 2011, Aydin et al. 2010). Distance to cities (urban areas) is in range from 1000 m (Tegou et al. 2010, Latinopoulos and Kechagia 2015, Andros) to 2000 m (Nguyen, Baban and Parry 2001, Wang et al. 2014, Atici et al. 2015, Aydin et al. 2010, van Haaren and Fthenakis 2011) usually. With some exceptions – two researchers recommend bigger distance - 2500-3000 m.

In most of researches the maximum distance to urban settlements is 2 times higher than to rural ones (Yue-Wang, Andros, Aydin et al. 2010, Latinopoulos and Kechagia 2015, Tegou et al. 2010). I am doing the same. Maximum buffer distance to villages is 1000 m, which matches with UWEA standard for all settlements. Accordingly, maximum buffer to cities and settlements of urban type is 2000 m.

Latinopoulos and Kechagia (2015) suggests 500 m distance from settlements with up to 2000 inhabitants and 1000 m for settlements with over 2000 inhabitants. It exactly corresponds to administrative division of Ukraine, because villages in Ukraine are the settlements with up to 2000 inhabitants. There is also a special type of settlement called “selyshche”, which corresponds to English “town”, “township” or “settlement”. It’s a settlement of 2000 to 10000 people, majority of which are occupied in industry (Supreme Council of Ukraine, 2012). I count them as cities, and they have bigger safety zone than villages.

There are few reasons why wind turbines should be located on a safe distance from living area: noise, icing, flickering, falling parts of turbines. Let’s take a look if those factors can anyhow extend the zone of 700 m, which I initially plan to set as minimum distance to all settlements.

1. ***Noise***

Noise from wind turbines may disturb people nearby. The bigger distance, the lower is noise. The regulations of EU countries say that the level of noise in living areas shouldn’t exceed 45 dB. It includes all cumulative noise in the area, not only from wind turbines. (Dalla Longa et.al. 2018) Noise standards in Ukraine are the same as in most of EU countries – 55 dB during the day and 45 dB during the night. Daytime is defined from 7:00 to 23:00, night time – from 23:00 to 7:00. (KCSA 2019).

According to technical report of the European Commission (Dalla Longa et.al. 2018), the noise from large scale wind turbines reach the acceptable threshold of 45 dB at distance 500 m and level of 40 dB at 700 m (Figure 7). As a standard a turbine with capacity of 3 MW, pole height 80 m and rotor diameter 90 meters was taken. Each EU country has regulation about distances from wind turbines to living areas (Annex 1). Therefore it is another reason to have distance from living areas as 700 m.

From European Commission JRC report we can see that no country in EU has a minimum setback distance from large wind farm to houses less than 400 m. Only Wallonia and Netherlands have minimum possible 400 m. Except of them, 500 meters is a minimum. (Annex 1). Usually, the distance is influenced by a population density of regions. Bigger population density – shorter are the setback distances. Population density in Ukraine is lower than in Germany. Therefore, distance should be bigger. Mainly, the distances vary from 500 to 1000 m, with only exceptions of Niederösterreich (1200 m), Baden-Württemberg and Poland (1250 m) and Scotland (2000 m). Therefore, it makes sense to define 1000 m as another setback distance from settlements.

According to study of environmental effect of projected wind farm in Lviv Oblast of Ukraine, the distance from housing is accepted as 400 m (Bota 2018). Though it is not in accordance with Ukrainian law. Author says that even 300 m is enough according to regulations, without any reference to national legislation. Another source on the internet says that in Ukraine distance of 350 meters is enough, but also doesn’t contain reference to this information. [1]

[1] http://tvoemisto.tv/exclusive/viter_peremin_yak_za_sto_km_vid_lvova_pratsyuie_vitroelektrostantsiya_78878.html

In this case, I create a model for assessment, where I give the percentages to distances suggested by different authors. On suitability map, I consider distance of 700-1000 m as area of low suitability.

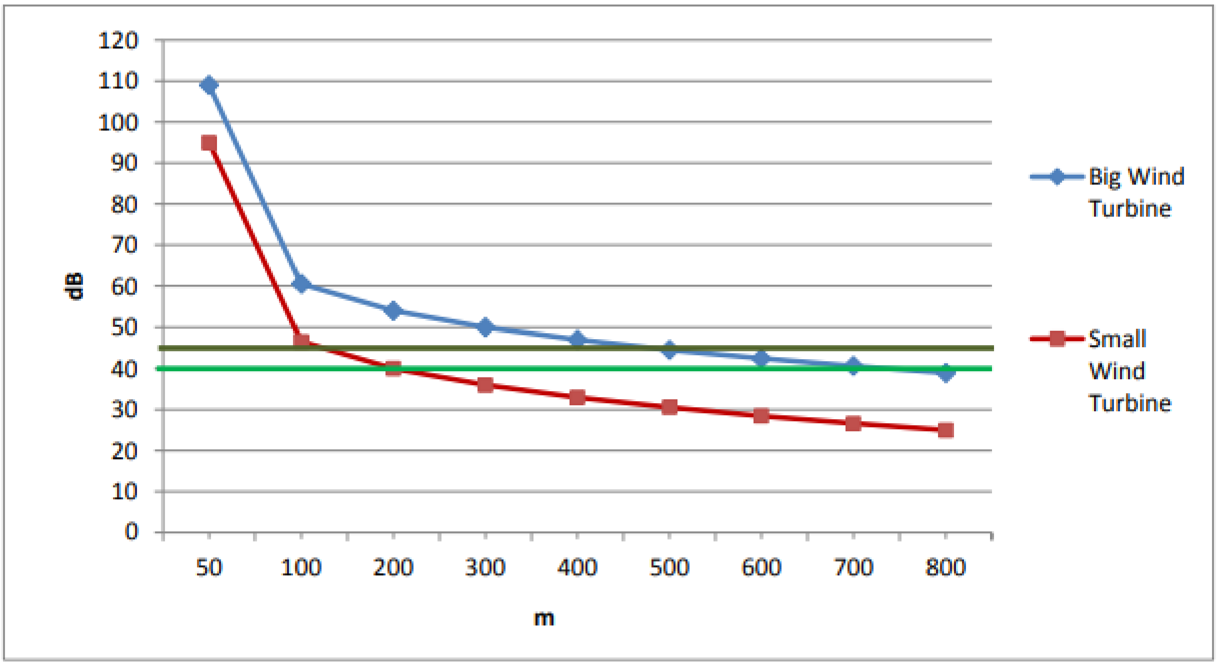


Figure 7. Noise level of wind small/large wind turbine in relation to distance (Dalla Longa et.al. 2018)

The level of noise may depend on type of terrain, wind direction (in the direction of the wind the noise is bigger), number of wind turbines (2 more turbines increase sound level by 3 dB, cumulative effect), frequency (of rotation), temperature and humidity. (Dalla Longa et.al. 2018)

There is also a rule of thumb, which states that if distance is three times of blade tip height – it's enough to ensure acceptable distance to living houses. (Clarke 2019 and Rogers 2006). Nowadays it would be around 600 m.

2. *Icing*

During wintertime, ice particles start to form on wind turbines blades. This ice can be then be scattered because of movement of the turbine in the direction of the wind. These particles may be dangerous for people walking or living nearby. That's why, during the construction of the wind farm, the probability of ice forming on the blades should be taken into account and safety buffer zone created for case of ice throw. The probability of ice throw depends on how frequently temperature on the site may go below 0°C. In the Southern Ukraine, climate is not as harsh in winter as it is in northern latitudes. Therefore, the probability of icing is comparatively low. Probability of icing increases with increase of moisture and wind speed during below-zero temperature.

According to Kjeller (2017), the maximum possible ice throwing distance is 350 m. And according to their research, ice pieces were found at 69% of maximum distance. So, buffer zone can be even shorter. According to Cattlin research, only 3% of ice particles were found in a zone exceeding the tip height of the turbine.

According to paper of conclusions on installation of wind turbines in Zaporizhzhia oblast of Ukraine, distance from turbine of height of 117 meters the distance of ice scattering is about 364,5 meters. (Luczak and Dembinska 2017)

Kjeller (2017) suggests that different zones for different probabilities: inner zone, middle zone, outer zone and outside outer zone. According to both CanWEA and Kjeller (2017) the maximum ice throwing distance can be defined by next formula (Figure 8):

$$dt = 1.5(D + H),$$

where: dt = maximum throwing distance (m), D = rotor diameter (m), H = hub height (m)"

CanWEA (2017) also defines a formula for ice fall:

$$df = 1{,}5H,$$

where: df = maximum falling distance (m), H = hub height (m)

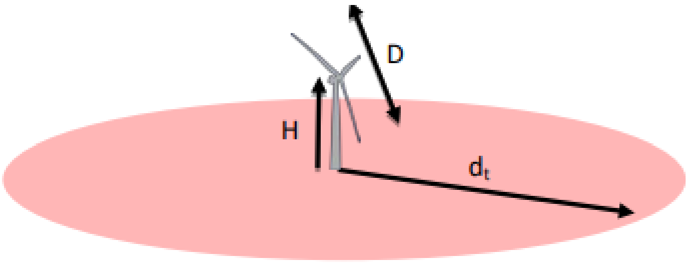


Figure 8. Maximum throwing distance area (CanWEA 2017)

Besides this, the factors influencing the distance and landing place of thrown ice are also: wind speed, it's direction, size and position of ice on the blade and speed of blade rotation. The cases of harm to people from wind turbines ice happened in Stockholm and Oslo.

3. *Flickering*

Another obstacle for installing wind turbines is flickering. Flickering is an effect of shadow blinking from rotation of wind turbine blades. It occurs mostly during sunrises and sunsets. It has negative effect on human and animal health. The illustration of flickering effect is shown in Figure 9.

Figure 9. Illustration of Flickering effect (source: American Wind Energy Association)

The bigger the distance from wind turbine, the smaller probability that it will affect inhabitants nearby.

4. *Falling parts of turbines*

UkrNDNC (2017) suggests the next safety distance in case of fall of wind turbines parts:

r = H+D,

where: H – hub height, D – diameter of turbine.

From here we can see that the maximum distance of fall is approximately 251 m (133+118) (Wind Turbine, 2019).

According to Bota (2018), wind turbine blades in case of their chip, can fall around in range of 300 m from turbine.

To conclude, all the danger factors suppose restrictions of no more than 700 m, which are set by UkrNDNC (2017) and which I used as a mandatory buffer for exclusion.

Water bodies and coastline

All the water bodies were excluded from suitability map. Additionally, Ukrainian laws envision the safety zone for them. Wind turbines cannot be built there as well.

1. Rivers, lakes, reservoirs, wetlands

According to Ukrainian legislation, the order "State Sanitary Rules for planning and development of settlements" (Ministry of Health, 2019), the coastal safety zone is:

- for big rivers, reservoirs and lakes – 100 m
- for medium-sized rivers, reservoirs and ponds with area of more than 3 ha – 50 m
- for small rivers, ponds and streams up to 3 ha – 25 m.

According to Article 79 of The Water Code of Ukraine, big rivers are those whose basin is exceeding 50000 km^2, medium – from 2000 to 50000 km^2, and small – up to 2000 km^2 basin.

In coastal safety zones it's forbidden to erect any types of constructions, except hydrotechnical ones. Meaning that wind turbines are not allowed.

2. Coastline

Both oblasts have wide coastline. And majority of currently built wind stations in region are situated near the coast. Works of some authors include coastline as a restriction factor. Hansen (2005) suggests 100 m, Georgiou et al. (2012) - 300 m, Yue and Wang (2006) – 1500 m, and Andros (2018) – even 2000 m.

In our case, situation is different. Water Code of Ukraine (2019) defines coastal safety zone around seas, gulfs and estuaries is 2000 m, but according to Article 90 of the Code, coastline can be used for "the construction of ... objects that produce energy through the use of wind, sun and wave energy". It means that no coastal safety zone is needed.

Natural protection areas

1. Protection areas

According to Ukrainian legislation (law "On Nature Reserve Fund"), any construction on territory of nature reserves, not connected with activity of the reserve, is forbidden. Therefore, all the nature protection areas in two oblasts are excluded from the potential construction sites.

According to this law, Nature Reserve Fund of Ukraine includes:

1) nature areas and sites: nature reserves, biosphere reserves, national parks, regional landscapes, nature reserves and nature monuments.

2) artificial objects - botanical gardens, arboretums, zoological parks, nature monuments, park and garden monuments.

Additionally, the need for safety zones is envisioned. Though, the size of safety zones is not defined. “The sizes of the safety zones are determined according to their intended purpose on the basis of special surveys of landscapes and economic activity in the neighboring territories.” Construction in safety zones is forbidden as well. It is only said that safety zones should be taken into account during development and planning phase. The only present regulation - zones around forest monuments should be at least 2 times height of trees. Safety zones around bird reserves is a common practice, though buffers around other types of reserves are not always set during wind farm planning.

According to Aydin et.al. (2010) there should be 1000 m away from areas of ecological value, 400 m away from water bodies (Baban and Parry, 2001). It is suggested 250 m from ecologically sensitive areas and 500 m away from nearest bird habitat (Yue and Wang, 2006).

Höfer et al. (2016) defines 0 m buffer to nature reserves areas, only buffers around bird reserves. In my work I did the same.

2. Bird reserves

Special attention has to be paid to such type of protection areas as bird reserves, as wind turbines are especially dangerous for birds.

According to University of Sydney research, every year about 400 000 birds die because of wind turbines in USA only. (Chapman 2017). And building of wind turbines in the proximity to bird reserves may increase the number of deaths significantly.

Höfer et al. (2016) differentiates types of nature protection areas to those, which contain populations of birds and/or bats, and those, which don’t. Areas without bird protection don’t require any buffer zone, but bird reserves need at least 300 m buffer zones, according to paper.

Regulation of North Rhine-Westphalia state (MWIDE NRW) recommends a 300 m no-building zone from any bird reserves and nature protection areas where birds or bats are present.

According to latest regulation in Germany by Working Group of German State Bird Conservancies (LAG VSW, 2015) the minimum required distance from all types bird reserves should be not less than 1200 m. I make 1200 m buffer around bird reserves. Researchers Höfer et al. (2016) and Derdouri and Murayama (2018) cite this regulation and use same distance (1200 m) in their work.

There is one bird reserve in Kherson and three bird reserves in Zaporizhzhia oblast. These reserves are considered separately from other protected areas during the GIS analysis and buffer zones are assigned differently.

Concerning already existing cases in Ukraine, in environmental assessment report for Yavorivska wind station in Lviv oblast of Ukraine (Bota 2018), the distance from Cholgynskyi bird reserve is 300 m. Author says it is enough. But, I think it is not sufficient to reduce the noise impact and distance has to be bigger, taking to account the type of nature reserve. I use respective distances of 300 m and 1200 m for buffers.

Wind speed

Wind speed, in some way, is a most important factor influencing wind farm construction suitability. Because no wind energy production will be unfeasible if wind speed is not high enough. Though, high wind speed itself is not sufficient reason to build a power plant in some location. Because other factors may not allow to do it. For example, good wind speed (maybe even better than in study area) is in Carpathian mountains in Ukraine. But elevation, slope and other factors don't allow to build there.

Most of the researchers define the minimum wind speed at which the energy production is feasible. In earlier works authors said that speed should be at least 5 m/s (Baban and Parry 2001), 5,5 m/s (Molodan 2013) or 5,6 m/s (Miller and Li 2014).

But more recent researches define 6 m/s as minimum speed (Höfer et al. (2016), Wang et al. (2014), Derdouri and Murayama (2018), Bili (2018)). Carlino M. (2013) considers wind speed over 6 m/s as minimally feasible and >8 m/s as 'great'. There is a clear trend of increasing the minimum required speed in works of researchers over the years. But no researcher set a minimum threshold higher than 6 m/s. Taking into account the above mentioned information, I consider wind speed of 6 m/s as minimum acceptable for wind energy production in my study area.

The height of wind measurements is important. Höfer et al. (2016) considered average speed of wind at a height of 135 m. Van Haaren and Fthenakis (2011) use measurements at 80 m height. Carlino M. (2013) measured on 100 m height. Most of researchers don't specify at which height they got measurements. I take into account that during last 4 years average height of wind turbine hubs increased. Also, if to look at turbines currently installed in study area, the hub height of turbines are 117-149 m for Vestas V126, 119 m for Vestas V112, 120 m for Nordex N131 and 105 m for Nordex N149. The average hub height of turbines in USA in 2017 was already 142 m (Roberts 2019). And in future the height of wind turbine hubs will grow. Therefore, on my map I use a wind speed at height 150 m.

All wind speed at height 150 m in my study area is in range of 6,5-9,5 m/s. Therefore, the lowest score for suitability mapping is 6-7 m/s (70% suitability) and highest one is >9 m/s (100%). And as 6,5 m/s is a lowest speed in the study area, there is no need to exclude any areas due to low wind speed.

Roads, power lines and railways

I grouped these three factors together because they have one feature in common. Major roads, all power lines and railways should be located on a distance safe enough in case of fall of the turbine. It means that distance to above mentioned objects should be at least bigger than the height of wind turbine.

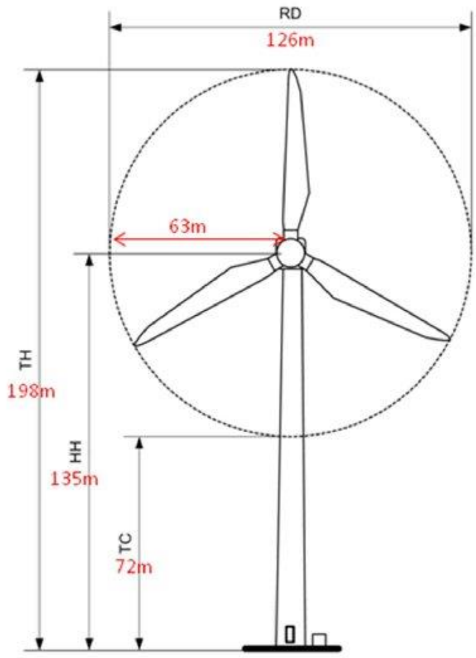


Figure 10 . Wind turbine scheme. TH – turbine height, HH – hub height, RD – radius diameter, 63 m equal to blade length. (author: Hakam Saffour, example: Enercon 126 dimensions)

The height of wind turbine (also referred as “tip height”) is a sum of hub height and blade length (Figure 10). Blade length equals to a half of rotor diameter (63 m in Figure 10).

Wizelius (2007) recommends distance to railways, roads and power lines to be height of the turbine plus 50 meters.

For defining the best buffer distance I checked for the average and maximum turbine heights in the world. Wind Turbine (2019) research shows that average hub height in Germany in 2018 was 133 meters and average rotor diameter was 118 m. It means that the average turbine height was about 192 m (133+118/2).

Average rotor blade diameter of wind turbine in the world in 2019 was 129 meters (Wang 2019). Average turbine height in US in 2017 – 142 m. Based on this, average total height is around 200 m. All the turbines nowadays installed in Zaporizhzhia and Kherson oblasts have height in range of 150-200 meters. Lowest turbines Vestas V112 installed in Botievska station in Zaporizhzhia oblast have height of 149 meters in total. Highest turbines of Syvas’ka station have 185 m of height.

In my opinion, it is better to keep the distance of 250 m (additional 50 m) for reserve, as in future heights of turbines may grow. 50 m is my second buffer. Also currently the biggest onshore wind farm in the world has 246,5 meters in height (Max Bögl Wind AG).

In the analysis, the areas, closer than 200 m to major roads, power lines or railways are marked as 10% suitable, areas in range of 200-250 m – as 50% suitable.

1. Roads

Roads are included in analysis for two reasons: economic and social. There should be proximity to roads in order to reduce the cost of construction, and they should be located on some distance from the biggest highways for safety reasons. Another reason for safety distance – visual impact.

It is one of the novelties of my research, because many researchers include only economic factor.

Roads should be located close enough to wind farms in order to make the construction cost-effective. Also - to reduce impact from construction on environment. As well as to avoid soil sealing and not to damage the adjacent land.

According to chapter 9 of Ukrainian law (UkrNDNC, 2017), the wind farm site should be in proximity to existing roads, to allow construction. Though, no reqiurements to roads are not specified, nor what distance to roads is accepted as close enough.

Road should be wide and solid enough to allow transportation. According to German regulation (LANUV) it has to be at least 4 m wide and have a solid pavement. Same suggestion has Ukrecoconsult (2018) - solid surface and 4,5 meters of width. I used layer with all solid roads for mapping proximity to roads.

Baban and Parry (2001), Tegou et al. (2010), Miller and Li (2014) and Gorsevski et al. (2013) suggest the distance from the roads to not exceed 10000 m, for better access during the construction. Latinopoulos and Kechagia (2015) and Georgiou et al. (2012) say that 5000 m and Höfer et al. (2016) that 9000 m enough. I took 10000 m, as most of the researchers recommend this distance.

Latinopoulos and Kechagia (2015) suggests 150 meters as distance to main roads. Distance of 150 m worked for wind turbines in the past, but most recent turbines are higher. According to Bili and Vagiona (2018) Greek Ministry of Environment suggest 1,5 diameters of the rotor blade. In case of currently installed turbines it would be a distance of 196,5 m for Nordex N131 (131*1,5) and 189 m for Vestas V126 (126*1,5). It's exactly around 200 m – same as I set in previous part. The safety distance rule (200 and 250 m) applies only to major roads.

Same distance (200 m) is suggested in Envrionmental Assessment of Dnipro-Buzka wind station in Kherson oblast. (Ukrecoconsult, 2018) Concerning grading, suitability decreasing by 20% with every 2000 m, similar to how Höfer et al. (2016) did it. And maximum distance is 10 000 m (Tegou et al. 2010, Gorsevski et al. 2013, Miller and Li 2014, Baban and Parry 2001, Höfer et al. 2016).

2. Power lines

Same as for roads, power lines included for two reasons: economic and technical. Wind parks should be located close to already existing power lines, in order to make the installation of wind turbines economically reasonable. So that new power lines don't have to be built, increasing the cost of installation.

Not all power lines suit for connection of wind farms to grid, but only the ones with high voltage. According to Molodan (2013) the minimum appropriate voltage of power lines to connect a wind farm is 110 kV. Lower voltage lines may cause problems with transmission of energy. Thus, I considered only lines with voltage higher than 110 kV, though their network is not that dense as network of 35 kV lines.

Salameh (2014) suggests the maximum distance from high voltage power lines to be 10 miles. Almost same distance – 10000 m - is suggested by Baban and Parry (2001) for economical reasons. Höfer et al. (2016) suggest 9000 m as maximum. Some researchers suggest 20000 m (Gorsevski et al. 2013, Miller and Li 2014), some – 5000 m (Georgiou et al. 2012). In my study area high voltage network is not very dense and it may be a limiting factor.

On the other hand, power lines should be on sufficient distance from turbines for safety reasons. In this analysis I included power lines lower than 110kV as well.

According to German regulation of North Rhine-Westphalia (Wind Energy Enactment) the distance from wind turbine to power line should be at least equal to rotor blade diameter. According to same

Greek regulation mentioned by Bili and Vagiona (2018) distance from power lines should be the same, 1,5 diameters of the rotor blade. Nowadays it's approximately 193,5 m (129 m by Wang (2019) multiplied by 1,5).

3. Railways

Researchers (Hansen 2005, Baban and Parry 2001, Tegou et al. 2010, Wang et al. 2014, Höfer et al. 2016, Derdouri and Murayama 2018, Nguyen 2007, Atici et al. 2015) include railways as constraint factor but not everybody define the buffer zone around it.

All of them set a buffer of 100 m around railways, except of Atici et al. (2015) who set 500 m. But that criteria was influenced by early works, especially Baban and Parry (2001). And since then the height of turbines changed. Same as roads and power lines, railways have safety distance of 200 and 250 m.

Slope

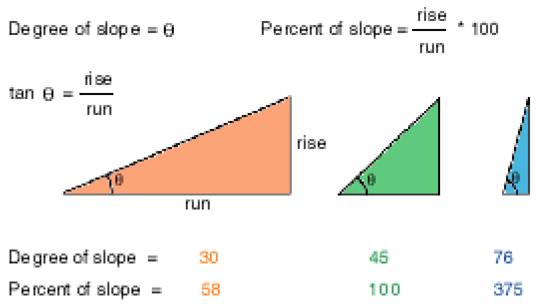


Figure 11. Slope measurement types (source: resources.esri.com)

The site for wind farm location should be on a fairly level in order to make construction technically possible. Lower slope degree allows tucks and cranes to transport parts and lift parts of turbine easier. Majority of researchers define slope as factor (Table 3).

There are two ways to measure the slope gradient. Degree (°) and percent (%). 45° slope corresponds to 100% slope (Figure 11) Some researchers confuse these two dimensions, and use ° sign instead of %. Degree way of measurement is used in almost all the papers I analyzed. Therefore, it is more convenient to use degrees in my work as well.

According to papers the suitable slope gradient for wind farm location should be less than 10-30%. The maximum acceptable slope gradient percentage varies in works of authors from 10% (Baban and Parry 2001, Watson and Hudson 2015, Atici et al. 2015, Georgiou et al. 2012) to 30% (Höfer et al. (2016), Derdouri and Murayama (2018)). Other researchers recommend values in between, 15% (Villacreses et al. 2017, Bennui et al. 2007), 20% (Wang et al. 2014, Japanese Ministry of Environment), 25% (Kozani 2015, Tegou et al. 2010). No researcher defined minimum acceptable degree smaller than 10%. And only Miller and Li (2014) defined 40% slope as a maximum value. Therefore, in my work, all the areas with slope lower than 10% have 100% suitability.

There is no consensus among researchers about the critically possible slope degree. Their assessments vary from 10% to 30%. Therefore, I create a gradual buffer and my suitability scale has slope degree values from 0 to 30% (not to confuse with suitability values, which are from 0 to 100%). It is the only factor which is measured not in m or in m/s, but in the same unit as suitability itself (in percent (%)).

Airports

According to paper of Airsight company, with reference to ICAO (International Civil Aviation Organization) Annex 14, objects higher than 150 m are regarded as obstacles for airplanes. Modern wind turbines reach a height of 200 m and more. That's why it's important to ensure a sufficient interval between airports and wind stations.

Yue, and Wang (2006) suggest 2500 m away from airports. Aydin et al. (2010) suggests from 3000 to 6000 m, according to Turkish legislation. Airsight company in their paper gives examples of wind plants built near airports in Germany with range from 1500 to 4700 m of distance from the airport. Most of researchers suggest minimum distance of 2500 m (Villacreses et al. 2017, Wang et al. 2014, Andros 2018, Nguyen 2007), and no researcher suggest distance less than it. Exception is Derdouri and Murayama (2018) – 200 m, but this distance is too small. Maximum suggested is 5000 m (Hansen 2005, Atici et al. 2015). Many researchers suggest 3000 m (Aydin et al. 2010, Degirmenci 2018, Bennui et al. 2007, Sliz-Szkliniarz 2011, Latinopoulos and Kechagia 2015) or 4000 m (Georgiou et al. 2012). Hence, these distances will have suitability buffers. In suitability map zones closer than 2500 m are excluded and areas with distance of more than 5000 m have 100% suitability.

Land use

I exclude all the areas where building of wind farms is technically or legally impossible. These places include quarries, cemeteries, recreational and military areas).
There are a lot of agricultural land allotments in counties. But it is not an obstacle for building wind turbine and it's possible to agree about it with land owners. As wind turbines don't require much space for its installment, agricultural lands can co-exist with turbines. The same applies to industrial, or former industrial areas. Also, dumps nowadays are very good locations for wind plants.

Other factors

Elevation. Some researchers include elevation as factor. For example, Değirmenci et al. (2018) suggest not to build turbines on heights above 1500 m, with reference to a regulation by General Directorate of Renewable Energy in Turkey. But as my study area is flat, and highest point there is 327 m, I don't include elevation factor in my work.

3. Data and methods

3.1. Data

I contacted 17 organizations and governmental institutions in Ukraine to get the data for my research. Official governmental data for the region I study doesn't exist. I wrote to a number of people and organizations, including The State Service of Ukraine for Geodesy, Cartography & Cadastre.

Due to this, I had to use open-source data (e.g. OSM) and data of international and foreign organizations (NASA, UN, Technical University of Denmark). Mentioned data is a best source available for spatial analysis is in Ukraine nowadays.

Settlements (urban and rural)

1. Source: UN Office for the Coordination of Humanitarian Affairs in Ukraine (OCHA Ukraine) (https://data.humdata.org/dataset/ukraine-administrative-boundaries-as-of-q2-2017)

Type: Administrative division and settlements borders.
Format: shapefiles
Information: type of settlement (city, urban-type settlement, village), area
Update: 12.09.2019

2. OSM data

Nature protection areas

For nature protection areas I used World Database on Protected Areas (WDPA) data in combination with data from National Ecological Center of Ukraine, Open Street Map, satellite images and topographic maps. WDPA data contains more full information about nature protection areas, while OSM extracts data has higher precision.

Reason: exclusion of ecologically sensitive areas and reducing negative impact on them.

1. Source: World Database on Protected Areas (WDPA) by United Nations ((https://www.protectedplanet.net/country/UA)

Type: information on location of reserves
Format: shapefile (polygon)
Information: name, designation, type and category of protected area.
Authors: United Nations
Year of data: 03.03.2020 (update monthly)

2. Source: OSM extracts (http://opengeo.intetics.com.ua/osm/pa/)

Format: shapefile (polygon)
Information: national parks, ramsar sites, nature reserves, parks, protected areas and nature conservation areas
Authors: National Ecological Center of Ukraine,
Date of download: 03.03.2020 (updated daily)

3. Source: OSM (http://download.geofabrik.de/europe/ukraine.html), layers ”natural” and”points of interest”.

I combined seven-eight different layers to get a final map with all protection areas. five layers from OSM extracts, layer from World Database of Protection Areas and other OSM layers.

Open Street Map (OSM) data

Open Street Map data is created by governmental and educational institutions in Ukraine, and by volunteers. The data there is a best available GIS data in Ukraine.

Source: Open Street Map website (http://download.geofabrik.de/europe/ukraine.html)
Type:
Format: Shapefiles (points, lines, polygons)
Update: 02.03.2020 (daily)

Information: shapefile (shp) layers which contain information about water bodies, roads, railways, settlements, nature protection areas, recreation zones, military zones.

OSM data I used:

Roads - layer “roads”,
information: class and type of road
type: lines

Water bodies – layers “waterways”
type: polygons

Railways – layer “railways”
type: lines

Land use (military, recreational, airports, cemeteries) – layers “landuse”.

Roads

From two sources:

1. GRIP (Global Roads Inventory Project) by World Bank

Source: https://datacatalog.worldbank.org/dataset/grip-global-roads-inventory-project-2018 or https://www.globio.info/download-grip-dataset
Type: layer with all roads in World and Ukraine
Format: shapefile (lines)
Information: road type, road surface
Date: 10.2018

2. OSM data

Contains layer with biggest highways (roads of international importance).

Slope

Source: Shuttle Radar Topography Mission of NASA (http://dwtkns.com/srtm/, https://www2.jpl.nasa.gov/srtm/, http://srtm.csi.cgiar.org/download)
Type: raster, resolution – 90 m.

Power lines

Source: map created by volunteers who digitized power lines on territory of Ukraine. (nadoloni.com)
Format: shapefile (lines)

I compared this map with map from official source - website of state company Khersonoblenergo - http://ksoe.com.ua:10080/ksoe. I also checked it with satellite images (Google Satellite, Bing Aerial).

Wind speed

Source: Global Wind Atlas by Technical University of Denmark (DTU) (https://globalwindatlas.info/area/Ukraine)

Information: wind speed and wind power density at heights of 50, 100, 150 and 200 m. I use 150 m. Type: raster, resolution – (250x250) meters.
I found three other sources of spatial data about wind speed in Ukraine. But GWA has a best quality and resolution of data.

Airports

There are two civil (Kherson Airport and Zaporizhzhia International Airport) and two military airports in study area. Source: State Aviation Administration of Ukraine
Based on this official information and satellite images I created a vector layer with airports myself by drawing a polygons in places where airports are, by myself. Layer with polygons of military airports is taken from OSM.
Type: shapefile (polygons)

Legislation

I used many regulations and legal acts, while writing my thesis. Such Ukrainian laws as "On the Power Engineering Lands and the Legal Status of Special Zones of the Power Engineering Objects", "On Energy Industry", "On Nature Reserve Fund of Ukraine", "On Alternative Energy Sources", "On Motor Roads", "On classification of motor roads, "Convention on wetlands of international importance", "Requirements for wind and solar power plants operation in parallel with the unified energy system of Ukraine", "On safety zones of Electricity Networks", "On Rules of technical operation of railways in Ukraine" and many other. Also I used legislation of other countries e.g. Germany, Greece, Turkey.

3.2. Methods

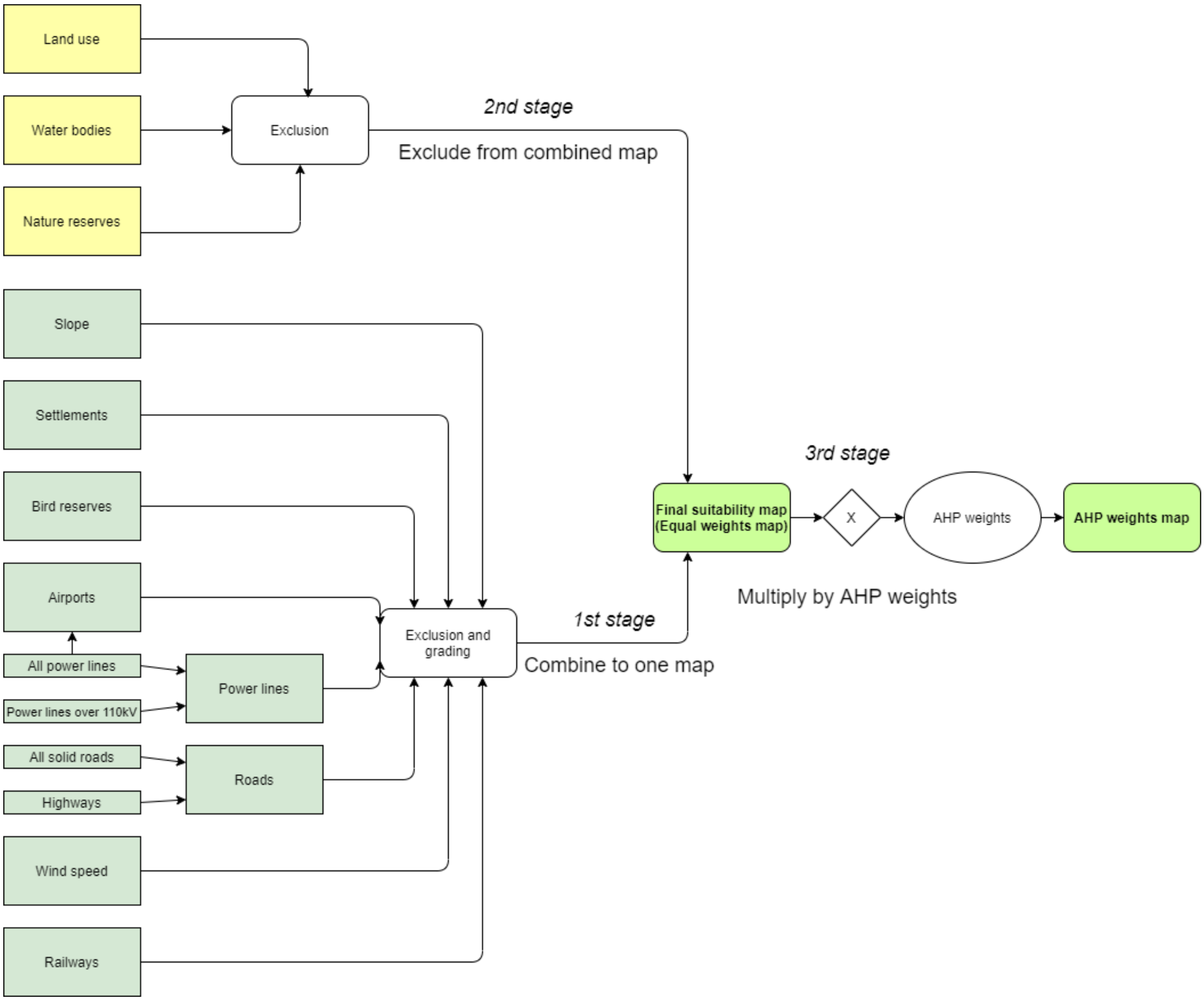


Figure 12. Flowchart of the work process

All inputs (light blue and light brown), results (green) and some methods (white) are shown on a Figure 12.

Main methods in my research are Multi-criteria decision-making (MCDM) and Analitic hierarchy process (AHP) (both used by Höfer et al. (2016), Latinopoulos and Kechagia (2015) and others).

Multi-criteria spatial analysis is used in a big amount of studies on wind farm suitability, as well as in many other fields, in different countries. It was used by van Haaren and Fthenakis (2011), M. Troldborg, S. Heslop, R.L. (2014), S. Al-Yahyai, Y. Charabi, A. Gastli, A. Al-Badi, (2012), Latinopoulos and Kechagia (2015) and others. Höfer et al. (2016) and others are using analytical hierarchy process (AHP) method. This method is consecution of multi-criteria analysis, as it grades chosen factors according to their importance.

I combine different datasets for comparing and better determination of suitability. For combining different vector (nature protection data, OSM data) and raster (satellite images, topographic maps) datasets, I use possibilities of GIS software. Combination of different sources and methods helps to get as precise as possible shapes and buffers. I correct some layers based on more precise information from other.

3.2.1. GIS method

I used GIS based approach to study wind energy sites. This method was used by Wang et al. (2014), Garegnani et al. (2018), Miller and Li (2014), Hansen (2005), van Haaren and Fthenakis (2011) and many others. GIS-based approach for spatial planning is used for sites evaluation (application of GIS systems (ArcGIS, QGIS)).

Processing of data was done in ArcGIS and QGIS software. The paper of Holbrow et al. (2018) contains explanations about data processing in ArcGIS especially for this purpose. In the end I also used Excel to calculate area percentages.

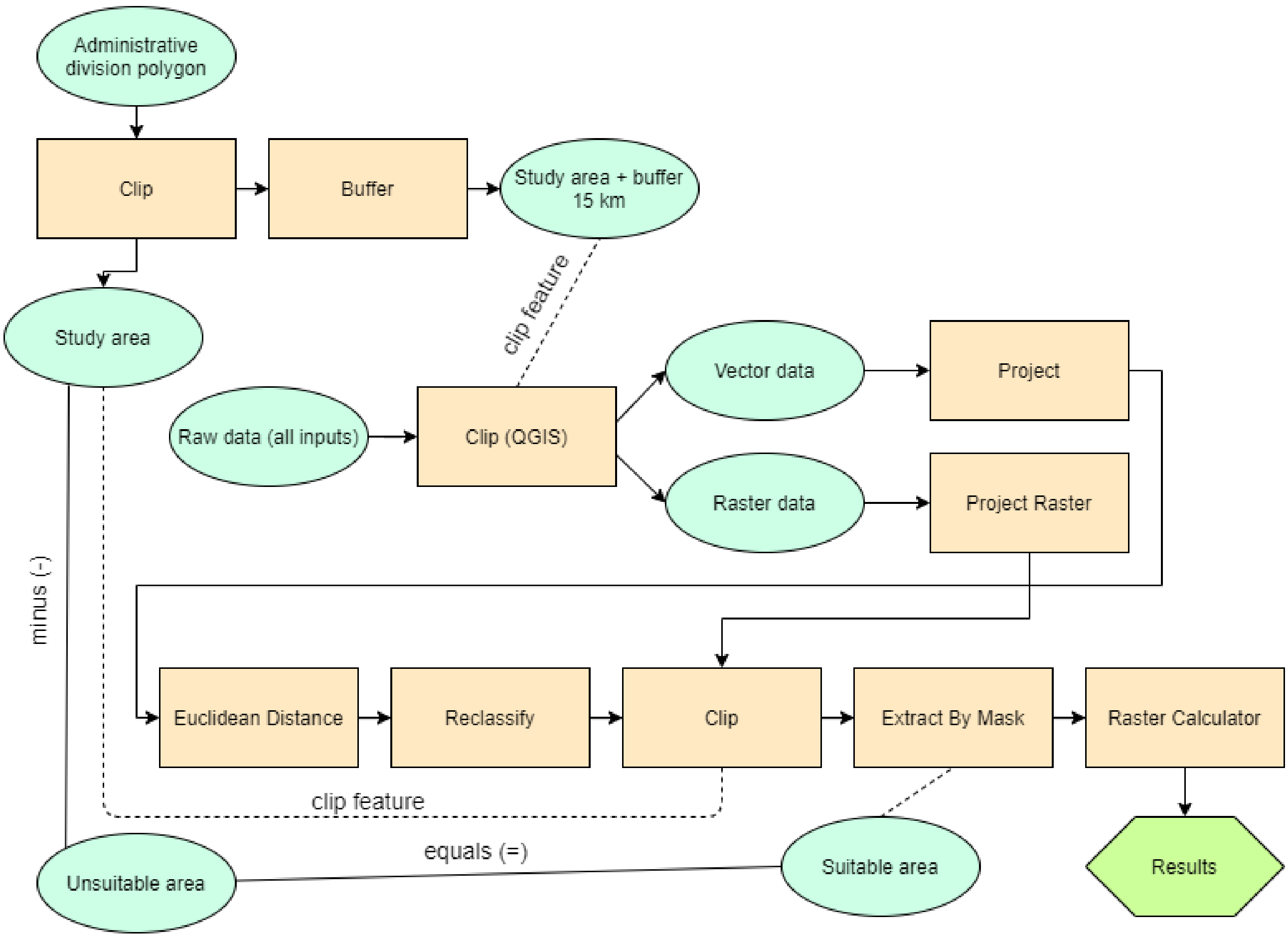


Figure 13. GIS tools and input data

I used QGIS to prepare my data. I used *Clip*, *Buffer* and *Difference* tools for cutting all the necessary spatial data to the borders of my study area. Before that, I clipped the border of my study area and added a buffer of 15 km around it, so that settlements, power lines, roads etc. in neighboring oblasts are also included in case if their buffers zones are reaching Kherson and Zaporizhzhia. 15 km because the biggest buffer distance I have in my work is 10 km (to power lines and roads). Same layer, with 15 km buffer was later used for defining a Processing Extent in *Euclidean Distance* analysis in ArcGIS. (Figure 13)

Almost all processing of data I made in ArcGIS. I reprojected clipped data into EPSG:5564 using *Project* and *Project Raster* tools for vector and raster layers accordingly. To do it quicker, I ran tools in Batch mode.

First I used *Buffer* tool in ArcMap to create mandatory buffers around settlements and rivers. Such way of clipping made the analysis more precise.

I used *Euclidean Distance* and *Reclassify* tools for creating raster layers with buffers based on vector data (settlements, power lines, roads, airports, bird reserves). I created zones with different levels of suitability and reclassified values. With *Erase* tool I created a layer with suitable locations, excluding all unsuitable. To cut raster layer by polygon of suitable areas I used tool *Extract By Mask*. For combining all layers together in Equal Weights map and for multiplying values for AHP Weights map I used *Raster calculator*.

3.2.2. Multi-criteria decision making (MCDM) analysis

This method is also called MCDA (Multi-criteria decision analysis). Essence of the method is that I use multiple factors that influence the suitability of wind farm sites. The amount of factors available to select is bigger than the amount I actually need to use. I am deciding which of them are the most relevant.

I choose these factors based on works on other researchers. For example, such criteria as wind speed, slope degree, power lines, roads and nature protection areas are used in almost every research about wind farm siting. Criteria can be chosen for economic (roads, power lines), social (living houses) or environmental (nature reserves) reasons.

This method is used in works of Höfer et al. (2016), Villacreses et al. (2017), Bennui et al. (2007), Watson and Hudson (2015), Tegou et al. (2010), Uyan (2013) and others. In general it is included in almost any research work made in topics of wind farm siting and wind energy suitability planning.

MCDM requires next steps:

1. Choosing the objective of analysis
2. Defining possible factors
3. Choosing most relevant of them

A result of application of this method is a final suitability map with equal weights.

3.2.3. Analythic hierarchy process (AHP)

This method means that considered criteria are sorted by the level of its importance. After creating a final map with equal weights, I create another one, more precise. In new map my factors don’t have equal weights anymore

So when I make a final map, I have a methodology to calculate the percentage of suitable land.

If by MCDM method I chose the relevant criteria, by AHP method I define which of these criteria have higher importance and which have lower.

AHP method is a part of MCDM method, it’s later stages. After I chose relevant criteria, I:

4. Grade factors by their importance
5. Assign values to factors for further calculation.

Weights are assigned to each factor according to its importance. This method in my work has three stages:

- ranking of researchers' critria
- pairwise comparison
- standardized matrix

AHP method is used by Höfer et al. (2016), Latinopoulos and Kechagia (2015), Villacreses et al. (2017), Bennui et al. (2007) and others. Not the method, but same approach was used by Baban and Parry (2001).

For example, Höfer et al. (2016) made survey among local experts and defined that wind power potential, distance to natural environments and distance to urban areas are the most important factors while planning. Each of these parameters scored about 20%. Other, less important factors are: distance from electricity grid, distance from road network, places of interest, landscape, land cover and slope. Other researchers did surveys among experts too. But some graded components based on their own expert evaluation. I grouped together grades of factors from papers of researchers I analysed and got Table 5.

I defined two types of areas:

1. Unsuitable (0%). Some territories were completely excluded from potential sites. For example settlements and 700 m buffers around them, water bodies, nature protection areas, slopes over 30%. Because of impossibility to install turbines there due to legal or technical reasons.
2. Suitability of 0-100%. Some places can be partly suitable depending on legislation, natural conditions or methods used while planning. Wind speed, proximity to power lines, roads, railways, settlements, airports, bird reserves, slope degree.

In the end these two approaches are combined in a final map. The land use data is combined with a wind speed data for wind power potential picture of a region. The comparison of two oblasts suitable area is done.

Researchers use different scales to assess factors. I used a scale (0-100%) for suitability of wind sites.

Harper et al. (2019) and IRENA use scale of 0-100%, Baban and Parry (2001) and Höfer et al. (2016) use grades for each value, from 1 to 10. Latinopoulos and Kechagia (2015) rates factors from 0 to 1.

Table 4. Scales used by researchers

Country		Denmark	Germany	Greece	Ecuador	USA	Thailand	South England	Greece
Author		Hansen	Höfer	Latinopoulos	Villacreses	Miller	Bennui	Watson	Tegou
Place		Northern Jutland	Aachen	Kozani		Nebraska			Lesvos
Year		2005	2016	2015	2017	2014	2007	2015	2010
Scale	0-100%				+				
	0-10	+	+						
	0-1			+				+	+
	1-5					+			
	1-6						+		

I created a Table 4, which summarizes the scales used by different researchers. I use scale of 0-100%, because it allows to assign a wider range of values to criteria and more easy to understand for a viewer. Though principles of grading are the same independent of the type of scale.

3.2.4. Other methods

Content analysis method was used for dealing with legislative documents about restrictions of land use in Ukraine. Expert-knowledge based zonation was used as a complementary method. The maps generated in result of data analysis are divided into zones with different suitability.

4. Results – Suitability maps

4.1. Projection (Coordinate system)

For best precision in measurements I used coordinate system “Ukraine 2000 GK Zone 6” (EPSG:5564 or UCS-2000/Gauss-Kruger zone 6). My study area has wide range in longitude, but it fits almost perfectly to the range of this projection. UCS-2000 system was adopted in Ukraine in 2017 and replaced outdated Soviet one. Now it is a most precise projection for Ukraine. General projection UTM WGS 1984 36N also could be used but it is not that precise as UCS-2000.

4.2. Buffer zones and distances

I created a table with a new suitability scores for the region based on information form part number 2. Below you can see the Table 5.

Table 5. Final suitability scores

	All roads (m)	Highways (m)	Slope (%)	Nature reserves	Bird reserves (m)	Wind speed (m/s)	Power lines (m)	PL 110 kV (m)	Urban (m)	Rural (m)	Airports (m)	Water (m)	Railways (m)
0%			>30	0	0				0-700	0-700	0-2500	<25-50-100	
10%	>10000	0-200			0-300		0-200	>10000					0-200
20%	8000-10000				300-1200			8000-10000			2500-3000		
30%			20-30						700-1000				
40%	6000-8000							6000-8000					
50%		200-250					200-250			700-1000	3000-4000		200-250
60%	4000-6000							4000-6000					
70%			10-20			6			1000-2000				
80%	2000-4000					7		2000-4000			4000-5000		
90%						8							
100%	0-2000	>250	0-10		>1200	9	>250	0-2000	>2000	>1000	>5000	>25-50-100	>250

Distances and limits for factors, simplified (Table 6):

Table 6. Distances and limitations

Factor	Buffers, min-max value
1. Settlements	700-2000 m
2. Roads	200-10000 m
3. Power lines	200-10000 m
4. Railways	200, 250 m
5. Nature protection areas	Exclusion
6. Bird reserves	300-1200 m
7. Slopes	0-30%
8. Airports	2500-5000 m
9. Water bodies	25-100 m
10. Wind speed	6-9 m/s

4.3. Exclusion areas

Areas of complete exclusion from suitable sites (suitability is 0%) are :

1. All settlements and 700 m buffer around them
2. Water bodies and buffers 25, 50 and 100 m around them accordingly.
3. All nature protection areas
4. Airports and buffer 2500 m around
5. Slopes above 30%
6. Areas with restricted land use

There are three layers, all features from which are excluded:

1. **Water bodies**

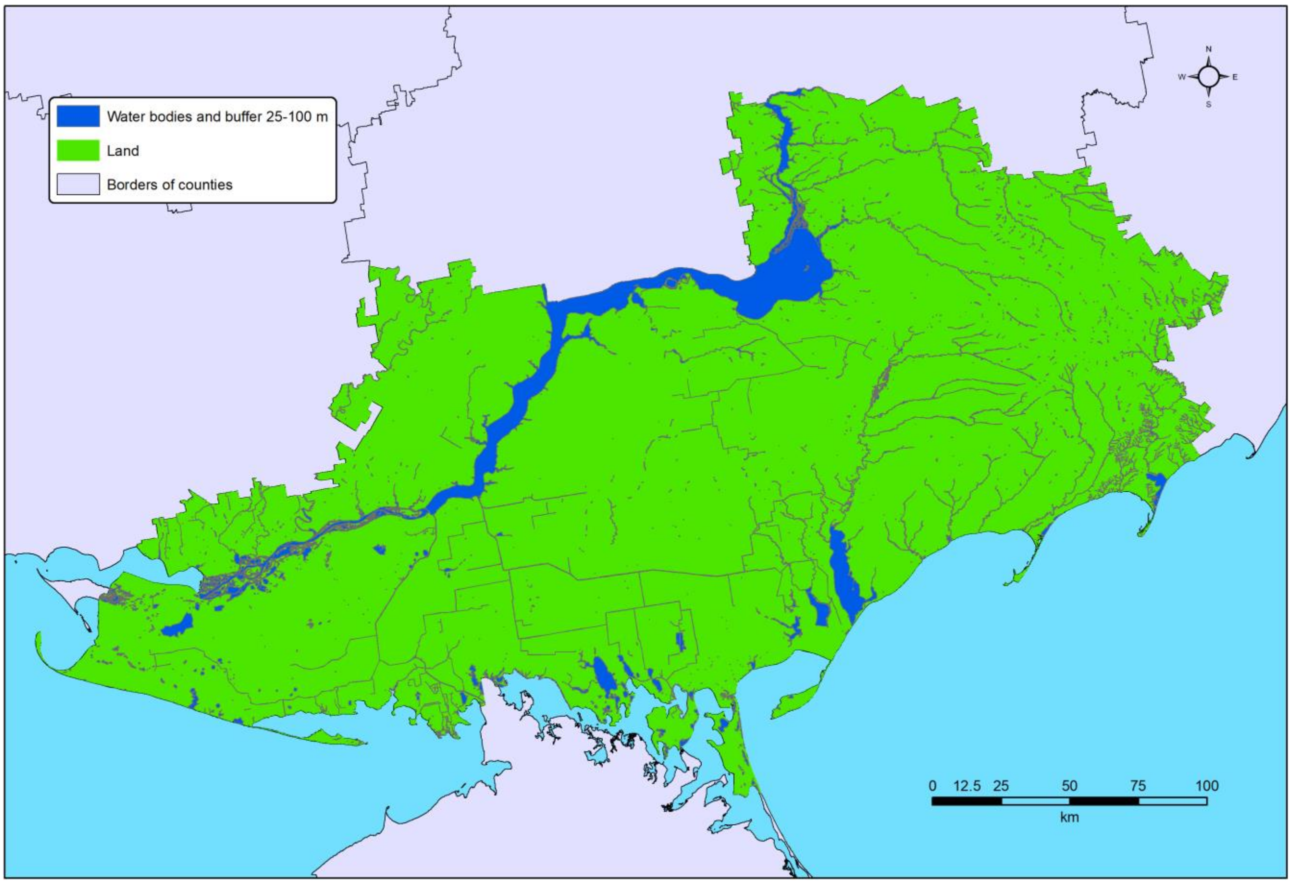


Figure 14. Water bodies

On the picture (Figure 14) all the water bodies are indicated already with buffer zones. As the size of buffer zones is small in comparison to the scale of a map, there is no distinction between water bodies themselves and their buffer zones on a map. There is only one big river in the region – Dnipro (Dnieper). Buffer from it is 100 meters. Buffers from other water bodies are 25 m and 50 m depending on a size. Visually, the river density in Zaporizhzhia oblast is higher than in Kherson.

2. **Nature protection areas**

In my work I exclude the next types of nature protection areas: nature monument, botanical nature monument, forest reserve (zakaznyk), botanical reserve (zakaznyk), geological nature monument, arboretum, biosphere reserve (zapovidnyk), entomological reserve (zakaznyk), zoological reserve (zakaznyk, including herpetological one), landscape reserve (zakaznyk), national park, landscape park, historical and archeological reserves (zapovidnyk), ramsar sites (Figure 15).

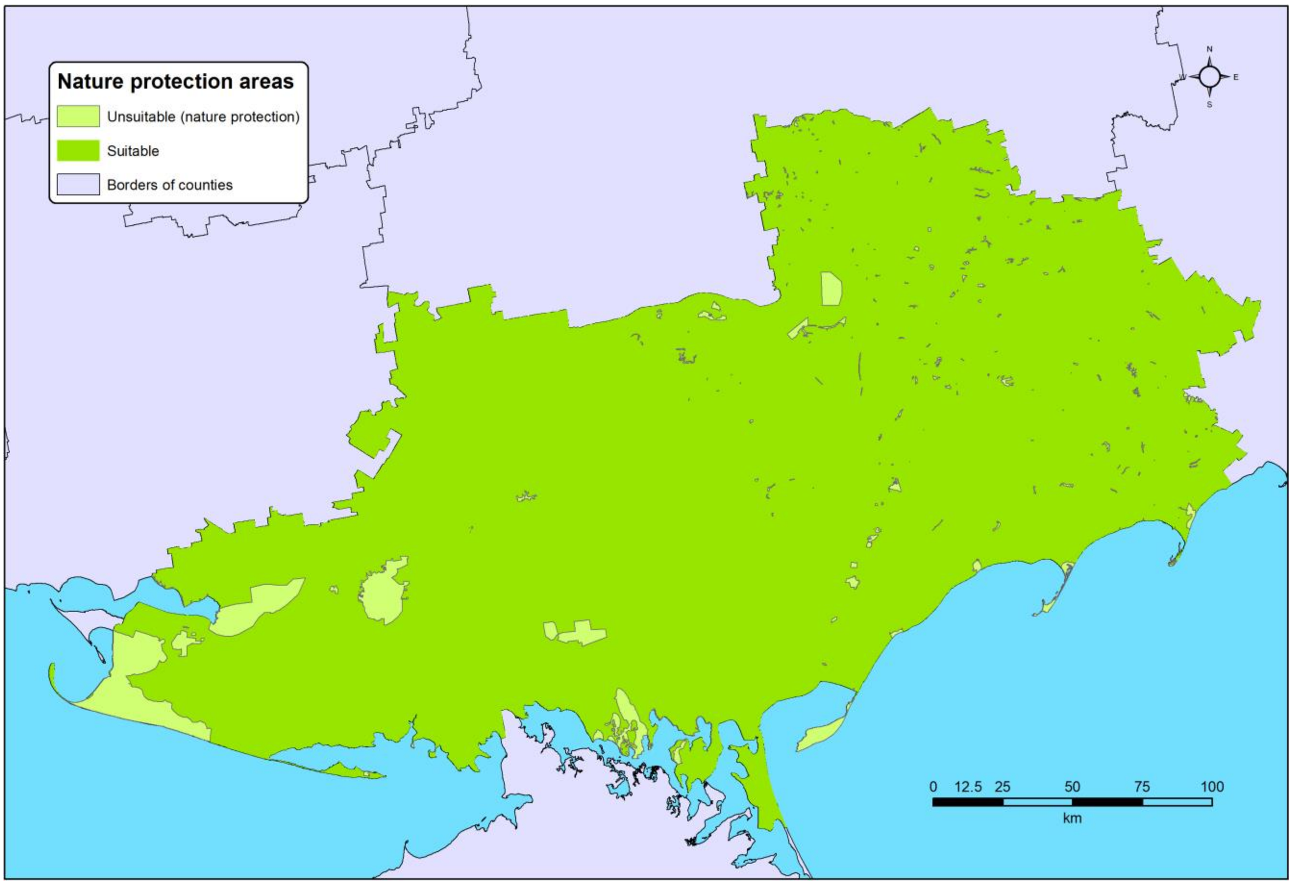


Figure 15. Nature protection areas

3. Land use

Map with all excluded quarries, cemeteries, recreational and military zones in red (“Unsuitable” on Figure 16).

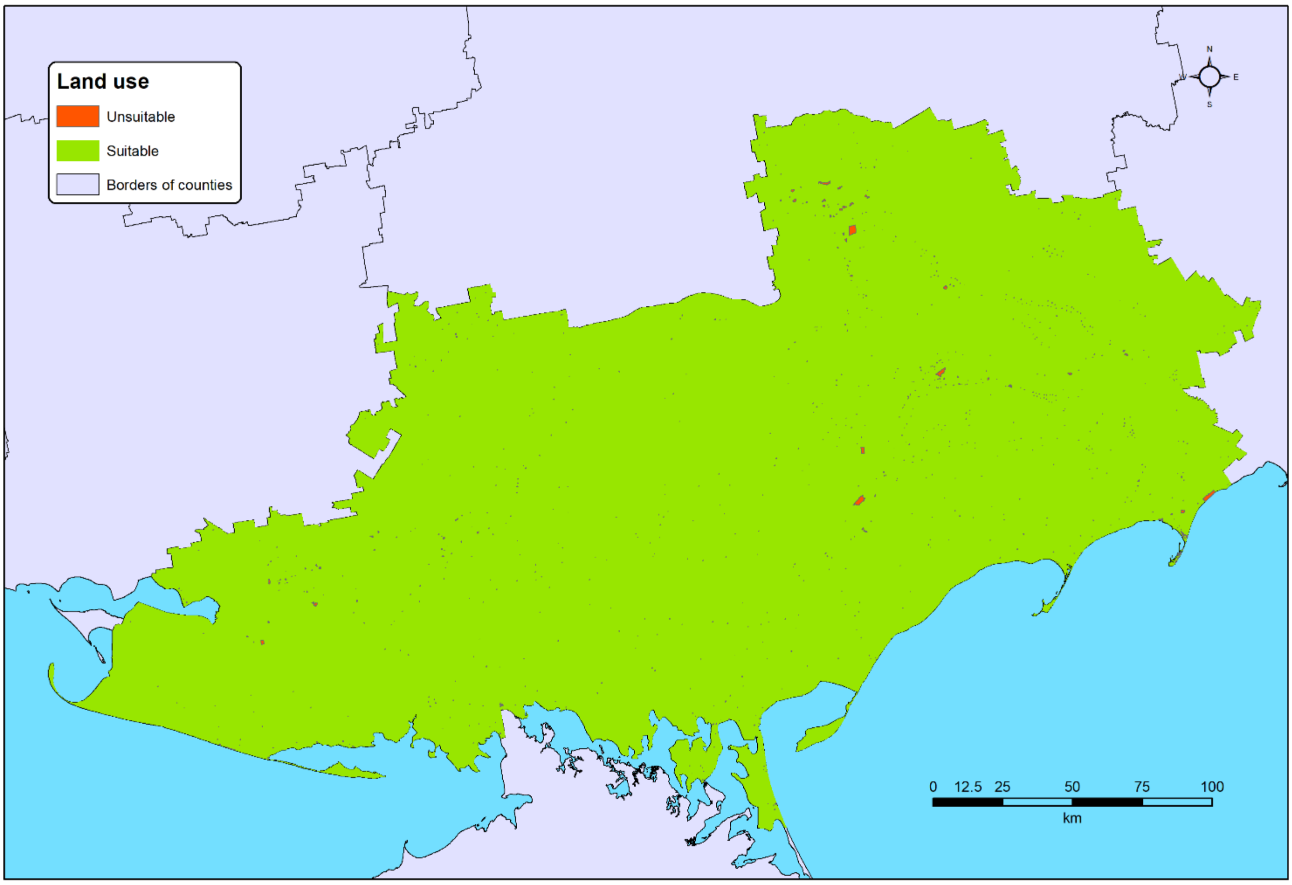


Figure 16. Nature protection areas

All exclusion areas combined look like this (in pink, Unsuitable):

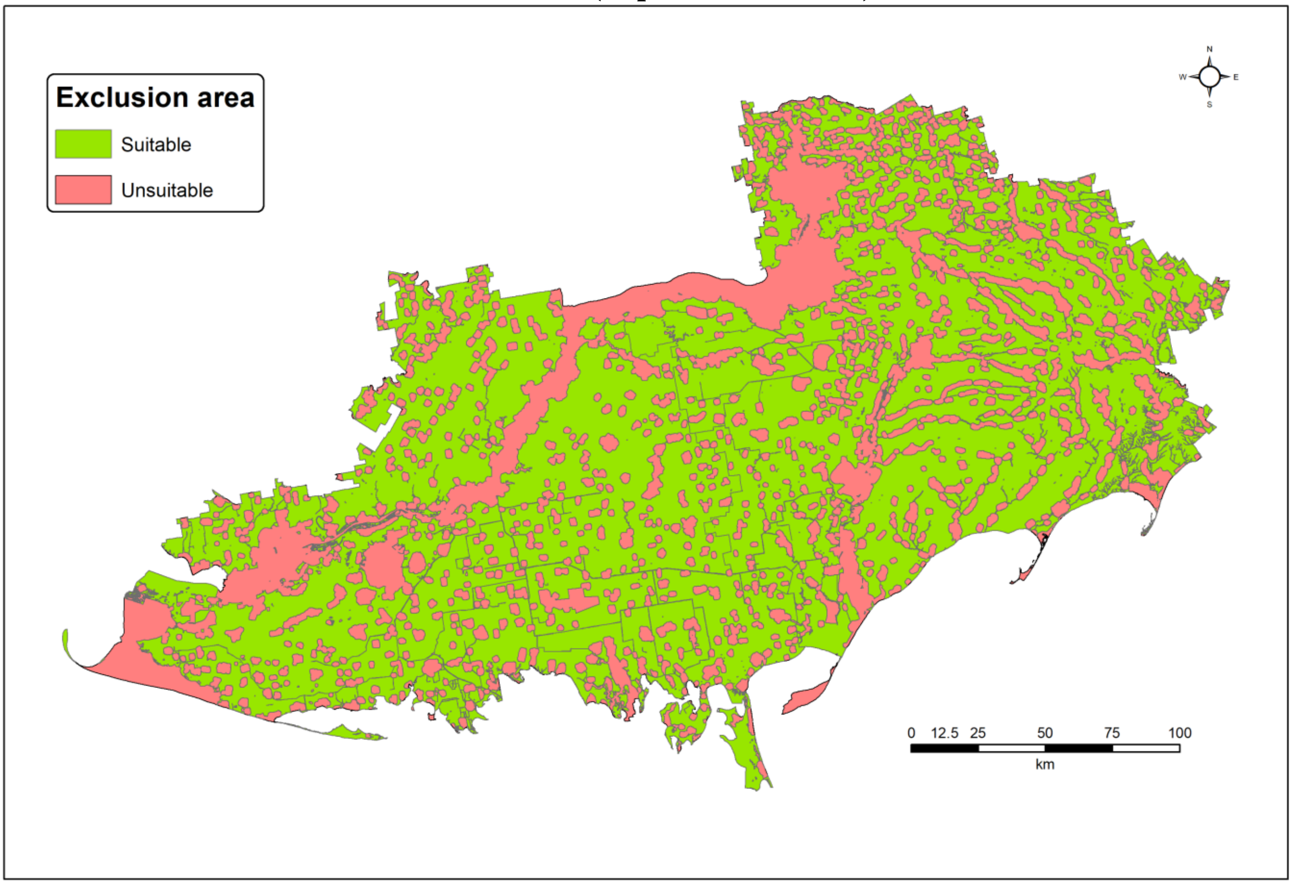


Figure 17. Exclusion area map

The final exclusion map (Figure 17) is not just a composition of three previous maps (Figures 14-16, water bodies, land use and nature protection areas). It also contains settlements with 700 m around them, bird reserves and airports with 2500 m buffers in exclusion area (layer Unsuitable).

Based on visual observation, we can see that biggest exclusion areas are settlements and water bodies. Especially big is a Dnipro river. As well as big exclusion areas are those corresponding to locations of Kherson and Zaporizhzhia cities. Nature protection areas are also a significant exclusion factor. The area of excluded zones due to land use is relatively small.

Exclusion areas constitute 35,75% of territories of two oblasts. Suitable are **64,25%** of territory, 65,25% in Zaporizhzhia and 63,31% in Kherson oblasts. Here is the answer to one of my research questions: Zaporizhzhia has bigger percentage of suitable territory. Though Kherson has bigger suitable area, because of it's bigger size (17,73 km^2 in Zaporizhzhia and 18,02 km^2 in Kherson). I calculated areas using *Add field* and *Field Calculator* functions in the Attribute Table. Then I exported tables to Excel and calculated percentages.

4.4. Graded factors

Next are the areas which contain zones with suitability 0-100%:

1. **Wind speed**

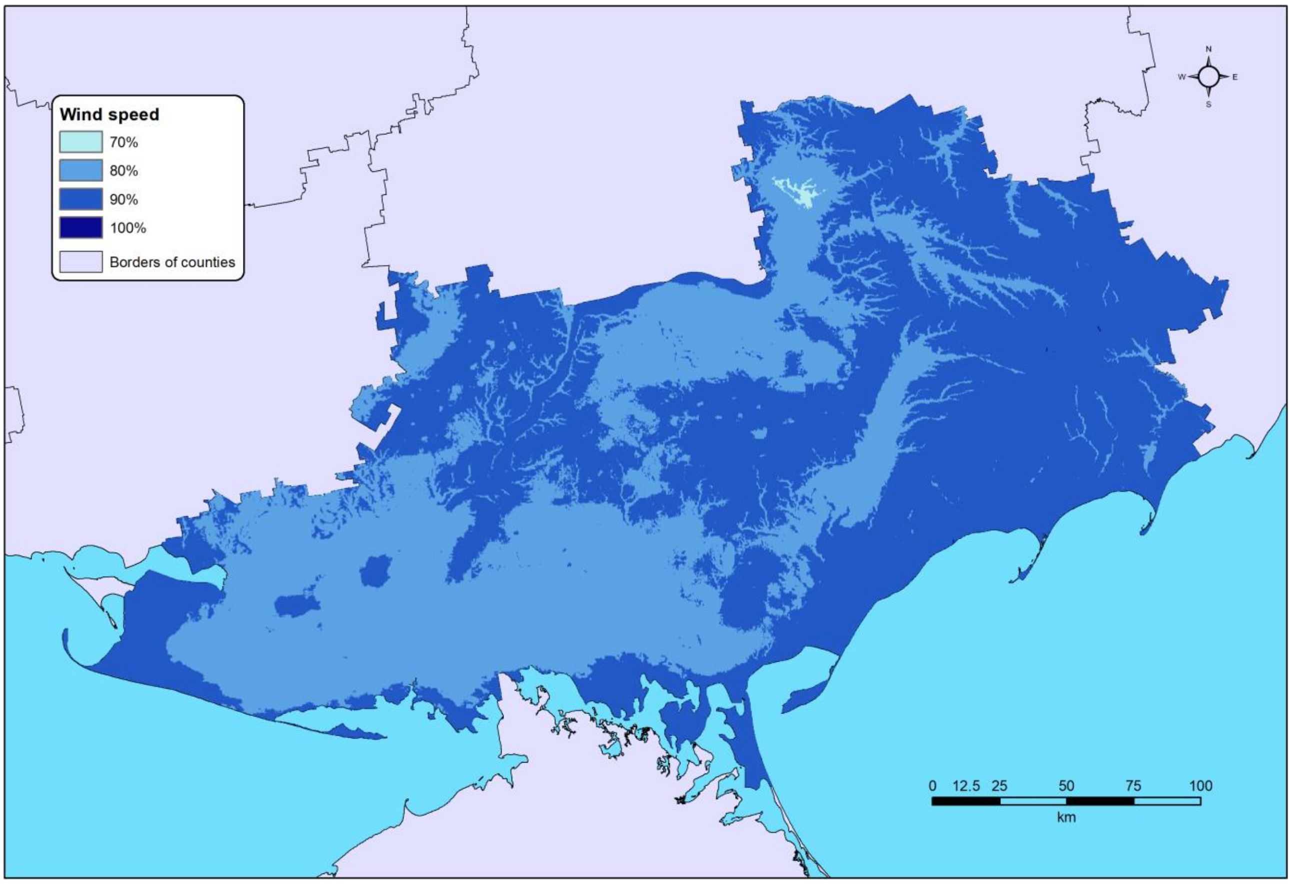


Figure 18. Wind speed

Whole territory of oblasts are suitable for wind farm allocation. As lowest average wind speed is 6,6 m/s (>6 m/s is enough). We can see that Zaporizhzhia oblast has better wind conditions and especially high wind speed near the coast. Light spot with suitablility 70% (6-7 m/s) corresponds to location of Zaporizhzhia city, the biggest city in the study area. Wind speed map is painted in different colors because it is a most important factor, and because it has significant influence on decisions to build a wind farm.

Only **0,004%** of the area has average wind speed over 9 m/s (100%). It means that maximum 0,004% of the area can get a final suitability score of 100%. Majority of territory has speed of 7-8 (42,16%) or 8-9 m/s (57,72%). That means that majority of territory has wind speed suitability of over 80%. It means that wind conditions in the area are really good. 0,113% has wind speed less than 6 m/s. I calculated the percentages in same way as in Exclusion area.

2. Settlements

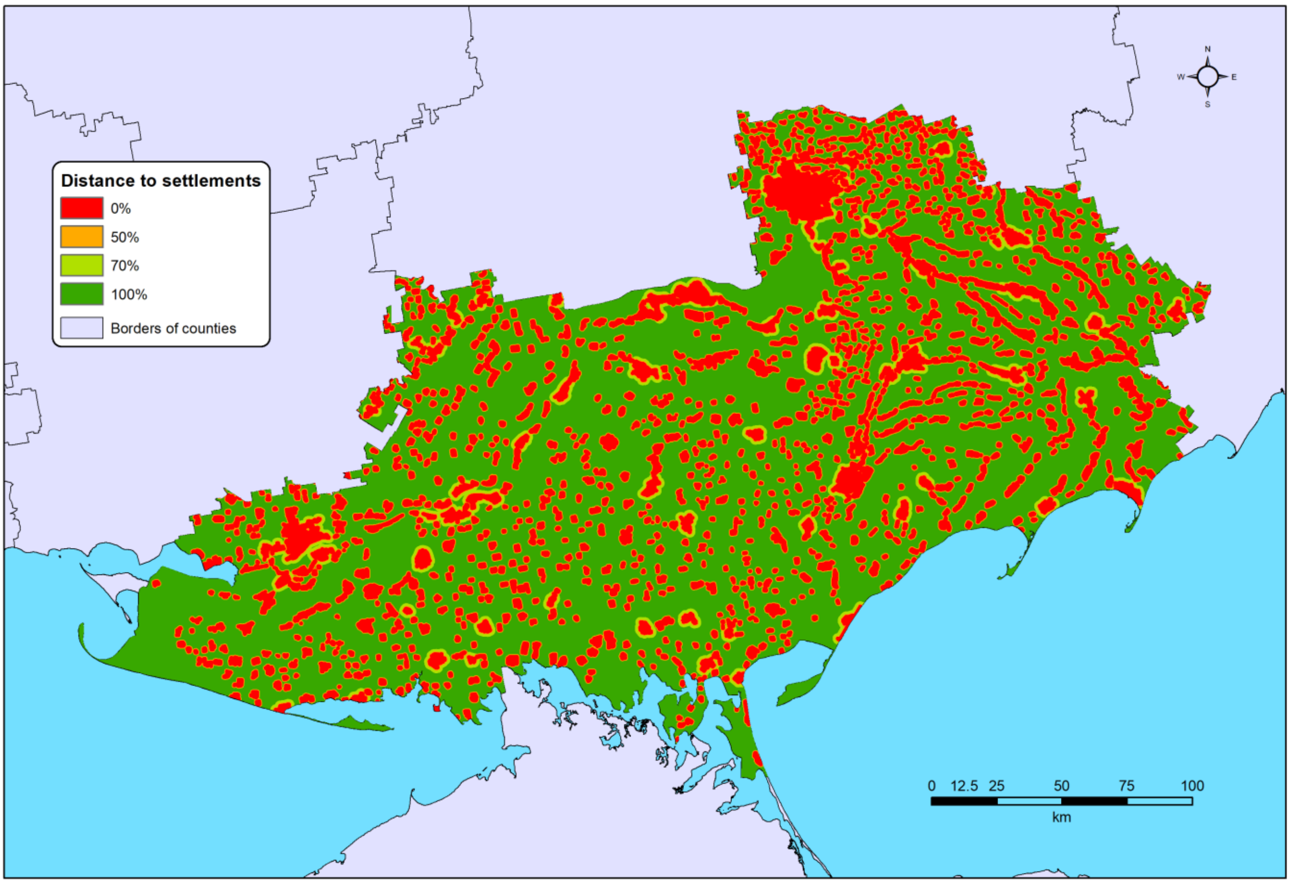


Figure 19. Settlements

Maximum buffers for cities and settlements of urban type (2000 m) are two times bigger than for villages (1000 m). Minimum buffers (700 m) are same for all types of settlements. Zaporizhzhia oblast is much more urbanized. But if to look on a map, it seems that amount of cities and settlements of urban type in Zaporizhzhia oblast is not higher than in Kherson.

3. Bird reserves

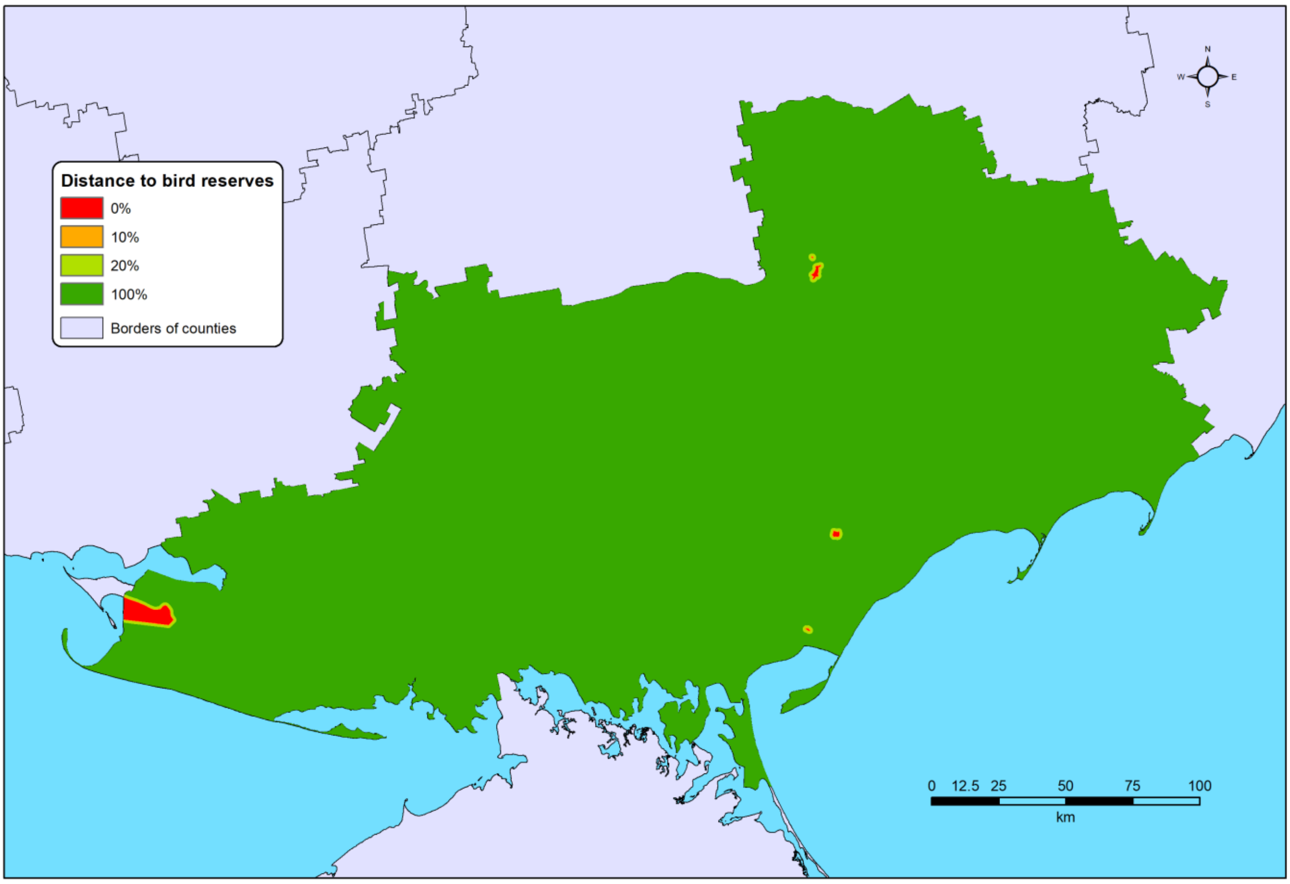


Figure 20. Bird reserves

There is one bird reserve in Kherson and three bird reserves in Zaporizhzhia oblast. As there is only four bird reserves in a study area, the map doesn't contain a lot of information.

4. Roads

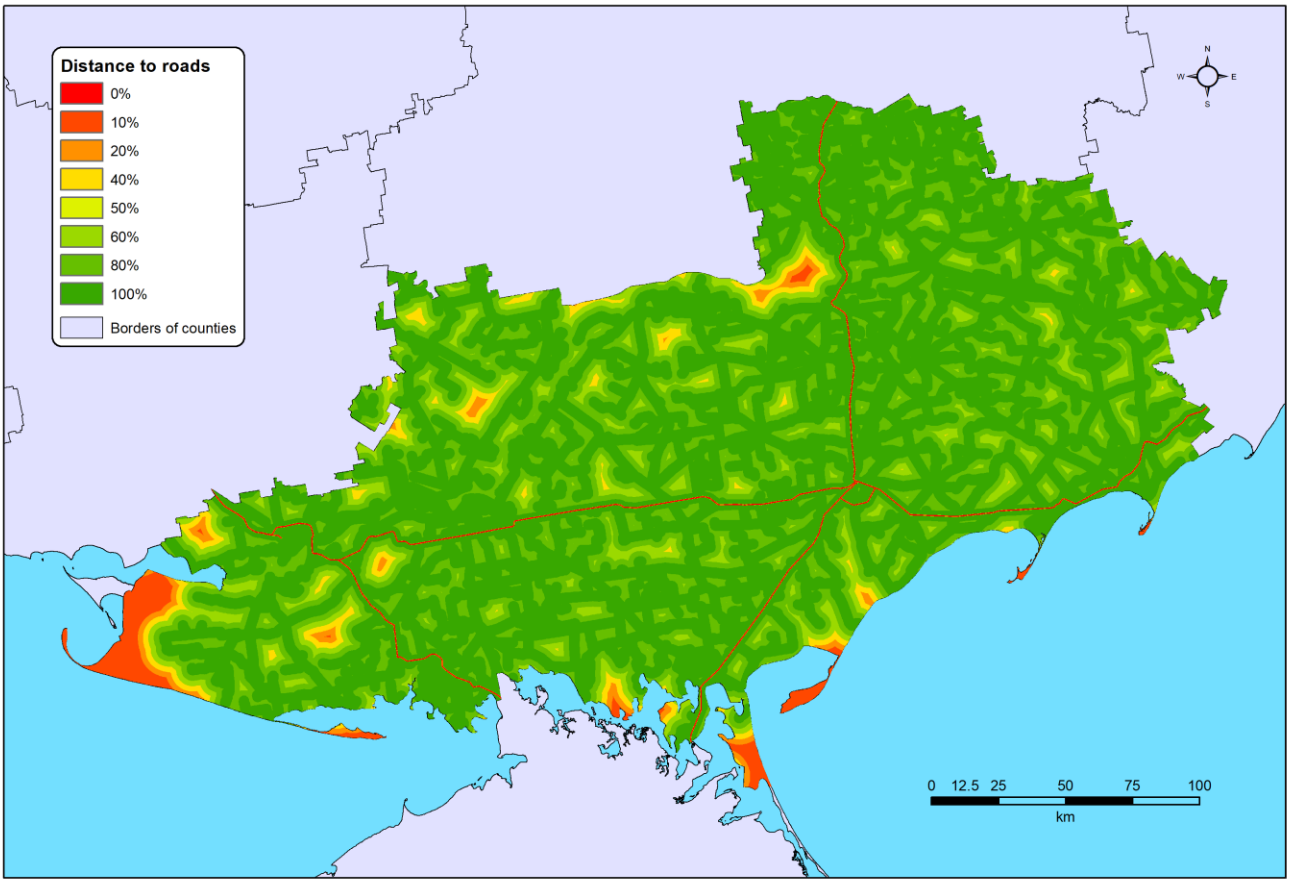


Figure 21. Roads and highways

Roads have two layers:
- Biggest highways (highways of international importance on the map) for keeping the safety distance buffers of 200-250 m. (technical factor)
- All solid roads, which can be used for transportation of turbines' parts. (techno-economical factor)
Merged with *Raster Calculator* and *Reclassify* tools

5. Power lines

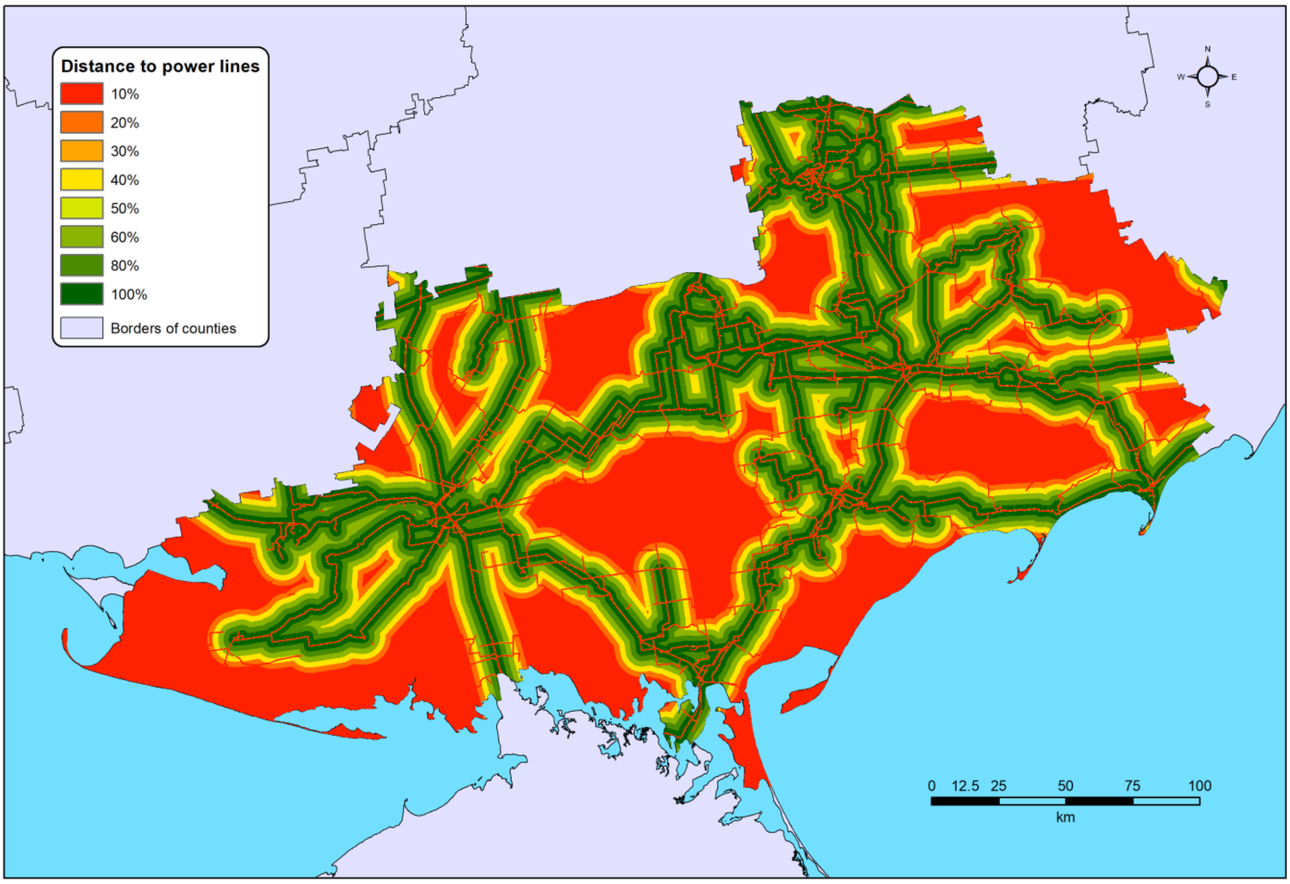


Figure 22. Power lines

Two layers:
- All power lines (technical component),
- Power lines over 110 kV (economic component).

Merged with *Raster Calculator* and *Reclassify* tools.

6. Railways

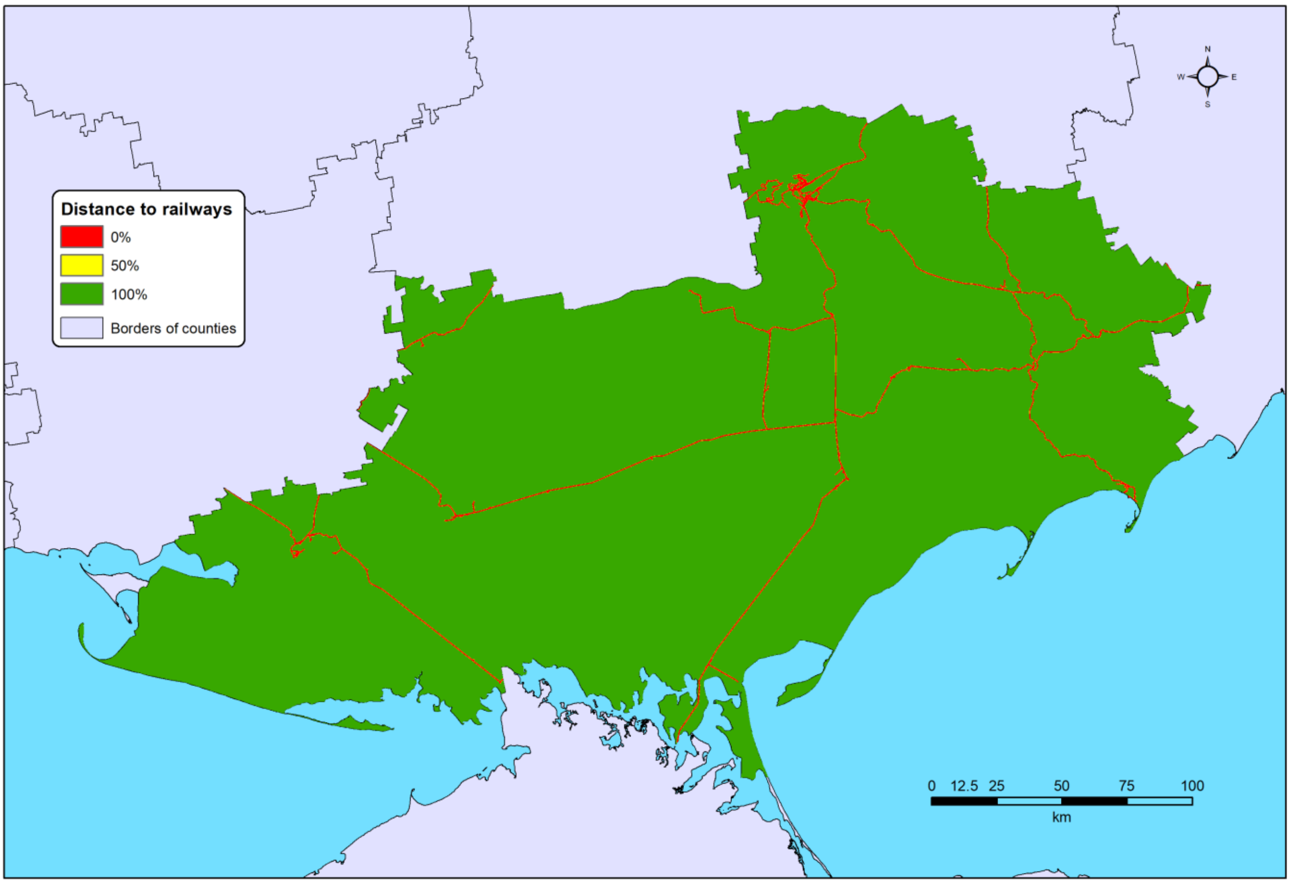


Figure 23. Railways

Railway network is less dense than networks or roads and power lines. And it's good, because railways is not a big obstacle for wind farm planning.

On the other hand, railway network can be, same as roads, used for transportation. Then, the low density of network has a negative impact on suitability. This question is further discussed in Discussion and Conclusions part.

7. Slope

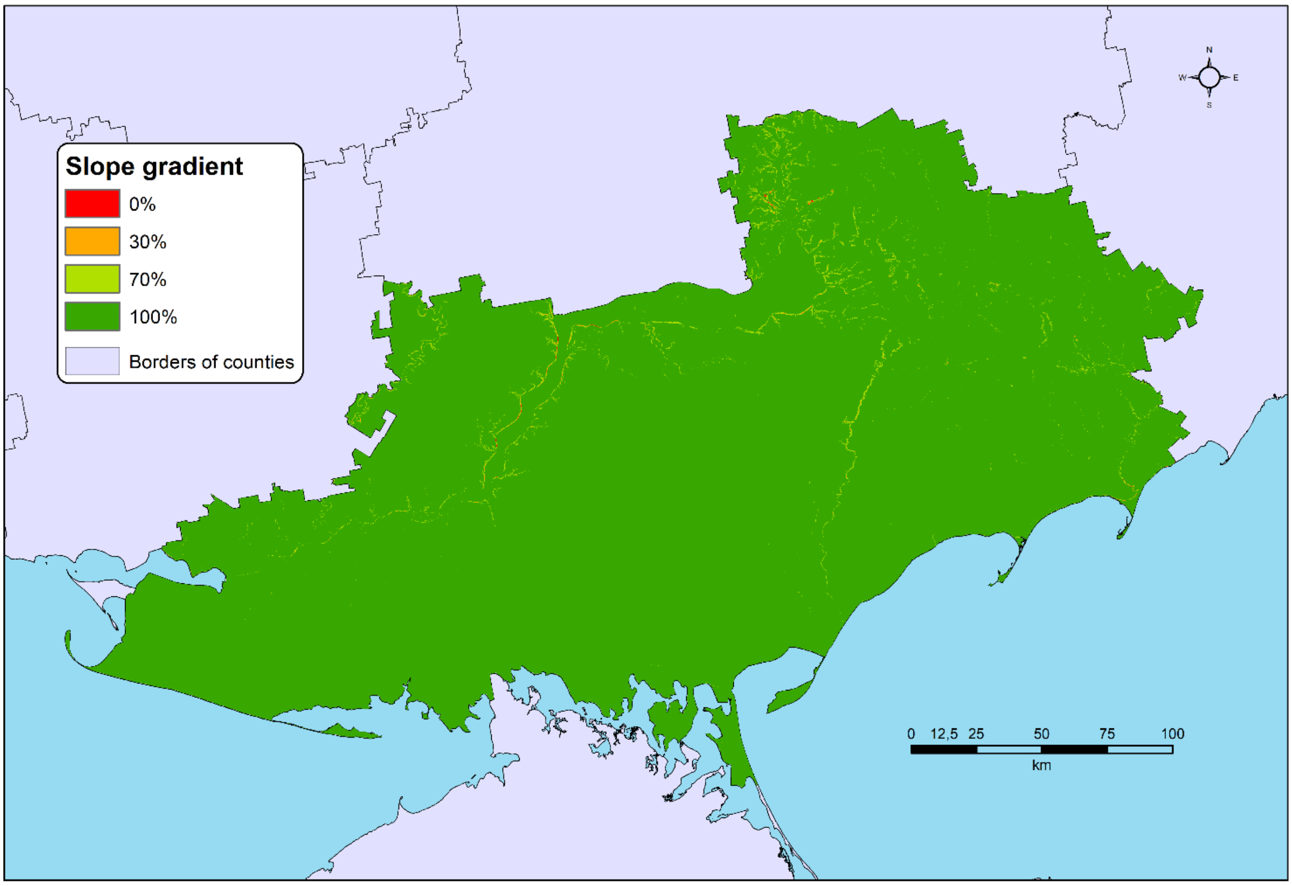


Figure 24. Slope degree

Initially I had elevation data. I used few tools to create a Slope layer: *Create Mosaic Dataset → Add Rasters to Mosaic Dataset → Extract by mask → Slope*. Thus, I converted elevation data to suitable slope format and calculated the slope degree to assign values. For creating exclusion zone of slopes over 30%, I used *Reclassify → Raster to Polygon*, clipped the unsuitable vector out and added it to all unsuitable zones.

The study area is very flat. Slope degree has very low influence. Only 0,01% of the study area has slope steeper than 30% and is excluded. 0,07% has slope over 20%, 0,92% of territory has slope over 10%. And vast majority of territory (99%) has slope under 10% and therefore has 100% suitability.

8. Airports

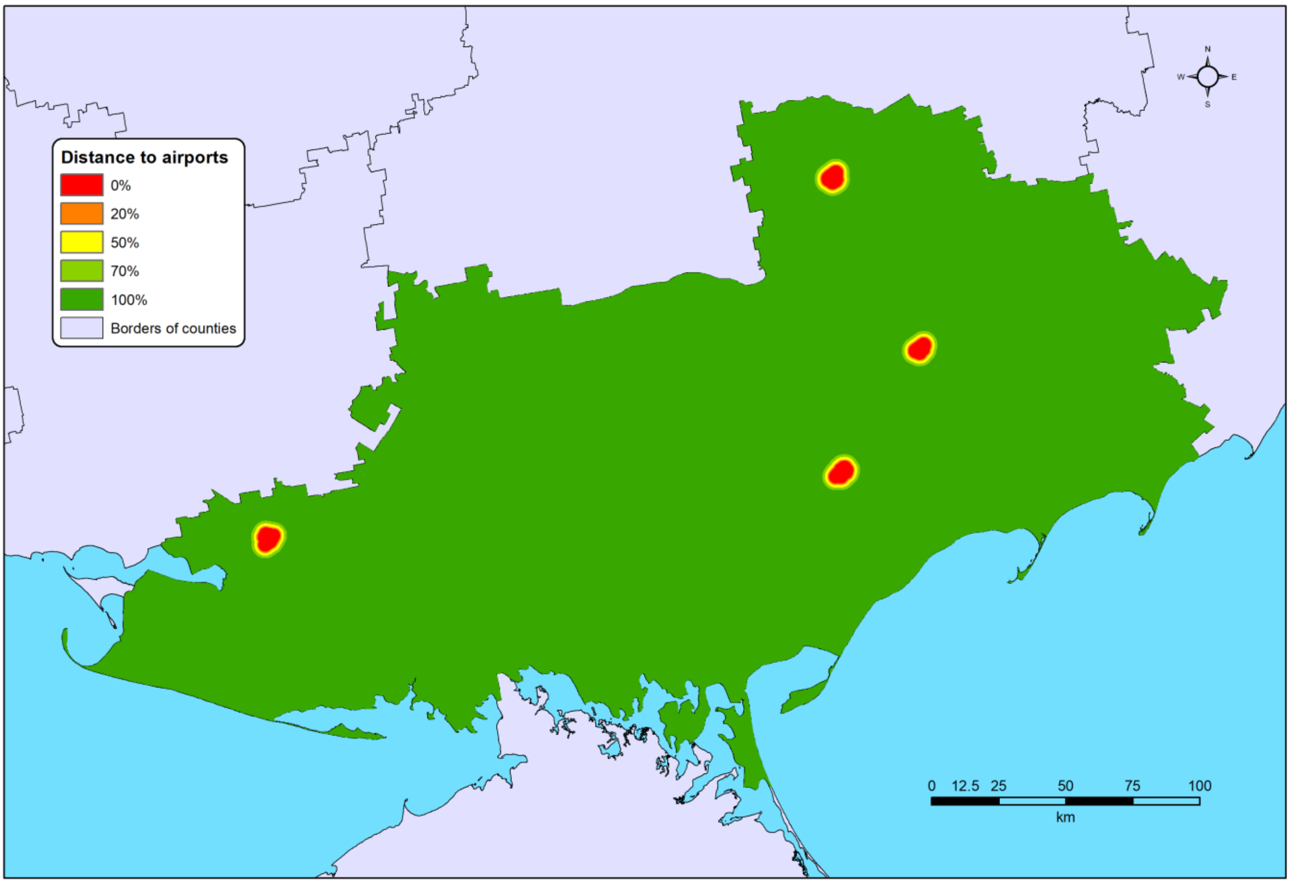


Figure 25. Airports in study area

4.5. Final suitability maps

1. Equal importance suitability map

Areas of 90-100% importance are clearly concentrated around zones that are close to 110 kV power lines. Same importance in this scenario have roads with solid pavement, but their network is much denser. Factors like airports and bird reserves have impact only locally.

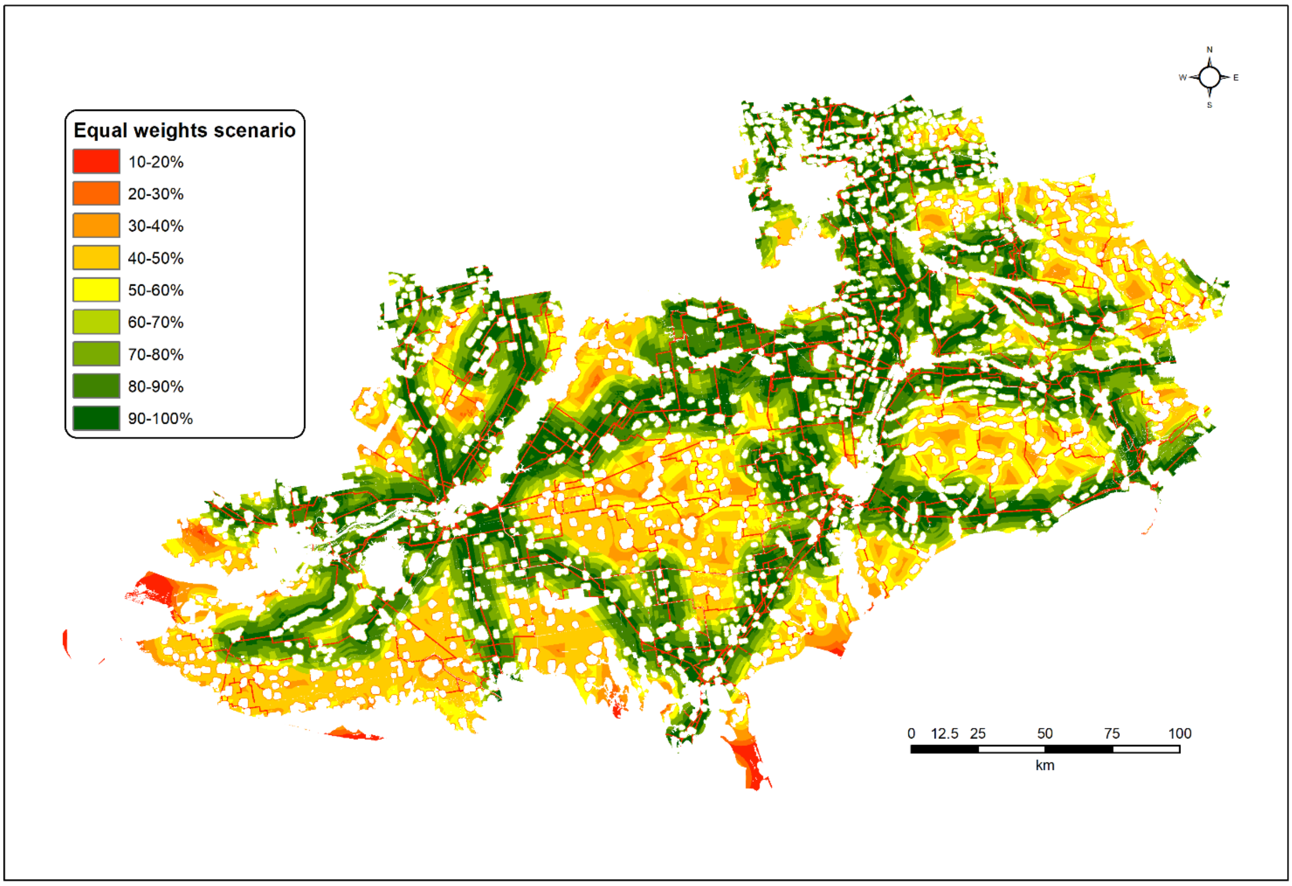


Figure 26. Equal weights map

Areas of highest suitability are concentrated around power lines of 110 kV and more. The distribution of highly suitable land is approximately equal in both oblasts. Areas of high suitability (over 80%) constitute **31,07%** of all suitable areas. Red areas (10% suitability) are buffers around highways, power lines and railways. **0,005%** of suitable territory has very high wind speed (over 9 m/s).

2. AHP criteria suitability map

Majority researchers rank criteria according to their importance to get more precise suitability map (Table 7). I graded factors by their importance according to AHP method. I did it in a way as other researchers. Their works contained evaluations based on surveys of specialists in the field, or gradings by authors themselves. I gathered information from all papers that have rankings and based on calculations in Excel created my own ranking. (Table 8)

Country	Germany	Denmark	Greece	Ecuador	USA	Thailand	South England	Turkey	Japan	Cyprus	Greece	
Author	Hofer	Hansen	Latinopoulos	Villacreses	Miller	Bennui	Watson	*Değirmenci*	Derdouri	Georgiou	Bili	
Place	Aachen	Northern Jutland	Kozani		Nebraska				Fukushima	Larnaca	Andros	
Year	2016	2005	2015	2017	2014	2007	2016	2018	2018	2012	2018	Final
Priority												ranking
Wind speed	1		2	1	1	1	1	1	1	1	2	1
Nature reserves	2	2	5	4			2		3			2
Settlements	3	1		6		2	2		4			3
Power lines	4			7	3		4		2	2	3	5
Roads	5	1	4	5	4	5	5	5	5	3	3	6
Slope	9	1	1	3	2			2	6	4	3	4
Railways		2										8
Airports						3						7

Table 7. Ranking of criteria

In next step I made a pairwise comparison of factors in Excel. It is a next stage of the AHP method. Pairwise comparison allows to create weights of factors according to their importance.

	Wind speed	Nature reserves	Settlements	Slope	Power lines	Roads	Airports	Railways
Wind speed	1,00	2,00	2,00	3,00	4,00	4,00	5,00	6,00
Nature reserves	0,50	1,00	1,00	2,00	3,00	3,00	4,00	5,00
Settlements	0,50	1,00	1,00	2,00	3,00	3,00	4,00	5,00
Slope	0,33	0,50	0,50	1,00	2,00	2,00	3,00	4,00
Power lines	0,25	0,33	0,33	0,50	1,00	1,00	2,00	3,00
Roads	0,25	0,33	0,33	0,50	1,00	1,00	2,00	3,00
Airports	0,17	0,25	0,25	0,33	0,50	0,50	1,00	2,00
Railways	0,13	0,20	0,20	0,25	0,33	0,33	0,50	1,00
Sum	3,13	5,62	5,62	9,58	14,83	14,83	21,50	29,00

Table 8. Pairwise comparison

I divided values in each criteria (row Sum) by their total sum and got table with standardized matrix, which contains column Weights with final values for each criteria for AHP analysis:

	Wind speed	Nature reserves	Settlements	Slope	Power lines	Roads	Airports	Railways	Weights
Wind speed	0,32	0,36	0,36	0,31	0,27	0,27	0,23	0,21	29,05%
Nature reserves	0,16	0,18	0,18	0,21	0,20	0,20	0,19	0,17	18,60%
Settlements	0,16	0,18	0,18	0,21	0,20	0,20	0,19	0,17	18,60%
Slope	0,11	0,09	0,09	0,10	0,13	0,13	0,14	0,14	11,70%
Power lines	0,08	0,06	0,06	0,05	0,07	0,07	0,09	0,10	7,28%
Roads	0,08	0,06	0,06	0,05	0,07	0,07	0,09	0,10	7,28%
Airports	0,05	0,04	0,04	0,03	0,03	0,03	0,05	0,07	4,50%
Railways	0,04	0,04	0,04	0,03	0,02	0,02	0,02	0,03	3,00%

Table 9. Standardized matrix

Percentage values from Weights column are converted then to float values and these weights then used to create new suitability map with *Raster Calculator*. (Figure 23)

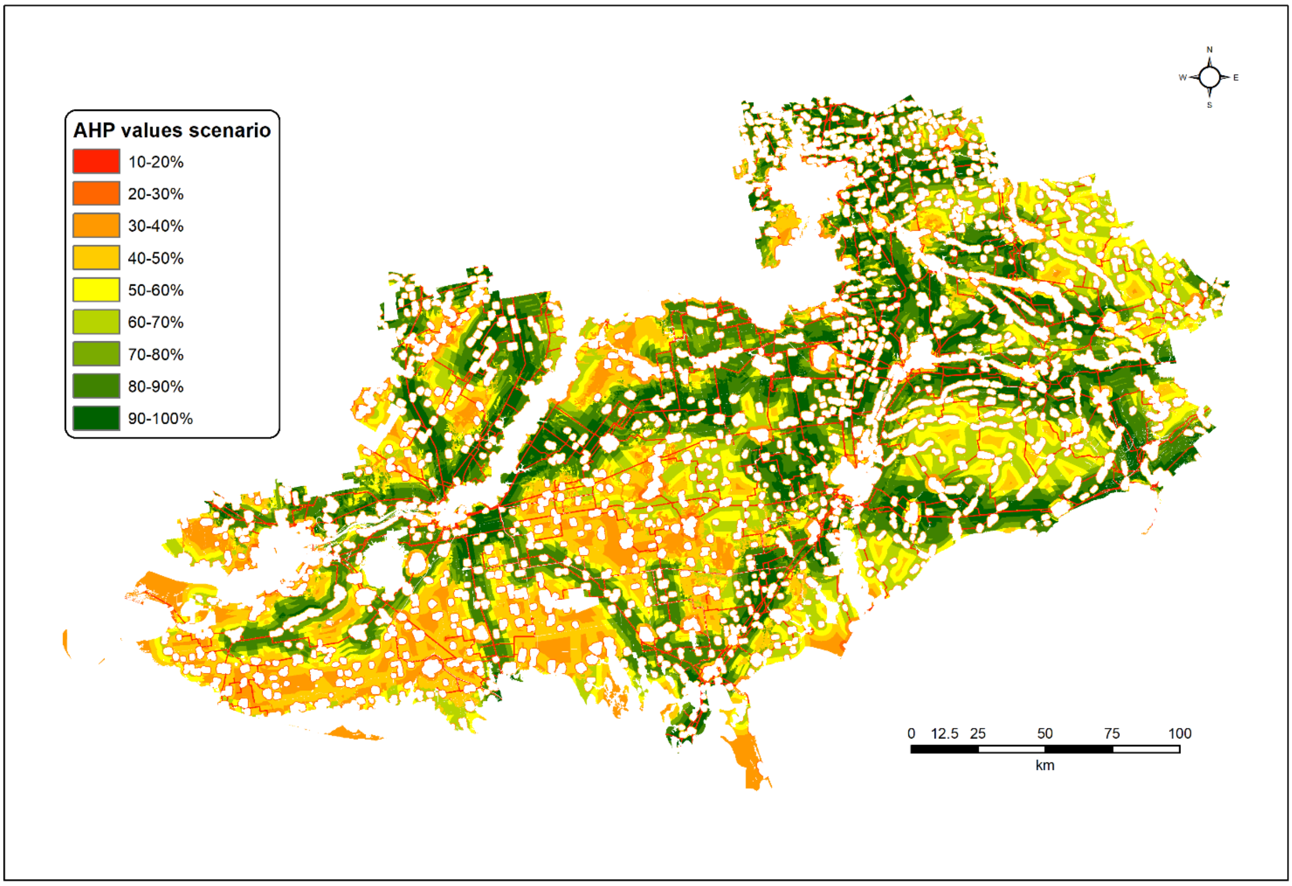


Figure 27. AHP suitability map

Distinction from Equal Weights map is that Kherson oblast visually looks less suitable than Zaporizhzhia. It can be explained by growth of influence of wind speed factor in AHP analysis and by higher speed of wind in Zaporizhzhia oblast. Safety zones around settlements are more clearly distinguished, as in AHP, settlements have higher importance than power lines and roads.

We can see from both, equal weights and AHP weights maps that power lines of over 110 kV are influential factor. Zones can get 80-100% suitability only if they are not further than 4-6 km from 110 kV lines. Despite that power lines got lower importance score on this map. Road network, used for same economic reason, is dense enough almost everywhere in the region. With exception of places where restricted areas (water bodies and nature protection areas) are situated.

Factors like railways, bird reserves and airports have small area restricted in comparison to all study area. Some researchers even don't include these factors. Therefore, in my analysis railways and airports got the lowest influence in AHP. It was important to exclude 2500 m zones around airports and 200 m zone around highways. Bird reserves, same as airports and railways occupy minor territory, but their influence is relatively high. Same with slope. It doesn't change much a general picture, as 99% of territory has degree of less than 10%. It's a favorable condition.

5. Discussion and conclusions

First of all, it was important to define the distances regulated by currently existing Ukrainian legislation. Because it's not possible to build wind farms in places where it is forbidden by law. For example, it was necessary to find out what are the legally acceptable distances to settlements and to mark and exclude all the nature protection areas.

Main regulation in Ukraine is currently a National Standard of Ukraine "Wind farms. Evaluation of environmental impact of wind farms" by UkrNDNC (2017). It regulates safe distance to living areas and some of the other requirements. Though not all the aspects I studied in my work, are regulated there. Some of them needed specification, e.g. about roads required for construction or distances to bird reserves. That was a reason why I made research of papers in the field from other countries.

I think that the overview of practices used in other countries by other researchers can contribute to the research made in Ukraine. Based on works of other researchers I found out how to deal with factors, which have significant influence on construction, but are not defined by Ukrainian law.

Economic and technical factors are more flexible. Usually there are no strict rules about them. They are those, which are commonly reviewed in other researchers' works. In my opinion, the growth of wind energy industry will cause the development of new legislation in Ukraine in future. For example, safety zones to nature and bird reserves, and about distances to airports. Like in Germany, Turkey or Greece, where law regulates distances to highways, power lines, bird reserves and other features. I think that, with time, the sizes of wind turbines will grow and it also may change rules for wind farm siting. Safety zones to power lines, railways and major roads may need to be increased as well.

Sizes of buffer zones can be assigned differently. Law defines only the minimum acceptable distance to settlements, but it may be bigger based on influence of other components. For example, optimal distances to power lines may be also 5 km, or 20 km, not only 10 km, according to researchers (Table 3). But influence of some factors are more of economic question, and companies answer it according to their possibilities. Some companies in Ukraine spend additional money on building high voltage power lines and substations, if they can afford it.

For analyzing the impact of factors, I classified them according to their type. First, I grouped them to economical, social, environmental and technical (Table 1). Next they are divided into two bigger groups: socio-environmental and techno-economic. Such division is frequently used by other researchers.

Socio-environmental restrictions are usually set in regulations and are more precise. It's obligatory that construction complies with them. Some EIAs of wind power stations in Ukraine are compiled without fulfilment of legal requirements.

Techno-economic factors allow to reduce costs and show where construction is technically possible. But sticking to them is not mandatory. If construction company can afford additional expenses, it can build in places of low techno-economic suitability as well. Proximity to roads is required in legislation (UkrNDNC, 2017), but distances and types of roads are not mentioned. Technologies are improving with years, and some places, which were unsuitable in the past, can become suitable, or constructions costs become lower. In order to make the research as precise as possible, 38 works of other researchers were analyze. It allowed to set distances in buffers with high accuracy.

Current Ukrainian legislation regulates next aspects of wind turbine installation: distances from settlements and water bodies, exclusion of nature protection areas. Some factors are technical and their exclusion caused by physical reasons: slope, land use, water bodies. Other aspects are not regulated by legislation - distances from airports, roads, power lines and bird reserves. Wind speed is another economical and technical factor, which can be assessed differently.

To create a grading of factors in AHP analysis I collected grades of other researchers, which they created after surveying the specialists in wind energy in their countries. And my AHP analysis is based on their grades. It is possible to assign different importance values to the factors in AHP. Almost everybody rank wind speed as most important factor. Some rank slope as second, next most influential are usually nature reserves and settlements. And, in my opinion, there is no universal grading. Specialists surveyed were from different fields, some of them were environmental activists, some were representatives of wind energy business, politics or academics. And each expert could grade factors being influenced by his specialization. For example, environmental activist would put distance to bird reserves on first place, businessman would grade high the wind speed or proximity to power lines, politician would put distance to settlements on first place, etc. I tried to make the grading as balanced as possible. Another possible contribution of my paper is a review of data sources available today in Ukraine for this type of spatial analysis.

It is possible to build wind turbines on territories of settlements. If the distance from living houses, inside these settlements, is high enough. But at least 700 m should be still kept. Though, the distance may be bigger than 700 m depending on a separate case. The actual suitable territory may be a little bit smaller or bigger than it is in final map, if to take into account other factors. Though it’s hard to find such places inside settlements.

Railways in my thesis are considered as a possible obstacle for wind turbine construction. But it also may be a favorable condition. As wind turbine parts can be transported by railway transport, same as by roads. Though I didn’t find any researcher considering railways as mean of transport for turbines, railways are used for wind turbine transportation. Another question is, however, about unloading of parts from trains. I think it is easier to find a place to unload parts e.g. from roads than from railways. Probably, the location of train stations should be taken into account in GIS analysis as well.

Another factor is a slope degree. Its grading may differ depending on approach. I used the scale of 10-30%, because there is no commonly accepted value of maximum possible slope degree. Most popular values among researchers are 10% and 30%, no more than 30% (with one exception), not less than 10%. It is a reason why I have such a scale. Though, maximum value can be set differently, and this topic needs separate research and discussion.

Another discussion question is whether there is a need in buffer zones around nature reserves without birds. Laws in Ukraine (and in some other countries where researches were done) don’t define a size of buffer to nature protection areas. But the need of such buffers may arise.

I looked at EIA reports of wind power stations in Ukraine. Some of them contain references to legislation and take into account neighboring settlements and protected areas. But some are setting rules without any reference to legal documents. It also may be good idea to check if stations from those reports are built in accordance to all the rules.

Result of GIS analysis is that 64,25% of the study area is suitable for wind farm construction. It is a high share if to compare with results in regions used by other researchers. Only 9,4% of suitable area in a similar analysis of Höfer et al. (2016). It may be explained by a difference in population density, as Städteregion Aachen has 21 times higher population density than Kherson Oblast, and 13 times higher than Zaporizhzhia.

In case of Equal Weights analysis, areas of high suitability (over 80%) constitute 31,07% of all suitable areas. The share of high suitability areas using AHP method map is bigger – 32,24%. 0,005% of suitable territory has very high wind speed (over 9 m/s). It’s possible to conclude, there is a high percentage of suitable land in the study area. Territory has fortunate wind conditions, together with highly suitable land cover, even surface and low elevation.

Summary

Wind energy development, undoubtedly, has positive impact on environment by reducing the greenhouse gas emissions. But it may also cause damage, if turbines are installed inappropriately. It's important to take into account people living nearby, nature (especially birds and bats), technical and wind conditions, and many other factors.

The aim of thesis is to determine regulations for wind farm siting in Ukraine and to create a suitability map for the most perspective region in terms of wind conditions. I chose Ukraine because no such research was done in my country before.

The site for wind plant installation should be chosen very carefully. Best wind conditions are in Kherson and Zaporizhzhia oblasts (counties) of Ukraine. Therefore, the installation of turbines in this region is most economically efficient, and I chose it as a study area. Despite vicinity, two oblasts have different settlement structure and population density. These factors may affect suitability in positive or negative way. In the end, these two regions are compared by size of suitable area. There is a big amount of unpopulated land available in Ukraine. Density of population in study area is one of the lowest in the country.

Thesis starts with brief insight into the topic of wind energy. I compare situation in Ukraine with same in World and European Union. There are many arguments for development of wind energy in Ukraine.

Thesis has an overview of wind power legislation in Ukraine. Current regulations only set distance from settlements as 700 m. Legislation for wind turbines in Ukraine is not complete yet, and methodology, which I develop, can be helpful for other researchers, who will study this topic in Ukraine, and not only. Methodology is one of the aims of my thesis.

It shows what are the possible data sources available for wind farm suitability analysis. It also shows the tools for processing of the data and explores some common rules for better wind energy planning. I found 72 papers of researchers on this topic, analyzed 38 of them and defined 22 most relevant and helpful for my research.

There are some rules for siting. Wind turbines have to be situated on safe distances from living areas because of number of factors (noise, flickering, icing, or to prevent damage from fall of wind turbine), which may negatively effect human and animal health. Turbines shouldn't be a menace for birds. Highways, railways and power lines should be on safe distance in case if turbine falls down.

Results of the thesis are suitability maps of counties, with areas marked in different colors, depending on suitability extent. Places not suitable for wind farms are excluded from map and are marked accordingly.

I defined next research questions:

1. Which percentage of territory is suitable for wind power development in two oblasts? Which oblast has bigger percentage of land available to install wind turbines?
2. What percentage of suitable land has high suitability (over 80%) according to equal weights and AHP scenarios and high wind speed (over 9 m/s)?
3. What are the most important factors affecting the suitability of sites for wind turbines in the region? Are road and power lines networks dense enough to support the development of wind energy in study area?

I answered research questions by creating maps in ArcGIS and calculating areas in Excel.

Methods used in my research are GIS analysis, Multi-criteria decision-making (MCDM) and analytical hierarchy process (AHP). These methods are most commonly used for this type of research in the field. MCDM means that I use multiple factors that influence the suitability of wind farm sites. The most important and commonly used factors are: settlements, road network, nature protection areas, bird reserves, power lines, railways, slope degree, airports, water bodies, wind speed and land use. I chose these factors based on works of other researchers.

I graded chosen factors by their importance according to AHP method. I created my ranking after calculating the grades from other papers. Works of other researchers contained evaluations based on surveys of specialists in the field, or grading by authors themselves. I used Excel to create a new ranking from them. Wind speed is a most important factor, railway network is a least important.

I excluded from map all settlements with 700 m buffer around them, water bodies with 25-100 m buffers around them, nature protection areas, airports with buffer 2500 m around, slopes steeper than 30%, and areas with restricted land use. As result, the total share of suitable areas is 64,25%, 65,25% in Zaporizhzhia and 63,31% in Kherson oblast.

In case of Equal Weights analysis, areas of high suitability (over 80%) constitute 31,07% of all suitable areas. The share of high suitability areas using AHP method map is bigger – 32,24%. 0,005% of suitable territory has very high wind speed (over 9 m/s).

In both cases, Equal Weights and AHP maps, power lines over 110 kV are significant factor. Suitable zones get 80-100% suitability only if they are not further than 4-6 km from power lines of 110 kV or more.

Factors like railways, bird reserves and airports have comparatively small restriction areas. Some researchers don't include these factors at all. Therefore, in my analysis railways and airports got the lowest influence in AHP. Bird reserves, same as airports and railways occupy minor territory and their influence is relatively low on a big scale. But their exclusion is very important. Same with slope degree. As 99% of territory has degree of less than 10%, it doesn't have significant negative influence.

Factors in my research were divided into four categories, depending on type: economic, social, environmental and technical. Later into two bigger groups: socio-environmental and techno-economic. Socio-environmental restrictions are usually set in official regulations and are more precise. It is obligatory to do all the construction in accordance with them. Techno-economic factors allow to reduce costs and to make construction technically possible. Though sticking to them is not mandatory.

Ukraina Hersoni ja Zaporizhzhia oblastite tuuleenergia potentsiaali GIS-põhine mitmekriteeriumiline hinnang

Denys Dmytrenko

Kokkuvõte

Tuuleenergia laialdasemal kasutuselevõtmisel on kasvuhoonegaaside emissiooni vähendamise läbi kahtlemata keskkonnale positiivne mõju. Kuid samas võib see põhjustada ka soovimatuid kaasnevaid häiringuid, kui tuulikud rajatakse ebasobivatesse kohtadesse. Oluline on arvestada planeeritava tuulikupagi lähedal elavate inimestega, loodusega (eriti lindude ja nahkhiirtega), tehniliste tingimuste ja tuuletingimustega ning paljude teiste teguritega.

Selle uurimistöö eesmärk oli luua teiste rahvusvaheliste uuringute alusel reeglistik tuulikuparkide asukoha valikuks Ukrainas ning koostada tuuletingimuste poolest kõige sobivama piirkonna kohta tuuleenergia kasutuselevõtu sobivuskaart. Ma valisin uurimisalaks Ukraina, kuna minu kodumaal ei ole varem sellist planeerimistingimusi suunavat uurimistööd tehtud.

Tuuleelektrijaama paigaldamise koht tuleb valida väga hoolikalt. Tuuletingimustelt on Ukrainas parimad piirkonnad Hersoni ja *Zaporižžja* oblastid. Seetõttu on tuulikute paigaldamine nimetatud piirkonda majanduslikult efektiivne. Kuigi need kaks oblastit asuvad lähestikku, erinevad nad asustuse struktuuri ja rahvastikutiheduse poolest. Need faktorid võivad mõjutada sobivust nii positiivselt kui negatiivselt. Töö tulemusena valminud tuuleenergia kasutuselevõtu sobivuskaardi alusel võrreldi neid kahte piirkonda nii tuuleenergeetikaks sobiva ala suuruse alusel kui piiranguid põhjustavate tegurite osakaalu alusel. Ukrainas on tuuleenergia tootmiseks saadaval suures koguses asustamata maad. Uuritava piirkonna rahvastikutihedus on üks madalamaid riigis ja seetõttu on siin piirkonnas tuulikuparkide rajamiseks suur potentsiaal ilma oluliste kahjulikke kõrvalmõjudeta.

Uurimistöö algab tuuleenergia valdkonna lühitutvustusega, kus ma võrdlen olukorda Ukrainas olukorraga maailmas ja Euroopa Liidus. Tuuleenergia arendamise kasuks Ukrainas on hulgaliselt argumente.

Uurimistöö sisaldab ülevaadet tuuleenergiat puudutavast seadusandlusest Ukrainas. Hetkel kehtivate määrustega seatakse kaugus asulatest üksnes 700 meetrile. Tuuleturbiine puudutavat seadusandlust ei ole Ukrainas veel lõplikult valmis saadud ning minu poolt koostatud metoodika ning reeglistik võib olla kasulik teistele teadlastele, kes uurivad tulevikus seda valdkonda Ukrainas ning planeerijatele. Metoodika arendamine on üks mu uurimistöö eesmärke.

Ruumiandmete sisuanalüüs näitab, millised potentsiaalsed andmeallikad on tuulefarmide sobivusanalüüsi läbiviimiseks saadaval. Samuti toob see osa tööst välja vahendid andmete töötlemiseks ning käsitleb peamisi üldlevinud reegleid tuulikuparkide asukohavalikuks ning paremaks planeerimiseks. Ma leidsin selle valdkonna kohta 72 uurimistööd, analüüsisin neist põhjalikumalt 38 ning tõin esile 22 kui kõige asjakohasemat ja kasulikumat minu uurimistöös tuulenergia sobivusalade valiku reeglistiku väljatöötamiseks.

Tuulikuparkide planeerimisel on asukoha valikuks teatud tüüpreeglid. Tuuleturbiinid peavad

paiknema elupiirkondadest ohutus kauguses mitmete faktorite tõttu (müra, varjude teke, jäätumine, vajadus vältida kahjustusi tuuleturbiini ümberkukkumisel), mis võivad negatiivselt mõjutada inimeste ja loomade tervist või heaolu. Eelnevast tulenevalt turbiinid ei tohiks häirida linde, maanteed, raudteed ja elektriliinid peaksid olema ohutus kauguses, kui turbiin peaks ümber kukkuma ja teised taolised reeglid omavad planeerimisel ruumilist mõõdet.

Uurimistöö tulemusel sündisid oblastite kohta tuuleenergia kasutamise sobivuskaardid, mis on piirkondade sobivusmäära järgi märgistatud erinevate värvidega. Kaartidel on välja jäetud tuulefarmide jaoks mittesobivad alad, need on ka vastavalt märgistatud.

Defineerisin uurimistöö jaoks järgmised küsimused:

1. Milline protsent territooriumist on sobiv tuuleenergia arenduseks nendes kahes uurimisaluses oblastis? Kummas oblastis on tuuleturbiinide paigaldamiseks suurem protsent maast sobiv?
2. Milline protsent sobivast maast on kõrge sobivusega (üle 80%) vastavalt võrdsetele kaaludele ja AHP-stsenaariumitele ning kõige suurema tuulekiirusega (üle 9 m/s) aladest?
3. Millised on kõige tähtsamad faktorid, mis mõjutavad tuuleturbiinide asukohtade sobivust nendes piirkondaes? Kas teede- ja elektriliinide võrgud on piisavalt tihedad, et toetada tuuleenergia arendust uuritavas piirkonnas?

Ma vastasin uurimisküsimustele, luues kaardid ArcGIS-is ning arvutades pindalasid Excelis.

Meetoditena kasutasin ma oma uurimistöös mitmekriteeriumilist otsustamist (MCDM) ja analüütilise hierarhia protsessi (AHP) GIS-analüüsil. Neid meetodeid kasutatakse antud valdkonnas sedalaadi uurimistööde tegemiseks kõige sagedamini. MCDM meetodiga hinnatakse faktoreid, mis tuuleparkide asukohtade sobivust enim mõjutavad. Kõige tähtsamad ja enamkasutatud tegurid on asulad, teedevõrk, looduskaitsealad (sh. linnukaitsealad), elektriliinid, raudteed, nõlvakalle kraadides, lennujaamad, veekogud, tuule kiirus ja maakasutus. Need faktorid on enim kasutust leidnud ka teiste teadlaste uurimistöödes.

Edasisel analüüsil hindasin neid faktoreid tähtsuse järgi vastavalt AHP-meetodile. Tekitasin omaenda järjestuse, lähtudes arvutustes teistes uurimistöödes tehtud hindamisest. Teiste teadlaste uurimistööd sisaldasid hinnanguid, mis põhinesid valdkonna ekspertide hinnangutel või autorite enda hindamissüsteemidel. Kasutasin Excelit, et luua statistilise analüüsi alusel nende põhjal uus hindamissüsteem (järjestus). Kõige tähtsam faktor on tuule kiirus, kõige ebaolulisem on raudteevõrk.

Jätsin sobivate alade kaardilt välja kõik asulad, mille ümber oli genereeritud 700-meetrine puhver, 25–100-meetrise ümbritseva puhvriga veekogud, looduskaitsealad, 2500-meetrise ümbritseva puhvriga lennuväljad, järsemad kui 30% nõlvad ning normatiivaktidega piiratud maakasutusega alad. Sellest ilmnes, et sobivate alade üldpindala *Zaporižžja* oblastis on 64,25%, 65,25% ja Hersoni oblastis 63,31%.

Võrdsete kaalude analüüsi alusel moodustavad kõrge sobivusega (üle 80%) alad 31,07% kõigist sobivatest aladest. AHP-meetodi kaardi järgi on kõrge sobivusega alade osakaal suurem – 32,24%. Väga suure tuulekiirusega (üle 9 m/s) on vaid 0,005% sobivast territooriumist.

Mõlemal juhul, nii võrdsete kaalude kui AHP-meetodil loodud sobivuskaartide puhul on oluliseks faktoriks üle 110 kV elektriliinid. Sobivatele tsoonidele saab omistada 80–100% sobivuse üksnes siis, kui need ei ole kaugemal kui 4–6 km elektriliinidest pingega 110 kV või üle selle.

Selliste faktorite nagu raudteede, linnukaitsealade ja lennujaamade piirangualad on suhteliselt väikesed. Mõned teadlased ei kaasa neid faktoreid suuremate piirkondade väikesemõõtkavalisel planeerimisel üldse. Seetõttu omistati raudteedele ja lennujaamadele minu analüüsis AHP järgi kõige madalama mõju. Sarnaselt lennujaamadele ja raudteedele võtavad linnukaitsealad enda alla vaid väikese territooriumi ning suuremas mastaabis on nende mõju suhteliselt madal. Aga nende väljajätmine sobivusalade hulgast on väga oluline. Sama kehtib järskude nõlvade kohta. Kuna 99% territooriumi on nõlvakalle alla 10%, ei ole sellel olulist negatiivset mõju.

Minu uurimistöös jaotusid faktorid liigi järgi nelja kategooriasse: majanduslikud, sotsiaalsed, keskkondlikud ja tehnilised. Hiljem koondati need kahte suuremasse rühma: sotsiaalsed ja keskkondlikud ning tehnilis-majanduslikud. Sotsiaalsed ja keskkondlikud piirangud sätestatakse tavaliselt ametlikes määrustes ning need on täpsemad. Ehitustööde teostamine vastavalt nendele on kohustuslik. Tehnilis-majanduslikud faktorid lubavad kärpida kulusid ning teha ehitamise tehniliselt võimalikuks, samas ei ole nendest kinnipidamine kohustuslik.

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Annexes

Annex 1 - Current setback distances from housing in EU countries (Dalla Longa et.al. 2018)

Country	Region	Small Wind Turbine	Large Wind Turbine
Albania	all	120	500
Austria	Niederdsterreich	1200	1200
	Oberosterreich	800	800
	Steiermark	1000	1000
	Burgenland	1000	1000
	Vorarlberg	Not allowed	Not allowed
	Tyrol	Not allowed	Not allowed
	Salzburg	Not allowed	Not allowed
	Carinthia	Not allowed	Not allowed
	Vienna	Not allowed	Not allowed
Belgium	Flanders	600	600
	Wallonia	400	400
	Brussels	Not allowed	Not allowed
Bosnia and Herzegovina	all	120	500
Bulgaria	all	120	500
Croatia	all	500	500
Cyprus	all	850	850
Czech Republic	all	120	500
Denmark	all	600	600
Estonia	all	1000	1000
Finland	all	1000	1000
Former Yugoslav Republic of Macedonia	all	120	500
France	all	500	500
Germany	other	700	550
	Baden-Wurttemberg	1000	1250

Country	Region	Small Wind Turbine	Large Wind Turbine
	Bayern	1000	1000
	Brandenburg / Berlin, Hessen Niedersachsen	300	1000

	Hamburg	800	500
	Mecklenburg-Vorpommern	200	1000
	Nordrhein Westfalen	400	700
	Rheinland-Pfalz	400	1000
	Saarland	750	1000
	Sachsen	1000	1000
	Sachsen-Anhalt	400	1000
	Schleswig-Holstein	750	800
	Thuringen	700	1000
Greece	all	500	500
Hungary	all	1000	1000
Iceland	all	120	500
Ireland	all	500	500
Italy	all	200	750
Kosovo	all	120	500
Latvia	all	500	500
Lithuania	all	120	500
Luxembourg	all	120	500
Malta	all	120	500
Montenegro	all	120	500
Netherlands	all	400	400
Norway	all	120	500
Poland	all	550	1250

Country	**Region**	**Small Wind Turbine**	**Large Wind Turbine**
Portugal	all	120	500
Romania	all	500	500
Serbia	all	120	500
Slovakia	all	120	500
Slovenia	all	500	500
Spain	all	500	500
Sweden	all	1000	1000
Switzerland	all	120	500
United Kingdom	England	700	800

	Wales	500	500
	Northern Ireland	500	500
	Scotland	1000	2000

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