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A multiscale assessment of wind energy resources and suitability in the Russian Arctic

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A MULTISCALE ASSESSMENT OF WIND ENERGY RESOURCES AND SUITABILITY IN THE RUSSIAN ARCTIC

An Abstract of a Thesis

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Master of Arts

Narmina Iusubova

University of Northern Iowa

July 2017

ABSTRACT

Wind as a renewable and clean source of energy has begun to take a high position in the global dialog about energy production. Today, one of the big questions is to find the most suitable locations for wind farms, with the goal of achieving the highest rates of electricity production possible. In order to find most suitable places to build windfarms, we need to develop multifactor and multiscale dynamic models of windfarm suitability. The interest in the assessment of wind energy suitability in the Russian North regions comes from the expectation of the great potential of wind power in the northern regions in general. The Russian Arctic coastline can be considered one of the largest wind energy areas that provides an opportunity to implement wind energy technology. At the same time, northern communities face challenges of sustainable development associated with limited fuel energy resources. These challenges such as ecological sustainability and the problems of transportation of fuel in the harsh conditions of the North can be alleviated by the wind energy industry.

This research implements an improved wind energy resource characterization and suitability assessment methodology using multi-resolution datasets and a spatial decision support system approach. The wind turbine suitability assessment is based on collection and interpretation of study area environmental characteristics. The developed framework is based on multi-criteria decision systems approach and advanced for the particular study area with its regional features. The framework includes along with basic environmental criteria, such as wind speed or wind power, slope, elevation, proximity to road networks, settlements, protected federal areas etc., parameters specific for the Arctic regions and

cold environmental conditions, such as icing losses and permafrost. All those factors are taken into an account for more precise results of wind power assessment for the Arctic territory of Russia.

One of the important results of this research is an improved framework of wind resource characterization, where wind power potential of the study area was calculated for twelve-month using an examination and use of global meteorological reanalysis data. Average annual estimates of wind power potential were adjusted for such possible production impairment factor as icing occurrence and potential losses due to it. The inclusion of this variable influenced the results which tells about an importance of such methodological improvements of using this criteria for wind energy potential estimates.

Wind turbine suitability assessment was completed with the use of appropriate to cold climates multi-criteria decision making system, this system was developed and implemented in this study. Multi-criteria site assessment method included best available data for the Russian Arctic and included 11 criteria for enhanced site selection. One of the new improvements in this research is the use of permafrost as an economic criterion, where risks of wind turbine construction on unstable permafrost were considered. As a result of this study, regional wind power potential and suitability estimates were provided for all eight Russian Arctic regions and showed high potentials of wind energy development. This research included downscaling to the regional-scale process with the use of finer resolution meteorological reanalysis and elevation data for the area of Nenets-Autonomous Okrug. Results of this process showed that downscaled results

positively impacted on wind power potential assessments and negatively impacted on suitability site assessment.

The results of this study can be useful for an electric power industry development program in the Arctic region, where alternative energy sources can replace or reduce the use of the traditional fuel resources.

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has been approved as meeting the thesis requirement for the

Degree of Master of Arts in Geography

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CHAPTER 1
INTRODUCTION

For thousands of years wind has played an important role in humanity's unquenchable thirst for energy. In the past, wind energy has been utilized in applications as diverse as seafaring, milling grains, and crop irrigation systems. However, by the mid-20th century fossil fuels replaced the widespread use of wind energy in these applications. Since then, the depletion of fossil fuel supplies has invoked the interest in remaining reserve estimates, but availability is not the only factor to consider. Environmental contamination, transportation efficiency, and overall cost of fossil fuel consumption are all variables that have come under scrutiny. Thus, wind as a renewable and clean source of energy has begun to take high position in world dialog about energy production.

Wind is one of the fastest growing electricity technologies along with solar energy in the last decades (Watson & Hudson, 2015). According to the Global Wind Energy Council report 2015 was a record year with 60 GW of annual installed capacity for wind energy industry. China has been the largest wind energy producer since 2009, whereas Russia according World Wind Energy Association Resource Assessment Report 2013 (WWEA, 2013), held the 69th position by the end of 2013 within all one hundred three countries that use wind energy. Russia's use of wind power is far below its capacity (WWEA, 2013). When we see how rapidly wind energy is gaining ground in an economy as large as China, which is showing an example of successful renewable energy development, countries that do not use full or even small portion of possible wind energy capacity must inherit experience and develop new approaches that will be supportive of wind energy development within the country and in the world. Given the discrepancy between wind power potential and actual production, a country such as Russia would benefit from exploring development of wind resources, especially in areas with logistical difficulties in fuel delivery such as the Arctic.

One of the important components of wind energy development is the Wind Resource Assessment (WRA). World Wind Energy Association Resource Assessment Report 2014, with reference to the International Energy Agency, showed that the total global energy consumption reached 100,000 Terawatt-hours per year, with a world's wind power potential of at least 94.5 TW is enough to cover the energy supply of the entire world twice, assuming on average 2000 full load hours. This observation confirms wide opportunities for wind energy development, it has a lot of potential and low cost.

An estimation by the National Renewable Energy Laboratory (Moné, Smith, Maples, & Hand, 2013) of the levelized cost of energy for a reference land-based wind project installed in the US in 2013 ranges between $50–$103/MWh. However, if the installation of wind farms is expensive and too difficult for timely implementation within the framework of the national energy development, the electricity supply in remote areas that does not require building large wind farms is one of the important tasks. Northern regions, and particularly the Arctic, are located in harsh environments, and rely on transported fossil fuels. Regional growth depends on many factors, including uninterrupted electricity production and diversity from a range of different energy resources, including renewable wind energy that can be key for sustainable development

(Pryor & Barthelmie, 2010). Arctic communities also face the same challenges of sustainable development as other regions using fossil fuel resources. These challenges, such as pollution and the problems of transportation of fuel in the harsh conditions, can be solved by wind energy implementation.

One of the questions of wind energy implementation is the ability to find the most suitable locations for wind turbine installation, with the goal of achieving the highest rates of electricity production while minimizing ecological stress (e.g., Aydin, Kentel, & Duzgun, 2010; Latinopoulos & Kechagia, 2015; Petrov & Wessling, 2015). A variety of studies had the aim of evaluating land suitability for wind farm installation (e.g., Hansen 2005; Latinopoulos & Kechagia 2015; Malczewski 1999). These studies are based on a region's physical, environmental, and human characteristics and potential impact (Rodman & Meentemeyer, 2006). Although there are similarities, each study used different methods of creating suitability models. Some were based on ecological niche modeling methods using existing installed wind turbines (Petrov & Wessling, 2015), others were based on a multi-criteria evaluation using different sets of data with GIS-assistance (Hansen, 2005; Latinopoulos & Kechagia, 2015; Malczewski, 1999; Watson & Hudson, 2015).

So far, the studies in geographical assessment of wind energy in northern regions in Russia are limited to a few papers where authors reference a wind resource map from the Russian Wind Atlas (2000) by Starkov, Bezroukikh, Borisenko and Landberg (Archer & Jacobson, 2005; Soldatenko & Karlin, 2014). Lack of in-depth research shows some gaps around wind energy assessment in Russia. In Russia we have to take into consideration the scale of the country and length of its coastline, which contributes to high wind potential in this area. The Russian Arctic particularly has a considerable potential for wind power production (Starkov et al., 2000). The average annual wind speed at an altitude of 50 meters above the ground varies from 5 m/s in sheltered terrains, to 11. 5 m/s for hills and ridges (Starkov et al., 2000) that is high enough to provide opportunity to implement wind energy technology. This is a good start to think about what has not been done yet in the Russian North, where high estimates of wind energy correspond with lagging usage of wind energy resources.

The Arctic area of Russia includes two Nuclear Power Plants (NPP), one of them is located on the Kola Peninsula (Kolskaya NPP, 1760 MW), which produces 60% of the all energy in the Murmansk Region. This is the first nuclear station in Russia which was built above the Arctic Circle (ROSENERGOATOM, 2017). The second NPP is in Chukotka (Bilibinskaya NPP, 68 MW), which is the northernmost operating nuclear plant in the world, and was built to provide electricity for gold extraction. Bilibino station operates on 35% of its total capacity due to its age. It is very dangerous to continue utilizing this station, leading to a plan for its shutdown in 2019. This station will be replaced with a floating nuclear station “Akademik Lomonosov” in the port of Pevek 378 km from Bilibino (Ozharovsky, 2010). The development of coastal infrastructure for the floating nuclear construction began on October 4th, 2016, and will begin energy production in 2019 (Douraeva, 2003; Golubchikov, 2002; ROSENERGOATOM, 2017)

In addition to NPP, in Murmansk region, there are 17 Hydroelectric Power Plants (HPP), with a total capacity is 1589.5 MW and three thermal power plants with total capacity of 293.7 MW (Energy Base, 2017). Not every region in the Russian Arctic has such a diversity of power production resources. Russian Arctic regions have high demand for energy that will continue into the future. Looking at the power supply of settlements in the global Arctic (Figure 1) we can see that many communities in Canada, Alaska US, and Russia are located outside of centralized electric grids (Poelzer et al., 2016).

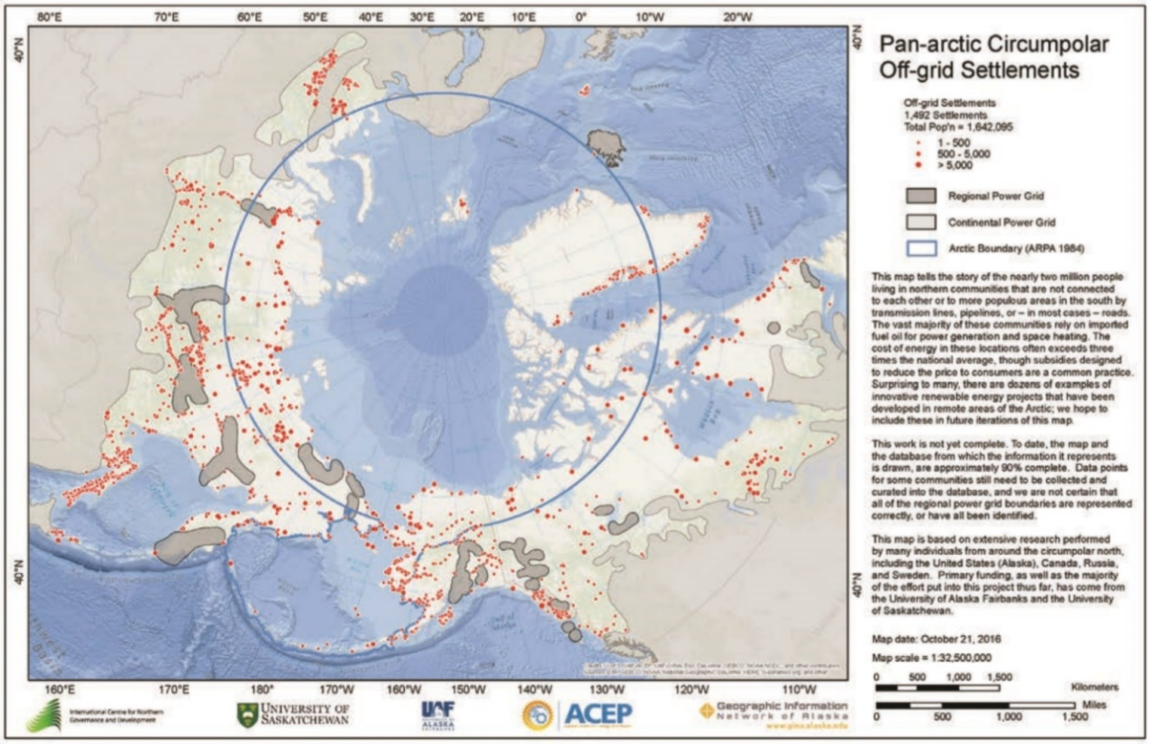


Figure 1: Map of Pan-arctic Circumpolar Off-grid Settlements (Poelzer et al., 2016)

Communities in the Arctic are dependent at on fossil fuels due to the remoteness of the region from the centralized power source and they use power from small dieselfueled power plants (Minin, 2012). According Marchenko and Solomin (2004) Northern Russia had 6600 diesel power plants with a total capacity of 3.3 GW and used 2 million tons of diesel fuel at prices of US$ 250-500/toe (tonnes of oil equivalent, where 1 toe = 41.87 GJ). Average fuel consumption for those diesel power plants is 0.3-0.4 kg/KWh. Before each winter season due to very difficult climatic conditions in the Far North, remote regions in Russia receive food and fuel supplies from the "mainland," as a part of the "Northern supply" distribution system. It is a very time-consuming process to bring supplies in harsh conditions. It is also expensive for both regional governments and for the end consumer.

The electricity price in the Arctic significantly increases based on the type of transportation used. Minin (2012) showed that the prime cost in remote communities compared with the cost of energy production in developed areas increased by 1.2 to 1.5 times compare by road transport, and higher by boats and by air. As an example, the cost for end users in Moscow Oblast (Region) is about 5 rub/KWh and 8 rub/KWh for Chukotka Autonomous Okrug (ENERGO24, 2017), demonstrating a price is increased of 1.6 times. Arctic regions also have the longest heating season which sometimes lasts between 300 and 350 (Minin, 2012). High winds cool down the Arctic in the winter, but at the same time can be good support of heating cities by clean energy.

The use of fossil fuels creates atmospheric pollution including carbon dioxide (Pryor & Barthelmie, 2010). This is one of the reasons to change practices and consider renewable energy, and wind power in particular, to replace fossil fuel resources. Remote communities can develop more sustainably and faster with independent renewable energy, and have their own supplies and opportunity to manage them.

Russia-based studies of wind energy assessment are limited providing little knowledge about regional or even national scales. Some research show potential of wind power production based on economic aspects or high wind speed in regions, but there are no existing geographical data for wind turbine installation sites and suitability models based on different criteria. No studies have attempted to downscale using high resolution data.

My research will provide estimates of wind resource characterizations and develop multifactor multiscale models of windfarm suitability in northern Russia that can be used for the electric power industry in Arctic development program, where alternative energy sources can replace or reduce the use of the traditional fuel resources.

1.1 Research Goal and Objectives

The goal of this research is to develop multifactor multiscale models of windfarm suitability for the Arctic regions of Russia, therefore providing a deeper understanding of the complexity of wind energy implementation in remote areas and filling research gaps in respect to renewable energy assessment in remote areas of northern Russia.

Objectives:

1. Using existing weather, climatic, and environmental data, complete a terrestrial wind resource characterization and wind farm suitability modeling framework.

2. Provide spatially and temporary resolved regional estimates of terrestrial wind energy potential in the Arctic regions of Russia.

3. Develop (downscale) multifactor suitability models for regional-scale wind farm installations.

1.2 Thesis Structure

Chapter 2 of this thesis provides a literature review that illuminates the status of wind energy in Russia, highlight current government regulations, and provide information about existing wind energy projects in the Russia and in Russian Arctic particularly. This chapter includes reviews of practices of wind energy implementation in cold climates, including difficulties and methods of their resolution. Chapter 2 examines worldwide and Russian studies of wind resources assessment. It also, reviews suitability modeling algorithms and summarizes different approaches. Chapter 3 provides detailed description of environmental characteristics of territories for the two scales study areas. This Chapter describes acquired for this research geospatial datasets over study area and methodological workflow for multi-criteria site assessment. Chapter 4 presents the results of this study. Chapter 5 provides discussions of methodological improvements and assessment of downscaling approach results; this chapter summarizes wind resource availability and suitability for Russian Arctic regions. Chapter 5 also includes limitations, and future directions.

CHAPTER 2

LITERATURE REVIEW

2.1 Status of Wind Energy in Russia

Russia is the world’s largest country, having a large territory and long costal line with a great potential for wind energy development. Since 1918 Russia has been engaged in wind energy research and production. Russian professor Zalewski created the “theory of the windmills” and formulated several principles for wind turbines development in 1918. In 1925, Professor Zhukovsky developed the theory of wind turbine and headed the Design Department at the Central Aero-Hydrodynamic Institute. The industry began to develop rapidly, and by 1930, the Soviet Union was a leader in the use of wind energy. Subsequently, Russia has handed over leadership positions in the world of wind energy production due to cheap petroleum (Zatoplyaev, Livinsky & Red'ko, 2003).

Scientists from the Geography department at Moscow State University have studied renewable resources of Russia and presented work about estimating renewable energy potential in Russia, proposed goals, and future directions, they also touched upon the problems of remote regions. Kiseleva, Rafikova and Shakun (2012) indicated that an interest in renewable energy in some regions of Russia is growing. Some government regulations have already been taken to stimulate this area of energy production. Based on modern legislative base of the Russian Federation in the field of renewable energy the work on first law about renewable energy had been completed in 1997 but it was rejected by the president. In 2007 it, however was adopted by the State Duma. In January 2009 Decree №1-r of the Government of the Russian Federation "On the Main Directions of the state policy in the field of improving energy efficiency of the electricity from renewable energy sources for the period until 2020" was adopted. This program included policy of decreasing use of carbon-based fuels to reduce environmental pollution. Mechanisms for promoting the use of renewable energy in the wholesale market of electric energy and power have been developed. (Government Resolution of May 28, 2013 N 449). According to the head of the Energy Project Greenpeace Russia, the regulations for the government support are not transparent. Some of the requirements to receive subsidies are hard to meet: for example one of the requirement asks for internal or Russian-made equipment production. Under this requirement, potential producers of wind energy face a problem of finding wind generators and accompanying equipment complies with regulations (Julia Pronina, Energy Project Head Greenpeace Russia, date of meeting: 27.09.2016).

According to the World Wind Resource Assessment Report (2014) Russia has 36 TW summarized wind energy potential (excluding offshore), i.e. more than one third of global (Table 1).

Table 1: *Total worldwide potential for wind (in TW). Source: WWER, 2014*

Region	Power Potential
US	11
EU	37.5
Russia	**36**
Rest of the World	10.4
Total	**94.9**

However, looking at reports on wind energy production in 2010 – 2013Russia slid from 56th position in 2010 to 69th position by the end of 2013 within all 103 countries in terms of wind energy production. Total capacity installed in Russia changed from 15.4 MW in 2010 to 16.8 MW. The growth rate was 8.8% in 2011, while in 2013 there was a 0% growth rate (WWER, 2010-2013).

Based on data from the online web GIS “Renewable energy resources of Russia” (www.gisre.ru, 2017), distribution of installed and planed Wind Power Plants is shown in Figure 2. Some of them existing wind turbines, some are planned; there are wind turbines, combined wind-diesel plants, and solar-wind plants. Today the biggest wind power plant in Russia is located in Kulikovo village, Zelenograd Okrug, Kaliningrad Region and named as Kulikov windfarm (total capacity 5.1MW, acting within grid), Table 2. It was built in 2002 on the basis of an international contract between JSC "Yantarenergo" and the Danish company SEAS Energy Serves AS is installed 21 wind turbines (www.yantarenergo.ru, 2015).

Table 2: *Wind Power Plants in Russia.*

Source: Russian Association of Wind Power Industry, 2016

Wind Power Plant	**Total Capacity, MW**	**Amount and type of wind turbines**
Kaliningrad WPP	5.1	1 × Wind World 4200/600, Denmark 20 × Vestas V27/225, Denmark
Chukotka WPP	2.5	10 × Vetroen, Russia
Kalmyk WPP	2.4	2 × Vensys V62 1.2MW, Germany
Tyupkeldy WPP	2.2	4 × Hanseatische AG, ET 550/41, Germany
Vorkuta WPP	1.5	10 × AWS-250 «Uzhmash», Russia
Murmansk WPP	1.2	1 × Micon, Denmark

According to the Russian Association of Wind Power Industry (2016), the national renewable energy system contains wind power plants listed in Table 2. Various projects of combined solar-disesl powerplants exist, several project of building powerfull wind farms, such as one in Rostov region with a plan to begin constructin by the end of 2017 with 90 MW total capacity. There are around 250 installed wind power plants with capacity from 1 kW to 5 kW within Russian territories that are increasing total wind power production in Russia.

Figure 2: Map of planned and installed wind and solar plants in Russia, 2014.

Source: GISRE, 2017

2.2 Wind Energy Development in the Russian Arctic

Russian northern regions have several small projects of wind turbine installations. There are also a few projects which currently are frozen for the future development (Nord-News, 2016; RusHydro, 2016; Trigeneraciya.ru, 2016). Based on the reviewed sources total capacity in the Russian Arctic currently is around 5 MW (Table 3). One of the first wind farm projects was developed in the Russian Arctic in 1993, was the “Zapolyarnaya” wind farm 30 km away from Vorkuta, Komi Republic, which was unique and first in the world wind farm above the Arctic Circe. This project had to bring 1.5MW of energy to the Vorkuta area, but unfortunately technical characteristics of wind turbines were not suitable for the environmental conditions of the north and the farm was not maintained properly. Currently the wind power plant doesn’t operate due to its unsuitable condition for operation, wind turbines have rusted and have not been maintained for several years (Vorkuta-Online, 2016). Another big project was developed in Anadyr, Chukotka in 2002 with its total capacity of 2.5 MW. Anadyr Wind Power Plant works in the unified energy system of the Anadyr energy center, currently due to the maintenance issues the plant doesn’t work on it full capacity. According to the decree about the approval of the scheme and program for the development of the electric power industry of the Chukotka Autonomous Okrug for 2016-2020, wind energy takes 1 % of total installed capacity of power plants of Chukotka region. Turbines threshold to start producing energy are wind speeds which are over 6 m/s, there was a plan to build a new project with 17 wind turbines to replace Anadyr power plan or replace turbines to Vestas brand which can produce energy starting from 3 m/s wind speed, but both projects are not completed (Timchenko, 2016).

Table 3: *Wind Power Plants in Russian Arctic. Source: Russian Association of Wind Power Industry, 2016.*

Power Plant	**Type**	**Wind Total Capacity, KW**
Cape-Navolok Network, Murmansk region	wind-diesel plant	100
Pyalitsa village Murmansk region	combined solar- wind-diesel plant	95
Tonisoar Island, Murmansk region	private project, wind-diesel plant	5
Paloschele, Arkhangelsk Region	private project, wind-diesel plant	32
Salyuk Mine, Usinsk, Arkhangelsk Region	private project, wind-diesel plant	5
Zapolyarnaya Wind Farm, Komi Republic, Vorkuta	wind plant	1500
Labytnangi, Yamalo-Nenets Autonomous Okrug, Tyumen region	wind plant	250
Zhelaniya Cape, Novaya Zemlya, Arkhangelsk Region	solar – wind plant	8
Bikov cape, Saha Republic	wind plant	40
Tiksi Village, Saha Republic	wind – diesel plant	250

Today the Government of Sakha Republic is actively creating different approaches to develop renewable energy in the region, according to Yulia Pronina, Greenpeace Arctic Program Coordinator. Sakha Republic energy providers found new approaches to develop renewable energy production in the region. The basic idea is a renewable energy production implementation through the financial assistance program from federal budget on fuel costs. Since the fuel cost is high in the North due to the lack of transport accessibility, these regions receive government support to even out a cost per KWh for citizens. The Sakha Republic electric providers use the unspent subsidy for the fuel saved using renewable energy to cover the cost of installing new renewable energy generators.

The Finish Meteorological Institute is taking part as an expert in the field wind power production to help with monitoring and construction of wind turbines in Nenets Autonomous Okrug. The project is carried out with the help of the cross-border cooperation program Kolarctik. For the Nenets Autonomous Okrug combined pilot wind-diesel units were developed for year-round energy supply and more ecological provision of power to villages (Kolarctic program, 2015). Based on several news articles the projects is described as future development in the Amderma community (Abc-energo.com, 2013; Goodnewsfinland.ru, 2015).

The Far North and the Far East regions “Mobile Energy” company, a subsidiary of “RAO ES of the East,” produces up to 2425 KW using wind and wind-diesel installations (Mirchevsky, 2014). This company has 13 wind measuring systems in which weather observations and the collection of the planned installation location data turbines are performing. Installed wind systems by this company are located mostly in the Far North: (1) Nikolskoye village, Kamchatka region, Bering island, two wind turbines at 275 kW; (2) Ust –Kamchatsk village (Kamchatka Region) one turbine -275 kW and three wind turbines of 300 kW; (3) Labytangi city (Yamal Nenets Autonomous Okrug) one turbine - 250 kW these turbine units are adapted for operation in the Arctic conditions, as well as two turbines (450 kw) in the Novikov village (Sakhalin Region). For the Novikov village the projected level of diesel fuel substitution will be 195 tones. Wind monitoring carried out on the coasts of the Russian Arctic (Saskylakh, Tiksi, Nizhneyansk, Chokurdakh, Cherskiy, Lawrence locations) and the Kamchatka Peninsula (Mirchevsky, 2014). Everything listed above shows some interest of wind energy renewable resource use in Russia, it gives a bigger hope of future of energy dependence, or better to highlight independence for remote communities in Russia.

2.3 Wind Energy in Cold Environments

Canada, United States (Alaska), Greenland (Denmark), Iceland, Norway, Sweden, and Russia are countries that partially included in the Arctic region. All of them have an experience in installing wind turbines in cold climates grew substantially (Baring-Gould et al., 2010). The total installed capacity map of the Arctic is presented below in Figure 3, this data was collected over various resources, all wind turbine farms locations were manually checked using high resolution global maps, news article, photos with coordinate tags for map creation.

Canada is Ranked No. 7 in wind capacity worldwide (WWRAR, 2014), current installed capacity is 11,898 MW these digits grow up from a hundred MW in one decade (Canadian Wind Energy Association, 2013). As was mentioned earlier Yukon Territory of northwestern Canada has significant experience in wind turbines installations in low temperatures and severe in-cloud icing environment. Another example of Canadian cold experiences in Northwest Territories is Diavik Wind Farm (9.2 MW), designed to operate in temperatures near -40 C, this wind farm supplies mining operation of Diamond Mines Inc. on the small island which is accessible by land only 8 to 10 weeks of the year (CANWEA, 2013).

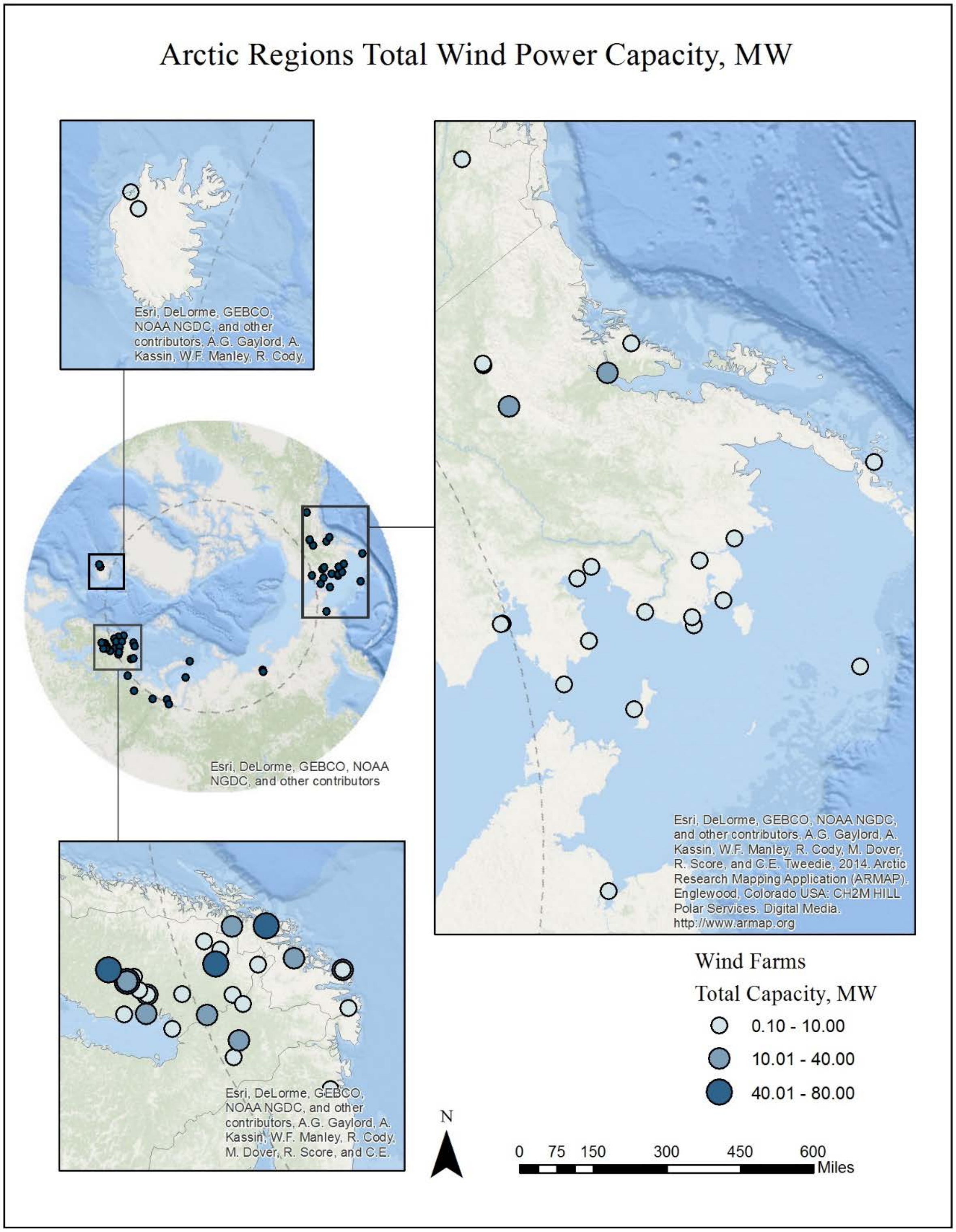


Figure 3: Arctic total installed capacity map of the inland built turbines.

The US’s production of wind power energy is rapidly growing. The State of Alaska which is located in the Arctic has large potential for wind power capacity (Figure 4), especially in coastline area. In Alaska, there are many types of projects that have been accomplished from off-grid, hybrid power plants in remote areas, to large industrial wind farms near Anchorage (17.6 MW), Healy (24.6 MW), and Delta Junction (1 MW).

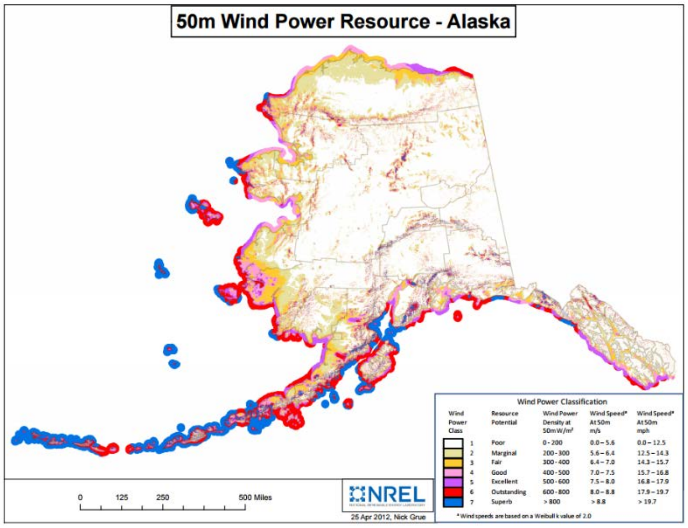


Figure 4: Alaska 50-meter wind power resource map (NREL).

Source: Renewable energy atlas of Alaska (2013)

Recently community scale wind-diesel systems have been developed in rural areas, with Kodiak Electric Association (KEA) installed six 1.5 MW turbines (more than 18% of the community’s electricity) serving as an example. The great combination with Terror Lake hydroelectric plant project allows to decrease use of diesel generators, they can stay off during almost all year (Alaska Energy Authority, Renewable energy atlas of Alaska 2013).

Cold climate regions have great wind energy potential. However, these regions present some challenges of wind turbine installation, because of such difficulties as atmospheric icing and low temperatures that impede wind turbine technology application (Baring-Gould et al, 2010). Many experiments showed that icing of blades and other parts of wind turbine can decrease production of wind energy (Tammelin et al., 2000). Icing of measurement tools can cause an underestimation of the wind speed by approximately 30 % at a wind speed of 10 m/s (Baring-Gould et al., 2010). This creates danger to wind turbine operation, since automatic systems that stop wind blades from over fast rotation will not work due to mistaken wind speed measurements by frozen sensors. Despite these difficulties, there are many projects in cold regions that have utilized wind turbine installations in icy conditions. The way to decrease potential losses of wind energy production is using de- and anti-icing systems that can also provide more of safeties and help to avoid increasing noise from blades covered by ice (Baring-Gould et al., 2012; Ronsten, 2008)

Since methods of wind turbine adaptation for cold climate conditions already have been developed, we can analyze the experience of using them by countries with cold climate. As an example, a study by Maissan (2002) of the wind power development in the Yukon Territory in northwestern Canada. There are eight communities in the region that don’t have connections with hydro-electric power plants and these communities are supplied by diesel plants. Wind assessment of the site showed that if the low temperatures and rime icing effect were possible to overcome, then production of wind energy will be below the cost of diesel plants. This project, used an existing and proven turbine unit and adopted to the severe conditions unit. For first wind turbine Bonus Energy A/S of Denmark 150 kW MARK III unit was chosen for installation. This turbine was put into operation in August 1993. After several years of service some aspects of operating have been taken into account and were solved with 1998 and 1999 being the best production years. In 2000 a second wind turbine (Vestas 660 kW V47 LT II) was installed. This version of turbine was manufactured for unlimited operation down to -30 ° C (Maissan, 2002).

Based on reviewed existing projects of wind energy applications in cold climates, four different groups or scales of development were defined: industrial, enterprise, community scales and research and development (Table 4). Many of these projects are indicated reduce of energy cost by 10-11 cents per kWh while using wind energy resources combined with diesel or hydro plant in the regions (www.kodiakelectric.com)

Table 4: *Types of Wind Energy Production in the Arctic with examples.*

Source: http://www.thewindpower.net/, Tammelin et al., 2000.

Scale	**Location**	**Wind farm name**	**Number of turbines**	**Type of turbine**	**Total power KW**	**Operator**
Industrial	Masøy, Norway	Havoygavlen	16	*Nordex N80/2500* (power 2 500 kW, diameter 80 m), *Siemens* (2 500 kW)	**40000**	Artic Wind AS
Community	Banner Peak Alaska, USA	Nome Newton Peak	2	*EWT Directwind 900/54* (power 900 kW, diameter 54 m)	**1800**	Utility. Wind Turbines : 2.
Enterprise	Diavik Island, Canada	Diavik Mine	4	*Enercon E70/2300* (power 2 300 kW, diameter 71 m)	**9200**	Rio Tinto and Harry Winston Diamond Corp
	Name	***Purpose***		***Location***		***Results***
Research and development	Research project “Wind Energy Production in Cold climates” WECO (JOR3-CT95-0014)	Investigation of wind turbines under cold climate operation. In-cloud icing, icing of WTs and icing effects on loads and power production		Several test sites at various locations in Europe		91 published papers

Since 2002 the International Energy Agency has begun the Wind Task 19 Wind Energy in Cold Climates project. This project proposes to provide information on wind turbine development in cold environment based on studies and experience of projects in cold environmental conditions. The use of wind turbine solutions for cold conditions opened possibilities to compete with traditional wind energy projects. Today, the total installed wind capacity in cold climate is about 127 GW (2016) located in Scandinavia, North America, Europe, and Asia (IEA Wind Task 19, 2016) there are not only arctic regions, but also mountains cold climate areas. Task 19 Wind Energy in Cold Climates in 2011 developed a report that includes recommendations and best practices.

One of the recommendations is performing site assessment of wind turbines installation area that should include at least one year of weather measurements, including ice measurements. Data on icing can provide opportunities to estimate capacity loses and associated financial losses at the site (Baring-Gould et al., 2012; Ronsten, 2008). Icing measurements are not included in traditional meteorological observations, and this is where site assessment faces challenges. Icing measurements can be measured directly by using detectors or estimated indirectly using data on dew point detection, or two or three anemometers (heated and unheated), where a difference in measurements between them will show existing icing. Aviation models for ice estimation already have been modified for wind turbines but still have limitations (Ronsten, 2008)

There are several studies that estimated wind farm production losses due to icing (e.g., Jasinski, Noe, Selig & Bragg, 1998, Hellstrom 2013, Homola, Wallenius, Makkonen, Nicklasson & Sundsbø, 2010; Malmsten, 2011). All loss estimates lie between 5 to 27 % of total production. Therefore, icing is very important to consider while site selecting for wind turbine installation in cold climates. As a practical example, the Finnish Meteorological Institute and VTT Technical Research Centre of Finland produced icing atlas, including icing losses (hourly). The ice growth rate was calculated based on temperature, wind speed, cloud liquid water content and number concentration of the cloud droplets (was chosen to be constant 100 cm^{-3}). The ice melt was assumed to occur when temperature was higher than + 0.5 degree during 6 hours (two time steps).

The meteorological model AROMA was used for ice prediction model. (Tammelin et al., 2011). This map is an example of indirect ice loss prediction, with the use of icing map wind energy industry can rely on it for future development and can predict losses on specific site, plan budget or select different site for wind turbine placement.

2.4 Assessment of Wind Resources in Russia

Wind power assessment in Russia at the national level has been carried out mainly by two research groups: the Laboratory of Renewable Energy Sources (LRES), Geography Department, Lomonosov Moscow State University (MSU) and the Russian Danish Institute for Energy Efficiency. LRES's research included collection and evaluation of all types of renewable energy resources, including wind energy. The GIS with database includes 1 degree resolution maps of the average wind speed based on NASA SEE (Space Environments and Effects Program) to the height of 10 and 50 meters (Figure 5; Rafikova, Kiseleva, Nefedova & Frid, 2014).

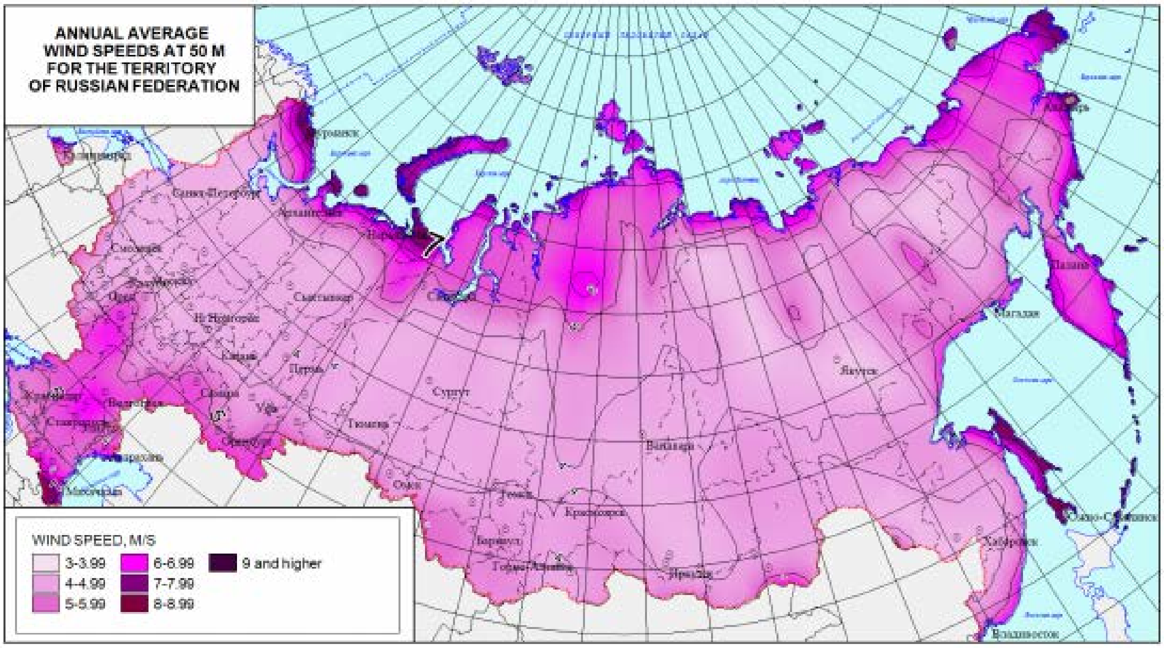


Figure 5: The average wind speed according NASA SEE to the height of 50 meters in Russia. Source: (Rafikova et al., 2014).

For a southern Russia site in Karachay-Cherkessia region (Figure 6) this research represented calculations of electric power output by standard wind installations (technical potential of renewable energy; Rafikova et al., 2014). In the series of maps that were produced by the Laboratory of Renewable Energy Sources, Lomonosov Moscow State University the evaluation of the wind energy potential of the territory used the following input data: (1) the series of measurements of wind speed at two heights (it is desirable that one on of them was equal to the height of the proposed wind wheel axis), (2) the series of measurements of wind direction, (3) the mean temperature for the period, (4) the average for the period of atmospheric pressure; (5) landscape type which determines the surface roughness; and (6) the terrain around the site of the proposed construction of renewable energy (Rafikova et al., 2014).

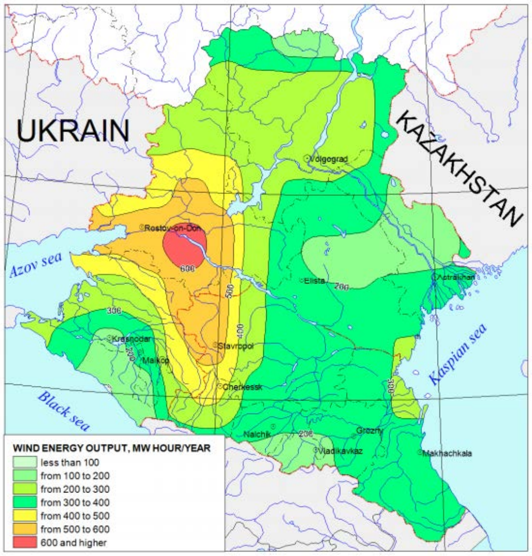
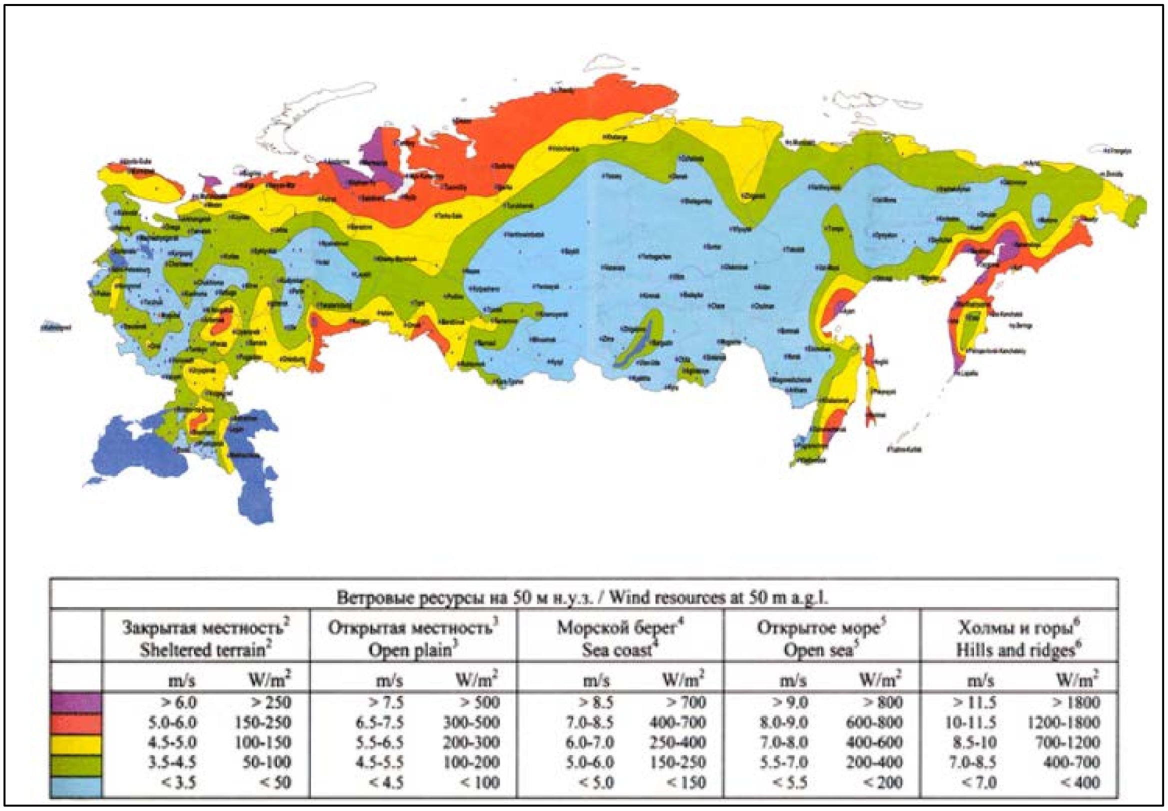


Figure 6: Distribution of wind energy output of VESTAS V44-50 wind turbine for the South of Russia. Source: Rafikova et al., 2014

Another Russian project carried out by the Russian Danish Institute for Energy Efficiency is Wind Atlas of Russia (Starkov et al., 2000). This atlas was created based on the model of the European Wind Atlas technology developed by the Riso National Laboratory in Denmark (Troen & Petersen, 1989). In this Atlas, the following data were used: (1) wind distribution statistics from 8-16 directions from over 10-15 years from 332 Russian meteorological stations; (2) information on the location of the stations the height and type of anemometers; (3) derived wind digital maps using data from weather stations with the radius 5-10 km from each other, maps had a sufficiently large scale (150 000 and 1 100 000) in a radius of weather station (Starkov et al., 2000).

The input data for each weather station were processed using the software package Wind Atlas Analysis and Application Program (WAsP) to eliminate local effects (orography roughness of the terrain obstacles as buildings etc.) that affect the strength and direction of wind. Due to vastness of Russia and weaknesses of meteorological network data for European territory can be considered reliable enough, but in opposite the Siberia, North Russian territories and Far East represent are not reliable data, due to long distance between met stations (Starkov et al., 2000). For different wind zones using the Danish Association Wind Industry online calculator (DAWI, 2003) was calculated the coefficient of installed utilization capacity, where a wind turbine Vestas V80 2000kW with a tower 80 m was used. (Figure 7. Table under map).



Ветровые ресурсы на 50 м н.у.з. / Wind resources at 50 m a.g.l.

	Закрытая местность[2] Sheltered terrain[2]		Открытая местность[3] Open plain[3]		Морской берег[4] Sea coast[4]		Открытое море[5] Open sea[5]		Холмы и горы[6] Hills and ridges[6]	
	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
🟪	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
🟥	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10-11.5	1200-1800
🟨	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10	700-1200
🟩	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
🟦	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 7: Wind resources at 50 meters above the ground, Russia

Source: Starkov et al., 2000.

Based on this research we can see that the assessment of wind energy in Russia was carried by couple of projects. But no articles or literature were found about the sites for wind turbine installation and multi criteria assessment in the Russian Arctic. One of the few studies of wind energy assessment in Russian Arctic region is solely devoted to small-scale renewable energy development in remote settlements (Minin, 2012). Minin's (2012) research was based mostly on economic aspects of wind energy implementations, but gave valuable ideas of how to better combine renewable energy with already formed energy system. The study area was the Kola Peninsula in the Russian Arctic. This research showed that wind energy application can solve the problem of lack of stable electricity supply in remote areas. Minin (2012) showed that combined wind-diesel plants are a good remedy from total dependency on fossil fuel. The author also demonstrated a decrease in carbon dioxide production by using combined wind-diesel power plant. A combined wind-diesel energy system in Kharlow Island, Murmansk Region evidenced a reduction in carbon dioxide emission by 51%, if diesel power plant will produce 73.5 thousand kilowatts per hour - 49% of total production and wind power plant will produce 76.5 (51%), the research showed environmental benefits (Minin, 2012).

In the article by Ivanova, Nogovitsyn, Tuguzova, Sheina and Sergeeva (2013) the authors evaluated the effectiveness of different types of wind turbines in Verkhoyansk city, Sakha Republic, Russia. This town is located in the Russian Arctic. Estimation of wind resources was based on the analyses of the current situation of electricity supply of remote areas consumers, and wind resource endowments. Calculation of possible electricity production was completed for different wind turbines by German companies Nordwind, Turbowinds and Sudwind (150,270,400 and 850 kW) As a result, most coefficient of installed capacity of 7.3% showed Sudwind wind turbine (270 kW), also as the analysis showed that the full coverage of electricity needs must be 200 installations, the payback period for such amount of wind turbines could be 189.7 years, based on the calculations in the article. So, reducing the amount of power of plant decreases the time for payback period, such as ten wind turbines may recoup in 26 years (Ivanova et al., 2013).

Wind energy can be used in many different parts of Russia, Table 5 shows the distribution of wind energy resources in economic regions of European, Siberian and Far East parts of Russia based on VetrEnergo 2001 report (Dmitriev, 2001). The distribution shows how much potential for wind energy exploitation is available in northern regions.

Table 5: *Distribution of wind energy resources in Russia. Left - European part, right- Siberian and Far East. Source: Dmitriev, 2001.*

European part			***Siberia and Far East***		
Economical region	**Gross wind energy resources, TWh/year**	**Technical resources, TWh/year**	**Economical region**	**Gross wind energy resources, TWh/year**	**Technical resources, TWh/year**
Northern	11040	860	West Siberia	12880	1000
North-West	1280	100	East Siberia	13520	1050
Central	2560	200	Far East	24000	1860
Volgo-Viatskij	2080	160			
Central-Chernozem	1040	80			
Volga	4160	325			
North Caucasus	2560	200			
Ural	4880	383			
Total	**29600**	**2308**	**Total**	**50400**	**3910**

2.5 Worldwide Assessment of Wind Resources that Includes Arctic Russia

The key worldwide wind energy assessment was carried out by The Global Wind Atlas project of The Technical University of Denmark (DTU), Department of Wind Energy (Figure 8). This project is coordinated by International Renewable Energy Agency (IRENA). The Global Wind Atlas (GWA) was launched in fall of 2015, this is a new and the most detailed wind dataset at present. The GWA provided wind speed and power maps at three different altitudes (50, 100, 200 meters) with 1 km resolution, one of the key aspects of The GWA project was aggregating and downscaling of global open datasets that provide atmosphere and surface conditions. There are following global datasets that were used for atlas creation process: Global atmospheric reanalysis datasets: (1) Climate Forecasting System Reanalysis (CFSR), Climate Four Dimensional Data Assimilation (CFDDA), Modern Era-Retrospective Analysis for Research and Applications (MERRA), European Center for Medium Range Weather Forecast (ECMWF) Reanalysis (ERA-Interim); (2) Digital elevation models from Viewfinder Paroramas (150 m resolution, all areas above 60° N latitude is combining of the best available alternative sources). Roughness length produced by using two land cover global datasets GlobCover 2009 (300 m) by ESA and the Université Catholique de Louvain (UCL) and 0.5 km MODIS-based Global Land Cover Climatology above 60° (to avoid fill no data values of GlobCover 2009; Badger, Badger, Kelly & Larsén, 2015).

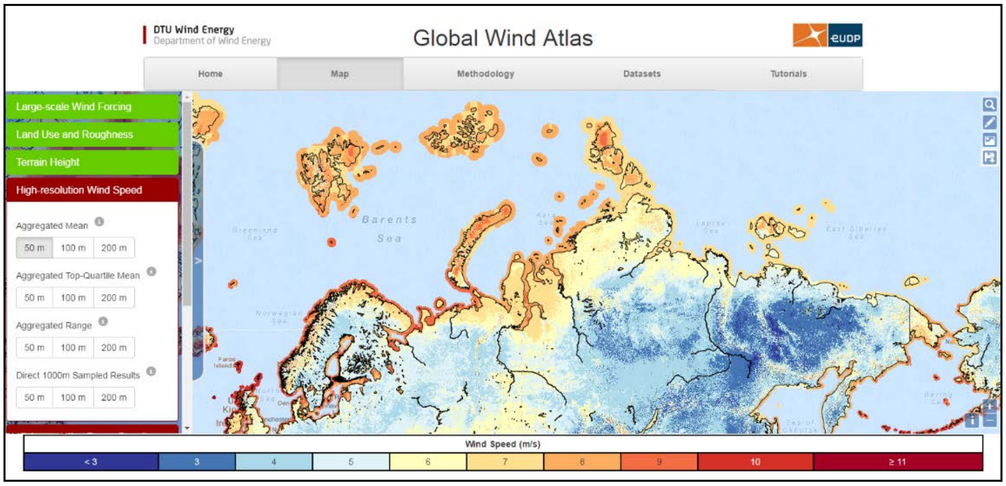


Figure 8: Aggregated mean wind speed at 50 m above the ground, high-resolution wind speed dataset of Global Wind Atlas. Source: www.globalwindatlas.com

Authors of this project used downscaling modeling based on the fact that at a lower resolution overall assessment of the average wind energy density becomes underestimated compare with an assessment of the same territory based on high resolution data (Badger, Frank, Hahmann, & Giebel, 2014). Methodology of the GWA was based on a generalization of the wind climatology obtained from the mesoscale or reanalysis of global modeling. There are two methods that DTU used, one of the methods is the KAMM/WAsP by Riso National Laboratory (Frank, Rathmann, Mortensen & Landberg, 2001) and another method is Weather Research and Forecasting.

The Global Wind Atlas can be accessed along with 3TIER's Global Wind Dataset trough online GIS interfaced Global Atlas for Renewable Energy by International

Renewable Energy Agency (IRENA). This atlas provides maps of wind, solar, hydro, bioenergy, marine and geothermal renewable energy across the world. GIS interface allows visualizing datasets of renewable energy resources, user can overlay additional datasets to produce maps for assessing the technical and economic potential of renewable energy. As an additional information, atlas provides population density, topography, local infrastructure, land use and protected areas maps. Russian Arctic territories are covered by two mentioned above datasets.

3TIER's Global Wind Dataset (Figure 9) is a project carried by Vaisala, Finish Company of manufacturing environmental and industrial measurement instruments. The dataset provides 5km resolution worldwide data of average of 10 years annual wind speed at 80 meters above the ground and power potential; it was produced by using numerical weather prediction (NWP) model (Vaisala 3TIER Services Global Wind Dataset, 2005).

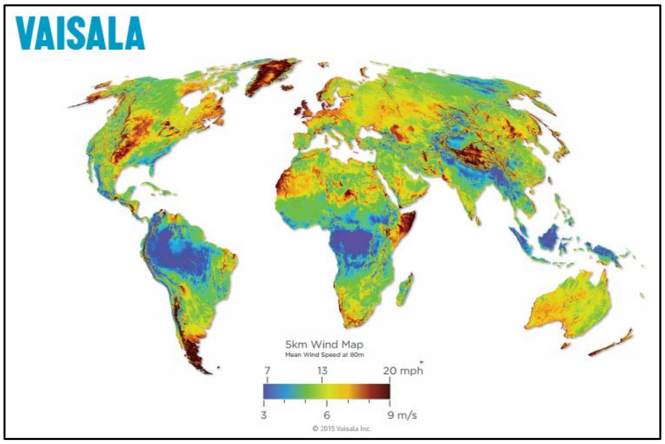


Figure 9: 3TIER's Global Wind Map. Source: www.3tier.com

2.6 Multi-Criteria Suitability Models for Wind Turbine Industry

The suitability modeling algorithms based on finding suitable location for installation a new object can be applied by overlaying multiply variables of different factors of object site suitability (Sugumaran & DeGroote, 2011). On the subject of wind turbine suitability models for placement the criteria of decision making has to be chosen (Watson & Hudson, 2015). A number of studies represented suitability models approach for wind farm suitability site selection on a different scales along with wind resource assessment (Latinopoulos & Kechagia, 2015; Rodman & Meentemeyer, 2006; Watson & Hudson 2015 and others). Many of them based on multi-criteria evaluation using GIS assistance for developing geospatial models of suitability. Another method that was adopted for wind turbine site suitability is ecological niche modeling, where known existing wind can be used to search for suitability environmental conditions and further multi criteria assessment can be based on those conditions (Petrov & Wessling, 2015). It is unlikely this method could be applied in the Russian Arctic due to the lack of known exact locations of turbines and total number of installed wind turbines there is very small. The most suitable method for the study area in turns of data availability of the research will be multi criteria decision analysis, which will be supported by GIS SSDS (Spatial Support Decision System).

Since the mid-1980's GIS applications for site selection models for wind turbines have begun to emerge. These models take into consideration environmental, physic and human impact characteristics for geographical analysis of wind turbine placement. These characteristics allow application of rule-based GIS models that provide methods to weight or evaluate different criteria for study areas. Every factor criteria requires its weight to fit into multi-criteria decision making system. The Analytic Hierarchy Process (AHP) is mostly used for the weighting purposes (Al-Yahyai, Charabi, Gastli & Al-Badi, 2012; Uyan, 2013). This process requires pairwise comparison of the input factor criteria based on expert judgments, in the way of evaluating what criteria is more import over another (Wind & Saaty, 1980), where for example average wind speed can have the highest importance because of the availability of sufficient wind resources for the particular study area (e.g. Rodman & Meentemeyer, 2015).

For geospatial modeling, it is very important to know which landscape characteristics within study area have to be implemented to have the most efficient results. Many factors (Table 6) effect on decision making of wind turbine suitable sites such as visualization, slope, altitude, and distance from road, urban, historical or recreational areas and many others (Latinopoulos & Kechagia 2015; Rodman & Meetemeyer 2005; Watson & Hudson 2015 and others)

Table 6: *Site selection criteria parameters. Source: Shaheen & Khan, 2016*

Name of factor	**Description**
Wind speed	Speed of wind in different directions
Elevation	Elevation from surface of earth
Slope	Slope of surface at anomalous points
Highways	Highways on or near the site
Railways	Railways on or near the site
Built-ups	Buildings on or near the site
Forest zone	Forest on or near the site
Scenic area	Scenic area on or near the site

There is a large number of papers that are related to multi-criteria suitability site assessment for wind energy (e.g., Acker, Williams, Duque, Brummels & Buechler, 2007; Aydin et al., 2010; Al-Yahyaia et al. 2012; Atici, Simsek, Ulucan, & Tosun,2015; Baban & Parry, 2001; Bennui, Rattanamanee, Puetpaiboon, Phukpattaranont & Chetpattananondh, 2007; Bravo, Casals & Pascua, 2007; Gass, Schmidt, Straussand & Schmid, 2013; Gigović, Pamučar, Božanić & Ljubojević, 2017; Gorsevski et al., 2013; Grassi, Chokani & Abhari, 2012; Haaren & Fthenakis 2011; Hansen, 2005; Krewitt & Nitsch, 2003; Lejeune, Gheysen, Ducenne, & Rondeux, 2010; Latinopoulos & Kechagia 2015; Nguyen, 2007; Noorollahi, Yousefi & Mohammadi, 2016; Ouammi, Ghigliotti, Robba, Mimet & Sacile, 2012; Phuangpornpitak & Tia, 2011; Ramachandraa & Shruthib, 2005, Rodman & Meentemeyer, 2006; Ramírez-Rosadoa et al., 2008; Tegou, Polatidis & Haralambopoulos, 2010; Sliz-Szkliniarza & Vogta 2011; Voivontas, Assimacopoulos, Mourelatos & Corominas, 1998; Yue & Yang, 2009; Watson & Hudson, 2015; Zhou, Wu & Liu, 2011). All these studies divide criteria into constraints and factors. The constraints reflect all unsuitable locations for wind turbine placement due to simple binary logics, i.e. the areas where construction is impossible because of the roads, urban areas or water bodies and the areas where construction is not recommended for the reason of environmental protection or cost benefits. Factor criteria include those environmental characteristics which can be classified across a range between minimum less suitable and maximum more suitable values.

Kidner, Sparkes and Dorey (1999) determined such parameters as different buffer zones for city centroids, airport or military danger zones, urban centers, built-up areas, village and small town centers, National Parks, motorways, roads and rivers. Voivontas et al. (1998) implemented GIS for the RES-DSS (Renewable Energy Sources Decision Support System), theoretical and then technological potential were defined. Baban and Parry (2001) developed GIS-assisted wind farm location criteria for locating wind farms. Factors were divided for four groups depending on their importance, pairwise classification was applied to these groups. Site selection criteria parameters have become more detailed in physical, environmental, and economic aspects (Table 7).

Table 7: *Detailed site selection parameters*. *Source: Shaheen & Khan 2016*

Name of factor	**Description**
Type of land	Type of land
Type of built-up	Types of built ups like school, mosques etc.
Land ownership	Whether Government or private
Type of surface	Whether rocky or sandy etc.
Geological structure of surface	Whether plain geology or mineral geology
Electric line cost	Cost of electric transmission line
Electric integration cost	Cost of integration system
Land cost	Land cost
Access road cost	Cost of road to access site
Visual impact	Esthetic impact to landscape
Safety distances from urban areas	Safe distance of wind turbine from urban area
Noise	Mechanical noise of operative turbine
Electromagnetic interference	Resistive EMI for wind turbine
Altitude	Height from surface of earth
Bird/habitats routes	Deaths of habitats

Some studies for example, considered type of surface or electric line integration cost (Shaheen & Khan, 2016), ecological aspect also wildly regarded by using such factors as distance from wildlife designations, presence of wetlands, water bodies presence of endangered plant species that represent a move to more complex analyses and more in-depth approach to the selection criteria. In the study of southern England by Watson and Hudson (2015) twelve factors variables that were found by literature review were reduced to seven, where some factors were combined in ones and some were withdrawn from examination because of low importance in site consideration. All seven variables were divided into four categories: technical, visual, ecological and economic where every factor gained a weight where one of the method was a pairwise comparison (Table 8a and 8b).

Table 8a: *Examples of factor variables and their weighting.*

Source: Watson & Hudson, 2015

Category	**Factor**	**Weighting**
Technical	Wind Speed	0.555
Visual	Distance from historically important areas	0.078
	Distance from residential areas	0.13
Ecological	Distance from wildlife designations	0.13
Economic	Distance from transport links	0.046
	Distance from network connection	0.062

Table 8b: *Examples of factor variables and their weighting.*

Source: Gigovic et al., 2017

Clusters/Criteria	**Weight coefficient**	**Rank**
Environmental	0.392	1
En1 – Wind speed	0.129	1
En2 – Land use	0.097	4
En3 – Distance from urban areas	0.095	5
En4 – Distance from protected areas	0.071	10
Economic	0.327	2
Ec1 – Distance from power lines	0.115	2
Ec2 – Slope of the land	0.076	9
Ec3 – Distance from roads	0.081	8
Ec4 – Aspect	0.056	11
Social	0.281	3
Soc1 – Distance from telecommunication infrastructure	0.09	6
Soc2 – Distance from tourist facilities	0.084	7
Soc3 – Population density	0.106	3

Noorollahi et al. 2016, used 13 constraints which were divided into three categories environmental, techno-economic and physiographic (DEM, slope), for factor variables classifying method was applied, classified layers were overlain using WIO (Weighted Index Overlay) method. Gigovic et al. in 2016 used combined GIS MCDA model, the fuzzy multi-criteria technique of Decision Making Trial and Evaluation Laboratory DEMATEL, ANP (Analytic Network Process) and Multi-Attributive Border Approximation Area Comparison (MABAC) model to apply for suitability assessment of wind turbine in Vojvodina, Serbia. Authors used 11 constraints and 11 evaluation (factor) criteria, which were grouped in economic, social, and environmental clusters.

Additional criteria, such as agricultural lands, mining areas, fault lines, sand dunes, tourist sites, population density, and military facilities were used for different studies (Atici et al., 2015; Noorollahi et al., 2016; Gigovic et al., 2017 and others). Thus, every particular study region requires a function of data availability. Both constraints and factor criteria are chosen based on unique characteristics of study area for the current research. The main and most common constraints are wind speed, elevation, slope, forests, woodlands, historical sites, protected areas, water bodies, roads, railways, urban areas, transmission lines, airports, radio and TV stations.

Table 9 displays all summarized contains criteria from different studies. The parameters vary across studies, but some repetitions appear, in some papers, listed criteria are considered as constraints without any chosen buffers. Along with parameters, this table shows the total amount of studies where every constraint criteria was used. The example with urban areas constraint shows that 97% of studies included this criteria as completely unsuitable areas. The distances of buffer zones vary from one study to another. The reason for this variation is the environmental characteristics of study area, sometimes some study areas have smaller buffers around roads or settlements due to high populated territories, where there is a lack of wide spread unsettled territories (Watson & Hudson, 2015), distances also depend on government restrictions of the country (Provincial Government of the Western Cape, 2006).

Table 9: *Suitability parameters for the most common criteria used in wind site assessment studies from 1998 to 2017.*

Reference	**Study Area**	**Wind Speed/ Power**	**Elevation**	**Slope**	**Forests, woodlands**	**Historical sites/ Protected areas**	**Water bodies**	**Roads**	**Urban Areas**	**Transmission Lines**	**Airports**	**Radio and TV stations**
Voivontas et al 1998	Crete, Greece	>6 m/s	<1000 m	<60%		>2000 m			>1000 m		>2500 m	
Baban and Parry 2001	UK	>5 m/s		<10%	>500 m	>1000m	>400 m	>100 m	>2000 m	>2000 m		
Krewitt and Nitsch 2003	Germany	>4 m/s			>500 m	>500 m			500 m		500 m	
Ramachandraa and Shruthib 2005	Karataka, India	< 4.5 m/s										
Rodman and Meentemeyer 2006	Northern California	>3 m/s			Constraint				Constraint			
Hansen 2005	Denmark	>250 W/m2			> 300 m		>150 m	>150 m	>500 m	>200 m	>5000 m	>1000 m
Provincial Government of the Western Cape, 2006	Western Cape			<40%		>2000 m	>500 m	>500 m	>800 m	>250 m	>2500 m	> 250 -500 m
Acker et al 2007	Arizons				Constraint	Constraint	Constraint	Constraint	Constraint		>3000 m	
Bennui et al 2007	Thailand		<200 m	<15%		>2000 m	>200 m	>500 m	>2500 m		>3000 m	
Nguyen 2007	Vietnam				>500 m	>500 m	>40 m	> 100 m	>2000 m	< 16000 m	>2500 m	
Bravo et al. 2007	Spain			<10 %	Constraint	Constraint	Constraint	Constraint	Constraint			
Ramírez-Rosadoa et al. 2008	La Rioja, Spain				>500 m	>500 m			>500 m		Constraint	
Lejeune and Feltz 2008	Southern Belgium	>5 m/s			>200 m	>2000 m		>40 m	>350 m	>150	>5000 m	>600 m
Yue and Yang 2009	Taiwan				>250 m	>250 m		Constraint	>500 m			
Aydin et al. 2010	Western Turkey					>2500 m	>2500 m		>2000 m		>2500m	
Tegou et al. 2010	Northeast of Greece	>4 m/s		<30%	Constraint	>500m		>100-<10000 m	>1000 m	>100-<2000 m		
Haaren and Fthenakis 2011	New York			<10%			>3000 m	>500 m	>1000-2000			
Sliz-Szkliniarza and Vogta 2011	Poland				>200 m	>500 m	>200-250 m	>100 m	>500 m	>200 m	>3000 m	
Ouammi et al. 2011	Italy			<10%		Constraint		<1500 m	>1000 m	< 1000 m	>2500 m	
Phuangpornpitak and Tia 2011	Thailand				>100 m		>200 m	>300 m	>500 m			
Zhou et al. 2011	China	>4 m/s <25m/s		<30%	>500 m		>400 m	>500 m	>500 m			
Al-Yahyaia et al. 2012	Oman			<10%		>2000m		>500 -<10000 m	>2000 m			
Grassi et al. 2012	Iowa			<20%		>300 m	>240 m	>60 – 240 m	>240 m		>2000m	
Gass et al. 2013	Austria		<2000 m	<15%		>200 m		>150 m	>1000 m		constraint	
Gorsevski et al. 2013	Northern Ohio	>5.6 m/s				>100m		>1000-<10000 m	>100 m	>1000 < 20000 m	>8000m	
Atici et al. 2015	Turkey		<1500 m	<10%		>2000m	>3000m	>500 m	>2000 m	>250 m	>5000 m	>600 m
Latinopoulos and Kechagia 2015	Greece	>4.5 m/s		<25%		>1000 m		>150 m	>500-2000 m		>3000 m	
Watson and Hudson 2015	UK			<10%		>100m			>500 m			
Noorllahi et al. 2016	Western Iran		<2000 m	<15%		>2000 m	>500 - 1000	>500m	>500-2000 m	>250m	>15000m	
Gigovic et al 2017	Vojvodina, Serbia	<3.5		<7%		>2000m	Constraint	>200m	>500 m	>200m	>3000m	>250 m
	% of total	**40**	**20**	**57**	**47**	**80**	**53**	**77**	**97**	**37**	**63**	**17**

Looking at the table we can see wind speeds threshold varies from 3.5 m/s to 6 m/s, where in Zhou et al. (2011) also maximum of 25 m/s thresholds was used. Wind speed minimum is changing regards to technological progress and becoming lower. Elevation height constraint is used in 20% of studies and suitable height is less than 1000 to 2000 meters, Bennui et al. (2007) used 200 meters' threshold as a minimum height to place wind turbine. Percent slope criteria parameter varies form lees then 10 to 60 % slope as a suitable for wind turbine construction due to cost-benefit and technological limits. Road criteria in some studies is used as a constraint of two different factors, one and mostly utilized in studies as a road by itself and distance from the road as a completely unsuitable area. The distance or buffer from the road is used for safety reasons due to flicker effect (Baban & Parry, 2001). This is described as an effect caused by the whirling blades of wind turbine which creates moving shadow, the movement can lead to driver distraction (Minnesota Department of Health [MDH], 2009). The second factor for the road constraint is cost benefit, several authors use maximum of 10000 m distance threshold to reduce economical loses on building wind turbines out of chosen buffer (Al-Yahyaia et al. 2012; Gorsevski et al., 2013; Tegou et al., 2010). The same approach of cost effectiveness is applied for transmission lines, the maximum distances from the lines variate from 2000 to 20000 meters (Gorsevski et al., 2013; Nguyen, 2007; Tegou et al., 2010). Urban area criteria is used in 97% of studies, the most important reasons are noise and visual burdens along with flicker effect, which can lead to human health effects (MDH, 2009). Distances from urban area depend on sizes of communities (Haaren & Fthenakis, 2011) and government restrictions, various from 240 m up to 2500 meters. Important to avoid wind constructions around airport areas where wind turbine can act as an obstacle for the airplane pass and as a radar interference, threshold varies from 200 to 15000 m (Sliz-Szkliniarza & Vogta, 2011; Noorollahi et al., 2016). Turbines also can influence an interference to telecommunication towers, 17 percent of studies used this as a constraint criteria with distances from 20 to 1000 m away from TV and radio towers.

The utilization of possible criteria depends on data availability for the Russian Arctic. The most common criteria available for the study area from worldwide datasets are weather and topographical data. The digital resources of urban, water or protected areas also can be acquired for the project. Good quality vector data of all airports or transmission lines are not available for the free access for this study. Considering special conditions in the Arctic, new criteria will be added for the multi-criteria decision support system. The criteria parameters will be based on common use or reasonable application for study area. The example of common use is a slope criterion with its < 10-degree suitability cutoff that is commonly used in studies. The most common distance from protected areas is 2,000 meters used in many studies, but for this research a 500-meter buffer zone will be chosen due to wide territories of national parks, with the idea that a smaller protected area represents a more fragile the ecosystem.

2.7 Literature Review Summary

Remote communities in the northern regions need to have continuous and uninterrupted electrification due to the lack and high cost of fossil fuel supplies. Renewable wind energy resources can provide stability in electrification, cost reduction, and also sustainable development for these regions. A potential decrease in carbon dioxide pollution is one of the important aspects of wind power production applications. Based on existing wind speed assessments, the territory of the Russian Arctic has considerable potential for wind energy industry implementation. Although some steps are taken in this direction, the wind energy sector is developing very slowly in comparison with another countries in the Arctic.

The reviewed studies showed that the wind power multi-criteria assessment in the Russian Arctic has not been yet undertaken. There are several global wind power potential assessments that include the Russian Arctic. However, no studies have developed multi-criteria assessment that are adjusted to cold climate condition, where such environmental characteristics as permafrost and icing exist or occur. There is also nothing exists with accounting for seasonal variations. Most of previous studies present wind speeds or wind power potential annual estimates. The current project will fill existing gaps and provide new enhanced resource characterization methods and new workflow of multi-criteria site wind energy assessment in cold climates.

CHAPTER 3
METHODOLOGY

3.1 Study Area

The study area for this research includes two areas of interests; the primary area of study is Russian Arctic (megascale) and with a more focus, a downscaling study, including Nenets Autonomous Okrug (mesoscale). This focus area was chosen based on such characteristics as energy consumption and population of the region.

3.1.1 Russian Arctic

The definitions of Arctic boundaries vary from source to source. For example the Arctic Council working groups have different definitions that reflect each of their interests. The Arctic Monitoring Assessment Program (AMAP) carries out environmental monitoring, having their arctic boundaries defined by temperature. Conservation of Arctic Flora and Fauna (CAFF) boundary line repeats the tree line with an idea of including the ecosystems that are the focus of CAFF. Emergency Prevention Preparedness and Response (EPPR), and the Arctic Human Development Report (AHDR) has own boundaries based on northern political units, due to socio-economic characteristics (Figure 10). The boundaries that were chosen for further assessment of wind energy in the Russian Arctic (Figure11) are based on the Presidential Decree that defined the composition of the Russian Arctic (Table 10; Presidential Decree of 05.02.2014, № 296).

Figure 10: Arctic boundaries of the Arctic Council

Table 10: *Arctic zone land territories of the Russian Federation.*

Source: Presidential Decree of 05.02.2014, № 296

Arctic Region	Districts included in Arctic
Murmansk region	
Nenets Autonomous Okrug	
Chukotka Autonomous Okrug	
Yamalo-Nenets Autonomous Okrug	
Republic of Komi	*Vorkuta*
Republic of Sakha (Yakutia)	*Allaikhovsky, Anabarsky National (Dolgan-Evenki, Bulunsky, Nizhnekolymsky, Ust -Yana uluses*
Krasnoyarsk Kray	*Taimyr Dolgan-Nenets Municipal District Turukhansk district: Norilsk city*
Arkhangelsk Oblast	cities: Arkhangelsk, Novodvinsk, Severodvinsk: Municipal Districts: Novaya Zemlya, Mezensky, Onega, Primorsky

Figure 11: Russian Arctic Administrative boundaries

In addition, the Arctic Zone of the Russian Federation includes islands located in the Arctic Ocean as defined in the Presidium Decree of the USSR Central Executive Committee (Council of People's Commissars of the USSR, DECREE of 20 May 1926). In declaration of the territory of the USSR the area of land and the island, located in the Arctic Ocean is defined as a range between the meridian 32°04’35’’ east longitude from Greenwich, passing through the eastern side of Vaida-mouth through triangulation mark on the headland Kekurskom and the meridian of 168 49’ 30’’ west longitude from Greenwich, passing through the middle of the strait that separates the island Ratmanova and Kruzenshtern group Diomede island in the Bering

Strait. The chosen boundaries will be useful from economic perspective where results of this study can be applied for the policy making purposes.

3.1.2 Nenets Autonomous Okrug (downscaling)

Energy consumption and population data were used as criteria to select a region of study with the highest indicators of energy consumption per capita to provide downscaled model of wind energy assessment. Both datasets for year 2015 were found on the Russian Federation Federal State Statistics Service web site (www.gks.ru). The data were formatted and imported to a GIS database. The energy consumption data had very significant outlier that was removed based on logical interpretation. The results can be seen on Figure 12, which shows the Nenets Region has highest energy consumption per capita.

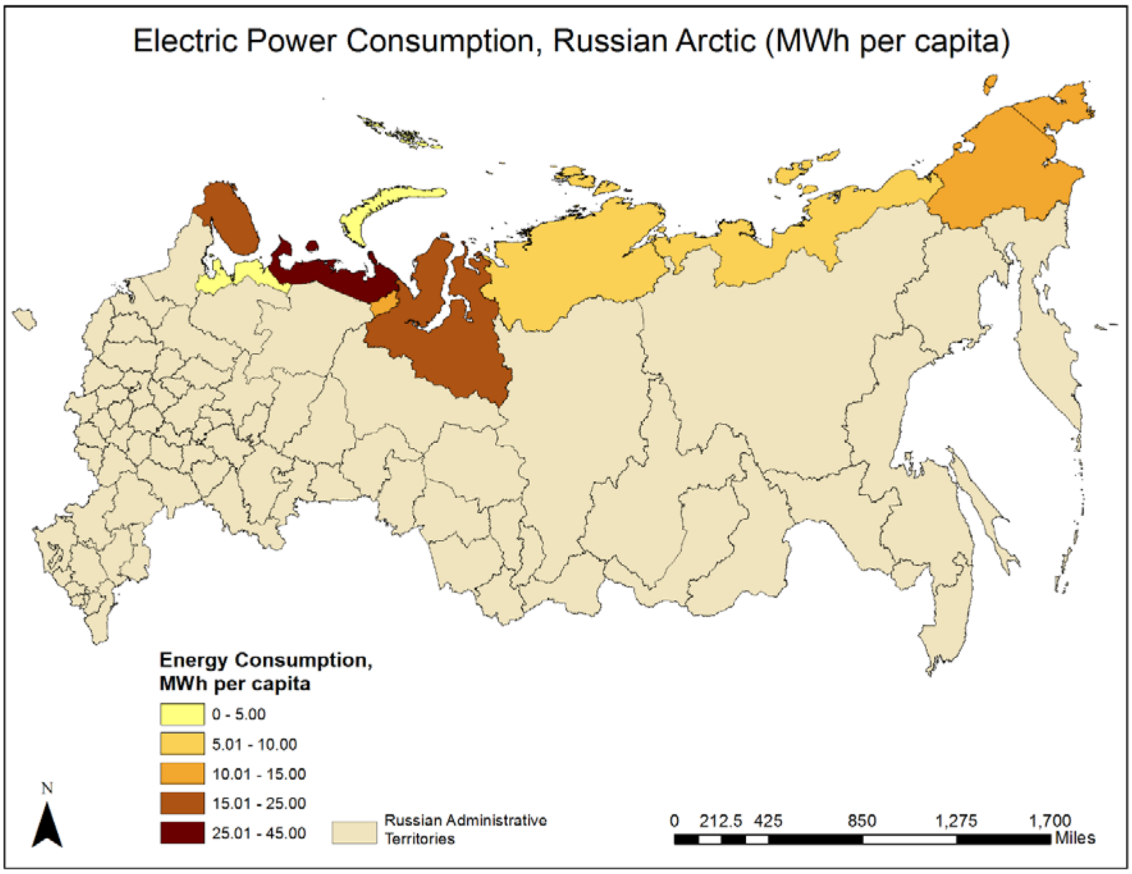


Figure 12: Electric Power Consumption in Russian Arctic Administrative Regions (MWh per capita)

The Nenets Autonomous Okrug (NAO) is a federal subject of the Russian Federation and is included in Arkhangelsk Oblast. Naryan-Mar City which is the administrative center of the region and has a population of 19,000 people. There are about 50 residential communities in Nenets Autonomous Okrug and the most populated are being Iskateley (7200), Krasnoe (1642), Nes'(1,446) and Nelmin Nos (1,008) settlements (Electronic map of the Nenets Autonomous Okrug, 2017). The area of the NAO territory is 17, 6810 sq.km, and it is mostly located within the polar circle in the northern part of the West European Plain. The elevation of the region is mostly represented by flat terrain with two ridges up to 500 meters high. The land is surrounded from the north by the White, Barrens, Pechora and Kara seas. Winds blow from the North in springs and summers, and from the South in winters and falls. Average wind speed is 4-8 m/s with maximum speeds in winter reaching up to 40 m/s. This region has substantial wind resources to consider for an assessment (Krivtsov, 2001).

3.1.3 Russian Arctic Environmental and Wind Resource Characterization

The Arctic Zone of Russia encompasses tundra biome which mostly covers the area, arctic deserts along the coast, forest tundra on the south, and taiga natural zone predominantly on the north-western side (Kola Peninsula). The topography of the Arctic zone is diverse varying from wide planes as the East European and West Siberian Plains which are divided by the Ural Mountains to highlands up to 1,194 m on the East-North side, on the Chukotka Peninsula (Shahgedanova, 2002).

The Arctic Zone temperature amplitudes vary from west to the east with removal from the Atlantic Ocean, -8-(-12) °C to -40 °C and lower from the in January, and 12-(-16) °C to 4 °C or lower for July in average (Figure 13; Krivtsov, 2001).

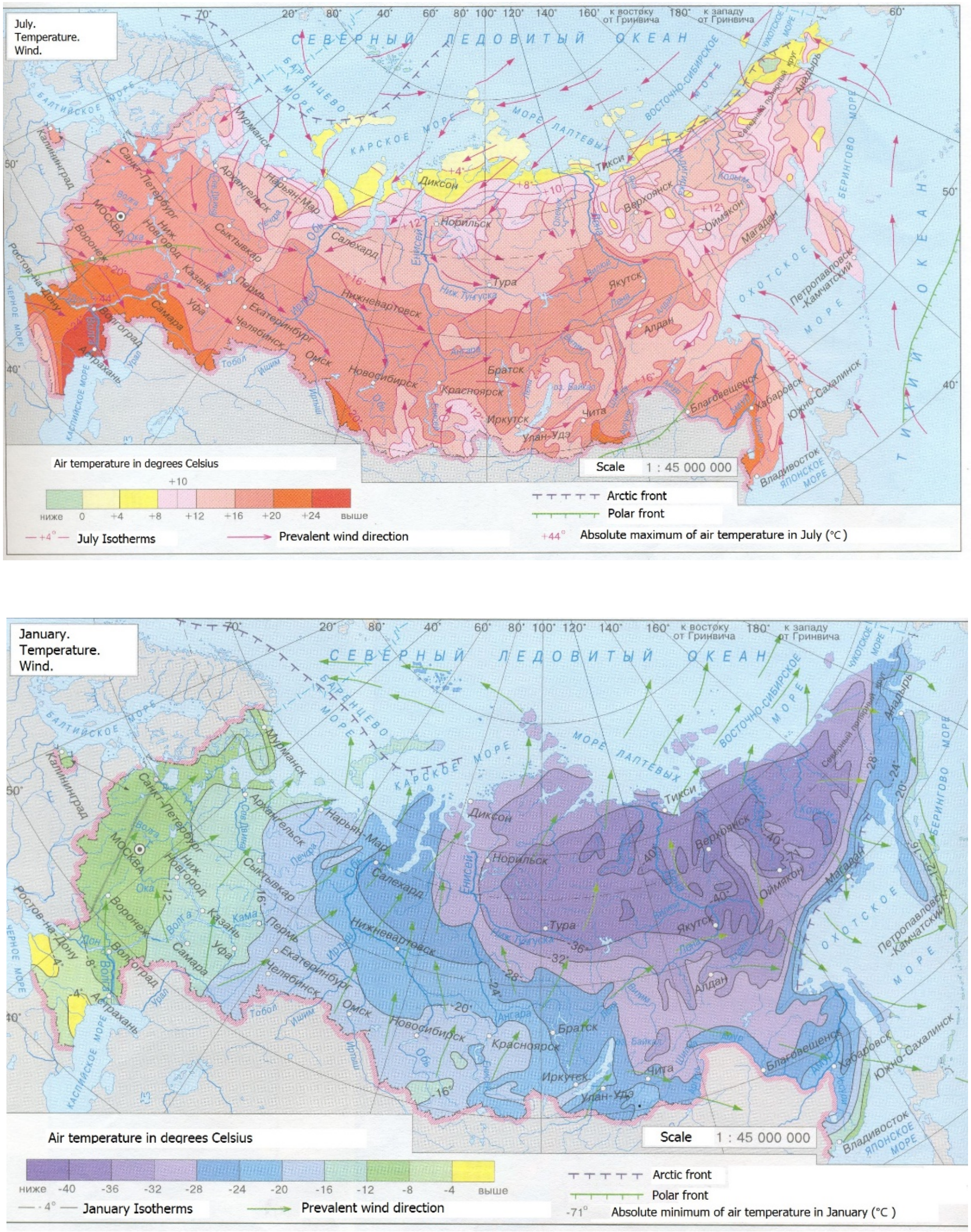


Figure 13: Average temperature and wind directions maps for July (top) and January (bottom) for territory of Russia. Source: Krivtsov, 2001

The arctic deserts are characterized by large amount of ice and snow throughout all seasons, yearlong arctic air masses, with annual precipitations around 400 mm, where most of precipitation falling in solid forms. Tundra covers most territories of the Russian Arctic, this is the zone of cold, strong winds and high cloudiness, where frosts are possible in any month. Climate in tundra changes from north to south, and from west to east, from the influence of Atlantic in the west dominants humid climate, from the east Pacific Ocean makes winters less harsh and with a snow cover, the continental and harsher climate is in between the oceans (Rakovskaya & Davidova, 2001).

Air masses moving over the Russian North create an abundance of wind with its high speeds and as well as great opportunities for clean energy implementations. Winds mainly blow from south to north in January and north-west (from western side) and north-east (from eastern side) to south in July. Wind speed and direction are a result of air mass movements, which are dependent on a difference in a pressure between the airs in two areas. Air masses move from the regions of high pressure to regions with low pressure, a bigger difference between pressures created a faster wind. Coriolis force is changing wind direction to the right in the northern hemisphere but also relief and roughness of the surfaces changes the speed and the direction of air flow (National Snow and Ice Data Center, 2017). For example, Western Transfer of air masses prevailing air transfer from west to east all year around dominants over the East European plane. Kola Peninsula and Karelia experience influence of cold Arctic Air Masses. The Arctic Front Cyclones pass the water area of Barents Sea in summers and winters. Warm, snowy and windy winter is a result of south-west flow of warmer sea air domination (Rakovskaya & Davidova, 2001).

The wind energy resources characterization in the Russian Arctic as was described in literature review to date is based mostly on two major studies where results of both are representing high wind energy potential in the Arctic. These studies showed a bit different areas of the highest wind speeds, but the common windiest region that is shown on the wind resources map (Figure 7) with 7.5 m/s wind speed over open plains is a region of Baydaratskaya Bay, which is a gulf of southern part of the Kara See, located between the coastline of the northern termination of the Ural Mountains and Yamal Peninsula, also characteristically distinguished by LRES, Moscow State University such areas as Kola Peninsula, and archipelago Novaya Zemlya and the eastern extremity of Chukotka Peninsula. The average wind speeds over open plains in the Russian Arctic are around 4.5 to 6.5 m/s (Starkov et al., 2000).

3.2 Data

The datasets for this project were acquired from several different sources. Meteorological data were acquired from global reanalysis systems such as MERRA (Modern Era Retrospective-Analysis for Research and Applications) and ASRv2 (The Arctic System Reanalysis version 2). These datasets are based on long time weather observations and analyses using weather forecast models with final products in the form of interpolated grids.

The topographical datasets are derived by GMTED2010 (Global Multi-resolution Terrain Elevation Data 2010) and ASTER GDEM (The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map). The MODIS (Moderate Resolution Imaging Spectroradiometer) - based Global Land Cover Climatology raster dataset was used in this study for roughness lengths determination. This research includes permafrost for suitability assessment, the permafrost estimates Global Permafrost Zonation Index Map by University of Zurich was used. For the road networks, water bodies and settlements OpenStreetMaps vector datasets by Russian regions were acquired. The Overview map of federal protected areas of Russia by Russian Non-commercial partnership "Transparent World" was used to compare with OpenStreetMap federal protected areas dataset. Below is the Table 11 of all acquired data products for this research.

Table 11: *List of Acquired Datasets and their resources for the study area*

Dataset	**Units**	**Resource**	**Resolution**	**Temporal Resolution**	**Time frame**
Meteorological data					
Wind speed at 50 m	m/s	MERRA*	~ 50 km	Monthly	1986-2016
Eastward wind and Northward wind components at 10 m	m/s	ARSv2	15 km	3 hours	2000 - 2012
Air Temperature at 10 m	K	MERRA*	~ 50 km	Monthly	1986-2016
Surface Pressure	hPa	MERRA-2*	~ 50 km	Monthly	1986-2016
Digital Elevation Models					
DEM for Russian Arctic	m	GMTED2010	225 m		2010
DEM for Nenets Autonomous Okrug	m	ASTER GDEM v2	30 m		2011
Land Cover					
Land Cover Type for Nenets Autonomous Okrug	m	MODIS-based Global Land Cover Climatology	500 m		2001-2010
Map of Permafrost	m	Global Permafrost Zonation Index Map	1000 m		2011
Raster data derived from OpenStreetMap Shapefiles					
Polygonal Water Objects	m	OSM	100 m		2016
Linear Water Objects	m	OSM	100 m		2016
Rail road and Highway Network	m	OSM	100 m		2016
Polygonal Settlements	m	OSM	100 m		2016
Federal protected areas	m	OSM	100 m		2016

3.2.1 Modern Era Retrospective-Analysis for Research and Applications

The NASA-MERRA (Modern Era Retrospective-Analysis for Research and Applications) data products were chosen to use as a resource of meteorological data for wind power calculations. These products represent NASA reanalysis for the satellite era using the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). MERRA accounts for historical climatic data throughout time of

1979 to 2016. MERRA has high temporal (one hour) and spatial resolution of the grids is 0.5° x 0.67°, where spatial resolution is about 50 km in the latitudinal direction. Using the Giovanni Web-based application developed by the GES DISC (Rienecker et al., 2011) all meteorological data including wind speed at 50 meters above displacement height (MERRA MATMNXSLV_5.2.0), temperature at 10 meters above the displacement height (MERRA M2TMNXSLV v5.12.4), surface pressure (MERRA-2 M2MNPASM v5.12.4) were acquired. Two Surface Pressure datasets were used for this project, one for the Russian Regional scale with its temporal average of 30 years 1986 to 2016 monthly, and another for Nenets Region with its temporal average of 13 years (2000-2012) monthly. As well as Surface Pressure datasets two Temperature datasets were used with the same temporal extents.

Displacement height is a reference surface for two datasets and it is important to understand what it is exactly. Displacement height is a height above the ground at which wind speed will go to zero due to flow obstacles on the ground, and this parameter usually is used for calculation of logarithmic wind profile (Jackson, 1981), MERRA's displacement height for the Russian Arctic region mostly equals to 0, and varies from 0 to 3 meters some areas based on average of 30 years displaced height dataset. The displacement height was considered as a height above the ground for future analyses.

MERRA reanalysis data was preferred to others worldwide leading models, such as ERA (the European Center for Medium Range Weather Forecast reanalysis series), CFSR (the Climate Forecast System Reanalysis), because of the organized data acquisition process with it is open facility to access data and one of the unique characteristics of MERRA data products in which wind velocity is provided at 50 m height, where others are not (Sharp, Dodds, Barrett, & Spataru, 2015). Based on analysis by Cannon et al. (2015) MERRA successfully reproduces the observed near-surface wind variability over large spatiotemporal scales, but less accurately reproduces localized wind variability, that means MERRA is applicable for large scale assessment (Cannon, Brayshaw, Methven, Coker, & Lenaghan, 2015). With use of Giovanni Web-based application with its User-Defined Climatology maps option of data computing grid data for 12 months averages of 30 years over study area was downloaded in NetCDF file format, exported to the GeoTIFF file format and projected to Albers Equal Area Conic projection since one minimally distorts shapes and keeps area proportions the same as area on the Earth (ArcGIS Desktop, 2016) for future analysis.

3.2.2. The Arctic System Reanalysis version 2 (ASRv2)

The Arctic System Reanalysis version 2 (ASRv2) reanalysis is provided by The University Corporation for Atmospheric Research and The National Center for Atmospheric Research (Bromwich et al., 2012).

Finer resolution of 15 km grid wind speed data subset was acquired by personal request to access NCAR Research Data Archive (UCAR, 2017). Subsetting was an important part of data acquisition since entire reanalysis dataset size is about 40.26 Tb. These datasets were launched only in the beginning of 2017 which means it is very new source of data and it doesn’t have many applications yet. The data acquisition required installation of Unix-like environment command-line on Windows system, such as Cygwin, to install wget application that allows applying provided by NCAR download script to download big sized datasets, without use of script data can be downloaded as a .tar archive which cannot be bigger than 2 GB in size. Wind Speed dataset for 13 years has size of 117 GB which shows that the use of Unix-like command was the most convenient approach for data acquisition.

Wind speed grids at 10 meters with resolution of 15 km were represented as Eastward (U) and Northward (V) wind components and contained 3-hourly data for 2000 – 2012 time period. These grids which cover entire Arctic are provided in NetCDF4 file format, every file includes 4 bands such as U10E, V10E, XLAT, XLONG, first two are U and V components and last two are bands with pixels' coordinates. Every band of wind components included around 248 band of 3-hourly average wind speed per month. Wind components are representing direction to where wind is blowing, for example eastward wind components represents wind blowing to the East. This research didn't include assessment based on prevalent wind directions and wind components were combined by equation (1) into average wind velocity (V_w) (UCAR, 2017):

$$V_w = \sqrt{U^2 + V^2} \qquad (1)$$

Since we needed only monthly averages for all 13 years available, a Python script was written and utilized to provide calculations over NetCDF files. As an output for the data processing wind speed averages for every Month for the time frame of 2000 to 2013 were calculated, with result of 156 rasters. Averages of 13 years were produced for every month thereby reducing amount of rasters to 12. All raster data were georeferenced and projected to Polar Stereographic projection and clipped for study area extend and projected to the Albers Equal Area Conic projection.

3.2.3 Digital Elevation Data

Two elevation datasets were used for this research. The GMTED2010 with its resolution of 7.5 arc seconds which approximately is 225 m was used to provide digital representation of elevation coverage for the entire Russian Arctic region (Danielson & Gesch, 2011). Global digital elevation data for north areas is one of the difficult issues, since most global data do not cover 100% of the Earth's land surface: for example ASTER data go up to 83° north, SRTM data up to 60° north (LPDAAC, 2014). GMTED2010 dataset product of collaboration of the United States Geological Survey (USGS) and the National Geospatial-Intelligence Agency (NGA) - provides a new level of detail in global topographic data, and it incorporates the current best available global elevation data and it is derived from 11 grid elevation datasets.

The elevation products have been developed using different aggregation methods, for this research mean elevation raster datasets were used (Danielson & Gesch, 2011). Grid tiles were acquired, mosaicked and projected to Albers Equal Area Conic projection.

ASTGDEMV2 2011 (The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map Version 2 was used for downscaling purposes. These data were produced by The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA), this second version of ASTGDEM is improved

ASTGDEM of 2009. These data products are generated by using stereo-pair images collected by the ASTER instrument on Terra satellite, it covers 99% of earth area. The enhanced version adds 260,000 additional stereo-pairs. The data represented by tiles of 1 by 1-degree grids with 30 m resolution (Tachikawa et al., 2011). The data for the second study area of the Nenets Autonomous Okrug with its fine resolution of 30 m were acquired and mosaicked for the future analysis.

3.2.4 Global Land Cover Dataset

Land Cover dataset is used to provide roughness length dataset which takes important role in wind speed extrapolation to a chosen height. In this study ARSv2 requires wind speed extrapolation from 10 m height above the ground to 50 m height of wind turbine hub. To produce dataset of roughness length with MODIS-based Global Land Cover Climatology raster data with resolution of 0.5 km was chosen.

These data describe land cover type, and are based on 10 years (2001-2010) of Collection 5.1 MCD12Q1 MODIS Land Cover Type Product land cover type data which includes adjustments for significant errors from previous dataset of version 5 (Broxton, Zeng, Sulla-Menashe & Troch, 2014).

The roughness coefficient calculation methods are an empirical or theoretical. Due to inability to obtain empirical data for study area, the theoretical approach will be chosen. The most common is the Davenport Classification (Table 12) of effective terrain roughness (Wieringa, 2001). The roughness length based on the Davenport classification was assigned to Global Land Cover dataset classes, see Table 13.

The worldwide dataset of Land Cover was downloaded from USGS Land Cover Institute (LCI, 2016) and clipped for the second study area of Nenets Region. The grid raster was resampled based on mode value to 15 km resolution to match the wind speed dataset resolution. Mode value is a representation of the most frequent value that occur within the coarser resolution pixel size. The final raster grid was prepared for future wind speed extrapolation to 50 m above the ground, using following equation (2) (Manwell, McGowan, Rogers, 2010):

$$V_2 = V_1 \frac{\ln(\frac{z}{z_0})}{\ln(\frac{z_1}{z_0})} \qquad (2)$$

where V_2 wind velocity to be estimated at height z, V_1 is known wind velocity at height z_1, and z_0 is a roughness length.

Table 12: *Davenport classification of effective terrain roughness*.

Source: Wieringa, 2001

Class	**Roughness Length (m) z_0**	**Landscape Description**
Sea	0.0002	Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
Smooth	0.005	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, marsh and snow-covered or fallow open country.
Open	0.03	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without wind breaks, heather, moor and tundra, runway area of airports. Ice with ridges across wind.
Roughly Open	0.1	Cultivated or natural area with low crops or plant covers, or moderately open country with occasional obstacles (e.g. low hedges, isolated low buildings, or trees) at relative horizontal distances of at least 20 obstacle heights.
Rough	0.25	Cultivated or natural area with high crops or crops of varying height, and scattered obstacles at relative distances of 12 to 15 obstacle heights for porous objects (e.g. shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g. buildings).
Very Rough	0.5	Intensively cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low densely-planted major vegetation like bush land, orchards, young forest. Also, area moderately covered by low buildings with interspaces of 3 to 7 building heights and no high trees.
Skimming	1	Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacle heights; e.g. mature regular forests, densely built-up area without much building height variation.
Chaotic	≥ 2.0	City centers with mixture of low-rise and high-rise buildings, or large forests of irregular height with many clearings

Table 13: *Roughness Length assigning based on Davenport classification*

Class #	Land Cover	Roughness Length z_0
0	Water	0.0002
1	Evergreen Needle leaf Forest	1
2	Evergreen Broadleaf Forest	1
3	Deciduous Needle leaf Forest	1
4	Deciduous Broadleaf Forest	1
5	Mixed Forests	1
6	Closed Shrublands	0.1
7	Open Shrublands	0.03
8	Woody Savannas	0.5
9	Savannas	0.5
10	Grasslands	0.03
11	Permanent Wetland	0.005
12	Croplands	0.1
13	Urban and Built-Up	1
14	Cropland/Natural Vegetation Mosaic	0.25
15	Snow and Ice	0.0002
16	Barren or Sparsely Vegetated	0.005

3.2.5 Global Permafrost Zonation Index Map (PZI)

One of the important geological characteristics of the high latitude regions is permafrost. Permafrost is a layer of the ground frozen during long period of time (Harris, 1986). In Russia, an area of frozen grounds occupies around 60 % of the territory of the country (Krivtsov, 2001). There are two layers of permafrost: active layer which is seasonally thaws during the summer and freezes back in winter, usually 0.6 to 4 m in thickness. The second is constant lower layer which doesn’t variate with seasonal change but reacts on climate changes (Krivtsov, 2001).

There are also two types of permafrost, continuous and discontinuous, where discontinuous forms in dismembered way in zones where mean annual temperature slightly below 0° C and permafrost forms with the influence of the aspect, when the best condition of permafrost occurrence is a slope facing north. Since permafrost can thaw with the temperature change, construction on this type of surfaces are difficult, one of the long-established in the Russian Arctic approaches to keep buildings stabilized is to use deep pile foundations, which are built in stable permafrost that doesn’t react with the seasonal change (Voytkovsky, 1968, Mirchevsky, 2016).

This study uses permafrost as one of many criteria for wind turbine site suitability assessment. Today there is no ideal permafrost dataset can be found. The Circum-Arctic Map of Permafrost and Ground-Ice Conditions published by the International Permafrost Association (IPA), according Gruber (2012) this is the most used and considered as a standard for many studies, this map was produced in 1990s and was derived from manual subdivision by regional experts creates uncertainties.

The PZI map (Figure 14) produced by Department of Geography, University of Zurich in 2011 proposes to have high credibility as IPA’s map with improved characteristics by consistent data and methods. The model uses aggregation of published earlier estimates (IPA’s map) with a high resolution (<1 km) global elevation data and air temperatures based on the NCAR-NCEP reanalysis and CRU TS 2.0 (Global Climate Dataset). The results of this aggregation provide more spatially detailed and a consistent extrapolation, where aggregation is accounting previous studies (Gruber, 2012).

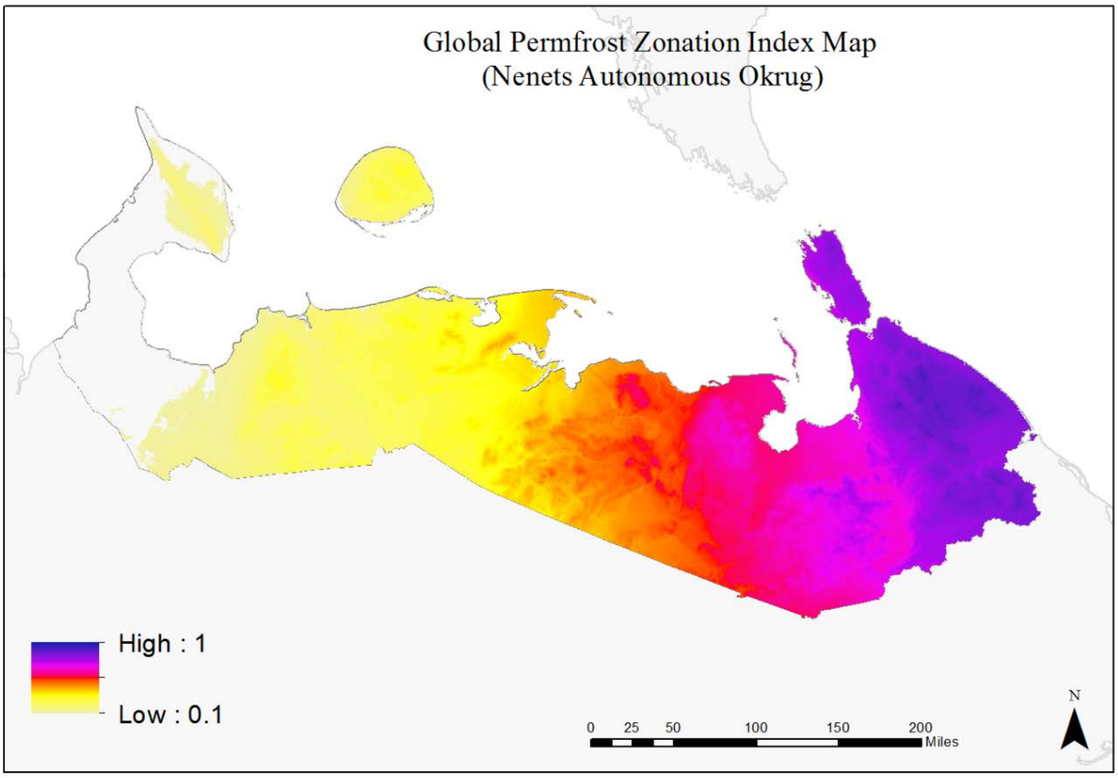


Figure 14: Example of Permafrost Zonation Index Dataset

Permafrost zonation is represented by a range of values from 0 to 1, where value of 0 (or yellow color on the map) represents permafrost occurrence only in very favorable conditions, which means permafrost is warm and shallow, where value of 1 represents permafrost that exist in nearly all conditions and is cold and deep (Gruber, 2012).

3.2.6 Constraint Criteria Datasets

Multi criteria site assessment for this research includes following constraints: water bodies (lakes, marshes, and wide rivers), linear water bodies (rivers, streams), rail road and road networks, settlements polygons and federal protected areas. Almost all of these criteria besides federal protected areas were derived from the OpenStreetMap available dataset of November 2016. OpenStreetMap (OSM) is a community project for the creation of a free, editable map of the world. This project was started in 2004 and through the period of 15 years OSM editors mapped significant amount of data for the world. Resolution of the data is very detailed. Russian Arctic regions have a good coverage of settlements and water bodies. As an example, a little remote village Shoyna in Nenets Autonomous Okrug is represented as a point location on Google Maps, and as a settlement with polygons of generalized streets and buildings in OSM (Figure 15), below comparative map of 1 mile resolution:

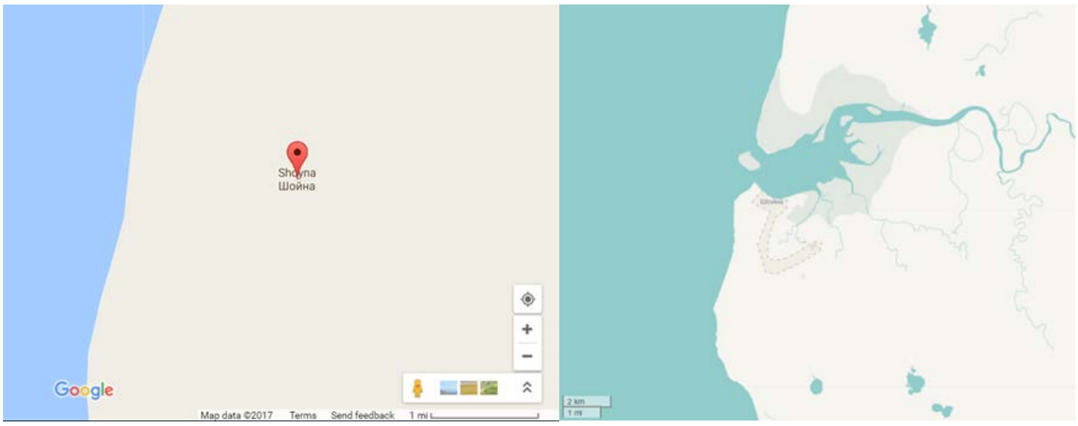


Figure 15: Google maps (left) and OpenStreetMaps (right) detalization for small remote community in Russian Arctic

All the shapefiles with the latest update of vector data for the Russian Administrative Regions freely available on NEXT GIS website for free downloading. NEXT GIS is a Russian team of QGIS (Quantum GIS) open software developers, which is the world's largest provider of QGIS extension modules. Several data archives of shapefile layers for the study area were downloaded and only necessary layers were used such as railway-line, settlement-point, highway-line, nature-reserve-polygon, settlement-polygon, water-line, and water-polygon. OSM’s road networks includes several classes for the road type from most important (motorway) to least important (service). Table 14 shows all utilized for this research classifications; the input road network dataset was filtered and combined in one class for future rasterization.

Table 14: *Utilized OpenStreetMap Highway Classes*

Source:http://wiki.openstreetmap.org/wiki/Key:highway

Class	Description
Motorway	A restricted access major divided highway, normally with 2 or more running lanes plus emergency hard shoulder. Equivalent to the Freeway, Autobahn, etc.
Trunk	The most important roads in a country's system that aren't motorways. (Need not necessarily be a divided highway.)
Primary	The next most important roads in a country's system. (Often link larger towns.)
Secondary	The next most important roads in a country's system. (Often link towns.)
Tertiary	The next most important roads in a country's system. (Often link smaller towns and villages)
Unclassified	The least most important through roads in a country's system – i.e. minor roads of a lower classification than tertiary, but which serve a purpose other than access to properties. Often link villages and hamlets. (The word 'unclassified' is a historical artefact of the UK road system and does not mean that the classification is unknown; you can use highway=road for that.)
Service	For access roads to, or within an industrial estate, camp site, business park, car park etc. Can be used in conjunction with service=* to indicate the type of usage and with access=* to indicate who can use it and in what circumstances.

The process included rasterization of all vector data and combining into one raster of constraints (Figure 16). Constraints parameters based on the previous studies were chosen as it shown in Table 15. Separately every vector layers were rasterized using Euclidian Distance tool which allowed automatilcaly include buffering zones around vectors based on chosen parameters (Table 12).

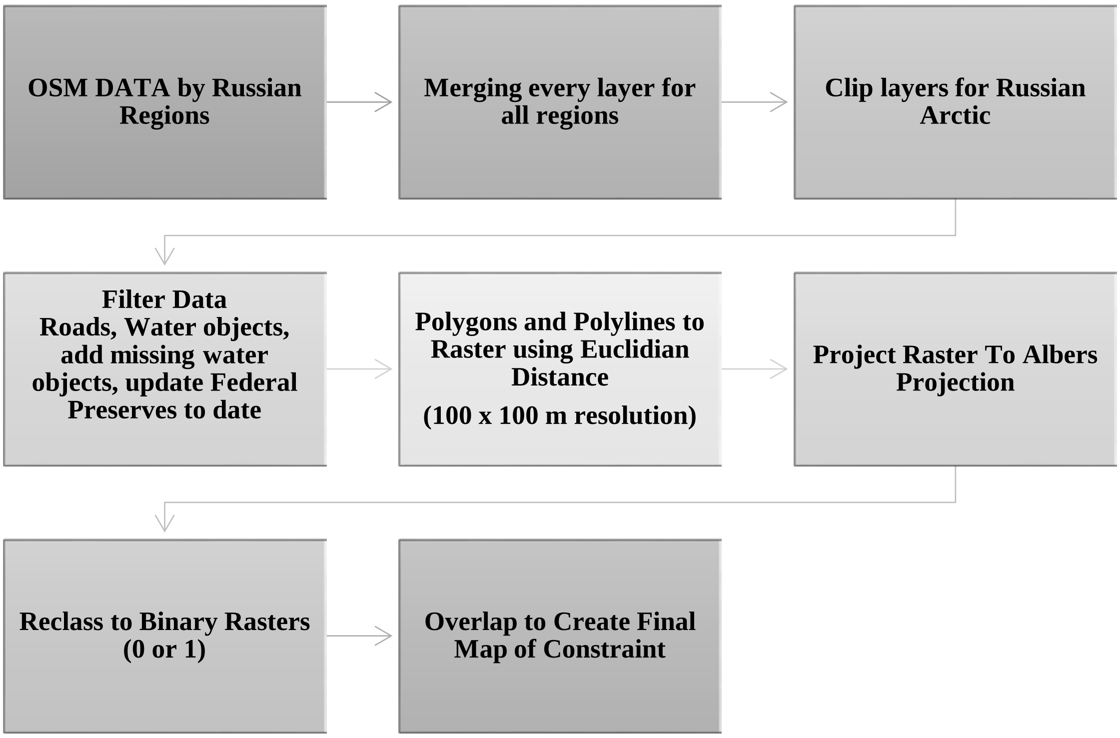


Figure 16: Processing Workflow of OpenStreetMap data rasterization

Every raster was rescaled to 100 by 100 m resolution with the study extend and reprojected to Albers Equal Area Conic projection. This resolution was chosen based on idea of saving geometries for linear objects such as rivers and roads and at the same time saving storage memory. By overlaying of all raster datasets final Map of Constraints (***CN***) was produced.

Table 15: *Parameters of Constraint Criteria for Site Assessment*

Constraint Criteria	**Suitable Parameter (Value of 1)**
Water objects	> 400 m
Urban build up	> 1000 m
Roads (flicker effect)	> 200 m
Federal protected areas	> 500 m
Slope	< 10 %
Elevation	< 1000 m

3.3 Multi-Criteria Site Assessment

A multi-criteria site assessment approach was chosen for wind turbine installation suitability model calculations. The site assessment included two different scales of study area. First was a large-scale analysis including the entire Russian Arctic, second was a more focused study analysis of Nenets Autonomous Okrug which was chosen based on energy consumption of the Russian Arctic administrative regions.

3.3.1 Assessment of Wind Power Potential

Wind power potential is a potential for the amount of electric power that can be produced with a particular wind speed and wind turbine (Chiras, 2010). Wind power is the kinetic energy of the air flow going through a wind turbine. As wind passes through a wind turbine and drives blades to create rotate, only part of wind power can be converted into electrical power due to wind turbines technical characteristics (Tong, 2010). Wind power is determined in equation (3):

$$P_w = \frac{1}{2}\rho A u^3 \qquad (3)$$

where $P_w$is a wind power, ρ is the air density, A is a swept area of blades, and u is the wind speed. This equation demonstrates a positive increase in P_w for all variables; however, the cube power of wind speed clearly demonstrates the importance of wind speed in power prediction. The swept area of the blades also is an important factor of wind power estimates (Shelquist, 2016, Tong, 2010). As an example, 10% increase in blade radius gives 21% increase in power output (Walker & Swift, 2015). The $P_w$power available in the wind is not the power wind generator will extract (Chiras, 2010).

The density of the air is the weight of molecules in the air per unit volume and helps produce the force in the wind. The air density directly related to the elevation above sea level, pressure and temperature, as temperature increases the density of air decreases. Likewise, increasing elevation, air pressure and air density decrease (Walker & Swift, 2015). The air density ρ can be calculated from the equation (4) below:

$$\rho = \frac{p}{RT} \qquad (4)$$

where p is the local air pressure (Pa), R is the gas constant (287 J/(kg-K)), and T is the local air temperature (K). Both pressure and temperature decrease with altitude. The pressure decreases by about 1 hPa for every 8 m of vertical ascent (Wallace & Hobbs, 2006) and the temperature decreases by 6.5 °C for every 1000 meters (Ahrens, 2012).

As was mentioned above electrical wind power depends on the technical characteristics of the wind turbine. In 1919, German physicist Albert Bets formulated that the maximum amount of the kinetic energy of the wind that can be converted into mechanical energy of rotor rotation is 59.3 %. This is called the Betz's limit coefficient (6) or "power coefficient" and is added into wind power equation (7) to calculate extractable power from the wind:

$$C_{p_{max}} = 0.59 \qquad (6)$$

$$P_w = \frac{1}{2}\rho A u^3 C_{p_{max}} \qquad (7)$$

Additionally, to calculate the wind power potential for a particular wind turbine, $C_{p_{max}}$can be replaced with a unique power coefficient of this turbine (Ragheb & Ragheb, 2011). In this study $C_{p_{max}}$ was used with the purpose of calculating the minimal scenario for wind power potential in the Russian Arctic. The methodology for wind power potential calculation was developed based on acquired meteorological data for the study area. The main datasets are described in Table 16.

Table 16: *Meteorological datasets used for Wind Power Potential maps calculations*

Dataset	**Variable**	**Units**	**Resource**	**Resolution**	**Year**
Wind speed at 50 m	u	m/s	MERRA*	0.5° lat x 0.625° lon (about 50 km in the latitudinal direction)	1986-2016 2000-2012
Air Temperature at 10 m	T	K	MERRA*	0.5° lat x 0.625° lon	1986-2016 2000-2012
Surface Pressure	p	hPa	MERRA-2*	0.5° lat x 0.625° lon	1986-2016 2000-2012

The study height above the ground of 50 m was chosen for future calculations. The wind speed MERRA dataset was used and no adjustment for altitude was made. The reason is that wind turbine heights for the community based application are not as tall as turbines for industrial use and can vary between 40 to 60 meters, the original wind speed data at 50 m height for MERRA fits the purpose. The rest of meteorological data was corrected to the 50 m altitude. The MERRA temperature dataset is presented at 10 meters above the ground. To adjust these data a 40 m correction of 0.26 degree was subtracted from all pixel values of the raster grids. The MERRA surface pressure represents data at the ground level height. To adjust these data a correction of 6.25 hPa was subtracted from all pixels of the raster grids. Wind power potential for all 12 months was calculated. The final formula for calculations took the form (8):

$$P_w = \frac{1}{2}\frac{(p-6.25)}{R(T-0.25)}Au^3C_{p_{max}} \qquad (8)$$

3.3.2 Annual Average Wind Power Potential with Adjustment for Icing Loss

The loss of energy production due to icing was discussed in the literature review. Icing is one of the biggest concerns for the future wind energy development in cold climate (Dilley & Hulse, 2007). One of the criteria in wind turbine placement in this study is icing loses. Since meteorological observation of ice occurrence for the study area are not available, a new approach was chosen to produce icing losses map for the Russian Arctic. The Icing map for Finland (Figure 17) was used as a standard material for ice map production of Russian Arctic. The map represents 7 classes of icing hours per year for 1994-2013 at 140 m above the ground level (Tammelin et al., 2011).

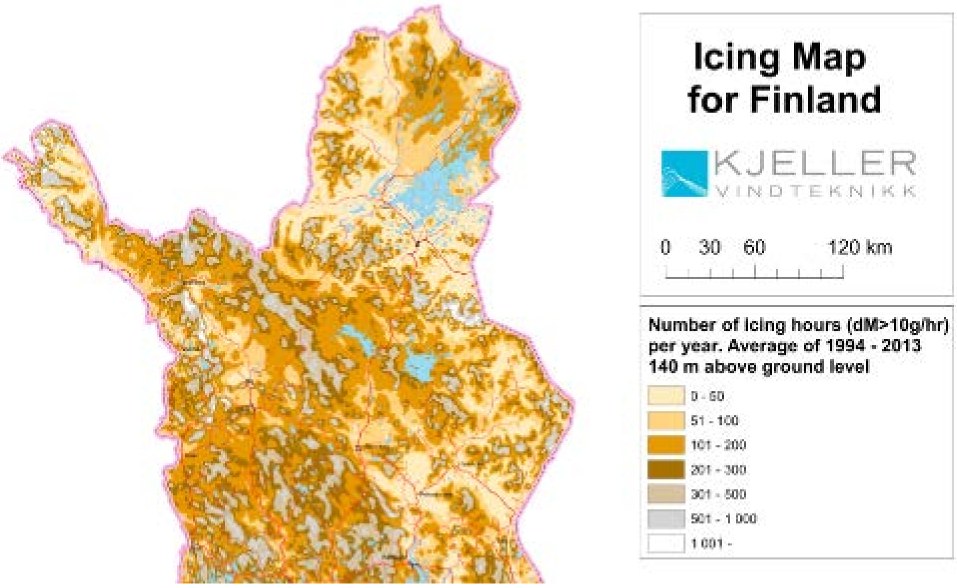


Figure 17: Fragment of Icing Map for Finland.

Source: http://www.tuuliatlas.fi/icingatlas

The main approach of using the Finish icing map as a basis for this study included automated data extraction of environmental variables over existing icing classes. In other words, the existing icing map of Finland (PDF available map consists of RGB bands) was classified into 7 classes using green band for classification based on color value of every class, seven classes were exported to vector polygon data to allow zonal statistic calculation over following datasets: wind speed at 50 m, temperature at 50 m, cloud liquid water content, humidity, elevation and slope data for Arctic territory of Finland. The main reason of collecting zonal statistics for every icing class was to find relationships between variables and icing class to apply those for icing map production over Russian Arctic study area using the same environmental datasets.

The results of zonal statistics showed high correlation between icing class, temperature and elevation variables, as higher altitude and lower the temperature determine more extensive icing occurrence. Due to the fact that the resolution of elevation data was much better (225 m and 30 m for both studies) and meteorological data covered wide area (50x50 km and 15x15 km for both studies) where many icing classes would fall into one pixel, the decision was made to use statistically identified relationships between elevation and icing class to produce icing map based on elevation data. Digital Elevation Data was classified by 7 classes based on found using zonal statistics mean values of altitudes that fall into one of the seven icing classes. The Table 17 shows icing classes and assigned elevation height per class. The Figure 18 demonstrates an applied workflow for icing map production.

Table 17: *Icing classes and assigned elevation height per class*

Class, hours per year	**Elevation Height, m**
50	0 – 160
100	160 – 170
200	170 - 210
300	210 - 270
500	270 – 350
1000	350 – 550
2000	550 - >1000

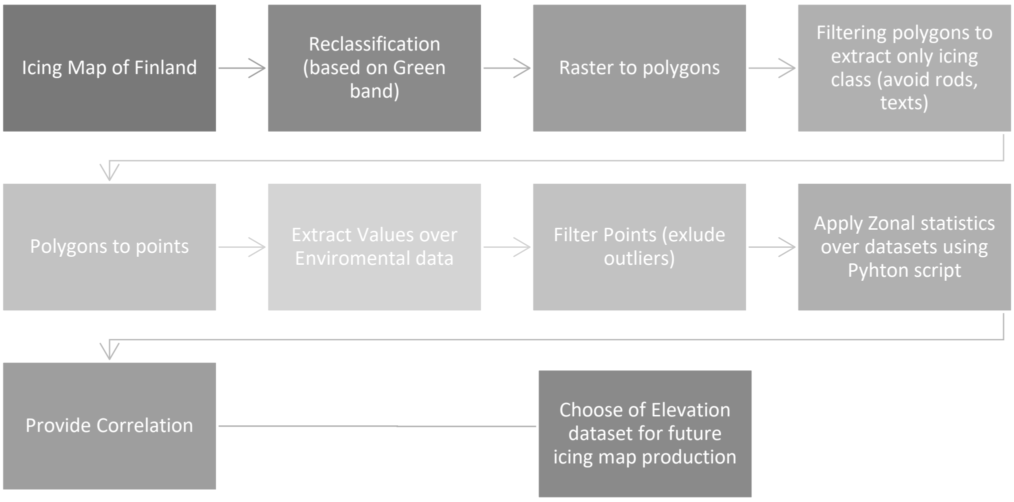


Figure 18: Workflow for icing map production

Average Wind Power Potential in MWh was calculated to provide results with aggregated icing loses. The Average Wind Power Potential was multiplied by 8760 hours (365 days) to calculate Annual Average Wind Power Potential in MW per year and Annual Icing Losses MW were subtracted from it to provide Final Wind Power Potential adjusted to icing losses.

3.3.3 Factor Criteria

The suitability modeling is based on overlapping two type of criteria: Constraint and factor criteria. Factor criteria usually represent gradients of more desirable and less desirable characteristics. For example, steep slopes lead to an increase of construction and maintenance cost (Tegou et al., 2010). Road proximity is another important factor, because closer and better road networks lower the price of construction (Baban, 2001). Some studies specify the maximum distance from the roads to define areas as unsuitable for construction therefore creating constraint criteria for multi-criteria model (Al-Yahyaia et al., 2012, Miller & Li 2014, Tegou et al., 2010). It is important to choose appropriate factor criteria for the study area to provide more accurate and most effective final results.

The availability of data limits the range of factor criteria for the study and allows to use following criteria: generated in this study Annual Average Wind Power Potential, Slope, Elevation, Road Proximity and Permafrost, all of these factors are summarized in Table 18. Wind Power Potential datasets were adjusted for icing losses; maximum values of potential were considered as more preferable unlike small values of potential. Elevation represented by the range from more suitable 0 to less suitable 1000 meters, where areas over the maximum altitude considered as unsuitable. The Slope ranges from 0 to 10 degree, where smaller slope is more preferable, Road Proximity ranges from 200 to 2500 m buffer areas along the roads axis as it was discussed the most beneficial areas are close to the road. Permafrost, which is considered to be more cost effective in the zones of and deep permafrost, where over the time constructions will not undergo foundation settling due to instability and weakness of permafrost and cost of maintenance will be reduced. The new suitably criteria was implemented in this study for multi-criteria decision making systems.

The factor criteria datasets were derived as rasters within the study extend. Every raster was linearly normalized or rescaled to the values range from 0 to 1, where 0 is less suitable and 1 is most suitable. The normalization is also presented in Table 18. Every factor requires its weight to fit into multi-criteria decision making system, to provide weights Analytic Hierarchy Process (AHP) was applied (Al-Yahyai et al., 2012; Uyan, 2013). This process requires pairwise comparison of the input factor criteria based on expert judgments, it the way of what criteria is more import over another (Wind & Saaty, 1980).

Table 18: *Factor Criteria parameters and normalization values.*

Factors	**Criteria**
Annual Average Wind Power Potential at 50 meters (50 km/15 km)	normalized to 0 to 1
Elevation (225 m/30 m)	0 – 1000 (normalized to 1 to 0)
Slope (225 m/30 m)	0 – 10 (normalized to 1 to 0)
Road Proximity (100 m)	200 – 2500 (normalized to 1 to 0)
Permafrost (1 km)	0 - 1 normalized to 0 to 1

AHP is a method to support multi-criteria decision making, mathematically it is based on the solution of an Eigen value problem. The pairwise comparison results are represented as a matrix and the first normalized right Eigen matrix vector gives the weighting, the Eigen value determines the consistency ratio. To implement this process an online AHP tool by Business Performance Management Singapore was chosen to provide pairwise comparison with given end results. The following scale of importance with assigning numeric rating from 1 to 9 to was used for the AHP: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between). The pairwise comparison was provided by 4 independent experts (IE) (Table 19). The mean weight per every factor criteria was calculated and used for the MCDS.

Table 19: *Assigned weight for Factor Criteria*

Variables	**IE1**	**IE2**	**IE3**	**IE4**	**Avg. Weights**
Wind Power Potential (***WPP***)	0.669	0.648	0.651	0.678	**0.6615**
Elevation (***El***)	0.033	0.04	0.09	0.08	**0.06075**
Slope (***Sl***)	0.116	0.16	0.172	0.145	**0.14825**
Road Proximity (***RP***)	0.116	0.076	0.057	0.055	**0.076**
Permafrost (***PF***)	0.064	0.076	0.03	0.042	**0.053**
total	1	1	1	1	1

Suitability map creation was carried by overlay of both constraint and factor criteria with assigned weight. The equation for the suitability map (SM) looks as it shown below:

$$SM = \boldsymbol{CN}(0.6\boldsymbol{WPP} + 0.06\boldsymbol{El} + 0.15\boldsymbol{SL} + 0.08\boldsymbol{RP} + 0.05\boldsymbol{PF})$$

where $\boldsymbol{CN}$ is binary Map of Constraints

The main and very simple idea behind this equation is that constraint criteria raster have value of 0 – completely unsuitable, and no matter how high values of factors will be for the site, if the area is unsuitable the end value by multiplying by 0 will give 0. The final study flowchart is represented in Figure 19, this table includes both study areas and all steps that were undertaken for the multi-criteria site assessment.

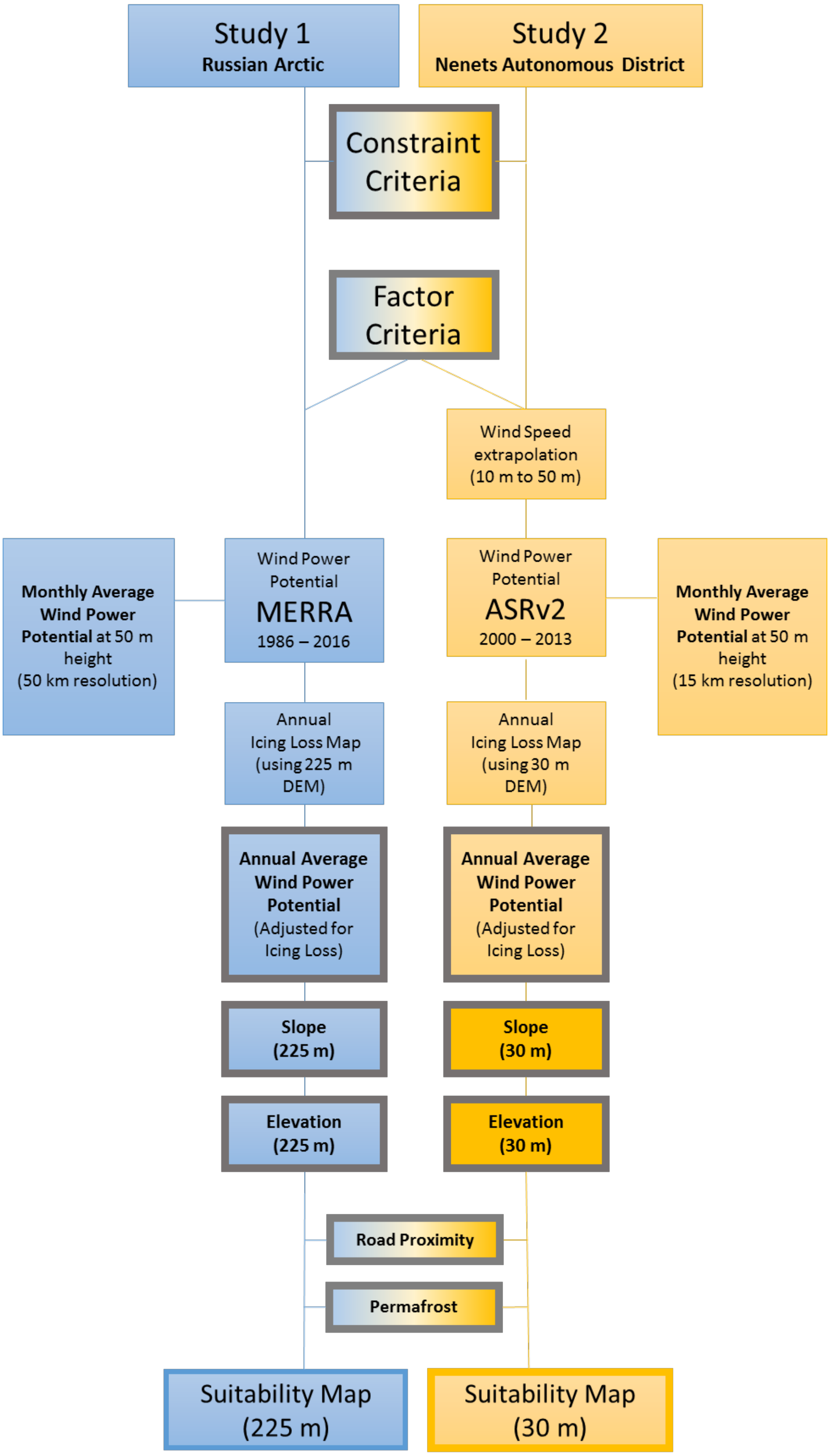


Figure 19: Multi-criteria site assessment flowchart

CHAPTER 4
RESULTS

4.1 Wind Power Potential of the Russian Arctic

Twelve maps of Monthly Average Wind Power Potential at 50 m height for the period of 30 years was produced for the territory of Russian Arctic with resolution of 50 km using MERRA reanalysis data (Figure 20).

Potential was calculated in consideration of minimum possible wind energy extraction by a wind turbine with the rotor radius of 30 m with productivity coefficient of 0.59 (based on Balz’s limit). The potential calculations used twelve monthly averages air density grid datasets that were produced using MERRA reanalysis data and included such parameters as average atmospheric pressure and temperature over 12 months for the region instead of using value of 1.225 kg/m3 that many studies use as a constant value at the sea level with 15 C temperature. The final results of potential in MW per hour can be seen on Figure 20, where maps of 12 months are grouped into four calendar seasons.

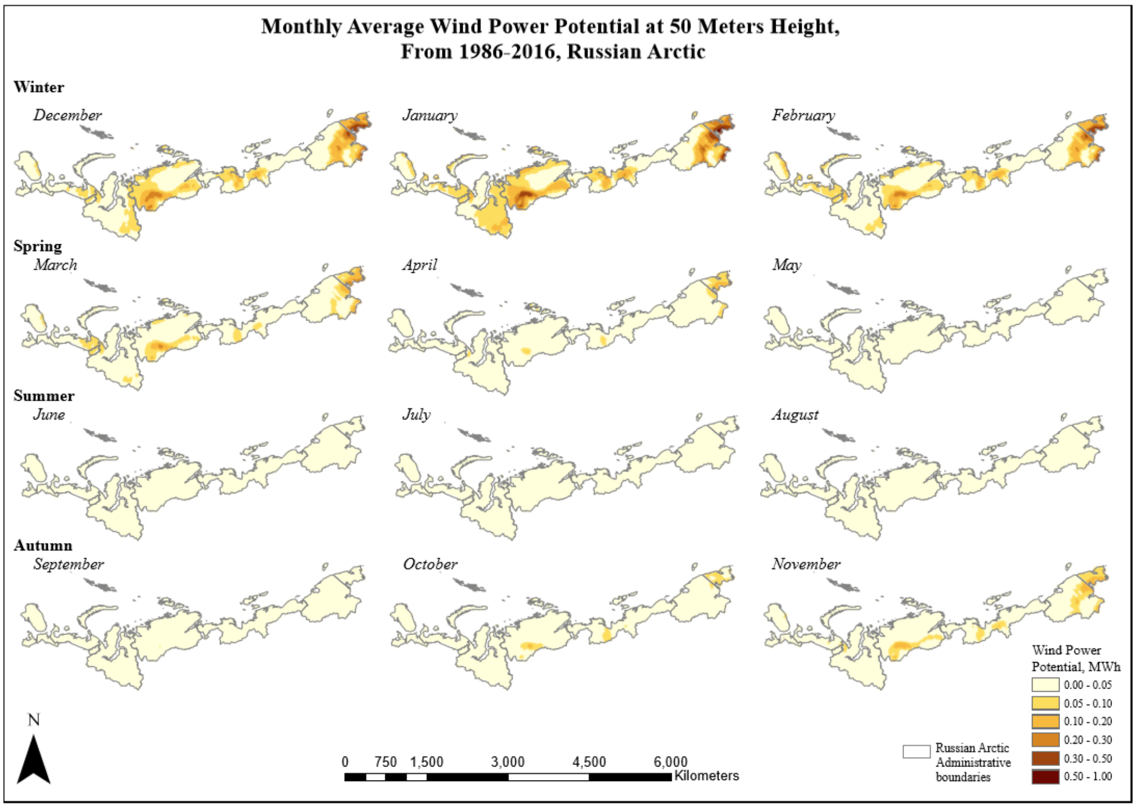


Figure 20: Monthly Average Wind Power Potential at 50 m height for the period 1986 – 2016, Russian Arctic based on MERRA reanalysis data, 50 km resolution

The resultant maps show that the highest potential in the region is during cold seasons. Figure 20 graphically shows differences in power potential between twelve months, where the lowest values are in May through September months. Figure 21 that shows monthly total Wind Power Potential with the assumption of 1% use of possible installed capacities', helps to recognize regions with the highest numbers of potential. These regions are: Chukotka, Taymyr (Krasnoyarsk Krai) and Yamal with Sakha regions. There are two zones in the Russian Arctic that are visibly seen as zones with significantly high wind power potential, the southwest of Taymyr

Autonomous Okrug of Krasnoyarsk Krai and east side of the Chukotka Autonomous Okrug. These maximums exist due to high mountains formation in these two regions and its characteristic for the mountain area wind processes.

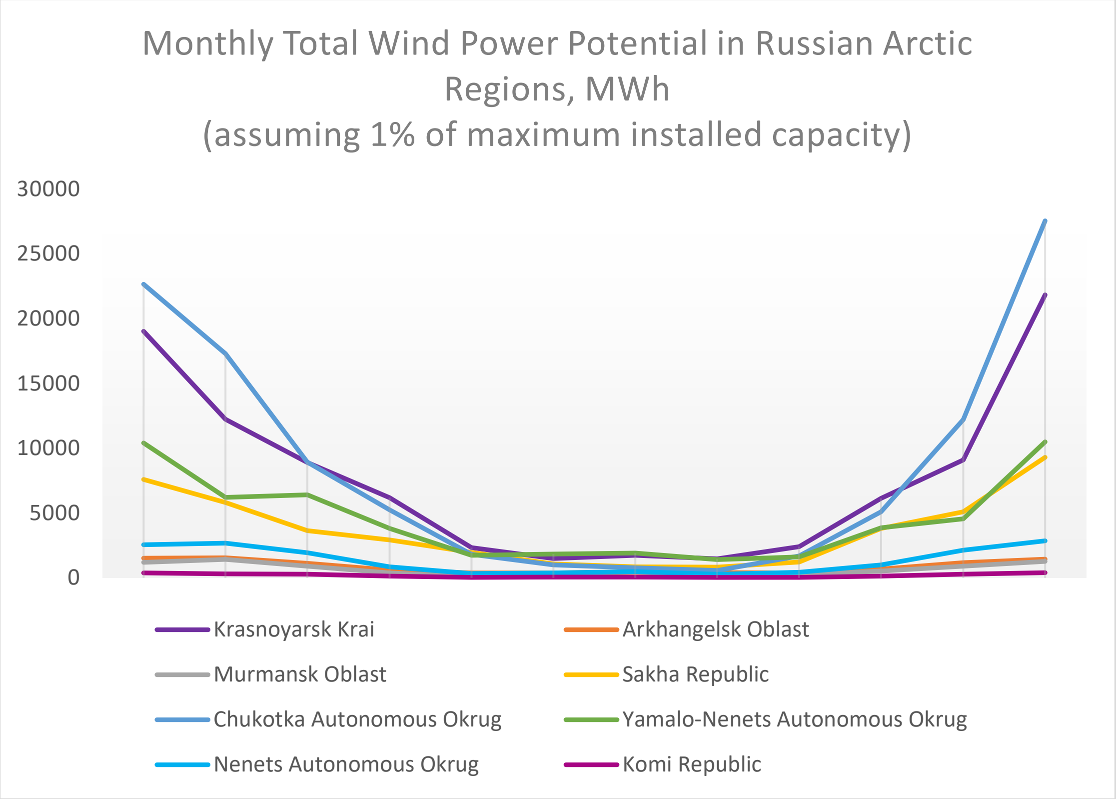


Figure 21: Chart of Monthly Total Wind Power Potential in Russian Arctic Regions, MWh (assuming 1% of max installed capacity, with installation of turbine by every 0.04 sq.km.)

This observation of the seasonal change, where cold seasons are presented with a higher potential can be explained by the transfer of Arctic air masses in winter versus summer. As we know wind is blowing from the areas of cold temperature to areas with warmer temperatures, as higher difference between temperatures as higher wind speeds. The prevalent wind directions in winter for the Russian Arctic were described in the literature review. Generally, winds are blowing from continent to the ocean in cold seasons and the difference in temperatures is greater than in warm season based on the fact that lands lose heat faster than water. In summer months, we can see the opposite effect where land warms up faster and cold air masses from the ocean moving inland creating winds, but speeds are slower since the difference in the temperature is not as high as in cold seasons.

Annual average wind power potential adjusted for icing losses (Figure 23) was calculated for the Russian Arctic study area by aggregating all monthly data to annual average and multiplying MW per hours' dataset by number of icing hours per year (Figure 22) and subtracting total amount of icing losses in MW per year.

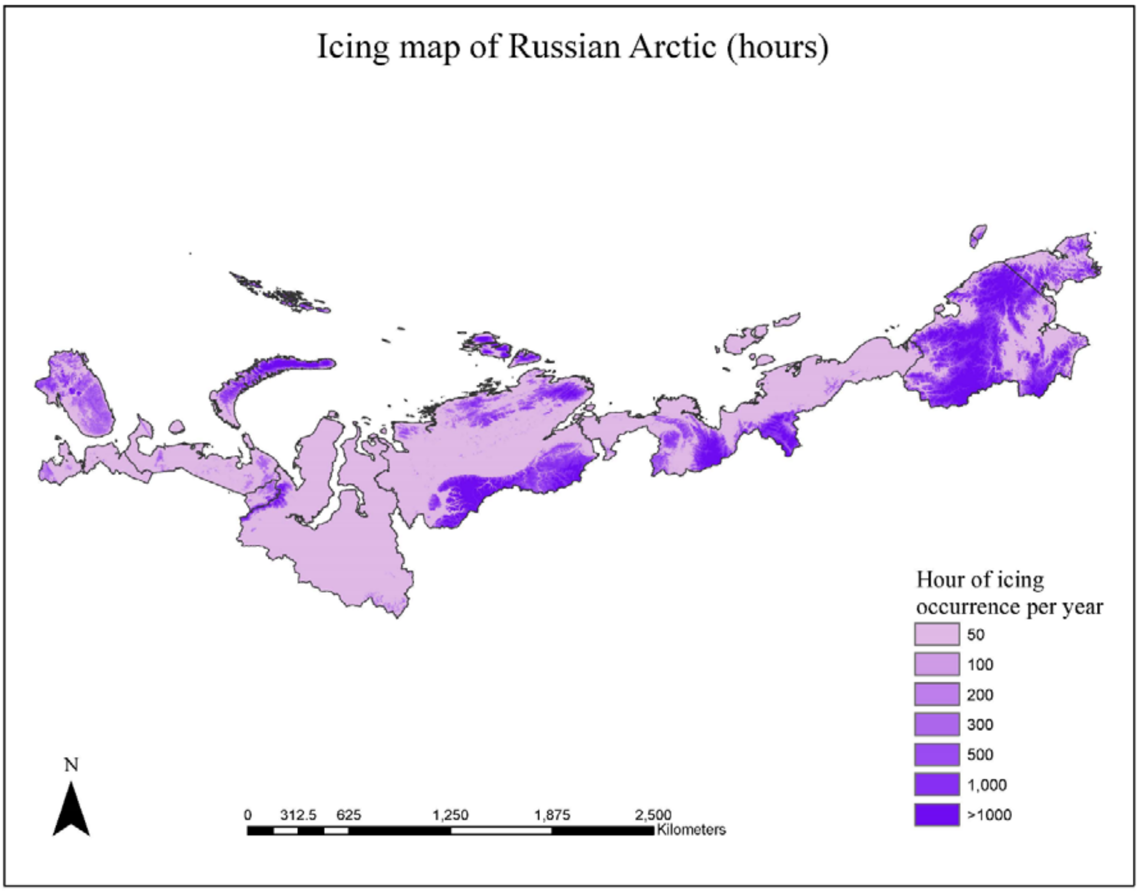
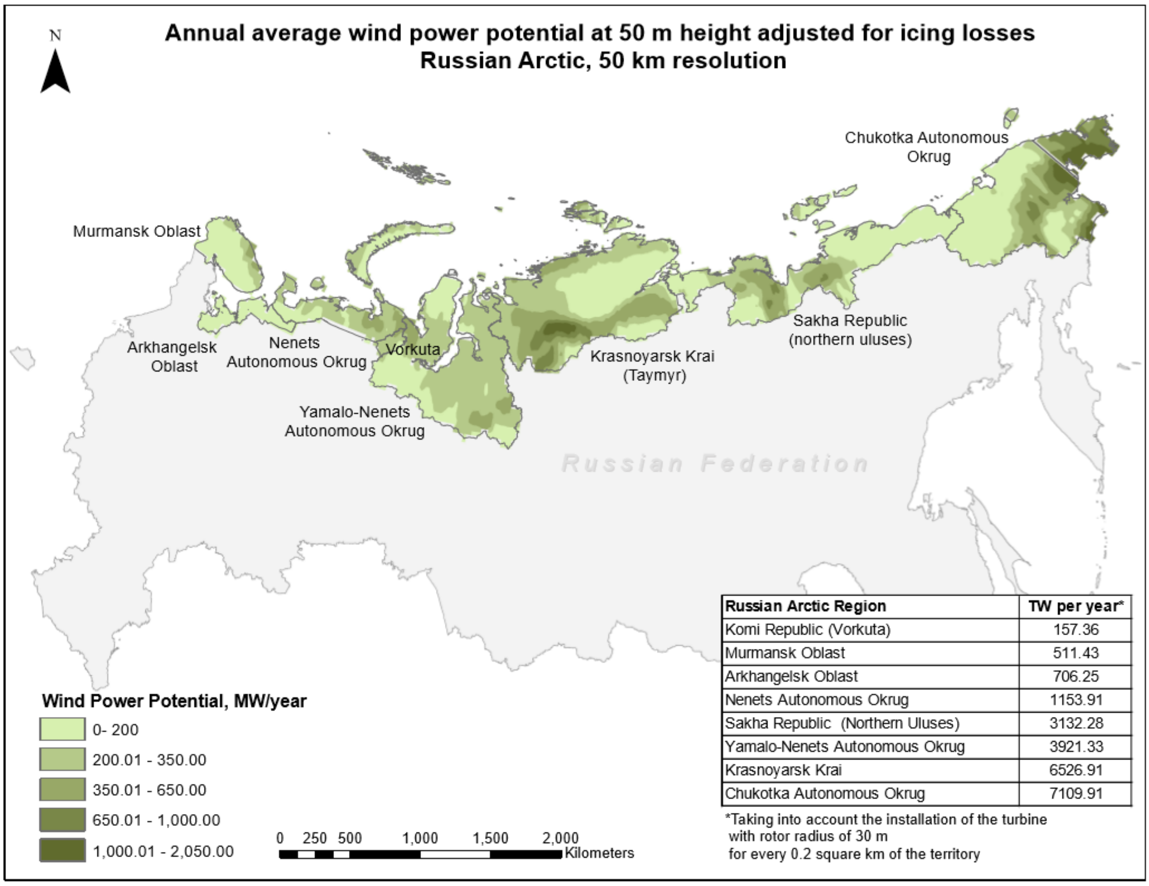


Figure 22: Icing Map of Russian Arctic, 225 m resolution

The finalized Wind Power Potential map is represented in Figure 23. The average keeps already observed highest potentials for the regions such as Chukotka, Taymyr (Krasnoyarsk Krai) and Yamal with Sakha regions. The table of total capacity in TW per year for the Russian Arctic regions represented on Figure 23. The availability of wind energy is generally higher in the coastal and mountainous areas.



Russian Arctic Region	TW per year*
Komi Republic (Vorkuta)	157.36
Murmansk Oblast	511.43
Arkhangelsk Oblast	706.25
Nenets Autonomous Okrug	1153.91
Sakha Republic (Northern Uluses)	3132.28
Yamalo-Nenets Autonomous Okrug	3921.33
Krasnoyarsk Krai	6526.91
Chukotka Autonomous Okrug	7109.91

*Taking into account the installation of the turbine with rotor radius of 30 m for every 0.2 square km of the territory

Figure 23: Annual average wind power potential adjusted for icing losses, Russian Arctic with a summarized table of total power capacity per region

4.2 Multi-Criteria Site Assessment for Russian Arctic

The Multi-Criteria Site Assessment for Russian Arctic to provide suitability assessment for wind turbine placement included 6 constraints and 5 factor criteria for the modeling Table 20. These criteria were chosen based on existing studies and availability of data for the area of study. Criteria are focusing on cost-effectiveness of facilities installation and future maintenance and in respect and conservation of the environment.

Table 20: *Multi-criteria Site Assessment criteria and parameters*

Criteria #	**Constraint**	**Suitable Parameter (1)**
1	Water objects	> 400 m
2	Urban build up	> 1000 m
3	Roads (flicker effect)	> 200 m
4	Federal protected areas	> 500 m
5	Slope	< 10 %
6	Elevation	< 1000 m
	Factors	**Suitable Parameter (0 - unsuitable to 1 - suitable)**
7	Annual Average Wind Power Potential at 50 meters (50 km/15 km)	normalized to 0 to 1 (min potential to maximum)
8	Elevation (225 m/30 m)	0 – 1000 (normalized to 1 to 0, maximum height to min)
9	Slope (225 m/30 m)	0 – 10 (normalized to 1 to 0), min degree of slope to max)
10	Road Proximity (100 m)	200 – 2500 (normalized to 1 to 0, min distance from road axes to max)
11	Permafrost (1 km)	0 - 1 normalized to 0 to 1 (weak and shallow to deep and stable)

All constraint criteria were combined into one grid dataset with resolution of 100 by 100 m. Factor criteria were normalized to values from 0 to 1 and the importance of one factor over another was assessed using Analytic Hierarchy Process The final Suitability Map was based on the resolution 225 by 225 m, that elevation dataset carried. The suitability map for the Russian Arctic is presented as a raster grip with range of pixel values from 0 to 1, where 0 is completely unsuitable location and 1 is the most suitable location (Figure 24).

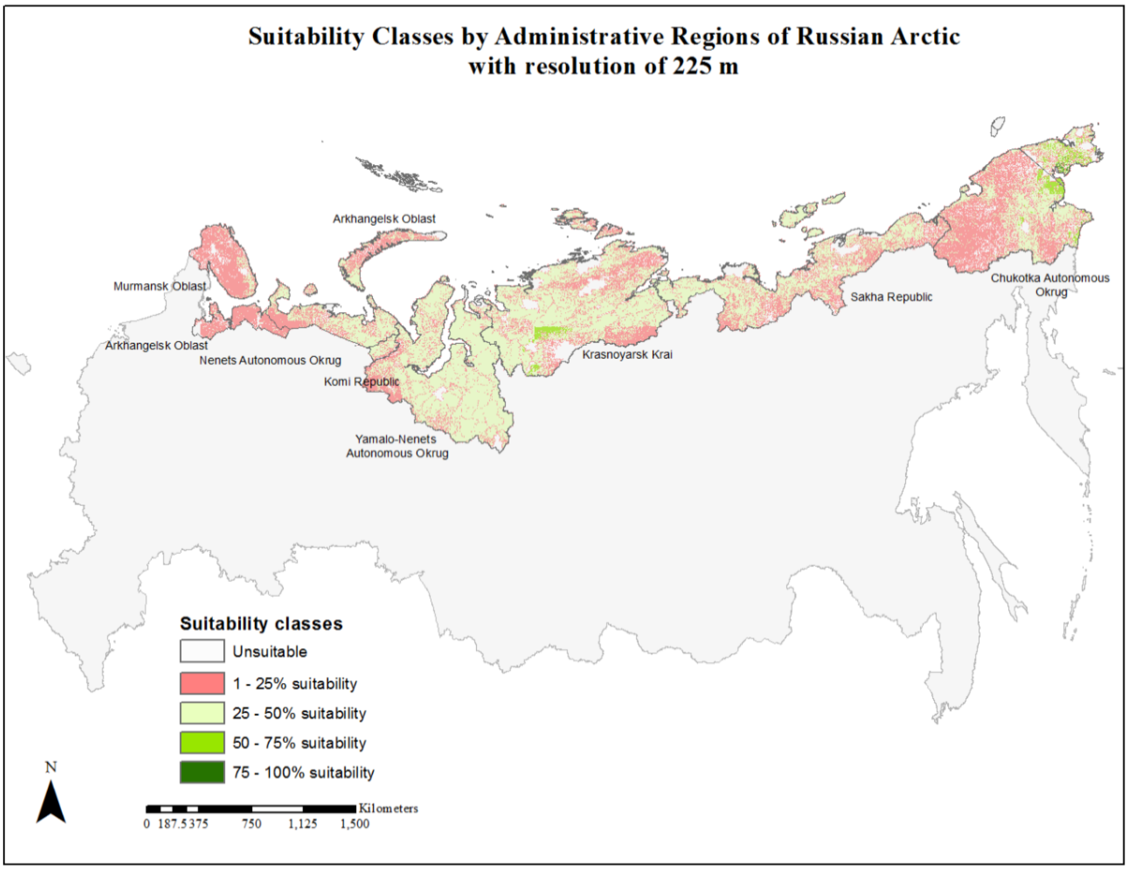


Figure 24: Suitability map for wind turbine placement in Russian Arctic, 225 m

Results show that 27.3 % of the entire territory considered is completely unsuitable due to chosen parameters for constraint criteria. The highest portion of unsuitable areas belongs to federal protected areas, which are spread over large areas of the regions. The high number of water bodies also have a high role in the present of unsuitable areas. Around 57 % of the area lies in between suitability values 0.25 and 1. The most suitable locations correlate with highest annual wind power potential. In the mountain regions, where altitude exceeds the threshold corresponding to constraint parameters (altitude > 1000 m), values these regions automatically are becoming unsuitable. As an example, a large portion of the highest potentials of the former Taymyr Autonomous Okrug is removed based on this cutoff. This region still, however, have had the highest rates of suitability factors along with Chukotka Autonomous Okrug.

4.3 Wind Power Potential of Nenets Autonomous Okrug (downscaling)

Twelve maps of Monthly Average Wind Power Potential at 50 m height for the period of 13 years were produced for the territory of Nenets Autonomous Okrug (NAO) with the resolution of 15 km using Arctic System Reanalysis version 2 (Figure 25). Wind profile extrapolation using logarithmic wind profile was performed to produce wind speed datasets at 50 m height above the ground. The same pattern is observed for the downscaled region, where highest potential belongs to the coldest season, but looking at chart results of two scales of power potential estimates (Figure 26), we can see that the drop down for the downscaled power estimates are less steep than the one for Russian Scale estimates. Also, the downscaled estimates are around 10 times higher than estimates for Arctic Russia.

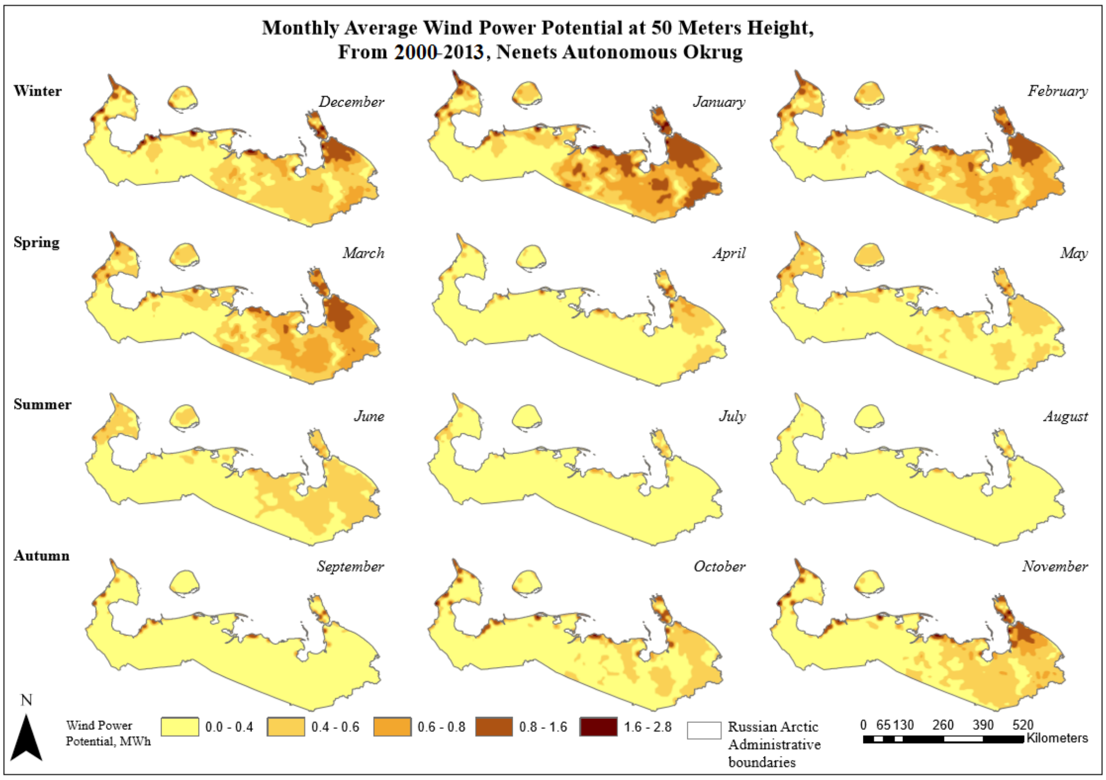


Figure 25: Monthly Downscaled Average Wind Power Potential at 50 m height for the period 2000 – 2013, Nenets Autonomous Okrug

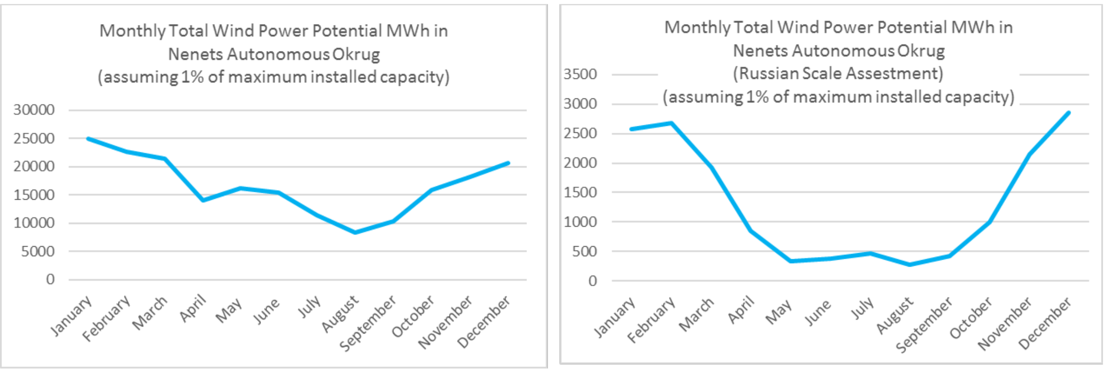


Figure 26: Monthly Total Wind Power Potential MWh in Nenets Autonomous Okrug (assuming 1% of maximum installed capacity, with installation of turbine by every 0.04 sq.km.)

Annual average wind power potential adjusted for icing losses for the Nenets Autonomous Okrug (Figure 28) was implemented using the same workflow of creating map of possible icing occurrence in hours per year (Figure 27) based on digital elevation model with the same classification as it was used for the first study area. The area of Ugorsky Peninsula, NAO has the highest potentials over a year. High potential in this area is due to the coastal location and elevations of about 450 m of Pai Hoi Range northern of Ural Mountains. The northern part of the Ural Mountains falls on the territory of the NAO and contributes to high values of wind power potential in the east side of the region. Several areas along the coast of the region have consistent high potentials throughout the year, the lowest potentials are observed in May. These following locations have high wind power potentials even in May: Bolvanskiy Nos, Gomsasale, Kanin Nos, Konushen Capes; Bolush'ya, Indigirskaya Bays; Chernaya, Farikha, Vangurey Kiya Settlements. There is also high potential is being recognizable in the close proximity to City of Naryan Mar will its 24,500 population.

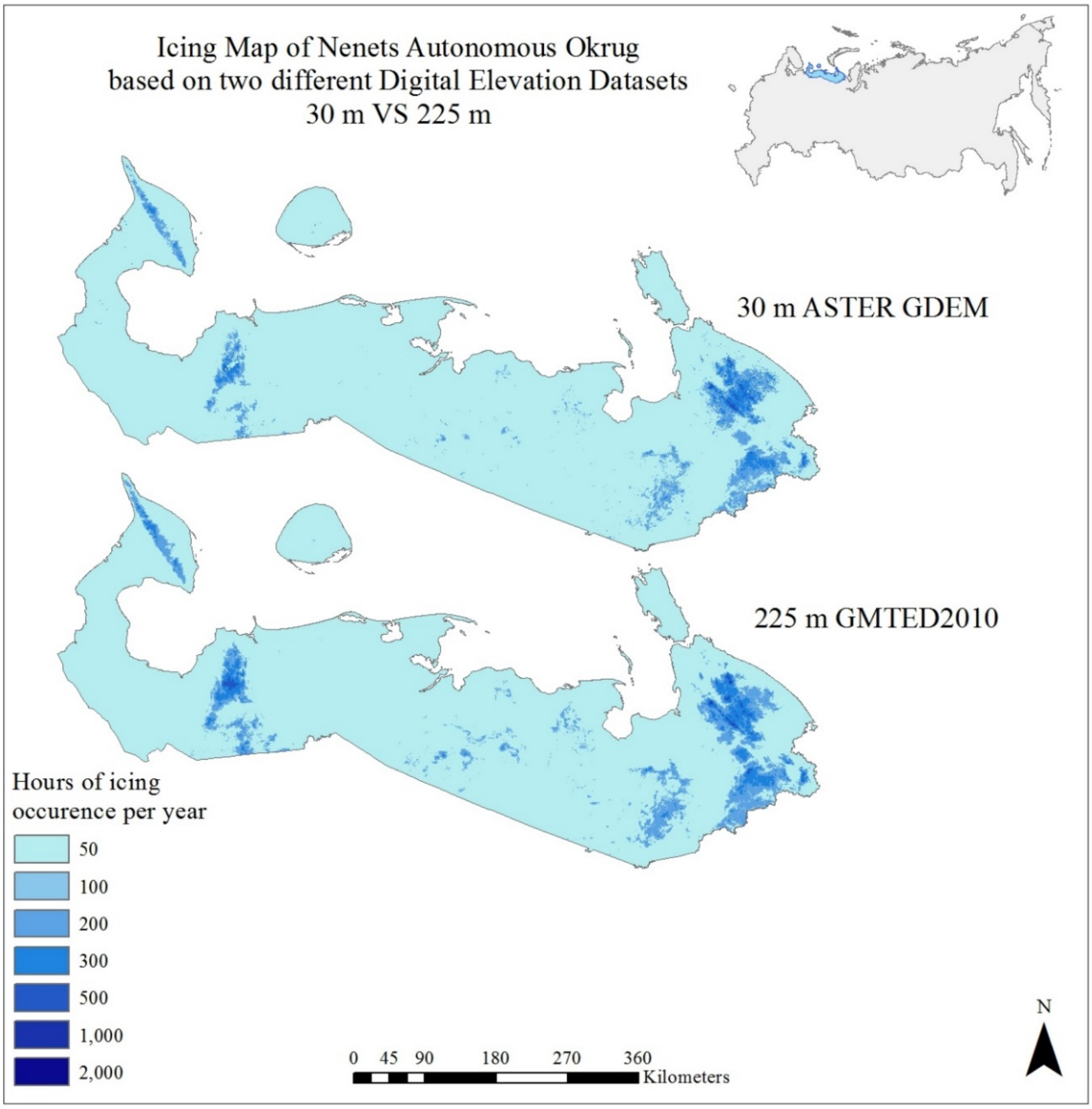
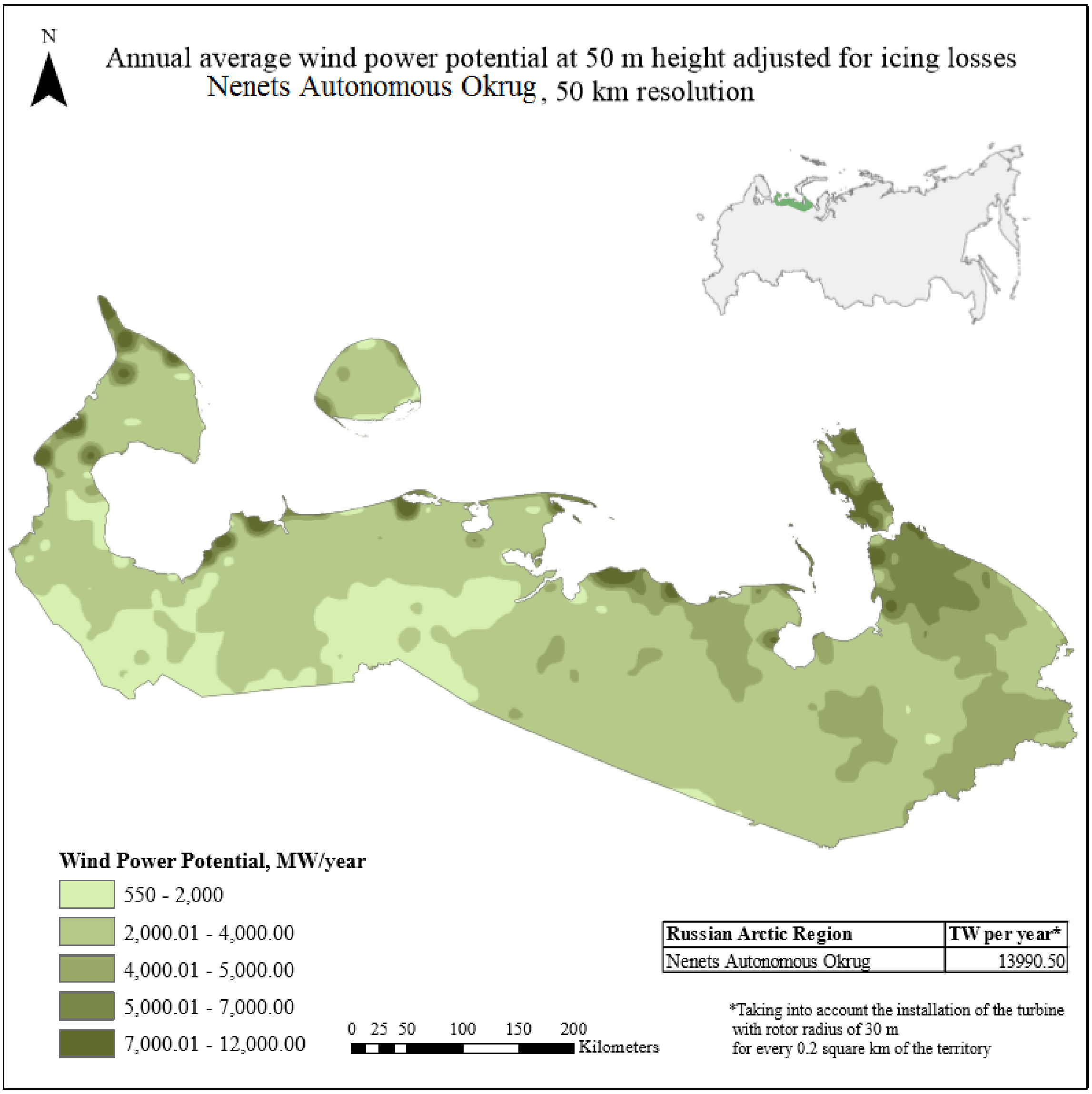


Figure 27: Icing Map of Nenets Autonomous Okrug based on two different DEMs with 30 and 225 m resolution retrospectively.



Russian Arctic Region	**TW per year***
Nenets Autonomous Okrug	13990.50

*Taking into account the installation of the turbine
with rotor radius of 30 m
for every 0.2 square km of the territory

Figure 28: Annual average wind power potential adjusted for icing losses for the Nenets Autonomous Okrug.

4.4 Multi-Criteria Site Assessment for Nenets Autonomous Okrug (downscaling)

The Multi-Criteria Site Assessment for Nenets Autonomous Okrug partially replicated the assessment for study area of the Russian Arctic. The downscaling was made by using two different input data with a finer resolution for the model. The wind power potential dataset Arctic System Reanalysis version 2 datasets were used with resolution of 15 km, and for the digital elevation model dataset and the derived from it slope dataset, the ASTER GDEM with it 30 meters resolution was used. The final Suitability Map for Nenets Autonomous Okrug (Figure 29, map below) was based on the resolution 30 by 30 m (according elevation resolution).

Downscaled suitability map results show that around 30 % of the territories are unsuitable for wind turbine placement in Nenets Autonomous Okrug. The biggest portion of unsuitable values, as it was observed for the first study area (Russian Arctic), belongs to the federal protected areas. Water bodies and elevation as well as large areas of unsuitable area were identified, due to steep slope exclusion. Because the resolution of analysis was more detailed, more pixels fall into the category of steep slopes (slopes eater then 10%) thereby increasing percent of unsuitable values.

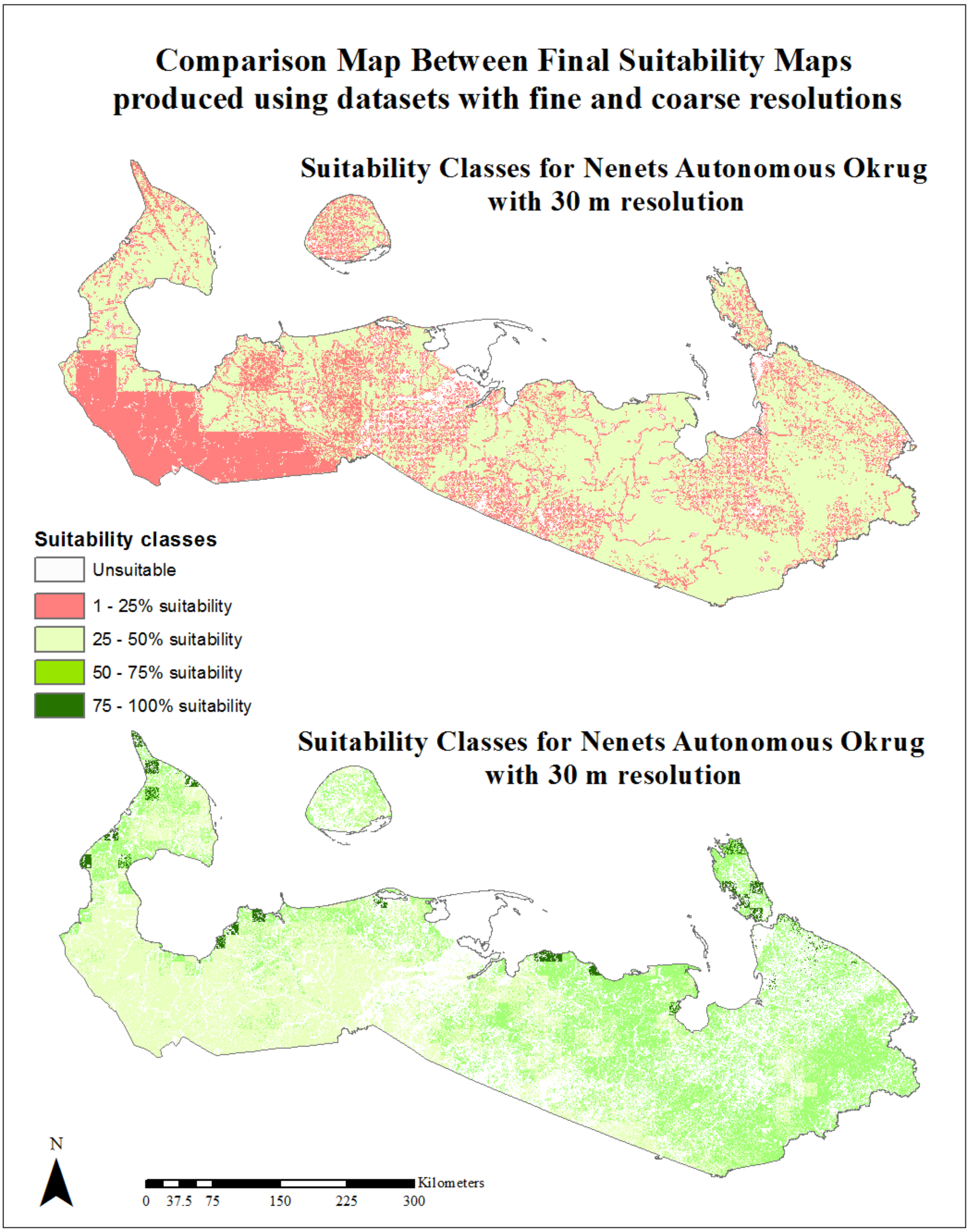


Figure 29: Comparison between Final Suitability Maps

Territories with higher suitability values correlate with the highest wind power potential areas. These are the most recognizable areas with higher suitability values:

West side of Kanin Nos Peninsula with it is the most suitable area in Cape Konushen, Norhrn of Vaigach Island, Pahancheskaya Bay, Volonga, Farikha and Vangurey Settlemnts.

4.5 Summary

The results of the Wind Power Potential Assessment for both study areas show that the seasonal change is observed over the monthly averages for 30 years of reanalysis data that was used for the large area assessment of entire Russian Arctic, and for the 13 years reanalysis data that was used for downscaling purposes. Estimated wind speeds and Wind Power Potential increase respectively in cold seasons and decrease in summer months. Results are show that there are some areas that consistently have high potentials across seasons. Downscaled wind Power Potential results provide 10 times higher estimates for the same areas and also showing less extreme change over seasons. Icing Maps produced on different scales (Figure 27) also showing better icing potential losses scenario for the finer resolution data, where less pixels fall into classes with longer period of ice occurrence such as 500 to 2000 hours.

With a help of the multi-criteria site assessment model suitability assessments for both study areas were made, and for both study areas assessment shows that at least 57 % of the area for Russian arctic and at least 31 % of the Nenets Autonomous Okrug are suitable for wind turbine placement. All these observations lead to the conclusion that even installing a small percent of possible potential turbines at the most suitable sites can provide a great source of electrification for the remote regions of the Arctic. Some of the highlighted above settlements with high possible productivity have to be considered without any hesitation for bringing wind energy into the area.

CHAPTER 5
DISCUSSION

5.1 Methodological Improvements

This research provides a new approach to wind turbine suitability assessment. The methodology of this study was developed for the special climatic conditions of the Arctic. It was important to produce enhanced monthly characterization of wind power potential which has not been done in previous assessments over Russian territories. The study included the calculation of air density and considered minimal scenario for the potential energy output that small-sized with 30 m blade radius wind turbine can produce over the study area at 50 m height.

The calculations of wind power potential were adjusted for the icing losses. Figure 30 is a comparison map between Wind Power Potential before and after adjustment for icing losses. Contours repeated on both maps on Figure 30, show the annual wind power potential for every 200 MW without adjustment. This contour helps visualize the difference between the maps and shows areas with high potential decrease due to icing. It helps to make a conclusion that consideration of icing is an important part of wind energy potential. Seasonality of calculated wind power potential datasets for both scales is important because it shows how wind potential is changing based on the time of the year and what areas continuously have high numbers. As we know icing occurs most likely in cold seasons, which means highest potentials of winter months can be slightly reduced by icing.

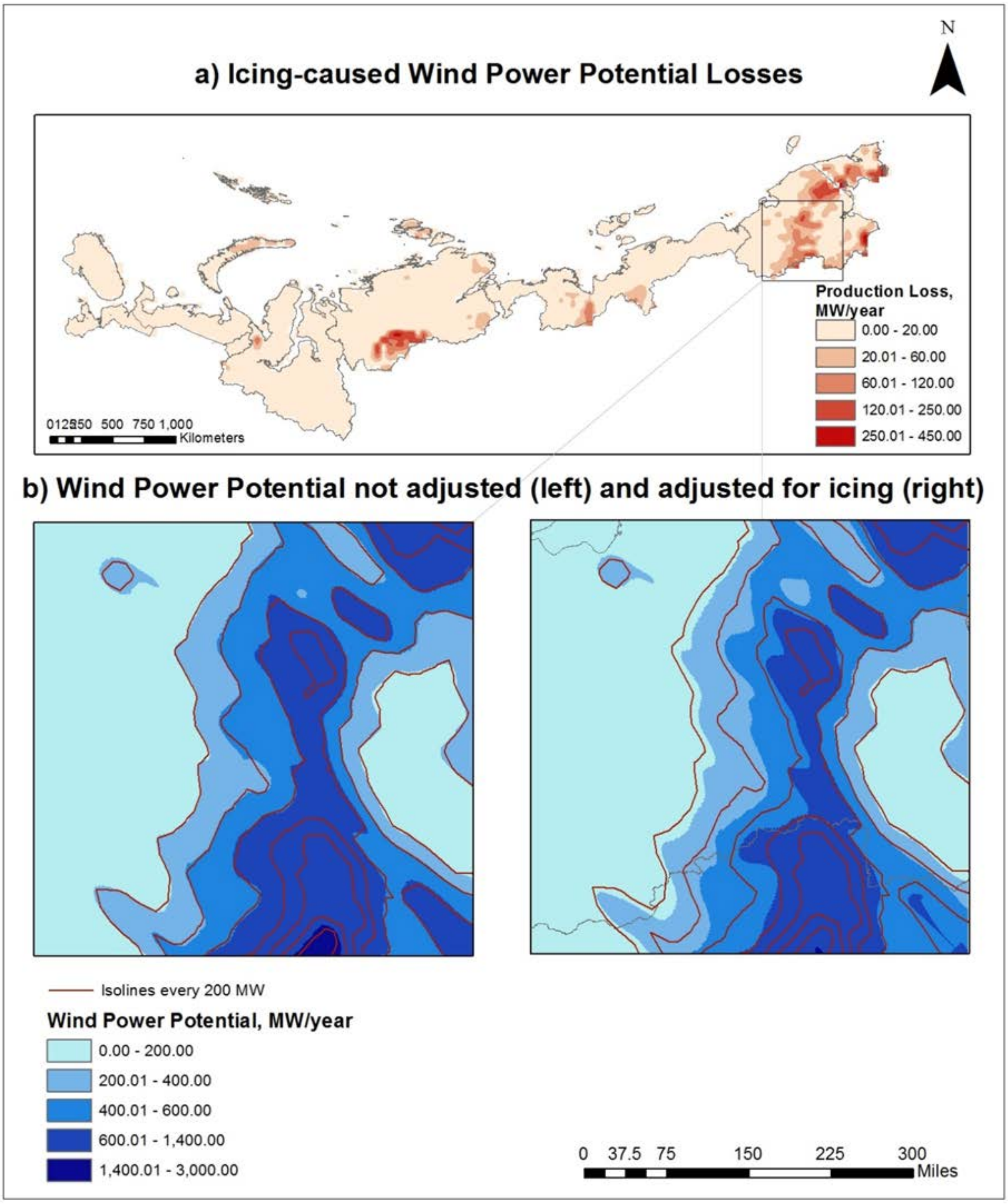


Figure 30: Comparison Map between Adjusted Wind Power Potential Due to icing losses VS not Adjusted Wind Power Potential

Wind Power Potential estimates were calculated for the small sized wind turbines, which was chosen to provide understanding of how much energy can be produced by community scale wind turbine. Investment for the small sized wind turbines should be much less than for the big-sized industrial wind turbine, due to transportation and installation cost. Also, to provide a realistic estimate only 1% of the total power potential was considered, when turbines are installed on every 0.04 sq.m area. The bigger wind turbine will be considered for the installation the more potential it will provide. Also, the better technical characteristics of the turbine, such as high productivity coefficient, or appropriate anti-icing system the higher will be potential.

This is the first wind farm Multi-Criteria Site Assessment completed the Russian Arctic. A large part of the workflow was adopted from previous studies, but for the first time ever data of permafrost zonation was added to the model as a factor criterion. Economic factors such as slope degree, road proximity and permafrost were included into the model to provide better estimates for the future cost of the turbine placement site. The AHP method was instrumental for the multi-criteria site assessment workflow, thus it helped to assign weights to criteria thereby creating a hierarchy between more and less important factors.

The study area was chosen based on administrative regional divisions, which was an important factor of the methodology, allowing calculation of summarized statistics over the regions about wind power potential and suitability assessment which can help for the future development over this region. Adding downscaling process into workflow provided opportunity to give more precise assessments for the downscaled region and helped to compare results calculated with use of different reanalysis data with its different resolution and weather prediction models with the use of which reanalysis data were produced.

5.2 Assessing Results of Downscaling Approach

The downscaling was implemented by replacing two datasets such as Wind Power Potential and Elevation with finer resolution for the study area. The results of the downscaled modeling process for one of the regions of Russian Arctic differ from the results as compared to the Russian Arctic overall. These differences can be influenced by the data provider and the method by which this meteorological data was produced, it is also different based on resolution factor. The map below (Figure 31) represents comparison between grid values of Wind Speeds at 50 m height using MERRA and ARV2 datasets. As we can see subtraction of MERRA 50 km data over ARV2 15 km (rescaled to 50 km) data shows that high difference of 4.5 to 7.5 m/s in wind speed are mostly in the coastal areas, which can be explained by difference in data resolution. MERRA data cannot catch high values of coastal winds because the coverage area of one pixel is 3.3 times greater than for ARV2 datasets. The difference for the winds that are blowing within inland areas varies from 2 to 4.5 m/s and spread evenly across the area. Finer resolution represents better and more precise wind speed characterization. The differences in wind speeds correlate with those of Average Wind Power Potential calculation, where calculated potential is increasing with use of better resolution.

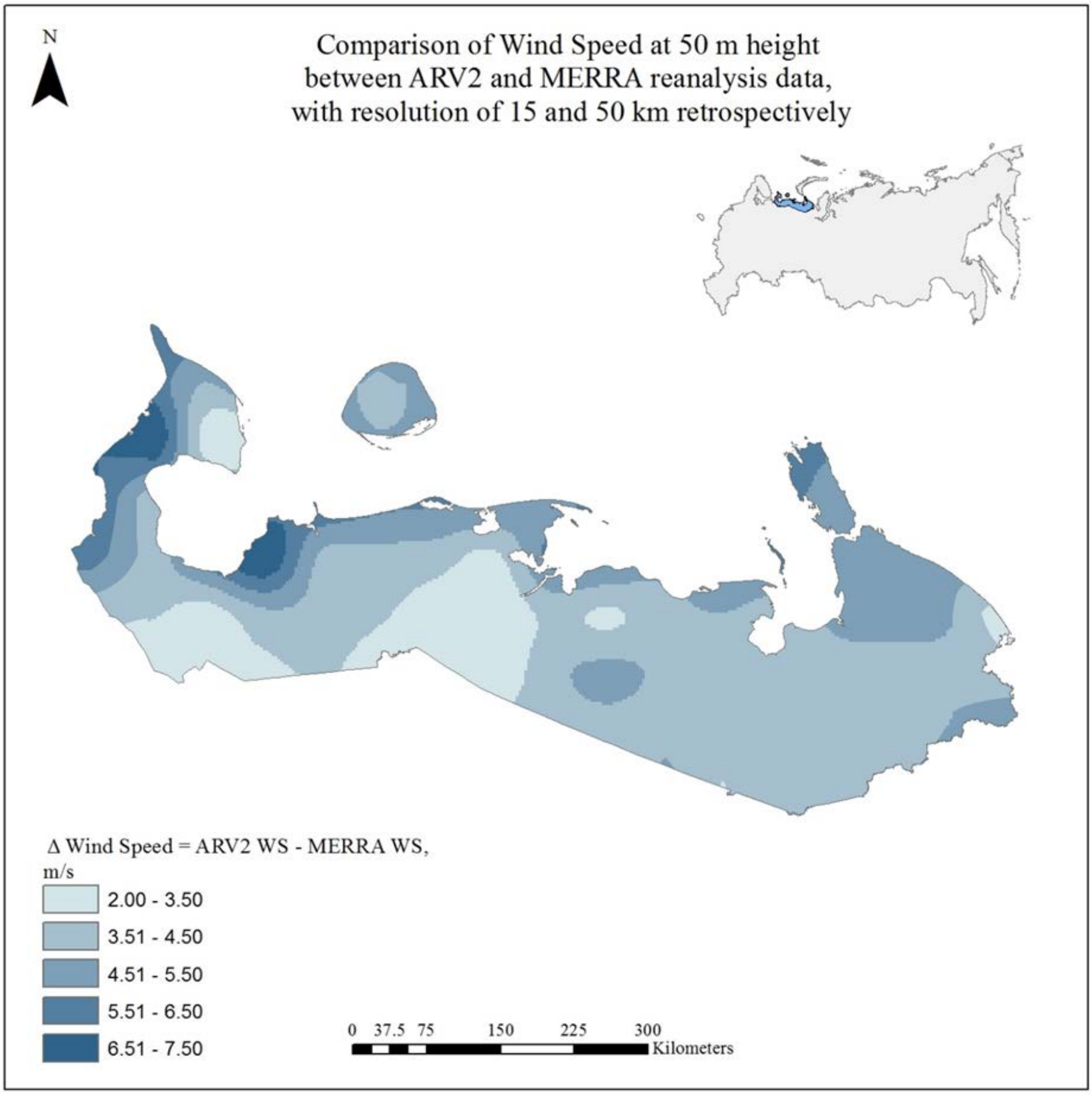


Figure 31: Average Wind Speed at 50 m height comparison between ARV2 and MERRA reanalysis datasets.

Icing maps comparison above (Figure 27) shows that with finer resolution less territories were covered by high production icing losses in hours. But if higher resolution affected icing prediction maps positively, the downscaled suitability assessment showed that finer elevation data played the opposite role. The higher number of unsuitable territories for Nenets Autonomous Okrug was observed for the downscaled suitability assessment and consisted 36.7 % compared with 21.2 % for the Russian Arctic scale assessment. The reason for this underestimation lies in the slopes derived from digital elevation data: slopes derived from coarser resolution dataset did not take into account the changes in altitudes lying within 225 by 225 m pixel size, where finer resolution data could catch elevation change and thereby contribute to slope dataset higher amount of slope degrees that do not meet requirement parameter to be less than 10 %. Thus, we can conclude that downscaling process can positively and negatively affect the output results of assessments.

5.3 Wind Resource Availability and Suitability for Russia's Arctic regions

The Russian Arctic certainly has a considerable potential for wind energy industry implementation. It is highly important to provide a deeper understanding what potential exists over the region for the future applications and decision making purposes. The wind power potential budget is a form of the realistic potential representation, for this study this budget is considered as only 1% of total possible installed capacity for the region.

The map (Figure 32) shows the percent of regional energy consumption this 1 % of installed capacities can cover. Looking at Murmansk Oblast with its total energy consumption of 12,267,600 MW per year, the use of only 1% of total wind energy potential will cover 42 % of all consumption, 404% of energy consumption for Arkhangelsk Oblast (northern part) will be covered by wind energy production.

Nenets Autonomous Okrug’s potential is almost 1.5 times higher than consumption, and wind energy potential almost 3.3 times higher than energy consumption in Yamalo-Nenets Autnomous Okrug, but for the region of Chukotka Autonomous Okrug this percent is overwhelming: the potential there covers nearly 10,385 % of total region consumption which is 100 times more than it is necessary for the region (and this is the region with an existing and planned nuclear plant).

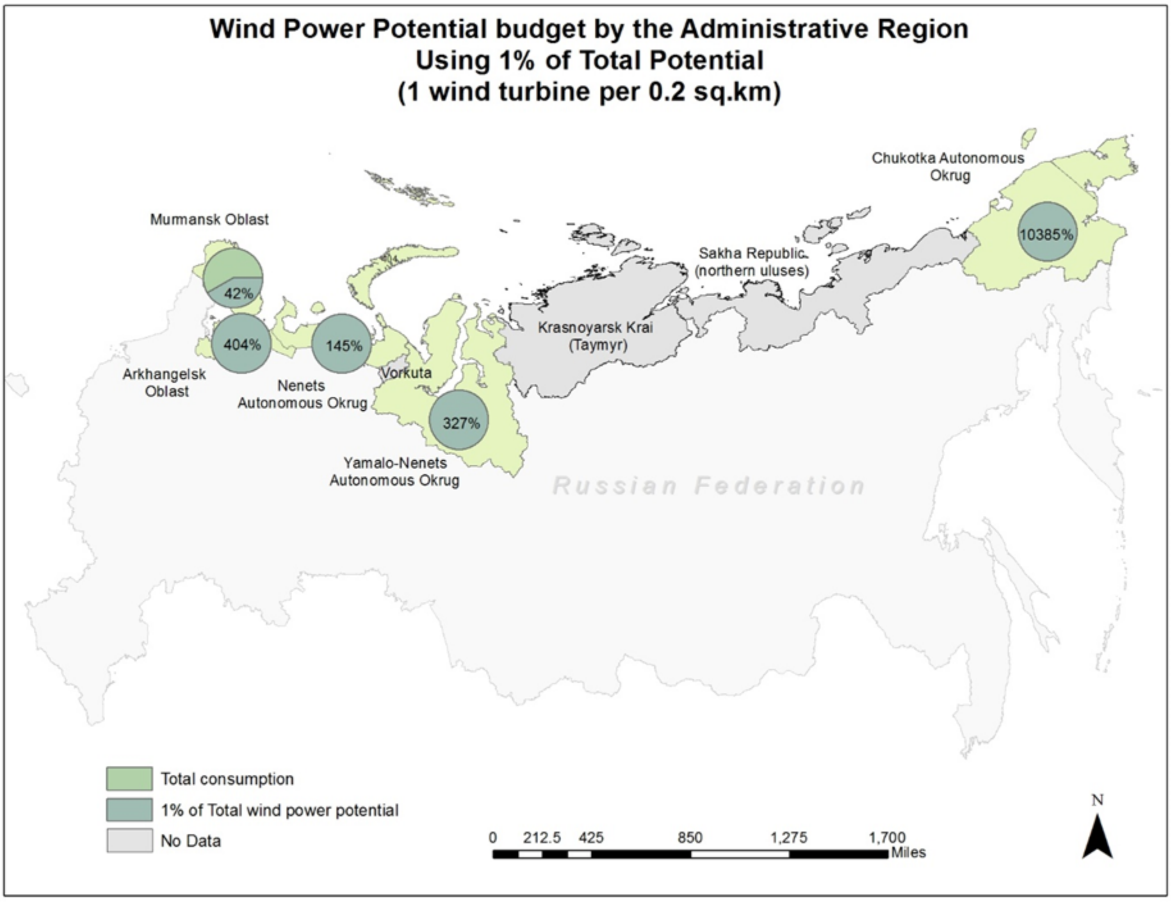


Figure 32: Wind Power Potential Budget by the Administrative Region of Russian Arctic

Since it is known that the total percent of suitable territories for Russian Arctic is 57 %, there is a broad opportunity for wind energy implementation. The map in Figure 33 shows the proportion of unsuitable and suitable areas by region, and demonstrates that almost two thirds of the territories are suitable for consideration. Table 21 represents percent of suitable values in the range from 0.25 to 1 for all Russian Arctic regions. The region with the highest percent of the suitability is Yamalo-Nenets Autonomous Okrug, while in terms of wind power potential, it was placed third of eight regions. Comparing suitability maps of two scales for Nenets Autonomous Okrug percent of suitable locations is changing based on resolution of data from 64% for the Russian Arctic Suitability Assessment to 31% of downscaled assessment, this difference show that results in the Table 21 below can be overestimated.

Table 21: *Percent of suitable values in the range from 0.25 to 1 for all Russian Arctic*

Region	**% Suitability**
Murmansk Oblast	11.43
Arkhangelsk Oblast	19.92
Chukotka Autonomous Okrug	38.72
Sakha Republic	60.30
Krasnoyarsk Krai	63.89
Nenets Autonomous Okrug	64.43
Komi Republic	71.27
Yamalo-Nenets Autonomous Okrug	81.50

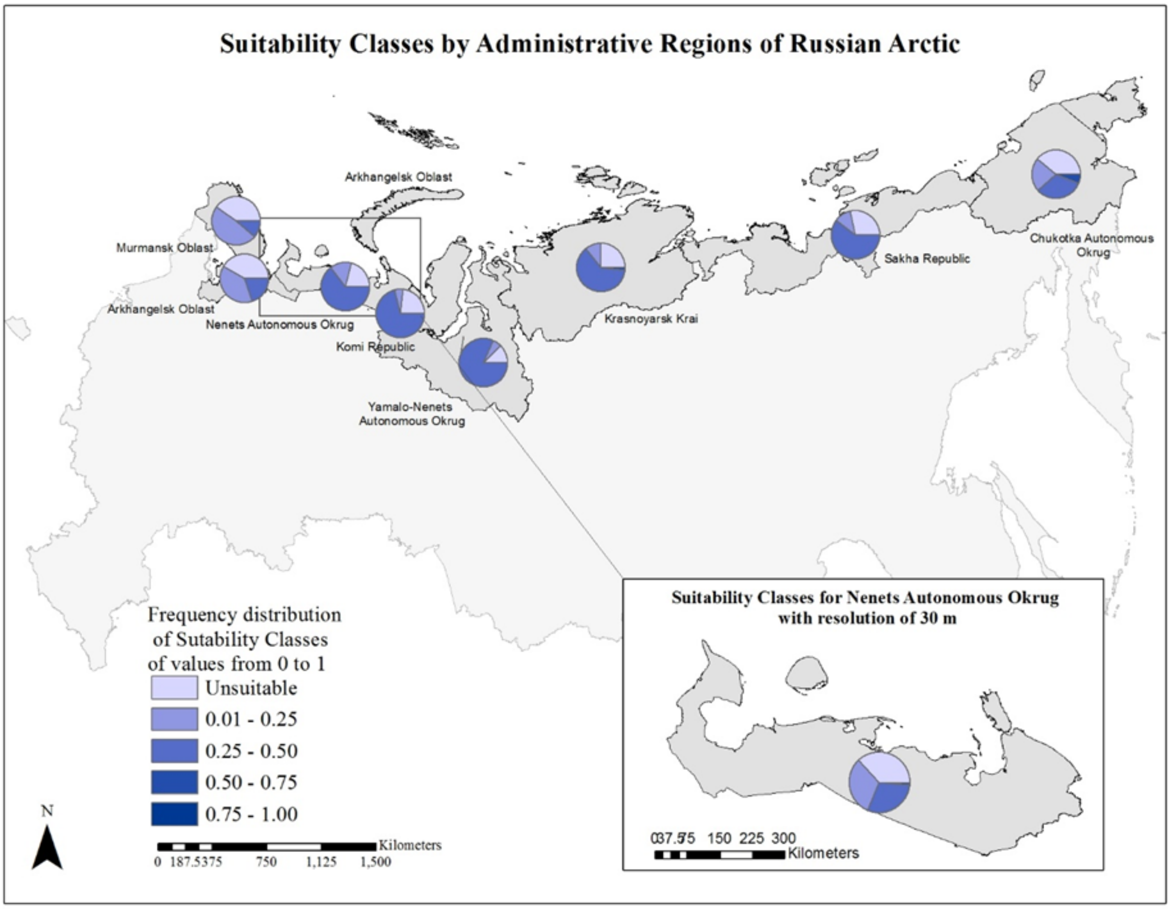


Figure 33: Suitability classes by Administrative Regions of the Russian Arctic

Despite possible overestimation of suitability assessment for the Russian Arctic there is still big potential for wind energy development to be considered in all regions. As we could see above even with using of only 1% of possible potential many regions would cover a substantial proportion or entire regional energy consumption.

CHAPTER 6
CONCLUSIONS

6.1 Conclusions

Wind energy industry has been producing thousandths of megawatts of energy in the Arctic regions. Many studies have provided assessments of wind resources and suitability site assessments. Wind farms distribution over the Arctic is growing with its highest density over Scandinavia and Alaska. Russia lags behind with only a few projects in the Arctic. Research gaps and lack of wind turbine suitability assessment in Russian Arctic inspired this research into finding new approaches and designing a framework for creating wind resource characterization and multi-criteria site assessment for this region. Russia's Arctic remote communities face energy supply difficulties due to harsh environments and remoteness, and many would benefit from community scale wind energy programs. This research was conducted to provide better understanding of where wind energy harvesting can be implemented with lower costs and greater benefits.

One of the important results of this research is a developed framework of wind resource characterization, where wind power potential of the study area was calculated for twelve-months using an examination and use of global meteorological reanalysis data. Average annual estimates of wind power potential were adjusted for such possible production impairment factor as icing occurrence and potential power losses due to it. The inclusion of this variable influenced the results which tells about an impotency of such methodological improvements of using this criteria for wind energy potential estimates.

Wind turbine suitability assessment was completed with the use of appropriate to cold climates multi-criteria decision making system, this system was developed and implemented in this study. Multi-criteria site assessment method included best available data for territory of Russia and included 11 criteria for enhanced site selection. One of the new improvements in this research was the use of permafrost as an economic criterion, where risks of wind turbines construction on unstable permafrost were considered. The regional wind power potential and suitability estimates based on assessments were provided for all eight Russian Arctic regions and showed high potentials of wind energy development. They also showed that regions with highest total wind power potentials were shifted from the first positions after suitability assessment was provided for the same regions.

This research included downscaling to the regional level with the use of finer resolution meteorological reanalysis and elevation data for the area of Nenets-Autonomous Okrug. It should be noted that the Arctic System Reanalysis version 2 wind speed data was used for wind resource estimates over the Russian Arctic for the first time ever. This data was acquired with the personal request and not available yet on resource website. Downscaled suitability as well as wind power potentials assessment were made for the Nenets-Autonomous Okrug. This workflow helped to conclude that for the different-sized study areas an appropriate scale for estimates must be chosen. Results of this research showed that downscaling positively impacted on wind power potential assessments and negatively impacted on suitability site assessment.

The goal of this research was to develop multifactor multiscale models of windfarm suitability for the Arctic regions of Russia. Models were developed and enhanced with the novel characteristics specific for cold climates zones for the Russian Arctic. Characteristic features of Arctic environment are creating additional challenges for the wind energy industry in these territories, but with the use of appropriate assessment model’s difficulties can be reduced. This research is filling some of the research gaps and gives a better, more realistic representation of renewable energy resources for the Russian Arctic.

Results of this study are contributing to the Arctic Renewable Energy Atlas (AREA) by the Arctic Council. Some of the data was given The Sustainable Development Working Group (SDWG) of the Arctic Council. The Atlas is going to be an online resource and will provide solar, wind, geothermal, marine and hydrokinetic resource maps. Overall, the findings of this study could constitute an important contribution for the sustainable development and resilient existence of remote communities.

6.2 Limitations

There are several limitations of this study: (1) the model that was used for wind power potential estimates includes extrapolation to the 50 m height of pressure and temperature methodological data based on the proportional decrease with height for both variables, instead of extrapolation with the use of sea level pressure and temperature at ground level, (2) the icing prediction model is based on existing Icing Map of Finland taken as a standard for reproduction to the study area, the lack of real data of wind turbine energy production based on icing occurrence limits the accuracy of icing prediction, but gives overall rough estimate for icing production losses, (3) downscaling models were based on 13 years reanalysis data, where megaregional scale assessment was based on 30 years average reanalysis data The absence of such data as airport locations over the study area, birds migrations limits suitability assessments.

6.3 Future Directions

Future work in this research could consist of the following: (1) enhance estimates of icing prediction model using meteorological weather prediction models, (2) provide deeper understanding over permafrost influence on cost estimates and physical process around it, (3) create cost effectiveness for the all factor variables, such as difference between cost of installing wind turbine on slope of 7% VS 1%, (4) provide a framework for estimating installation and operation costs in particular locations.

I would also like to suggest to the government to consider the obtained results for decision making purposes. There is substantial interest in the development of renewable energy across the world, by providing clean and cheap energy to the communities creating better and sustainable future for new generations of people.

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