TALLINN UNIVERSITY OF TECHNOLOGY

FACULTY OF CHEMICAL AND MATERIALS TECHNOLOGY
DEPARTMENT OF MATERIALS SCIENCE

TRANSPORT SCENARIOS FOR THE MAINTENANCE OF HIIUMAA OFFSHORE WIND FARM

Master Thesis

Maribel Mirontšik

Supervisor: Ivo Palu, Chair of High Voltage Engineering, Associate Professor
Co-supervisor: Siim Paist, Nelja Energia AS, Development Manager

Materials and Processes for Sustainable Energetics KAYM09

2015

Declaration

Hereby I declare that this master thesis, my original investigation and achievement, submitted for the master degree at Tallinn University of Technology has not been submitted for any degree or examination.

…………………………

Maribel Mirontšik

132485KAYM

TALLINNA TEHNIKAÜLIKOOL

KEEMIA- JA MATERJALITEHNOLOOGIA TEADUSKOND

MATERJALITEADUSE INSTITUUT

TRANSPORDI STSENAARIUMID HIIUMAA MERETUULEPARGI HOOLDUSE LÄBIVIIMISEKS

Magistritöö

Maribel Mirontšik

Juhendaja: Ivo Palu, kõrgepingetehnika õppetool, dotsent

Kaasjuhendaja: Siim Paist, Nelja Energia AS, arendusjuht

Materjalid ja protsessid jätkusuutlikus energeetikas

2015

TABLE OF CONTENTS

INTRODUCTION

In the future wind energy will move from onshore to offshore since many problems arising from onshore location can be eliminated in this way. At the present moment there are no offshore wind farms in Estonia. However, two applications have been submitted to Ministry of Economic Affairs and Communications of Estonia for construction license of offshore wind farms in Hiiumaa sea areas. [1] As Baltic Sea has strong winds investors consider it suitable for offshore wind energy. Apart from that, quite shallow waters and smooth sandy seabed makes the construction easier.

Nelja Energia is a company interested in developing offshore wind farm with total output of 700-1100 MW in three groups of wind turbines, situated on the shoals that are located in the north, northwest and west of Hiiumaa. Planned offshore wind farm will be the first offshore wind farm in Estonia, at the same time one of the biggest ones in Europe, and located in harsh climate conditions during winter. As Estonia has no previous experience in offshore wind energy this project has a remarkable significance in developing Estonia's offshore wind energy sector.

The main problem that comes with the Estonian climate when looking from the point of maintenance and accessibility is the sea ice making transportation of the crew to the site more complicated. Apart from that, when going technical, there are more problems: atmospheric icing and force of sea ice. The atmospheric icing may cause ice formation on turbine components. Sea ice can cause additional forces on the turbine structure. [2] However, this master thesis will focus on transportation of the maintenance crew while taking into account weather conditions in Estonia.

The aim of the master thesis is to provide most suitable transport scenario for Hiiumaa offshore wind farm while taking into account site accessibility problems that come from Baltic Sea freezing up during the winter. Long response time to turbine breakdowns means unearned profit. For planning the maintenance of Hiiumaa offshore wind farm two different transport scenarios will be provided. Vehicles included in the scenarios will be chosen considering the weather conditions in the planning area. The most cost-effective transport scenario will be chosen.

1. MAINTENANCE OF OFFSHORE WIND FARMS

Wind energy is clean and reliable energy source. Due to considerably stronger and more constant sea winds wind energy is moving from onshore to offshore. Apart from that, offshore wind farms have quite low visual impact while onshore wind farms raise reluctance in local communities because of aesthetical reasons.

The main difference between offshore and onshore wind turbines is that offshore wind turbines are located in the water. Most offshore wind turbines are placed in waters up to 30 meters deep. In Europe, the average water depth of wind farms completed or partially completed in 2014 was 22.4 m and the average distance to shore was 32.9 km [3]. Offshore environment makes construction, maintenance and operation costs higher than those of onshore wind farms.

Distance from the shore is one of the most important factors when planning the maintenance. There are also other factors that have to be considered such as average wave height and ice conditions. Workboats available on the market are limited by maximum wave height 1.5m that allows transferring of technicians from boat to the turbine [4]. In case of ice conditions, to enable the access to the turbines alternative vehicle has to be used instead of widely used workboats. At the same time transit time should be kept as short as possible because longer downtime of the turbine means greater unearned profit.

As more and larger offshore wind projects are built further from shore, accessing the turbines to carry out maintenance will require new logistical solutions. Increasing transit distances mean that strategies which include helicopter support and, eventually, offshore-based working will be needed. [5]

1.1 Preventive and corrective maintenance

Maintenance activity is the up-keep and repair of the wind farm and its systems. It is divided into preventative maintenance and corrective maintenance. Preventative maintenance is repair that is done while the turbine is still able to work. It can be a repair or a replacement of known components of the turbine. The information is received from routine inspections or from condition monitoring systems. In other words it is scheduled maintenance [5]. Scheduled maintenance includes oil and filter changes, calibration and adjustment of sensors and actuators, replacement of consumables such as brake pads and seals, housekeeping and blade cleaning. The specific tasks and how often these should be performed are stated in the maintenance manuals supplied by the turbine vendor. [6]

Corrective maintenance means that the component is already failed of damaged and due that needs to be repaired or replaced. This is called unscheduled maintenance. The response to such faults can vary from a simple inspection or a restart of a wind turbine, which can take a couple of hours, to a replacement of an offshore substation transformer, with repair time of weeks or months. [5]

It is very important to detect errors in turbines in time when it is not too late. For example, the cost of a bearing failure, when the turbine is shut down for two days to change the bearing, is some thousand euros. When the right time for maintenance is missed, the bearing will be driven to destruction and the gearbox of the turbine will be destroyed. [7] The cost of it can be enormous because repairs in that size need jack-up vessel. The waiting time can be some months.

Small and medium unscheduled repairs, also annual planned service, can be done with crew transfer vessels. For larger repairs field support vessel or jack-up vessel is needed. The parameters of these vessels are shown in Table 1.

Table 1. Parameters of vessels used for supporting offshore wind farms [8]

	Crew transfer vessel	**Field support vessel**	**Jack-up vessel**
Governing weather criteria	Wave	Wave	Wave/Wind
Weather criteria	1.5 m	Up to 2.5 m	2.0 m/ 10m/s
Mobilisation time	0 weeks	3 weeks	2 months
Speed	Max 45 km/h	22 km/h	20 km/h
Failure types used for	Manual resets, minor and medium repairs, annual scheduled service	Major repair	Major replacement

Crew transfer vessels are workboats meant for transferring technicians and lightweight equipment to the site. Some wind farms use helicopters instead of these for the same purpose as for some sites the wave height is too high or distance too long. Field support vessel costs at least twice of the price of one crew transfer vessel and due that usually service of those vessels is bought from companies providing offshore operations. As repairs in that size are not needed often, it is not reasonable for wind farm operators to own it. Field support vessel can carry more cargo and has higher crane than crew transfer vessel. The accessibility with field support vessel is higher because it allows access to turbines 24 hours while crew transfer vessels have daylight preference. Also, field support vessel can be used with wave heights up to 2.5 m. [8]

There are three different strategies that can be employed for offshore wind farm support shown in Table 2. Which one is the most suitable depends from the distance between the offshore wind farm and onshore facilities.

Table 2. Offshore logistics strategies [5]

Strategy	**Transport**	**Distance from the port**
Workboat-based	Only workboats operating from a port base	Less than 20 km
Heli-support	Helicopters supporting the workboats	20-70 km
Offshore-based	Fixed or floating offshore accommodation	70 km and more

Workboats are well suited for scheduled activity when the turbine is not at risk of unexpected power outage. Helicopters may be more suited to unscheduled activity when response time is critical [5]. The cost of using helicopter is high but the cost of lost production can be higher when turbine fails. Fast response may prevent a major breakdown.

As wind energy is moving more further from the shore it is possible that at some point offshore-based strategy is the only reasonable one. Offshore based strategy means that technicians live at a base near or in the wind farm for a number of days [5]. The base itself may be either fixed accommodation modules, similar to those used in the oil and gas sector, or boats of varying sizes such as motherships, offshore support vessels or jack ups [5]. The transportation from the base to the turbines would be by means of smaller boats.

1.2 Availability and accessibility

When it comes to the economics of operations and maintenance of the project there has to be balance between the money spent on maintaining the project and the revenue lost when the turbines are shut down due to technical problems. Performance of the project can be measured with availability, which is a proportion of a time when turbine is capable of producing electricity. Availability is used to measure the amount of electricity lost due to equipment downtime. Usually for offshore wind farms it is between 90% and 95% while onshore wind farms can achieve 97%. Following Figure 1 shows how cost of operations and maintenance influence the turbine availability. [5]

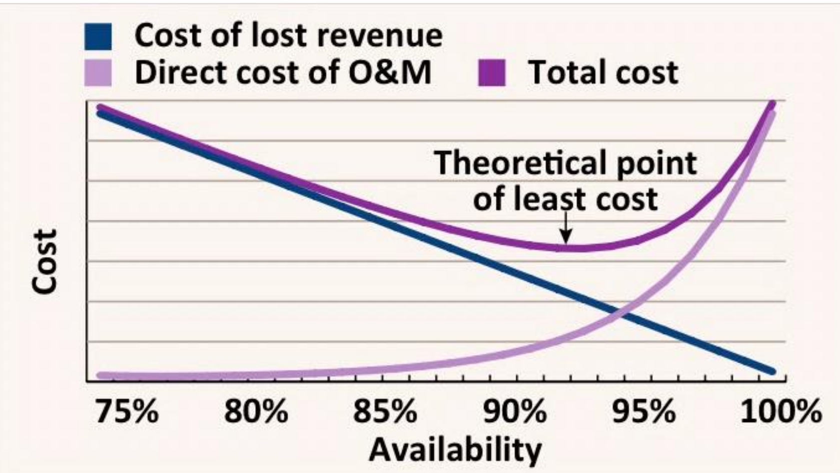

Figure 1. Balance between cost and lost revenue [5]

Although the cost of lost revenue declines to zero when the turbine approaches availability of 100%, the cost of maintenance that is needed to achieve it approaches exponential growth. This means that if the investment to the maintenance is too small the performance of the turbine drops and the result is bigger amount of lost revenue. On the other hand, when the owner over-invests in maintenance, the result is not greater profit but diminishing returns as each increment in availability costs more than the previous one. The theoretical point of least cost shown in Figure 1 is slightly different for every project, but it gives the idea how the balance between the maintenance costs and lost revenue has to be found. [5]

One of the main obstacles to maintaining offshore wind farms and keeping the availability of the turbines high is getting technicians on and off the turbines. The factors influencing it are the transit time and accessibility. Transit time is the time what it takes to shuttle the technicians from the base to the site. The time spent on transporting the crew to and from a job site cuts into the amount of time actually working to maintain the turbines. This means the further the project site is from the base, the longer is the transit time and the shorter is the time that can be used by crew on active work. Furthermore, long transit time is tiring workers. [5]

Under accessibility it is meant the time while the turbine can be safely accessed from the service vessel. No difference what kind of vessel is used, it is always dependent on the weather or sea conditions. The accessibility level for offshore wind farms is always below 100%. For example, if a project has significant wave height greater than 1,5 m for 40% of the time, a vessel that can be used with waves 1,5 m or less has an accessibility of 60%. [5]

2. OVERVIEW AND DATA OF HIIUMAA PROJECT

Offshore wind energy is widely used in the North Sea, but Baltic Sea is more unexplored area for that. In Finland there are no offshore wind farms in operation yet, but the first step has been made to develop 40 MW Pori Tahkoluoto offshore wind demonstration project starting to operate in 2016. The Finnish Government is covering the project to support a new renewable energy market in Finland. The aim of this project is to value the possibility of offshore wind in harsh conditions. [9] Pori Tahkoluoto has to cope with similar conditions as Hiiumaa project: iced up sea and low temperatures.

In the planning stage, the location of wind turbines of Hiiumaa offshore wind farm has been changed many times mainly because of the reluctance of the communities to the project. The planned locations for wind turbines are orange colored areas shown on Figure 2. From left: shoal (1), shoal Vinkov (2;3) and shoal Apollo (4).

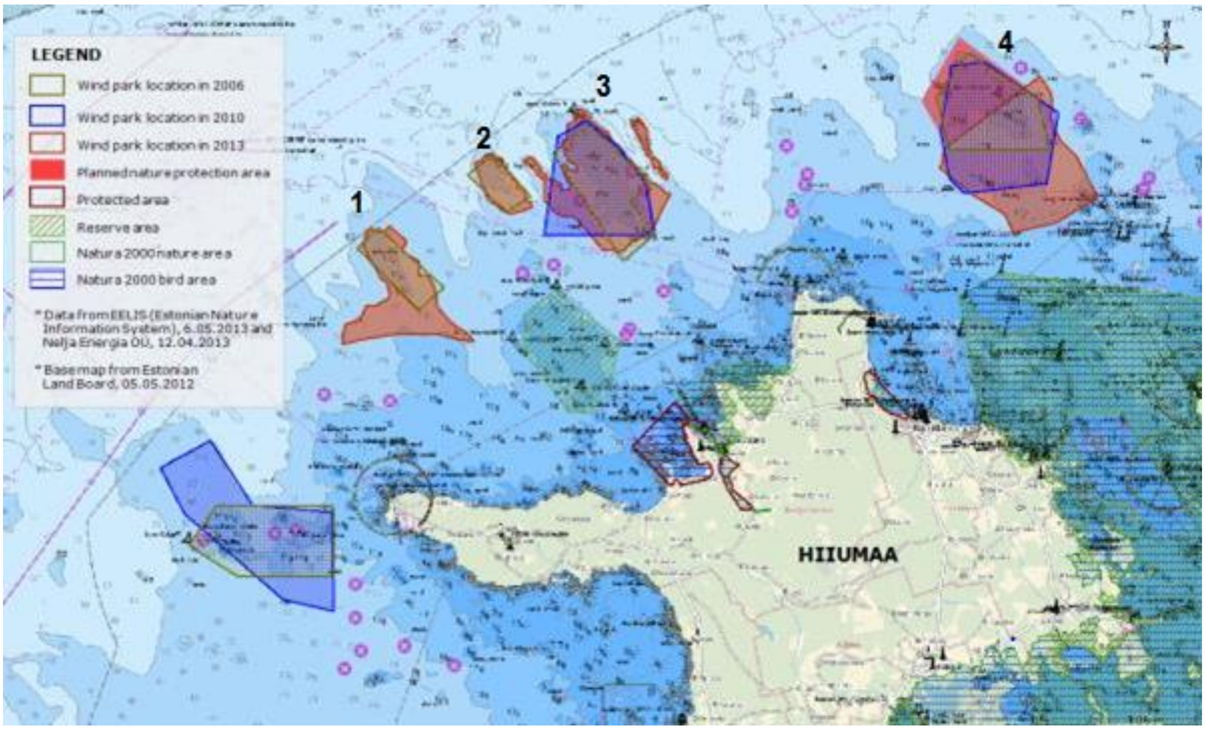

Figure 2. Location of wind turbines [10]

The main change when comparing the latest plan to the plans of 2006 and 2010 is that developer has excluded Neupokojev shoal in the west. The reason can be described with acronym NIMBY coming from the phrase “Not in my back yard”. This means the opposition of the local communities to the project because of the visual impact. Moreover, as the coastal sea near Kõpu peninsula, which is close to Neupokojev shoal, is very popular for surfing, surfing enthusiasts were against the project fearing that the wave height will decrease due to turbines. According to the studies it turned out that near the coast the decrease in wave height does not exceed 2 cm and 2-5 km from the coast the decrease will be maximum 7 cm [11]. This is not significant change but nevertheless the developer decided to exclude the Neupokojev shoal.

It is important to note that Apollo shoal is partly located in the Väinameri Sea while other turbine groups will be located more offshore. This means different wave heights and different ice conditions that have to be taken into account when planning maintenance and transportation possibilities.

Delay in allowing the construction of offshore wind farms in Estonia comes from the lack of comprehensive researches and assessments about Estonian marine resources. The Government of Estonia has started developing the framework how do use marine resources sustainably. The result will be identified maritime area of Estonia- different areas have their range of use. This will give investors confidence to plan new renewable energy solutions because currently competition for maritime space is growing and clearer rules need to be done to avoid conflict between different sectors like aquaculture, ocean energy, tourism and other. [12]

2.1 Main parameters of the project

The capacity of the wind farm is planned to be between 700-1100 MW. Lower capacity would not be reasonable because project in that size has very high costs. The larger the wind farm is, the lower are the operating costs per turbine as wind farm needs service vehicles, facilities, ports and personnel [5]. According to the developer the realistic output of the wind farm is 900-1000 MW.

The latest approved parameters of Hiiumaa project are shown in Table 3. As Hiiumaa offshore wind farm is in the planning stage, parameters given in the table may not be final and can change. Many parameters presented in Table 3 have a great importance from the viewpoint of maintenance and have to be taken into account.

Table 3. Parameters of Hiiumaa offshore wind farm [10]

Parameter	
Planned output	700-1100 MW
Number of turbines	155
Number of productive hours	3500
Distance from the coast	12 km
Depth	Max 30 m
Connection to the grid	Kanapeeksi substation
Foundation type	Gravity base
Distance between the turbines	1 km

The distance from the coast has a great impact on travelling time of the maintenance crew. Time is very important when there is a major failure and turbine is shut down. Longer downtime means greater unearned profit. The distance from the coast has to be at least 12 km because of the visual impact for the local communities. The last row of turbines will be located about 20 km from the shore.

In the planning area trawling is common action and is done at depth starting from 30 m. In order to avoid the planning area to interfere with fishing area the overall maximum depth for the project is 30-35m and 30 m when trawling area is in the immediate vicinity [13].

The area between the turbines is allowed to use for small ships, fishing vessels and vessels performing administrative tasks of the government (length up to 24 m) and vessels used in the economic activity. Vessels over 24 meters, with the exception of fishing vessels, shall not pass through wind farms, but have to keep a safe distance from the farm. The Maritime Administration may establish a ban of movement near the wind turbines if this is necessary to ensure the safety. [13]

The exact number of turbines depends from the capacity of the turbine. For example: with the output of 700 MW and turbine capacity of 3 MW the total amount of turbines will be 233; with the output of 700 MW and turbine capacity of 6MW the total amount of turbines will be 117. The number 155 in Table 1 is planned number of turbines with capacity 6 MW (930 MW in total) as the realistic output is 900-1000 MW.

For onshore sites in Estonia, number of productive hours is from 2000 to 3000 h/year while for offshore it stays in range of 3000-4500 h/year [14]. This means the amount of hours when the turbine can generate electricity at full power.

It is planned that with 6 MW turbines the distance between the turbines must be about 1 km to avoid energy loss through wind shadowing. On the other hand, the greater is the distance between the turbines the greater are the costs for maintenance. When planning the layout of the turbines the compromise has to be found between low capital cost and energy losses coming from shadowing.

Turbines will have gravity base foundation, also shown in Figure 3, which is the most environmentally friendly solution for the site as it does not require such amount of construction work at sea as other foundation types (monopile, jacket and tripile) [15]. The gravity type support is concrete structure that can be reinforced with steel, and is filled with ballast, for example sand or rock. This ensures that the whole turbine will be heavy enough to stay rooted even in the stormy conditions. As Baltic Sea has quite firm and smooth seabed this is the rational solution to use.

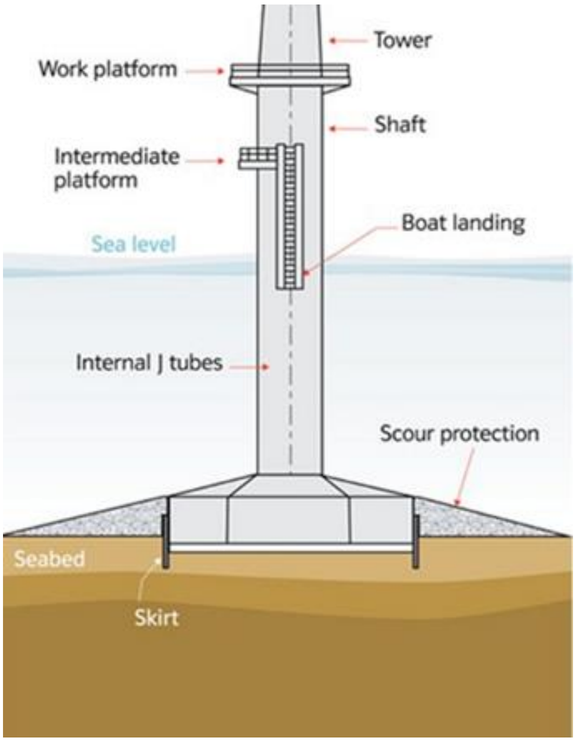

Figure 3. Gravity base support structure [17]

110MW Lillgrund offshore wind farm in Sweden has also gravity base foundations. For the construction five different foundations were used because of the different water depth. The deeper water the turbine had to be located the higher shaft was constructed and more ballast was used. [16]

Highest shaft had a height of 14.3 m while the lowest shaft had length of 10.3 m. To compare, the highest foundation was filled with ballast of 879 tons making the total weight of the foundation 2254 tons while the lowest was filled with ballast of 803 tons making the total weight 2102 tons. It is important to note that Lillgrund wind farm is located only 7 km from the shore and the maximum water depth is 4-8 m. [16]

Connecting transmission system of Hiiumaa to the mainland is prerequisite for planning offshore wind farm in Hiiumaa areas. Connection of local central and/or high-voltage grid with mainland transmission system improves the security of supply of electricity in Hiiumaa and Saaremaa. Exact technical solutions will be determined during the design and planning process. Probably the connection with Estonian transmission grid will be made through new 330 kV Kanapeeksi substation. [13]

All activities of operations and maintenance need access to port facilities. The distance between the project site and port facilities is the primary consideration as day-to-day personnel and tools transfers benefit greatly from short transit times. [5]

Major repairs of turbines or planned replacements of major components are not that sensitive on distance and usually need field support vessel or jack-up vessel [5]. Nelja Energia invests and creates its own maintenance unit that covers all personnel and equipment needed for small and medium repairs, but for major repairs Finnish Sea Service will supply the service. They have multipurpose jack-up barge under construction. It will be used for offshore operations covering the area of the Baltic Sea. [18]

According to the law, harbors in Estonia are classified into small ports and ports. Small port is a port or a part of a port where port services are provided for crafts with length less than 24 meters. All workboats that will be used as a crew transfer vessels will be less than 24 meters long. [13] It is estimated that for maintenance and operations three harbors Lehtma, Kõrgessaare and Kalana will be used. Locations of three ports are shown in Figure 4. There is no need to build new ports for Hiiumaa project, however it is possible that reconstruction of existing ports is needed. Kalana and Ristna ports have a great potential for development because in that area the natural depth of 5 m is closest to the shore. Kalana port could be deepened to a depth of 3.5-5 m. Right now Kalana port can serve only boats with a draft less than 2,5 m. [1]

Figure 4. Three main ports Kalana, Kõrgessaare and Lehtma that will be used as onshore facilities for supporting maintenance [1]

The maximum depth of Lehtma and Kõrgessaare are accordingly 4,2 m and 2,5m [13]. Lehtma is the main harbor where storage facility for spare parts and technical equipment will be located. During winter period Kalana harbor is ice-free for the longest time among three mentioned harbors.

It is estimated that Hiiumaa project will create up to 30 occupations. Most of the occupations are related to maintenance and operations of wind farm. The number of technicians will be around 26 persons. Work is organized according to the schedule. Each shift lasts for 12 hours. During the period of planned maintenance the schedule is tightest. In case turbine fails and needs unplanned service at the same period of planned maintenance, planned maintenance will be postponed and at least two technicians will go to repair failed turbine. [18]

2.2 Climate conditions

More detailed overview of wind, ice and wave conditions in the planning area will make clearer what are the factors that have to be taken into account when planning the maintenance. Climate conditions have a great importance when choosing suitable vehicles for transferring technicians to the site.

2.2.1 Wind conditions

There is meteorological station in Ristna quite close to the planning areas of Hiiumaa offshore wind farm, but it does not have enough precise data about wind speeds of offshore areas. However, it has accurate data about wind speeds on coastal areas. The mean wind speed at coastal areas in Ristna is 4.25 m/s. This is based on the data recordings of period 1977-1991 [19]. As the wind speed on sea is increasing with the distance from the shore, it can be said that the mean wind speed in the area of Hiiumaa offshore wind farm is considerably higher than 4.25 m/s.

The wind data from Vilsandi meteorological station can be successfully used to evaluate offshore winds, although it is located in Saaremaa. Weakest winds are in April to September, when the average speed stays less than 6 m/s. The period of strong winds is from October to February, when the average speed of wind is over 6.5 m/s. [1]

The seasonality of wind speed is better to notice when examining the occurrence of wind speeds >10 m/s and >15 m/s. For example, in November the occurrence of these winds is correspondingly 5 and 15 times higher than in May. [1] From Figure 5 it can be seen that the weakest winds are during summer and strongest winds in winter. Summer is the most reasonable period for doing the planned maintenance to turbines, as unearned profit coming from shutting down the turbines for maintenance, will be smallest.

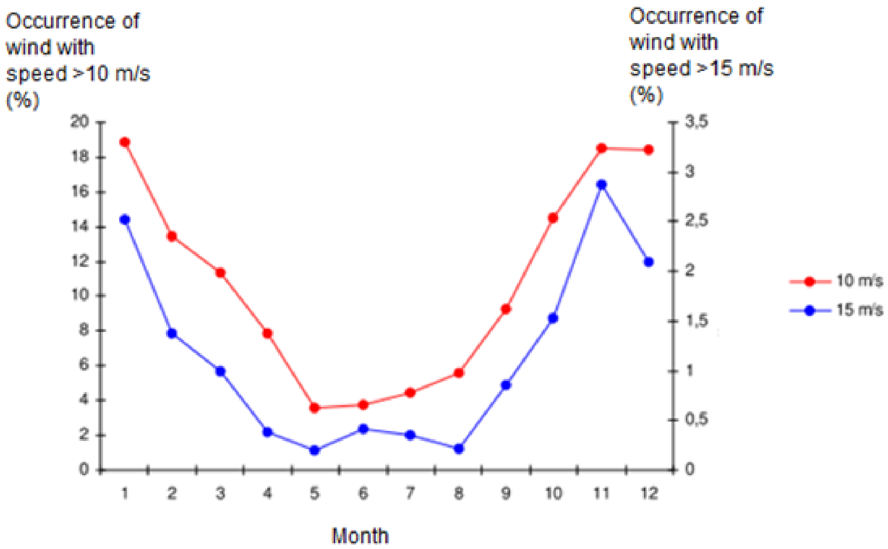

Figure 5. The occurrence of winds with speeds >10 m/s and >15 m/s by months [1]

In 2009 wind measurements were carried out on Vinkov shoal during period from July to December. Measurements showed that the average wind speed for hub height 80 m is 8.5 m/s during this period. To compare with onshore site, the average wind speed at Pakri was 2.0 m/s lower. [14] According to the data of 2000-2009 that is obtained from NASA satellites, the mean wind speed in the site of Hiiumaa Offshore wind farm is 9.02 m/s. This is calculated for hub height of 100m. [20] In Sweden, the mean wind speed for Lillgrund offshore wind farm is 8,5 m/s at the hub height of 65 m [16].

2.2.2 Storms

Storms, where the average speed of wind during 10 minutes measuring was at least 20 m/s, occurred 43 times during 21 years of data recordings in Vilsandi. 18 storms came from N and NW and 20 storms from S and SW. One of the strongest storms was registered in March 1992 when during 15 hours the measured average wind speed was ~26 m/s and maximum average wind speed during 10 minutes measuring was 28 m/s. In January 2005 the maximum average wind speed during 10 minutes measuring was 22,9 m/s. Wind gust, the maximum instantaneous speed in 10 minutes, was 33 m/s. The occurrence of storms has increased in recent decades. [13]

Wind turbines have a cut-out speed (Figure 6). This means that starting from the wind speed 24-25 m/s the rotor can be damaged and for avoiding it the turbine is shut down. As a result, the strongest winds are not as efficient as they logically should be. Most of the turbines achieve their maximum power output at wind speed 14-17 m/s.

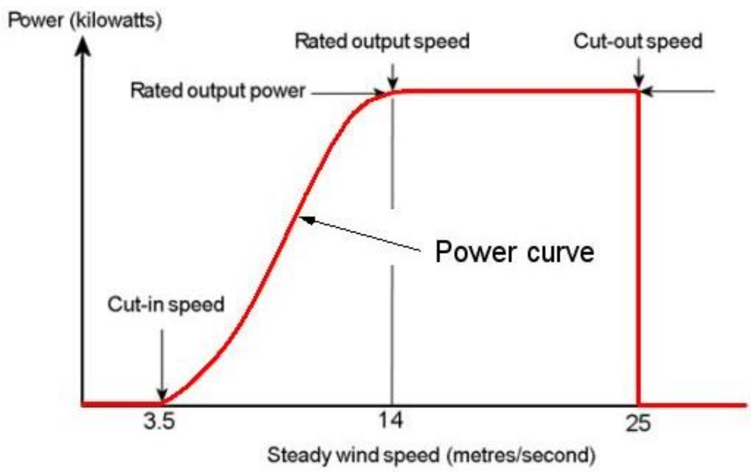

Figure 6. Typical wind turbine power output with steady wind speed [21]

2.2.3 Ice

The ice conditions in the Baltic Sea differ strongly from year to year. The abundance of ice is determined by the harshness of winter which in turn depends on the atmospheric circulation [1]. From Figure 7 it can be seen how ice extent varies with mild, normal and sever winters. For example, winter 2014/2015 was certainly in the category of mild winters as there was no ice in the planning area and any vehicle bought for maintenance during ice period would have been unnecessary. Winter of 2014/2015 was one month shorter than the duration of average winter of last 93 years [22]. Climatologically, winter is a period when the snow is permanently on the ground and average daily temperature is mostly lower than zero degrees. Continuous snow cover occurred in December 21 and melted in February 21 resulting in 61 days of winter [22].

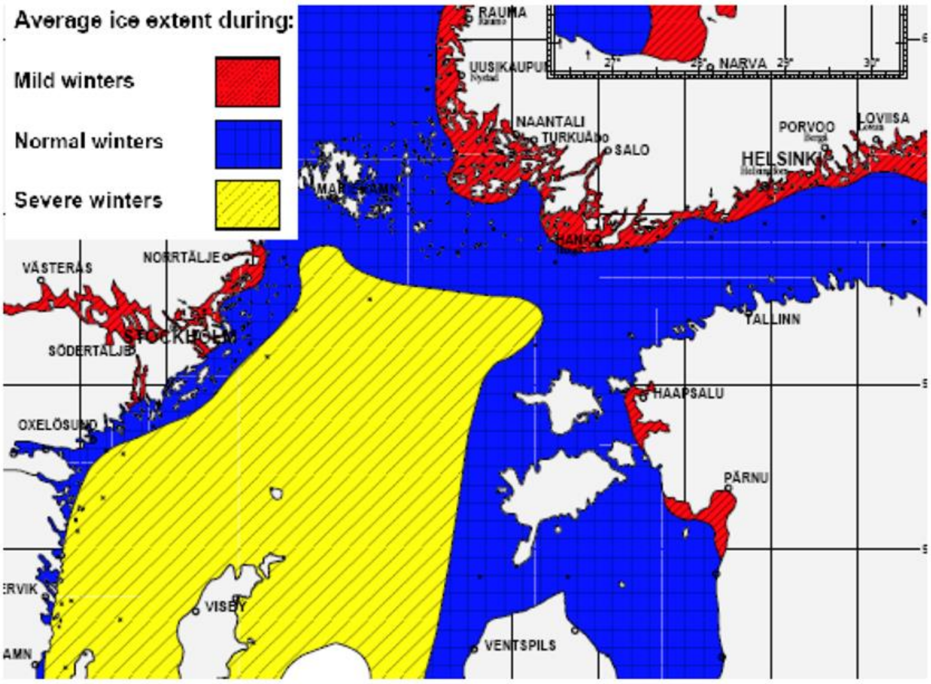

Figure 7. Average ice extent during mild, normal and sever winters [23]

When the airflow is coming mostly from west, the winter is mild as the airflow carries the North-Atlantic, warmer and more humid air to the Baltic Sea region [1]. As shown on Figure 7 the centre part of Baltic Sea freezes up only during severe winters.

Ice conditions depend not only on the harshness of winter but on other variables such as wind and rainfall. Thus, even in relatively harsh winter the coastal sea of Hiiumaa can be ice-free as favorable winds are pushing drift ice away from the shore. Also, wind can make the ice tight or more scattered. The more tight the ice is the longer it lasts. [24]

The abundant amount of snow can cause natural insulation to the ice cover, therefore, even in cold weather the ice does not grow very fast. This happened, for example, in the winter 2009/2010, when despite of the low temperatures the ice cover in the Väinameri Sea did not grow enough fast due to the thick layer of snow and it was not possible to open the ice road. [1]

In planning area during normal winters the ice conditions are lighter when situated offshore and heavy when in the Väinameri Sea. During the period 1949-2004 the average duration of the ice cover in Ristna was two months. Nevertheless there were years with no ice cover at all. In the same period the ice cover in Heltermaa was nearly four months. In very cold winters the ice cover duration can be even longer, for example, in 1966 it took 174 days from the formation of ice to final melt down in Heltermaa. In the Väinameri Sea the ice cover can reach the thickness of 40-50 cm, sometimes even more than 60 cm. It is possible that much thinner ice can occur near very thick ice. In February 1994, the study was carried out for Kuivastu-Virtsu ice road and the measured maximum thickness of the ice cover was 49 cm, average 38 cm and minimum 25 cm. [1]

In 16 March 2013 the Väinameri Sea was completely covered with ice. From Figure 8 we can see drift ice in three locations: in east part of the Gulf of Finland, between Hiiumaa and Saaremaa and in the Gulf of Riga. Probably because of the north winds most of the drift ice in these locations has been gathered to south coasts. [1]

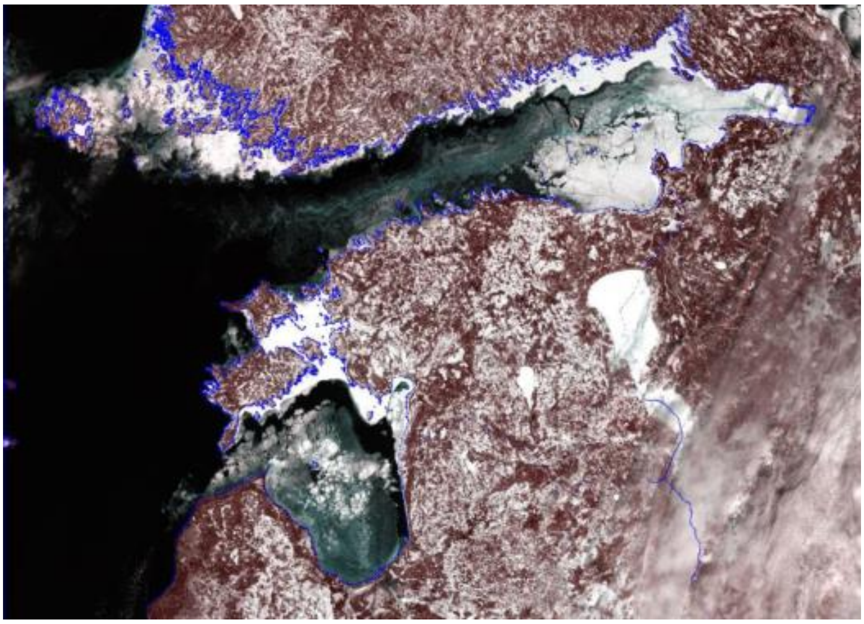

Figure 8. Ice conditions in the Estonian coastal waters. March 16, 2013. [1]

2.2.4 Waves

The planning area of Hiiumaa offshore wind farm can be divided into two parts when analyzing waves: open sea and the Väinameri Sea. One group of turbines on Apollo shoal is situated in the Väinameri Sea, while other three groups in the open sea. The wave height of the Väinameri Sea is limited to a low depth and short run available. As a result there is a difference in wave heights. From Figure 9 it can bee seen that the long-term average wave height is highest in the western part of the sea (1 m) when taking Hiiumaa as a center. Slightly lower wave height is in the north part (0,8 m). [1]

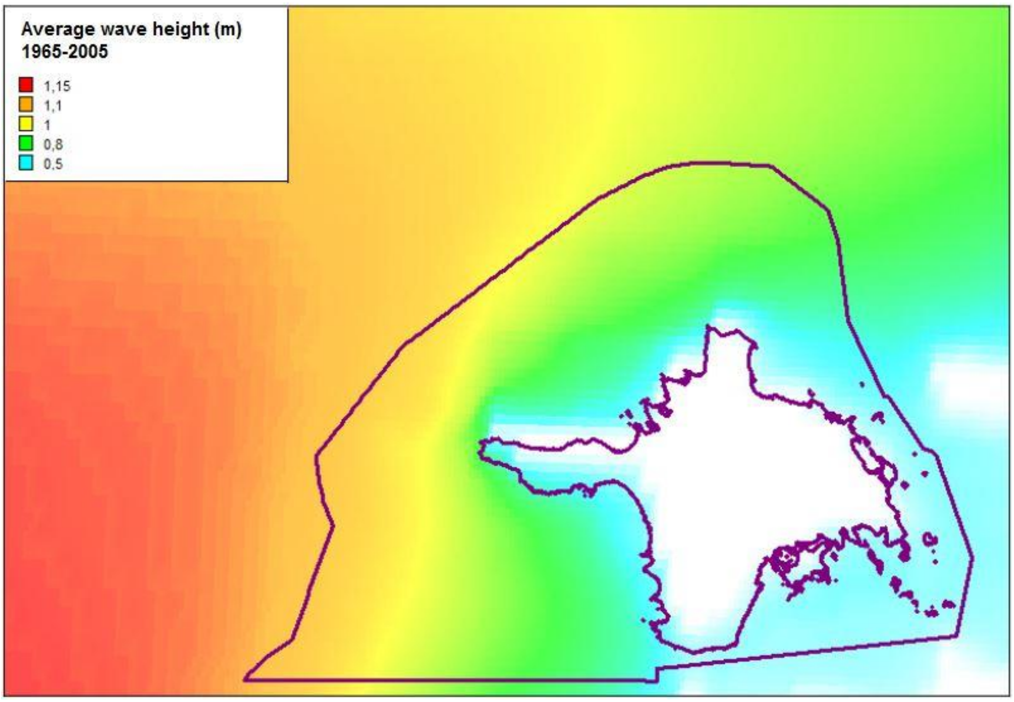

Figure 9. Average wave height measured during period 1965-2005 [1]

Seasonality of the wind causes seasonality of the waves in the planning area: a quiet period in the spring and summer and higher waves occurring in the autumn-winter period (if there is no ice). Near the Apollo shoal the more active period of the waves is in the fall and early winter, when the sea is not yet covered with ice. [1]

The average wave height in the planning area is important because most of the workboats in the market are limited to 1.5 m of significant wave height. 1.5 m or less is the threshold that allows the construction, operations and maintenance of a wind farm. The average wave height in the planning area during the period 1996-2012 by months was 1.5 or less from February to October. From November to January the average wave height was higher but still under 2.8

m. For comparison, the average wave height in the North Sea during years 1992-2007 was less than 1.5 m only from late April to the end of August. [25] This results in longer downtimes of turbines and greater revenue loss.

Weather window is a limited time when weather conditions are suitable for a particular project. For 1.5 m wave height threshold annual average accessibility of 10 hours weather window for the North Sea wind farms is around 60%. [25] For example, in 2011-2012 from October to March, the turbines in some areas of the North Sea were not accessible by sea 49 % of the time. In 2011 there were only two days in December when it was possible to transfer crew to one of the Horns Reef wind farms by sea. [26]

The higher is the accessibility the higher is availability. As previously stated, North Sea average accessibility is 60%. With that kind of accessibility the technical availability is 79,2% as shown in the Table 4. For Baltic Sea the average accessibility of 10 hours weather window with 1.5 m or less wave height is 90%. From that it can be estimated that with accessibility of 90% it is possible to achieve 90% availability. As the accessibility to Hiiumaa offshore wind farm is higher compared to the North Sea, the construction, operations and maintenance could be 1/3 cheaper than for North Sea offshore projects. [25]

Table 4. Availability of North Sea offshore wind farms [25]

	Availability %
OWEZ	80,1%
Barrow	72,5%
Scroby Sands	81%
Kentish Flats	83%
Average	**79,2%**

2.3 Possible vehicles for the Hiiumaa project

Theoretically most cost-effective logistics strategy, when the maximum distance of the project is less than 20 km, is workboat-based strategy [5]. The maximum distance for Hiiumaa offshore wind farm is 20 km, but there are site-specific factors that have to be considered.

One of which is iced up sea during winter. This means that another type of vehicle should be added to the transport scenario in addition to workboat.

One available strategy is heli-support. This means that helicopters are used when weather conditions are not suitable for using the workboats. As for Hiiumaa project the main reason for considering the use of helicopter for wind farm support are winter conditions, helicopter can be replaced with the vehicle that is able to move on ice even if it is stacked and hilly. This means that one possible choice is to use amphibious vehicle instead of helicopter. For the final decision all the pros and cons of both vehicles should be considered. It is important to note that the investment in maintenance has to be reasonable as each increment in availability costs more than the previous one.

Although it is important to keep the accessibility high, transit time has also great role to play. Too long transit time causes tiredness of the crew. Furthermore, if 6 MW turbines will be used, stopping the turbine for one hour at time of decent winds equals to 540 EUR of lost revenue.

Overview of possible vehicles that could be used for Hiiumaa project is given. These have been found by considering the climatic peculiarities of Hiiumaa project or the experience of already operating offshore wind farms.

2.3.1 Amphibious vehicle

Amphibious vehicle can be used on land and on water. The main purpose is to overcome the intermediates like ice, snow and mud. In general, amphibious vehicles are divided into hovercrafts travelling on an aircushion and others that use tracks. For crew transfer in Estonian climate the second category is more suitable as the iced up sea may not have smooth surface but bumps, jagged ice etc. This is particularly important when the ice has begun to melt or there is drifting ice. The space between the hovercraft’s base and the ground is not enough to overcome obstacles and higher bumps.

Amphibious vehicle that is suitable for crew transfer to the site is Arktos. Arktos uses tracks when on land and jet propulsion when in water. It was firstly developed because of the need for an evacuation craft from oil and gas industry. The machine has two separate units for mobility on severe terrain (Figure 10). The units are made of fiber reinforced plastic hulls that are permanently linked with hydraulically powered articulation arm. The craft is relatively light, as it has composite structure and it is hollow inside. [27]

Figure 10. Arktos consists of two separate units for better mobility [28]

Arktos Craft is powered by diesel engines in each unit. Driver uses a joystick to operate it. The fact that Arktos can carry 5000 kg of cargo through rough terrain and up to 10 tons of cargo in open water is important advantage when considering Arktos as a support to the offshore wind farm. [29] When transferring crew to the offshore site technicians can be seated similarly inside the units as shown on Figure 11.

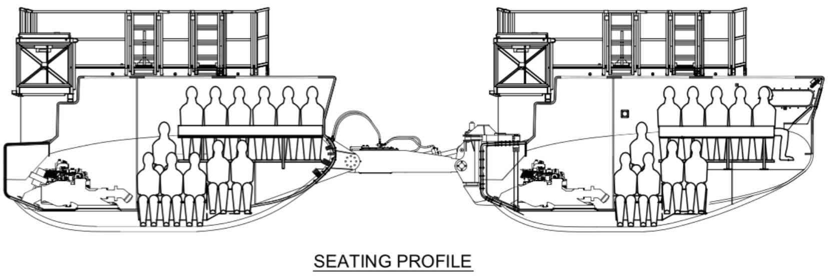

Figure 11. Seating profile of Arktos craft specialized for emergency situations [27]

The high mobility is achieved by having two units. When single unit climbs out of the water it reaches a certain angle before it starts to slide back. With two units, the front unit uses the back unit as a support and after getting on land or ice the tracks pull the back unit out of the water. [29]

As Arktos is developed for extreme environment conditions it has an ability to operate in working temperatures of -50 degrees Celsius [27]. Right now it is used in different locations around the world, including the North Caspian Sea and Alaska [29]. The main parameters of Arktos craft are shown in Table 5.

Table 5. Main parameters of Arktos craft

Parameter	
Mobility	High level Crosses transition between ice and water
Length (m)	15
Weight (tons)	32
Speed (km/h)	16 (on ground) 10 (in water)
Price (million EUR)	2.7
Applications	Geophysical survey, evacuation, exploration, fire fighting, rough terrain transportation

2.3.2 Helicopter

In Europe, UK is the country that can be used as an example to follow when choosing helicopter. UK is the leading country in offshore wind energy in European Union with the capacity of 4494,4 MW (2014). It represents 55,9 % of the whole capacity installed in European Union (8045,3 MW). There are 24 offshore wind farms in UK while the total number of turbines is 1301. [3] It is important to note that UK's experiences come from offshore wind farms in the North Sea, which is rather more complicated environment than the Baltic Sea. Helicopter has an irreplaceable role to play in offshore wind farm support in this area.

In Estonia there is no such company that could provide helicopter services to the offshore wind farm sector. For example, Bond Aviation Group provides maintenance services to Greater Gabbard (504 MW) wind farm in UK by delivering technicians directly to the turbine platform via an overhead winching mechanism [30]. Heli-support is used when access by workboats is not possible.

The necessary skills and equipment are available in Estonian state agency Police and Border Guard Board. It is possible to buy service from Police and Border Guard Board. Hourly rate for that kind of service will start from 2000 EUR. This includes fuel cost, employment costs, lease and other. [31] The other option for Nelja Energia is to invest in transportation and training and start providing aviation support. This is rather complicated because the company providing aviation support to offshore wind farms has to meet specific requirements.

As the purpose of the flight is commercial operation, it must comply with European Union law, specifically Commission Regulation (EU) No 965/2012. Offshore wind farm servicing is not directly regulated in mentioned regulation, but hoisting operations that are needed for the service are precisely regulated. Therefore helicopters used for maintenance of offshore wind farms are handled as helicopters used in commercial air transport hoist operations. [31]

Helicopter operator has to have required certificates and operating licenses. Technology used for operating has to be certified. In case of engine failure, helicopter has to have guaranteed capability to continue safe flight with one engine working. Commander has prescribed requirements for flight experience, including recent experience. [32] When the commander has no previous experience with helicopter hoist operations, required skills and work methods will be gained during training program of 20-30 h [31].

Requirements are imposed also to other team members and to their trainings. In case of helicopter hoist operations, technical crew member performs assigned duties related to hoisting. Helicopter hoist operation passenger is a person who is transferred by means of a helicopter hoist. In regulation it is stated that technical crew members have to complete trainings to perform their duties and have to be checked to be proficient in performing these duties. Within every 12-month period, each technical crew member shall undergo recurrent training relevant to the type or class of aircraft and equipment that the technical crew member operates. [32]

Weather conditions that allow helicopter service depends from take off area, whether it is an airport or a temporary base, what type of measuring instruments and navigation devices helicopter are supplied with, and competence of the commander. When helicopter is supplied with all needed equipment, for example with precision approach radar and instrument landing system then it is possible to start flight with cloud height 60 m from the ground and visual range 300 m. For the hoisting operation, in the offshore site the clouds have to be at least 300 m from the ground, and visual range some kilometres. In case the helicopter and/or the commander do not allow instrument flight, the weather conditions must be good both at the take off and landing. It is important to note that weather conditions may vary strongly at coastal areas and offshore, especially in spring and autumn. For example, fog at the take off area but good conditions for operating at the site and vice versa as well. [31]

For offshore operations, helicopters are limited to daylight hours. During the hoisting process the weather conditions at the site must be at least at the minimum level of visual flight terms. Meaning that during winching helicopter must be out of the clouds and the horizontal visibility must bet at least a couple of kilometres. Winching cannot be done with fog, heavy rain, snow and everything that can cause icing. The maximum wind speed that allows winching is 25 m/s. In general wind is helpful for winching process. Firstly, engine needs less power while hovering. Secondly, wind blows the airstream coming from the main rotor away from the technician who is winched down to the platform. During hoisting operation the front of helicopter is positioned against the wind. A small lateral component does not interfere as well. Wind is problem when it is gusty and changes direction quickly, because helicopter cannot keep the stability with respect to turbine platform. [31]

There are multiple factors to consider when deciding if helicopter should be used to support offshore wind farm. Apart from the type of the helicopter it is important to know inspection levels and approximate good performance time between the overhauls. This can vary from 25 hours to 100 hours. One of the most important steps is to investigate if the rotor of the helicopter and blades of the turbine do not interfere with each other. As the technician is hoisted from the helicopter to the heli-hoist maintenance platform, rotor of helicopter can come too close to the blades. [26]

2.3.3 Workboat

Wind farm support vessel is usually catamaran made of aluminum, which can accommodate up to 12 passengers and up to around 10 tons of cargo. Main usage is to transfer personnel to the site. These vessels need to be fast as transit time has to be as short as possible when the turbine has a failure. Also, the workboat must be highly maneuverable to access the foundations even with harsh weather conditions. [4]

For workboats there are two main transfer methods for a technician to get from a boat to the turbine. These are “bump and jump” and “walk to work” methods. First one represents method where the vessel is pushed to the “j-tubes”. J-tubes are the tubes that run vertically on the outside of the access ladder of the turbine. The workboat remains stationary at the point of contact with the foundation by using the thrust. This allows technicians to step over onto the access ladder. As large waves can cause the vessel to lose contact there is a safe zone between the j-tubes and turbine access ladder to prevent person on the ladder from being crushed. Mostly this transfer method can be used with waves of 1,5m significant height or less. [4]

Walk to work method means a bridging mechanism that attaches to the j-tubes creating a bridge that remains stationary relative to the turbine. For technician it means that he can “walk to work”. This is safe method for transfer and can take place with higher waves than bump and jump method. [4]

The disadvantage of above-mentioned transfer methods is that the equipment takes up valuable deck space, payload capacity and has a power demand. There is ongoing development and research for bringing new methods and systems to the market because the average significant wave height increases as the distance from the shore increases. [4]

3. RESEARCH METHODS

Different steps that were completed to find the most cost-effective transport scenario for Hiiumaa project are shown in Figure 12. The first step was to prepare two possible transport scenarios that later were analyzed. For this, different types of vehicles were chosen based on the weather conditions in the planning area. The next step after compiling the scenarios was to calculate working hours per year for every type of vehicle included in the scenarios. For financial comparison fuel cost calculations were made. As longer transit time means longer downtime of the turbine, revenue losses coming from the transit times were calculated for all types of vehicles included in the scenarios. The last step was to make financial analysis based on the found results and other factors such as capital costs and maintenance costs of the vehicles.

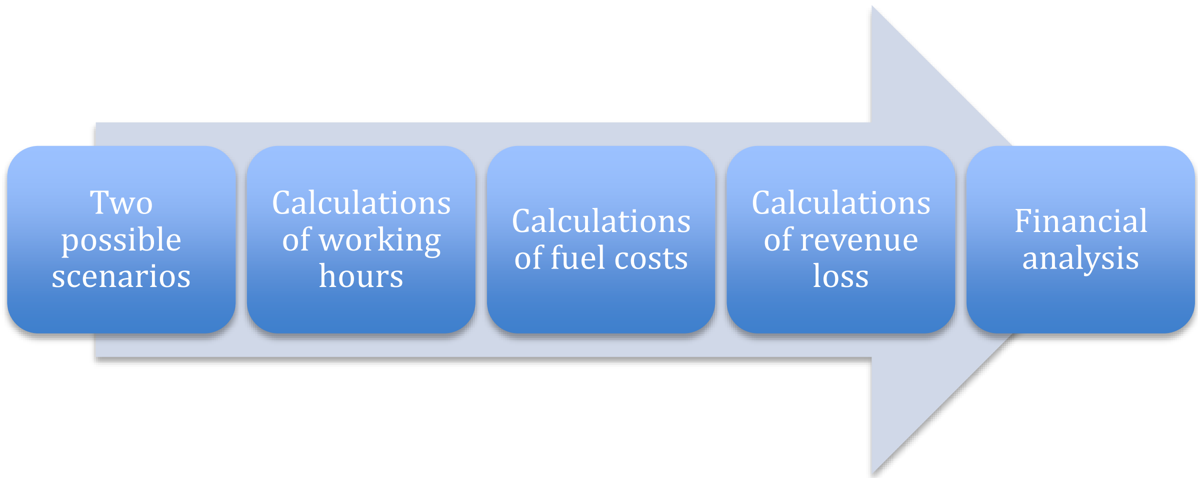

Figure 12. Process of finding the most cost-effective scenario

3.1. Compilation of transport scenarios

Two separate transport scenarios were provided. These consist of different vehicles that can be used for Hiiumaa project. Both scenarios were be made taking into account following factors:

- Climate
- Response time
- Personnel carrying capacity

- Safety
- Payload of the equipment
- Distance from the coastal facility

Maintenance year was divided into periods according to the state of the sea because weather conditions have a great impact on the choice of vehicles. Ice conditions vary from year to year and the exact months for each period were set based on the average. Apart from ice conditions, high wave height is also a limiting factor for vehicles. For every period suitable vehicles were chosen while taking into account ice and wave conditions.

It is important to note that while compiling the scenarios workboats were preferred in every situation where weather conditions allowed it. This means that in both scenarios all planned maintenances are held by workboats. In case of unscheduled maintenance, workboat is the main vehicle to use when significant wave height is 1.5 m or less and there are no ice conditions. The only limiting factor is urgency of the repair. When short response time is particularly important then faster vehicle can be used instead of the workboat.

3.2 Working hours of vehicles

Operating time for every vehicle type in the scenarios was calculated. Working hours per year means the amount of hours in a year when vehicle is operating and consuming fuel. Working hours were necessary to calculate fuel costs per year.

Average distances used in the calculations were estimated based on the map where the locations of turbines are quite precisely given. As Hiiumaa wind farm will consist of three groups of turbines, the average distance for a vehicle depends from the number of ports or bases where this vehicle is available. Figure 13 shows the location of each turbine and port that will be available to use for supporting the maintenance. The number of workboats that will be used is three. As shown on Figure 13, this means that workboats will have the shortest average distance among vehicles in the scenarios because in each port one workboat will be kept. In case helicopter will be used, it will be available only in one base and therefore the average distance becomes longer.

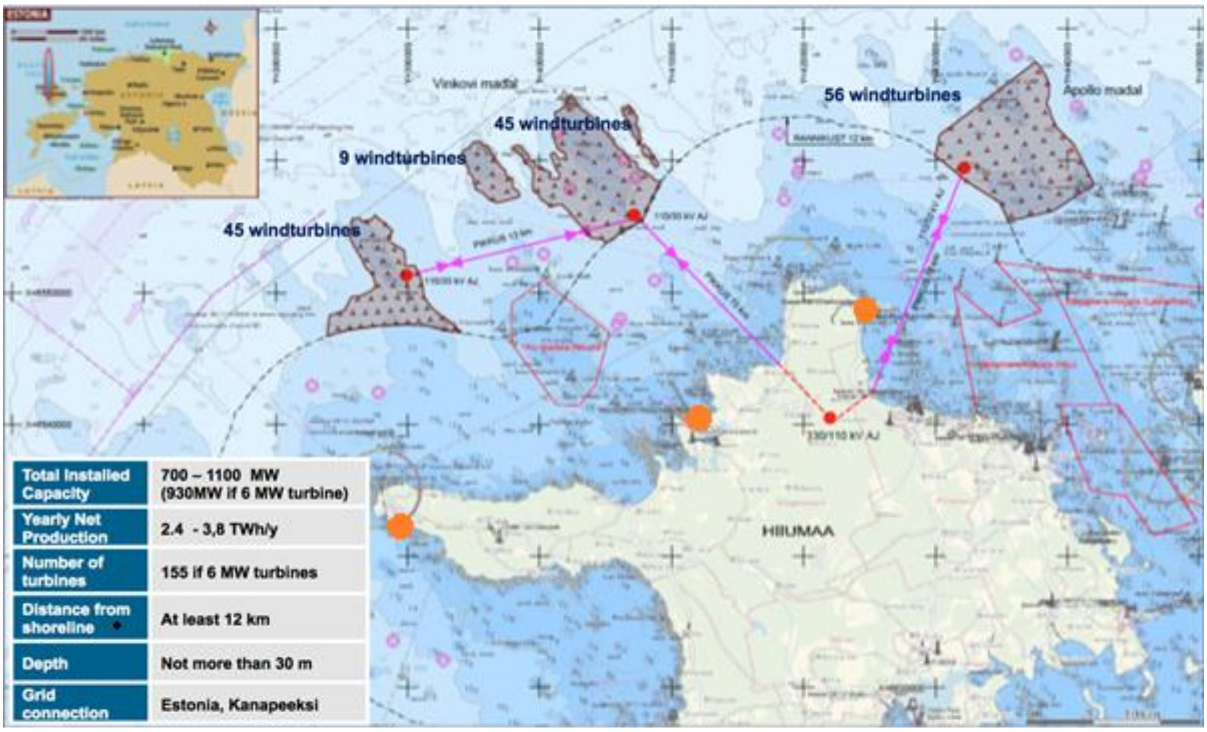

Figure 13. Location of the turbines and the ports (Kalana, Kõrgessaare, Lehtma) [25]

Apart from that, the reason why the average distances vary is that vehicles in scenarios are used for unplanned or both unplanned and planned maintenances. This means that they have different routes in case of planned or unplanned maintenance. For planned maintenance technicians are transferred to several turbines with one journey while in terms of unplanned maintenance at least two technicians are transferred to one turbine.

3.2.1 Planned maintenance

At first, working hours for a workboat per day were found with following equation:

$$W_1 = \left(\frac{d}{v}\right) + 2 * t_{t\&e} \qquad (3.1)$$

Where:

W_1 - working hours for boat per day (h)

d - total distance per day (km)

v - average speed of the workboat (km/h)

$t_{t\&e}$ - transferring time of technicians and equipment from boat to turbine (h)

The total number of operating hours of workboats in terms of planned maintenance was found by using equation 3.2.

$$W = W_1 * t * n_{wb} \qquad (3.2)$$

Where:

W - working hours per year (h)

W_1 - working hours per day (h)

t - total duration of planned maintenance in days

n_{wb} - number of workboats used at the same time

Total duration of planned maintenance (t) needed in equation 3.2 was found by using equation 3.3.

$$t = \frac{(n_{pm} * t_0)}{n} \qquad (3.3)$$

Where:

t - total duration of planned maintenance (days)

n_{pm} - number of planned maintenance works

t_0 - duration of service of one turbine (days)

n - number of serviced turbines at same time

The number of planned maintenances n_{pm} is equal to the number of turbines as every turbine has one annual service.

3.2.2 Unplanned maintenance

Operating time for specific vehicle per one day in case of unplanned maintenances was found with following equation:

$$W_1 = \left(\frac{d}{v}\right) + 2 * t_{t\&e} \qquad (3.4)$$

Where:

W_1 - working hours of vehicle per one unplanned maintenance (h)

d - total distance (km)

v - average speed (km/h)

$t_{t\&e}$ - hoisting time/transferring time of technicians and equipment from a vehicle to a turbine (h)

Operating hours of certain type of vehicle per year were calculated by using equation 3.5.

$$W = W_1 * n_{up} \qquad (3.5)$$

Where:

W - working hours per year (h)

W_1 - working hours of a vehicle per one unplanned maintenance (h)

n_{up} - total number of unplanned maintenances in a year made by vehicle under consideration

In case vehicle has different average speeds depending from the environment, equation 3.5 was modified.

$$W = W_1 * n_I + W_2 * n_{II} \qquad (3.6)$$

Where:

W	- working hours per year (h)
W_1;W_2	- working hours per one maintenance in terms of average speed I/average speed II (h)
n_I; n_{II}	- total number of maintenances done with average speed I/ average speed II

3.3 Fuel cost calculations

After calculating working hours for vehicles, fuel costs per year for every vehicle type in the scenarios were made. Expenses on fuel were calculated by using following equation:

$$E_f = W * c * p_f \qquad (3.7)$$

Where:

E_f	- expenses on fuel in a year (EUR)
W	- working hours per year for specific vehicle type (h)
c	- fuel consumption of a vehicle (l/h)
p_f	- fuel price (EUR/l)

3.4 Revenue loss

Revenue loss comes from the transit time of the technicians to the site in case of unplanned maintenance. This is the time when turbine is out of order. Vehicle that has a lower average speed causes greater revenue loss because the response time to the failed turbine is longer. Equation for revenue loss per year for specific vehicle type is following:

$$R = \left(\frac{d_{up}}{v} + t_{t\&e}\right) * C_t * p * n_{up} \qquad (3.8)$$

Where:

d_{up}	- average distance of unplanned maintenance
v	- average speed for specific vehicle type (km/h)
$t_{t\&e}$	- hoisting time/transferring time of technicians and equipment from a vehicle to a turbine (h)
C_t	- capacity of a turbine (MW)
p	- sales price of 1MWh
n_{up}	- number of unplanned maintenances made by vehicle type under consideration

After revenue loss calculations a short financial analysis was made to find the most cost-effective scenario. The amount of annual expenditures per scenario was calculated by using previously found annual fuel costs and revenue losses. Also, data about capital costs and maintenance costs were added. The final step was to compare the annual costs of both scenarios.

4. ANALYSIS

By taking into account ice conditions described in subchapter 2.2.3, year was divided into three periods according to the state of sea (Table 6).

Table 6. Maintenance year divided into three periods

Period	**State of sea**	**Months**
I period	Ice-cover	January, February
II period	Ice and water transition, or waves over 1.5 m	November, December, March
III period	No ice	April-October

According to the maintenance type held in the specific period and vehicles suitable for weather conditions in these periods, two transportation scenarios were put together. In period I and period II only unplanned maintenances are held. In period III, which mainly covers summer months, both planned and unplanned maintenances take place. Planned maintenance is held only in III period, because in the planning area this period has the weakest winds and revenue loss coming from shutting down the turbines will be lowest. Also, workboat is the main vehicle to transfer technicians because lower wind speed means lower waves. This in turn increases safety of the personnel because the contact between service boat and turbine's foundation is more stable with calm sea. Depending from the urgency, helicopter could be used because workboat is not the fastest possible solution.

It is probable that even if there is no ice formed during I and II period, wave height is most of the time too high for workboats. This means that alternative vehicles to workboats are needed. These are amphibious vehicle and helicopter. Response time, personnel carrying capacity, payload of the equipment and other parameters of mentioned vehicles are shown in Table 7. Each vehicle has its own advantages and disadvantages. For keeping the availability of the wind farm as high as possible, it seems reasonable to have all three types of vehicles as in that case almost all weather conditions would be covered.

Table 7. Main properties of different service vehicles that could be used for carrying out maintenance for Hiiumaa offshore wind farm

Workboat	**Helicopter**	**Amphibious vehicle (Arktos)**
II and III period	I, II and III period	I and II period
Scheduled and unscheduled activity	Unscheduled activity	Unscheduled activity
Relatively inexpensive	Expensive	Expensive
12 passengers	Up to 7 passengers	Can carry 10 000 kg of cargo in open water
Requires calm sea and moderate wind	Requires good visibility but can cope with strong winds	High level of amphibious mobility. Crosses the transition between ice and water
Long response time	Short response time	Long response time

The reason why all three possible vehicles were not included into one scenario is that investment costs will increase faster than the availability of the wind farm. The reliability of a system does not increase as fast as the investment costs increase. This means that the first actions taken to increase the availability of the wind farm will make a bigger difference than the following actions [33]. For example, helicopter support strategy (workboats with helicopter support) covers almost all weather conditions and adding amphibious vehicle to it is not cost-efficient as amphibious craft would not receive enough number of working hours. Prices of vehicles under consideration are shown in Table 8. The prices of all three types of vehicles are in the same range and due to that, two different scenarios were made.

Table 8. Prices of vehicles used in scenarios

Vehicle	**Price (EUR)**
Workboat	3 400 000
Helicopter	3 500 000
Amphibious vehicle	2 700 000

Scenario I includes three workboats and one helicopter. Workboats will be used during II and III period when there is no ice. In case of warm winters workboats can be used also during period I. Helicopter will be the main vehicle for unscheduled maintenances when weather or sea conditions do not allow use of workboats- mostly period I.

Scenario II includes three workboats and one amphibious vehicle. As for the Scenario I, workboats will be used when possible. Amphibious vehicle will be used during I and II period when sea is covered with ice or there is transition between water and ice.

4.1 Occurrence and duration of planned and unplanned maintenance

Planned maintenance will take place in period III containing mainly summer months. The number on planned maintenances is 155 - the same as estimated number of turbines because for every turbine one preventive maintenance will be held. The average duration of planned maintenance for one turbine is 30 hours or 2.5 days as one working day is equal to 12 hours. The whole duration of planned maintenance in days is calculated because service cannot be done in one day and for one turbine technicians need to be transferred to the site more than one time. The figures used in calculations are shown in Table 9.

Table 9. Figures used for calculating total duration of planned maintenance

Planned maintenance works	155		
Duration of one work	2.5	days	
Number of workboats	2		
Number of technicians per boat	12	Total	24
Technicians per turbine	2		
Serviced turbines at same time	12		

The total duration of planned maintenance is 32 working days or 387,5 hours.

For finding the total number of unplanned maintenances, failure rates of components from Figure 14 were used.

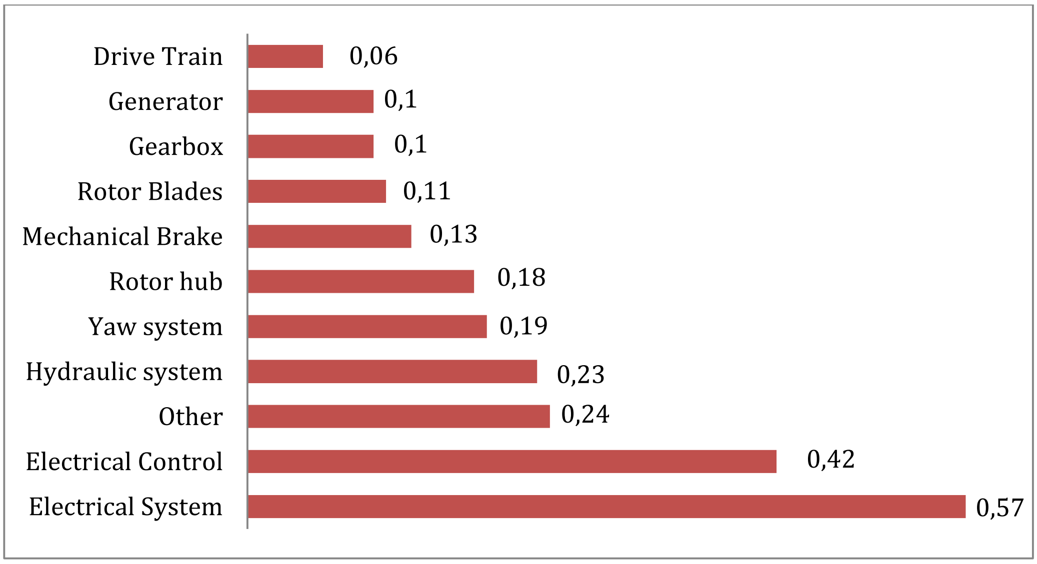

Figure 14. Failure rates of components [32]

Total number of failures of Hiiumaa offshore wind farm, consisting of 155 turbines, is 361 according to failure rates of components. The most frequently occurring fault among 361 unplanned maintenances is fault in electrical system with 88,4 failures per year (Figure 15).

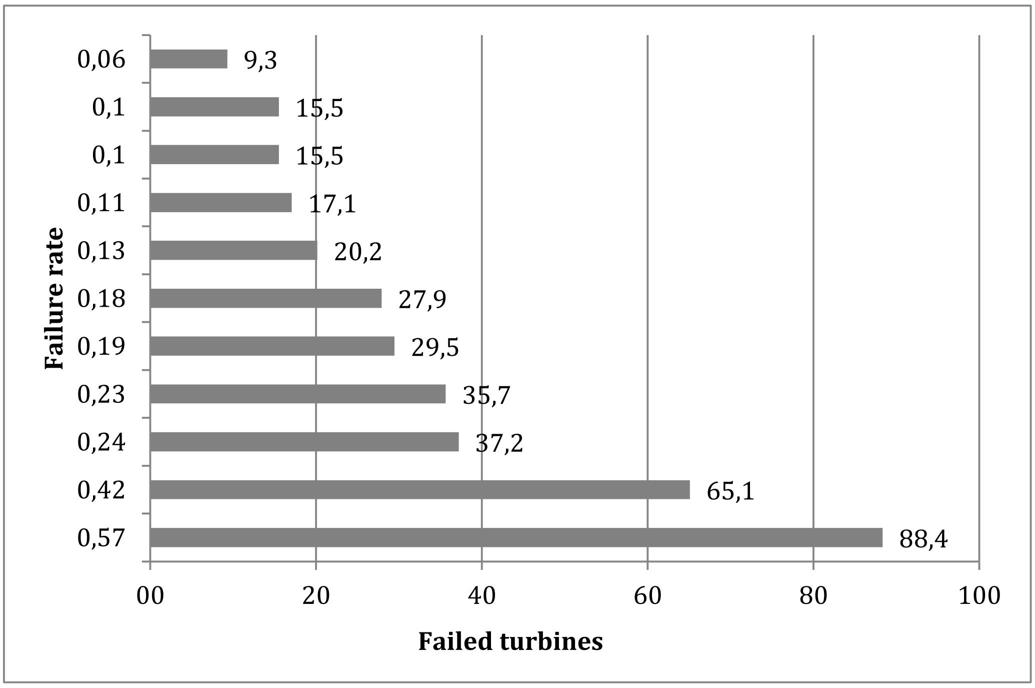

Figure 15. Number of failed turbines per year

For planned maintenance the duration of one annual service is 2.5 days. In case of unplanned maintenance the average duration of one unplanned service is not more than 1 day [34]. This means that per one repair technicians have to be taken to and from the turbine only one time.

Even if there will be more than one failed turbine on the same day, it is estimated that the distance between faulty turbines will be too long and time-consuming making the use of the same vehicle unreasonable.

The average number of unplanned maintenances in a year per turbine is 2.33. As there is also one planned service held in a year the average number of maintenances per year for one turbine is 3.33.

4.2 Working hours of workboats per year for planned maintenance

In both transport scenarios workboats are used for 100% of all planned maintenances. This means that working hours coming from planned maintenance for workboats in both scenarios are equal. Although there will be three workboats in total, two boats will be sent out at a time. The scheme of route is shown on Figure 16. Workboat transfers technicians to the site, heads to the port and in the evening goes back to pick up the technicians.

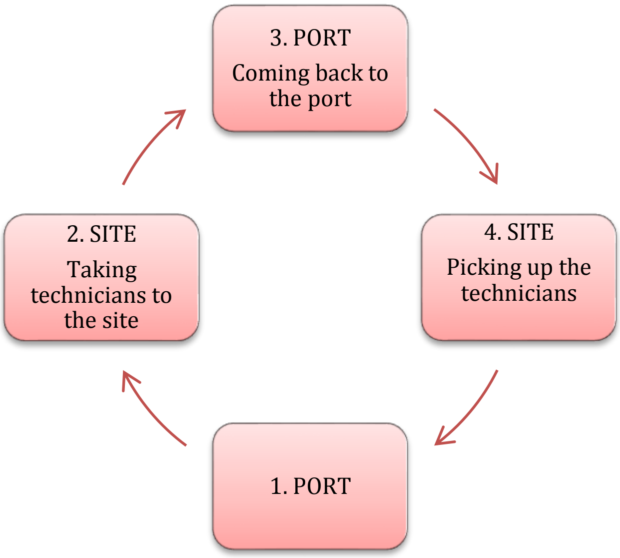

Figure 16. Route scheme of a workboat

It has to be noticed that one workboat accommodates 12 technicians meaning that with one journey it transfers crew to 6 turbines. Consequently, the average distance is around 23 km while taking into account 6 turbines per journey and the location of the ports. Data from Table 10 was used in calculations of working hours.

Table 10. Base values for calculating workboat working hours of planned maintenance

Average distance	23	km
Total distance	92	km
Average speed	35	km/h
Transferring time of technicians and equipment from workboat to turbine	0,5	h

Calculations indicate that working hours for a boat per one day are 3.6 hours. As previously it was calculated that planned maintenance takes 32 days in terms of using two workboats jointly the total operating time for workboats is 234 hours.

4.3 Scenario 1: three workboats and one helicopter

It is estimated that 50% of unplanned services will take place in III period and other 50 % during other two periods. For the first period 100% and for the second period 70% of all transfers will be done by helicopter (Table 11). During III period helicopters will be used when the repair is very urgent and therefore helicopter will be used for 10% of unplanned services.

Table 11. Number of unplanned repairs per periods and vehicles

Unscheduled maintenance	**State of sea**	**Months**	**Repairs**	**Workboat**		**Helicopter**	
I period	Ice-cover	January February	72	0 %	0	100 %	72
II period	Ice and water transition; high waves	November December March	108	30 %	32	70 %	76
III period	No ice	April to October	181	90 %	163	10 %	18
Total			**361**		**195**		**166**

The average distance of workboats for unscheduled maintenance is 17.5 km. It is shorter than for scheduled maintenance because even if several turbines need a repair on a same day, there is a high possibility that turbines are located too far from each other and using one workboat would not be reasonable. With helicopter the rule of one turbine per journey applies even more because helicopter has to be able to continue safe flight when one engine fails resulting in small cargo and rather empty fuel tank. The average distance for the helicopter is longer than for the workboat because helicopter will have only one base where to start the journey.

The figures used for calculating working hours of helicopter are shown in Table 12. Total distance is again four times of average distance because helicopter follows the same route scheme as the workboat.

Table 12. Base values for calculating working hours of helicopter

Average distance	24	km
Total distance	96	km
Cruising speed	254	km/h
Hoisting time of technicians and equipment from helicopter to platform	5	minutes

Calculations indicate that one unplanned service gives approximately 33 minutes of operating time to helicopter. The result is that helicopter will have 90 hours of working time per year in terms of 166 unscheduled maintenances per year.

For calculating working hours for a workboat during unplanned maintenances per year, same calculation process is used as for helicopter. Figures are available in Table 13.

Table 13. Base values for calculating working hours for workboats in Scenario II

Average distance	17.5	km
Total distance	70	km
Average speed	35	km/h
Transferring time of technicians and equipment from workboat to turbine	5	minutes

Calculations indicate that one unplanned service gives about 2.2 hours of working time to a workboat. The total operating time of workboats for unplanned maintenances is 423 hours per year.

4.4 Scenario II: three workboats and one amphibious craft

Unplanned repairs are divided between workboats and amphibious craft and shown in Table 14. Arktos Craft would cover all the unscheduled maintenances happening during ice-cover months. In average the ice cover lasts in the offshore wind farm site for two months.

Table 14. Number of unplanned repairs per periods

Unscheduled maintenance	**State of sea**	**Months**	**Repairs**	**Workboat**		**Amphibious craft**	
I period	Ice-cover	January February	72	0 %	0	100 %	72
II period	Ice and water transition; high waves	November December March	108	50 %	54	50 %	54
III period	No ice	April to October	181	100 %	181	0 %	0
Total			**361**		**235**		**126**

Using Arktos Craft during III period is not reasonable as the moving speed is too slow compared to workboats. The average speed in water is 10 km/h compared to maximum speed 45 km/h of workboat. This would mean loss on valuable time and tiredness of the crew. Consequently, Arktos Craft will have working hours only during I and II period.

Arktos craft’s different moving speeds on ice and in water have to be taken into account together with other figures in Table 15. It is important to notice that while workboats and helicopters return back to the onshore facility after transferring the technicians, Arktos will stay in the site.

Table 15. Base values for calculating working hours of Arktos craft

Average distance	24	km
Total distance	48	km
Speed on land/ice	16	km/h
Speed in water	10	km/h
Transferring time of technicians and equipment from craft to turbine	5	minutes

Calculations indicate that one unplanned service gives to Arktos 3.2 working hours during I period and about 5 working hours during II period. During I period the total working time of Arktos is 229 hours and during II period 269 hours making the total amount of working time 498 hours.

For comparison, if Arktos would follow the same route as workboats and helicopter in previous calculations, making the total distance 96 km in a day, Arktos would get around 6.2 hours of operating time for one unplanned service during I period and 9.8 hours during II period. The total operating time in that case would be 975 hours. As this is two times more than for the route where Arktos stays at the site, this route cannot be accepted because that long transit time would tire the crew and fuel costs per year would also double. Apart from that, it would leave less time to the technicians to do the actual repair at the site.

Total working hours of workboats during unplanned maintenance is calculated in the same way as previously for Scenario I. The amount of working hours per one day is around 2.2 hours. The only difference is the amount of unplanned repairs. For scenario II total amount of unplanned repairs made by workboats is 235. According to that there will be 509 working hours per year for workboats in terms of unplanned maintenance.

4.5 Fuel costs

Based on found working hours fuel cost estimations were made. Fuel prices and fuel consumptions of vehicles that were used in calculations are shown in Table 16.

Table 16. Fuel costs per hour for vehicles under consideration

Vehicle	Fuel consumption	Fuel price (purchase tax included)	Fuel cost per hour
Helicopter EC135	230 L/h	1.93 EUR/L (JET 1A) Kärdla Airport	443.9 EUR
Workboat (length 18,5m)	150 L/h	1.05 EUR/L (diesel) Jetoil AS	157.5 EUR
Arktos craft	50 L/h in water 38 L/h on ice	1.05 EUR/L (diesel) Jetoil AS	52.5 EUR 39.9 EUR

According to calculations fuel cost of Scenario I is 143 623 EUR and for Scenario II 140 269 EUR as shown in Table 17.

Table 17. Fuel costs per year for Scenario I and Scenario II

<table>
<tr><th colspan="3">Scenario I</th><th colspan="3">Scenario II</th></tr>
<tr><td rowspan="4">Workboats</td><td>Scheduled (h)</td><td>234</td><td rowspan="4">Workboats</td><td>Scheduled (h)</td><td>234</td></tr>
<tr><td>Unscheduled (h)</td><td>423</td><td>Unscheduled (h)</td><td>509</td></tr>
<tr><td>Total (h)</td><td>657</td><td>Total (h)</td><td>743</td></tr>
<tr><td>Fuel costs</td><td>103 460</td><td>Fuel costs</td><td>117 017</td></tr>
<tr><td rowspan="2">Helicopter</td><td>Unscheduled (h)</td><td>90</td><td rowspan="2">Amphibious craft</td><td>Unscheduled (h)</td><td>498</td></tr>
<tr><td>Fuel costs</td><td>40 163</td><td>Fuel costs</td><td>23 252</td></tr>
<tr><td>TOTAL (EUR)</td><td>Fuel costs</td><td>143 623</td><td>TOTAL (EUR)</td><td>Fuel costs</td><td>140 269</td></tr>
</table>

It must be noticed that for workboats in both scenarios calculations were made while assuming that workboats head back to the port after technicians are safely transferred to the turbines. Both scenarios can be made more cost-effective by reducing working hours of the workboats by anchoring boats near the border area of the wind farm. Anchoring in the territory of wind farm is not allowed because of safety. The total distance for one unplanned service will decrease from 70 km to 44 km. In case workboats will be anchored near the offshore wind farm for all unplanned and planned maintenances in period April-October when the sea is calm, fuel costs per scenario will decrease significantly as shown in Table 18.

Table 18. Fuel costs per year of Scenario I and Scenario II after changing the route for workboats during the maintenances held in period April-October.

Scenario I			**Scenario II**		
Workboats	Scheduled (h)	166	Workboats	Scheduled (h)	166
	Unscheduled (h)	302		Unscheduled (h)	375
	Total (h)	468		Total (h)	541
	Fuel costs	**73 693**		Fuel costs	**85 137**
Helicopter	Unscheduled (h)	90	Amphibious craft	Unscheduled (h)	498
	Fuel costs	**40 163**		Fuel costs	**23 252**
TOTAL (EUR)	Fuel costs	**113 856**	TOTAL (EUR)	Fuel costs	**108 389**

After changing the route for workboats fuel cost for Scenario I is 113 856 EUR and for Scenario II 108 389 EUR. To compare Scenario I and Scenario II more factors have to be taken into account in addition to fuel costs. These are capital costs, maintenance costs of vehicles and loss of revenue in a year coming from the transit time.

4.6 Financial analysis

At first revenue loss per vehicle in a year was calculated. For Arktos craft in Scenario II the transit time of technicians to the turbine are accordingly 1.6 hours and 2.5 hours for period I and period II. Previously it was stated that Arktos will take care of 72 unplanned maintenances in period I and 54 in period II. In calculations it was assumed that 6 MW turbines will be used and wind conditions during period I and II are good enough for the turbine to have maximum output. The sale price of 1 MWh including subsidies is estimated to be 90 EUR [25]. According to that the revenue loss per year for period I is 61 560 EUR and for period II is 72 414 EUR. Total revenue loss per year is 133 974 EUR.

For helicopter, transferring of technicians to the site takes around 10.7 minutes. Helicopter transfers technicians to the site for 166 unplanned maintenances in a year. Total revenue loss per year is 15 986 EUR.

For workboats the revenue loss was calculated by using the transit time of 35 minutes and number of unplanned maintenances. The revenue loss for workboats in terms of Scenario I is 61 425 EUR and in terms of Scenario II 74 025 EUR.

The lifetime of Hiiumaa offshore wind farm is 20 years. Capital costs, maintenance costs, fuel costs and revenue losses per year for specific vehicle type are shown in Table 19.

Table 19. Annual costs of helicopter and amphibious vehicle

Annual costs	**Helicopter**	**Amphibious vehicle**
Capital cost	175 000	135 000
Maintenance cost	10 850	4 844
Fuel cost	40 163	23 252
Revenue loss	15 986	133 974
Total	241 999	297 070

It is recommended for amphibious craft Arktos to have 2 maintenances in a year. Maintenance cost is stipulated by a day rate of Arktos Developments Ltd. technician that is 1422 EUR per 12 hours. Overtime rate is 180 EUR/hour for more than 12 hours shift. Travelling and accommodation expenses will come in addition to labor costs. [35]

Helicopter has to have a major maintenance work after 1200 flight hours. The cost of it is estimated to be around 217 000 EUR [36].

According to Table 19 the annual cost of helicopter in Scenario I is 241 999 EUR while for amphibious craft the annual cost is 297 070 EUR.

For more precise comparison previously found annual fuel costs and annual revenue losses of workboats were added. Table 20 describes the difference between the annual costs of Scenario I and Scenario II.

Table 20. Annual costs of Scenario I and Scenario II

Annual costs (EUR)	**Scenario I**	**Scenario II**
Helicopter	241 999	-
Amphibious vehicle	-	297 070
Workboats	61 425	74 025
Total	303 424	371 095

The capital costs and maintenance costs of workboats were not added into analysis because these are the same in both scenarios and do not effect the results of comparison.

5. RESULTS

Scenario I and Scenario II were provided taking into account states of the sea during the year. Two scenarios differ from the vehicle that will be used during winter conditions when workboats are not possible to use. Vehicles per state of the sea and scenario are shown in Table 21.

Table 21. Overview of two possible scenarios

Maintenance type	**Period**	**Sea state**	**Months**	**Scenario I**	**Scenario II**
Unscheduled	I	Ice-cover	January-February	Helicopter	Amphibious vehicle
	II	Ice and water transition or high waves	November December March	Helicopter or workboat	Helicopter or amphibious vehicle
	III	No ice	April-October	Workboats or helicopter if very urgent	Workboats
Scheduled	III	No ice	April-October	Workboats	Workboats

Working hours of vehicles per year for Scenario I and II are shown in Table 22. Workboats are used for all planned maintenances in both scenarios, therefore the amount of working hours is the same - 166 hours of working time in a year in case of scheduled maintenance. In terms of unscheduled maintenance workboats in Scenario II got more working hours than workboats in Scenario I because amphibious vehicle in Scenario II has a very low average speed and it is not reasonable to use it without ice conditions. Although amphibious vehicle has no limits for wave heights when it comes to moving, the part of transferring where technicians have to get from the craft to the turbine is still limited by wave height of 1.5 m. In those cases workboats will be used, and if it is not possible on the same day then the maintenance will be postponed.

Table 22. Overview of working hours and fuel costs of both scenarios

Scenario I		**Scenario II**	
Number of workboats	3	Number of workboats	3
Scheduled maintenance	166	Scheduled maintenance	166
Unscheduled maintenance	302	Unscheduled maintenance	375
Total (h)	**468**	Total (h)	**541**
Nr of helicopters	1	Nr of amphibious crafts	1
Unscheduled maintenance	90	Unscheduled maintenance	498
Fuel costs of workboats	**73 693**	Fuel costs of workboats	**85 137**
Fuel costs of helicopter	**40 163**	Fuel costs of amphibious craft	**23 252**
Fuel costs	**113 856**	Fuel costs	**108 389**

At first working hour calculations for workboats were made by assuming that workboats head back to the port for the time of a repair and then later go to pick up the technicians. For making the scenarios more cost-effective, it was possible to change the route of workboats in terms of unplanned maintenances into shorter one by assuming that during months from April to October the sea is calm and workboats can be anchored near the site. Calculations showed that when changing the route of workboats by this manner it is possible to reduce fuel costs of workboats in Scenario I and Scenario II 20,7% and 22,7% respectively.

Scenario I 143 623 -> 113 856

Scenario II 140 269 -> 108 389

For Arktos it was assumed from the very beginning that the craft stays in the site near the turbines because of very low average speed.

Helicopter in Scenario I got 90 hours of working time while Arktos in Scenario II got 498 h. Helicopter has 5.5 times less operating time than amphibious craft mainly because of significantly higher average speed.

Although amphibious craft got 5.5 times more working hours than helicopter, the fuel costs of amphibious craft are about 42% lower than for helicopter. The reasons are higher fuel consumption of the helicopter and two times higher fuel price per litre. Apart from that, while amphibious craft stays on the site during the repair, helicopter has to return to the onshore base and later pick up the technicians. The difference in total distance is 48 km for one unplanned service.

Annual fuel cost of Scenario I is 113 856 EUR and 108 389 EUR for Scenario II. The difference between two scenarios is 5 467 EUR which is not very remarkable. After taking into account estimated capital cost, maintenance cost, revenue loss coming from the transit time and fuel cost for helicopter and amphibious craft, it came out that total expenses for helicopter per year will be 55 071 EUR smaller than for amphibious vehicle when assuming that the lifetime of Hiiumaa offshore wind farm is 20 years. The main reason why expenses coming from choosing the helicopter are smaller than for amphibious craft is the short transit time that reduces the revenue loss.

When revenue losses coming from the use of workboats in terms on unscheduled maintenance were added to the analysis, the difference between Scenario I and Scenario II increased. Expenses of Scenario I are about 18% lower than for Scenario II. This final result is that helicopter will be more cost-effective choice for Hiiumaa offshore wind farm. The main reason is that helicopter is able to provide transportation to bigger number of maintenances while also the transit time is significantly lower than for amphibious vehicle.

CONCLUSIONS

For finding the most reasonable and economical transport scenario for Hiiumaa offshore wind farm two different scenarios were provided which later were analyzed. Scenarios were compiled based on the weather conditions in the planning area of Hiiumaa offshore wind farm and the experience of already operating offshore wind farms. While Scenario I included three workboats and one helicopter, Scenario II included same amount of workboats and one amphibious craft. Both helicopter and amphibious craft were chosen mainly for unscheduled maintenances during ice conditions because it is not possible to use workboats when sea is iced up.

The main steps for reaching the final result were calculating the working hours, fuel costs and revenue losses. All these steps needed preliminary work on gathering the data. Some basic values that were used in calculations, for example the amount of unscheduled maintenances during specific period, were calculated beforehand.

According to the calculations helicopter would get 90 hours of working time in case of Scenario I and amphibious vehicle Arktos would get 498 hours in case of Scenario II. The difference in numbers is in that range because Arktos has very low average speed in water and on land.

Although it was estimated that quite strong assumptions can be done after finding the fuel costs for both scenarios per year, the difference in fuel costs turned out to be quite insignificant. The annual fuel costs of Scenario I were 113 856 and for Scenario II 108 389 EUR making the difference 5 467 EUR.

When taking into account capital costs, maintenance costs, fuel costs and revenue losses coming from the transit time, using the helicopter would mean 55 071 EUR less expenses in a year than using the Arktos craft.

After adding the revenue losses coming from the use of workboats into analysis, the difference between Scenario and Scenario II increased. The reason is that workboats got more working hours in Scenario II and this resulted in higher annual revenue loss. When choosing Scenario I for supporting the maintenance of Hiiumaa offshore wind farm it is possible to reduce the costs coming from the transportation by 18% compared to the Scenario II.

RESUME

Offshore wind energy is a new area for Estonia as there are no offshore wind farms yet. Nelja Energia is a company who is planning the first offshore wind farm to Estonia. Turbines will be situated in three groups and on the shoals that are located in the north, northwest and west from Hiiumaa. The estimated capacity of the wind farm is 930 MW.

Offshore environment makes the maintenance more complicated and expensive than for onshore wind farms. As Estonian climate can have very harsh conditions during wintertime, it is probable that during most winters it is not possible to use workboats due to sea ice. Workboats are most widely used transport vehicles in terms of offshore wind farms. In addition to the sea ice, workboats are also limited by the maximum wave height of 1.5 m. Apart from that, short transit time is just as important as enabling the access to the site. The longer is the transit time the higher is the unearned profit coming from the turbine not generating electricity.

The aim of the thesis was to choose the most cost-effective transport scenario for providing the maintenance to Hiiumaa offshore wind farm. Therefore benefits coming from different vehicles had to be analyzed. The main question was if amphibious vehicle or helicopter should be used in addition to workboats in case of unscheduled maintenances. Under amphibious vehicle it is meant Arktos craft consisting of two units and able to cross the transition between water and ice.

The possible working time in a year for helicopter and amphibious vehicle were calculated. Under working time it was meant the time when vehicle is used and consuming fuel. Although amphibious vehicle got remarkably more working hours than helicopter, lower annual fuel cost and does not have that specific maintenance requirements as helicopter, it came out that helicopter is more cost-efficient choice. The reason is the annual revenue loss coming from the transit time which for amphibious vehicle was almost 118 000 EUR greater due to the very low average speed.

The main result of the analysis is that when choosing scenario including helicopter and three workboats the annual expenses on transportation including the revenue loss will be 18% lower than for scenario consisting of workboats and Arktos craft.

RESÜMEE

Nelja Energia AS plaanib Eestisse rajada esimese meretuulepargi võimsusega 930 MW. Praeguse plaani järgi kavatsetakse kasutada tuulikuid võimsusega 6 MW. Tuulikute minimaalne kaugus maismaast hakkab olema 12 km. Meretuulepargi eeliseks on tugevamad tuuled ning väiksem vastumeelsus ümbritsevatelt kogukondadelt, kuna müra ning visuaalne efekt on väiksemad kui maismaa tuulepargi puhul. Samal ajal on miinuseks kõrgemad kulud meretuulepargi ehituses, hoolduses ja opereerimises. Eesti kliima teeb hoolduse läbiviimise veelgi keerulisemaks, kuna talvel võivad tekkivad jääolud ning hoolduslaevade kasutamine tehnikute transportimiseks tuulikutele ei ole võimalik. Seepärast tuleb eelkõige talveperioodiks leida laevale alternatiive.

Tuulepargi hooldus jaguneb plaanitud ning planeerimata hoolduseks. Plaanitud hooldus viiakse läbi kord aastas ning suvekuudel, kui lainekõrgus on keskmisest madalam ning tuuled väiksemad. Nõrgem tuul tähendab omakorda ka madalamat kaotatud tulu, kuna tuulikud lülitatakse hoolduse ajaks välja. Töös arvestati, et Hiiumaa tuulepargi puhul võib aastas esineda keskmiselt 2.3 planeerimata hooldust tuuliku kohta. See tähendab, et vajaminev hooldus võib sattuda ka talveperioodile, kui ligipääs tuulikule on raskendatud.

Antud magistritöö eesmärgiks oli pakkuda välja transpordi stsenaariume, mis võiks sobida Hiiumaa projekti tingimustega, ning neid seejärel analüüsida, et leida kõige kulutõhusam variant. Esimese sammuna koostati kaks stsenaariumit, kus mõlemas olid planeeritud hoolduse jaoks valitud kolm hoolduslaeva ning jääolude ajaks, mil viiakse läbi ainult planeerimata hoolduseid, vastavalt helikopter või amfiibsõiduk. Amfiibsõiduki all peetakse silmas sõidukit, mis on võimeline sõitma nii vees kui maapinnal, ning suuteline ületama ka kuhjunud merejääd.

Mõlema stsenaariumi kohta arvestati välja transpordivahendite töötunnid aastas ehk tundide arv aastas, mille jooksul sõidukeid kasutatakse. Töötundide abil leiti järgmiseks kütusekulud aastas. Töötundide arvestamisel oli oluliseks faktoriks keskmine vahemaa, mida hoolduse läbiviimiseks läbitakse. Amfiibsõiduki puhul oli keskmine vahemaa lühem kui helikopteri puhul, kuna amfiibsõiduki jaoks eeldati, et sõiduk jääb hoolduse ajaks tuuliku lähedale ootele. Helikopteri puhul ei ole selline marsruut võimalik, ning helikopter peab pärast tehnikute transporti tuuliku platvormile suunduma tagasi baasi ning hiljem järgi minema. Seoses sellega tuli helikopteri keskmine vahemaa ühe planeerimata hoolduse jaoks 48 km suurem ehk kokku

96 km. Kuna amfiibsõiduki keskmine kiirus on oluliselt väiksem kui helikopteri oma, sai amfiibsõiduk 5.5 korda rohkem töötunde aastas. See omakorda ei tähenda seda, et amfiibsõiduki kütusekulud oleksid kõrgemad. Arvutustest selgus, et amfiibsõiduki kütusekulud aastas on 42% väiksemad. Põhjuseks on väiksem läbitav vahemaa ühe hoolduse kohta, madalam kütusekulu tunnis, ning väiksem hoolduste arv, mil amfiibsõidukit kasutatakse. Lisaks arvestati välja ka hoolduslaevade töötundide arv mõlema stsenaariumi korral. Vastavalt töötundidele saadi helikopteriga stsenaariumi aastaseks kütusekuluks 113 856 EUR ning amfiibsõidukiga stsenaariumi kütusekuluks 108 389 EUR.

Lisaks kütusekuludele arvestati välja aastane tulu, mis jääb teenimata aja tõttu, mis kulub tehnikute transportimiseks tuulikule. Mida pikem on transpordiaeg, seda kauem on tuulik planeerimata hoolduse puhul rikkis. Lisaks sellele, mida rohkem aega kulub transpordile seda vähem aega jääb reaalseks parandustööks. Arvutustest selgus, et amfiibsõiduki puhul on teenimata tulu aastas ligi 118 000 EUR suurem kui helikopteri puhul.

Viimaseks etapiks oli analüüsi lisada ka sõidukite investeerimiskulud, hoolduskulud ning hoolduslaevade kasutamisest tulenev teenimata tulu. Kuna helikopterit saab kasutada laiemate ilmastikutingimustega, sai helikopter osa hoolduslaeva töötundidest endale. See tähendab et amfiibsõidukiga stsenaariumis said hoolduslaevad rohkem töötunde kui helikopteriga stsenaariumis. Seetõttu on hoolduslaevade kasutamisest tingitud teenimata tulu suurem amdfiibsõidukiga stsenaariumi puhul.

Lõpptulemuseks leiti, et helikopteriga stsenaariumi kulud on 18% madalamad kui amfiibsõidukiga stsenaariumi puhul. Kuigi kütusekulud aastas on helikopteri korral kõrgemad kui amfiibsõiduki puhul, on amfiibsõidukiga stsenaarium vähem efektiivsem just teenimata tulu tõttu, mis tekib pikast vastamisajast tuuliku rikkele. Sellest järeldub, et Hiiumaa meretuulepargi hoolduse läbiviimiseks tuleks eelistada helikopterit amfiibsõidukile.

REFERENCES

[1] OÜ Alkranel, Tallinna Tehnikaülikooli Meresüsteemide Instituut, OÜ Artes Terrae. Hiiu maakonnaga piirneva mereala maakonnaplaneeringu keskkonnamõju strateegiline hindamine. 2012-2014. 9; 11-12; 16; 48; 55; 91

[2] Battisti L. Sea ice and icing risk for offshore wind turbines. University of Trento, Italy. 2006

[3] Corbetta, G., Mbistrova, A. The European offshore wind industry - key trends and statistics 2014. European Wind Energy Association

[4] Wind farm service vessels- an overview [WWW] http://www.4coffshore.com/windfarms/wind-farm-service-vessels-an-overview-aid246.html (26.02.15)

[5] GL Garrad Hassan. A Guide to UK Offshore Wind Operations and Maintenance. Scottish Enterprise and The Crown Estate. 2013

[6] Ghanbari, A., Oyelakin, M. Management System for Operations and Maintenance in Offshore Wind Turbine Plant: Master Thesis. 2011. Halmstad University, Sweden.

[7] Alcraft, B. Scroby Sands: offshore operations and maintenance [WWW] http://www.benalcraft.com/scroby-sands-the-future-of-offshore-operations-and-maintenance/ (15.02.15)

[8] Hofmann, M. Sperstad, I. B. Will 10 MW wind turbines bring down the operation and maintenance cost of offshore wind farms? Elsevier Ltd. 2014, 233.

[9] Hill, J. S. Offshore Wind Demonstration Project. [WWW] http://cleantechnica.com/2014/11/28/finland-approves-40-mw-offshore-wind-demonstration-project/ (11.04.2015)

[10] Aunapuu, A., Tikerpuu, L. Hiiumaa avameretuulepargi rajamise KMH- Lähteülesanne eksperthinnangute täiendamiseks. 2013

[11] Victor, A., 2008. Hiiumaa avamere tuulepargi mõju lainetuse režiimi muutusele Hiiumaa lääne- ja põhjarannikul. TTÜ Meresüsteemide instituut

[12] EL direktiivi eelnõu näeb ette merealade ja rannikualade planeerimise kohustuse. Keskkonnaõiguse uudiskiri. 4, 2013. [WWW] http://k6k.ee/uudiskiri/2013/aprill/merealad

[13] Hiiu maakonna merealade planeering. Köide 1. 2014. Hiiu Maakond. 18; 21-22; 37,

[14] Energiasalv OÜ. Hiiu Hiiumaa offshore wind farm & hydro pump storage PP in Estonia. 2011

[15] Czyzewski, A. Wind Energy Gets Serial. [WWW] http://www.theengineer.co.uk/in-depth/the-big-story/wind-energy-gets-serial/1012449.article (09.11.2014)

[16] Jeppsson, J., Larsen, P. E., Larsson, A. Technical Description Lillgrund Wind Power Plant, 2008. Vattenfall Vindkraft AB

[17] Gravity Based Support Structures [WWW] http://www.4coffshore.com/windfarms/gravity-based-support-structures-aid274.html (14.01.15)

[18] Paist, S. Development manager in Nelja Energia AS. Interview. 2015

[19] Soomere, T., Keevallik, S. Anisotropy of Moderate and Strong Winds in the Baltic Proper- Proceedings of the Estonian Academy, 2001. March, 38.

[20] Global Wind Speed Rankings. [WWW]

http://www.4coffshore.com/windfarms/windspeeds.aspx (11.04.15)

[21] WindPower program official website [WWW]

http://www.wind-power-program.com/popups/powercurve.htm (02.03.15)

[22] Mägi, R. Täpseim külmaennustaja oli Andrus Kukk. Vooremaa, 2015.

[23] Official website of Swedish Meteorological and Hydrological Institute [WWW] http://www.smhi.se/oceanografi/iceservice/iceextent_col.pdf (15.01.15)

[24] Ice conditions in the Baltic. Swedish Ice Service [WWW] http://www.smhi.se/oceanografi/iceservice/ice_condition.htm (26.02.15)

[25] Paist, S. How to reduce offshore energy costs in the Baltic Sea. 2015

[26] Drwiega, A. Helicopter Operations to Offshore Wind Farms; London Conference Update. [WWW] http://www.aviationtoday.com/rw/commercial/offshore/Helicopter-Operations-to-Offshore-Wind-Farms-London-Conference-Update_79581.html#.VRt-o0LB_dk (01.02.2013)

[27] Official website of Arktos Craft [WWW] http://www.arktoscraft.com/companyprofile.htm (25.03.15)

[28] Amphibious Vehicles Take on the Arctic [WWW] http://www.popularmechanics.com/military/a8030/amphibious-vehicles-take-on-the-arctic-11877750/ (04.03.15)

[29] McLeod, M. Extreme Mobility- Design Engineering, 2012, May/June, 26-27.

[30] Bond Aviation Group official website [WWW] http://www.bondaviationgroup.com/case-history/offshore-wind-farm-support (01.03.2015

[31] Annus, J. Interview. Tallinn, 05.04.2015

[32] Commission Regulation (EU) No 965/2012, Official Journal of the European Union 25.10.12

[33] Eriksson, E. Wind Farm Layout: A Reliability and Investment Analysis. Uppsala Universitet, 2008.

[34] Crabtree, C. J. Operational and Reliability Analysis of Offshore Wind Farms. Durham University, 2012.

[35] Gary Birchenko, Business Development, ARKTOS Developments Ltd. Interview 05.05.15.

[36] Einmann, A. PPA kopterite hoolduseks kulub 650 000 eurot [WWW] http://www.postimees.ee/2942327/ppa-kopterite-hoolduseks-kulub-650-000-eurot (02.05.15)