Universitetet i Agder

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Wind Energy

Wind Farm Simulation Using WindSim: A Case Study of Smøla Wind Farm

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Submitted By

Group 02

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1 INTRODUCTION

Repowering a wind farm involves the replacement of current wind turbines with newer models that offer either greater nameplate capacity or improved efficiency, thereby leading to a net increment in power generation [1]. Repowering allows the replacement of first-generation wind turbines with modern multi-megawatt versions, presenting a transformative process that, with half the existing infrastructure, doubles the capacity and triples the energy output [2].

Over time, wind turbines exhibit the signs of aging and undergo performance degradation like any machinery, prompting owners of wind power installations to confront decisions regarding the lifespan of their wind farms [3]. Repowering emerges as an alternative to extend the project's life. It presents a viable strategy to increase the operational lifespan of a wind farm, addressing factors such as the aging of turbines, reduced yield or revenue, the availability of new technologies, or increasing operation and maintenance expenses. Repowering is a technique to enhance the efficiency and productivity of wind farms, thereby providing a great way to optimize their longevity and performance.

The potential for wind farm repowering has seen substantial developments, with initiatives already underway in countries such as Denmark, Germany, Spain, California, and India [1]. The concept of repowering initiatives started from the early 1990s, initially observed in California (USA) and Denmark, followed by subsequent adoption in Holland and Germany during the 1990s and 2000s. India and various global regions have also shown a keen interest in repowering their existing wind farms. Denmark stands out as a frontrunner in implementing repowering practices and implementing support schemes, leveraging its early adoption and extensive deployment of wind energy, leading to the presence of aged and low-capacity wind turbines in its current sites [4].

Complete repowering denotes the complete disassembly and replacement of wind turbines in an existing wind farm, including the tower and its foundation [4]. Conversely, partial repowering involves installing a new drivetrain and rotor into an existing wind turbine, accompanied by potential structural modifications to the tower.

The enhancements in performance attributed to partial repowering are considered less extensive than those achieved through full repowering.

Repowering offers several advantages, including an increased energy production from the same area, which leads to enhanced efficiency of modern wind turbines compared to their older turbines [3]. These updated turbines are much more reliable and necessitate reduced maintenance. Moreover, the visual impact is minimized due to a decreased number of machines generating equivalent installed power, while modern turbines' reduced noise levels contribute to a less pronounced sound impact. Additionally, the reduction in the quantity of wind turbines decreases the wake effect, subsequently enhancing the overall performance of the wind farm. The modernized turbines align more effectively with power grid requirements, ensuring improved compliance.

The primary objective of this project is to provide an overview and a qualitative analysis of instruments and design options to support repowering of Smøla wind farms. The existing wind power plant at Smøla was developed in two phases; the initial phase, comprising 20 turbines, reached completion in 2002, followed by the second phase, involving an additional 48 turbines, which was completed in August 2005 [5]. Smøla was Europe's largest onshore wind power plant when it came on stream and retained its status as Norway's largest until 2017. With a combined total of 68 turbines, this wind farm generates an annual production of 356 GWh, enough to meet the electricity needs of approximately 17,800 Norwegian households. Situated in flat and open terrain, the wind farm spans elevations ranging from 10 to 40 meters above sea level, featuring rotors varying in diameter from 76 to 82.4 meters, while the tower height extends to 70 meters. The Smøla wind power plant was originally licensed for 25 years. However, in 2014 Statkraft presented their plans for repowering of the Smøla wind-power plant within 2020 to ensure the inclusion of the new turbines in the green certificate market [6]. A study conducted by the Norwegian Institute of Nature Research (NINA) indicated that repowering the farm with 30 turbines of 5 MW each could curtail collision risks by 68%. Our current task involves the redesign or replanning of the wind farm, utilizing 30 turbines of 5 MW each, aiming to estimate the Annual Energy Production (AEP).

2 METHODOLOGY

2.1 WIND FARM LOCATION

The Smøla archipelago is situated off the coast of Møre & Romsdal County in Central Norway, positioned at coordinates 63°24´N, 8°00´E (Figure 2.1) [7]. This cluster comprises a large main island along with approximately 5500 smaller islands, islets, and minor skerries. Characterized by a predominantly flat terrain, the highest elevation on the primary island barely reaches 64 meters [8]. The habitats in this region are distinguished by heather moors hosting a combination of small and expansive marshes. Developed in two phases by the Norwegian energy company Statkraft, the initial phase of the Smøla wind-power plant reached completion in September 2002, while the second phase commenced operations in August 2005. Since its establishment in 2005, the wind-power facility encompasses a total of 68 turbines. The wind-power plant occupies an expanse of 17.83 square kilometers, delineated by the minimum convex polygon encompassing the outermost turbines along with a 200-meter buffer zone.

Figure 2.1. Smøla wind farm site.

2.2 TERRAIN AND ROUGHNESS

The first step in the set-up of flow field simulations, is the generation of a 3D model of the area of interest. This is done in the Terrain module. But first the basis for the 3D model must be available, which is a 2D dataset with elevation and roughness data in .gws format. The .gws format contains elevation and roughness data in a regular grid.

The turbine height was selected at 70 m and a rotor diameter of 82 m. The layout of the terrain model then built into a system of cells called mesh. This computational domain is created based on the digital domain in .gws format and contained the information regarding roughness and elevation [9]. This information was then ready to be imported to WindSim. Figure 2.2 shows the terrain model with a graph of the elevation and the roughness with a graph of the surface height over the area ones the Terrain module has been run successfully.

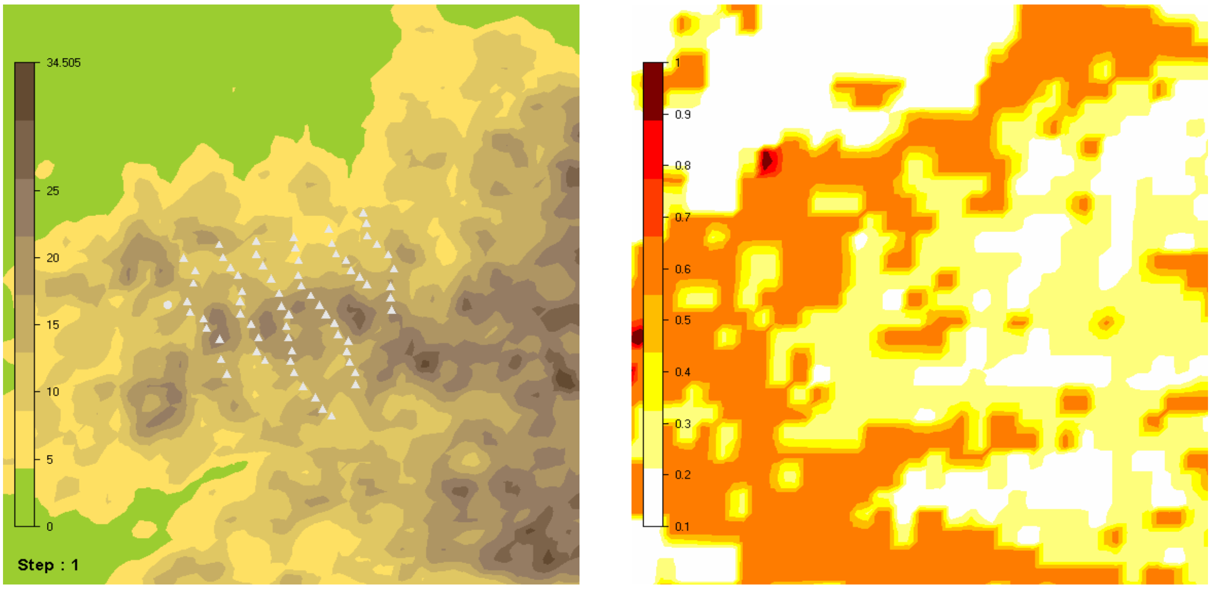
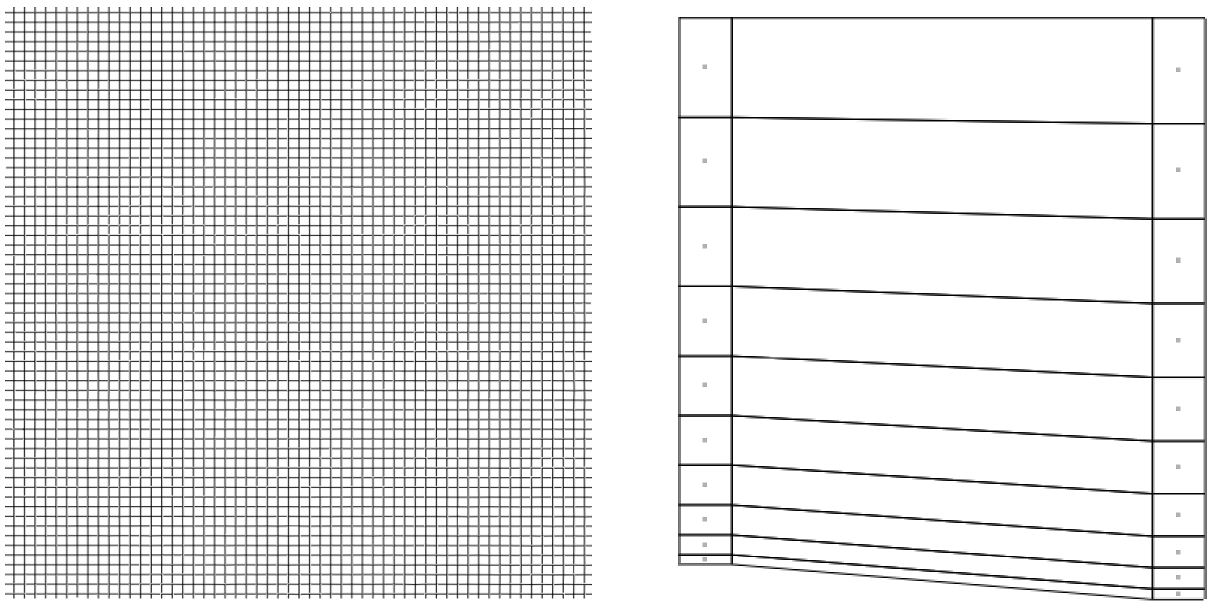


Figure 2.2. The terrain and roughness of Smøla site.

From Figure 2.2, the terrain model to the left shows that the wind farm site was located near the sea level. The surrounding height were over 25 m to 30 m above sea level. The site has a complex terrain, and the model shows an elevation that varies from about 25-35 m above sea level. Even though the terrain was complicated, as mentioned earlier, one could also see from the terrain model that the topography consisted of areas with elevations at about the same level.

The roughness map to the right in Figure 2.2 indicates that there was a considerable amount of surface roughness in the area. The roughness is important to look at because it can interact with the environment and in this case, reduce the wind resources and cause turbulence. In the right side of the model, the roughness was below 0.2, which meant that the roughness indicates a terrain with some tree stubs and rocks spread around [10]. Also, in the top left corner the roughness was below 0.2, which indicates that there is open sea. At the Smøla wind farm site, the elevation of the site decreases as the roughness increases. Here the roughness was at about 0.7-0.9, with some areas with lower roughness at 0.1-0.4. This suggests that there is some tree stubs and rocks spread around the site [10].

The Terrain module did also create a 3D model of the grid in the z-direction. This computational grid was set not to extend more than 800 m above the terrain in the properties and have 10 cells in the vertical direction. This was done because the wind resources at a higher elevation than what the wind turbines would be placed at are irrelevant for the amount of energy the wind farm would produce. Furthermore, was the properties set to have a refinement area with an x-range and y-range. This refinement area was made sure to cover the entire planned wind farm site so that the simulations would include all of the micro-sited wind turbines. Digital terrain model in the xy-direction and z-direction is shown in Figure 2.3. Number of cells in x direction is 56 and cell in y direction is 62. The number of cells in z direction is limited to 10.



(a) (b)

Figure 2.3. Digital terrain model (a). Grid -xy; (b). Grid-z.

2.3 WIND FIELDS

Upon acquisition of the topographical and roughness data of the designated site, the 3D model is subjected to Computational Fluid Dynamics (CFD) simulations for the entire area. Following the execution of the Wind field module, the simulation resolves four key variables: Pressure (P1), Velocity components (U1, V1, W1), Turbulent kinetic energy (KE), and turbulent dissipation rate (EP). In instances involving greater complexity, supplementary flow parameters such as temperature can be incorporated. With the border of the 3D model, information about the flow which is considered as boundary condition must be specified.

The assessment of wind field simulation convergence involves examining spot and residual values pertaining to velocity components (U1, V1, W1), turbulent kinetic energy (KE), dissipation rate (EP), or turbulent frequency (OMEG). All variables are normalized using the minimum and maximum values provided on the right-hand side. To ensure convergence, a predefined criterion is established via the properties panel, prompting the simulation to cease automatically when residuals drop below this convergence threshold.

Wind fields were segmented into 12 sectors aligned with wind direction, each sector spanning 30°. Within these sectors, wind data was graphically represented, utilizing WindSim's CFD-based analysis to depict the wind flow patterns.

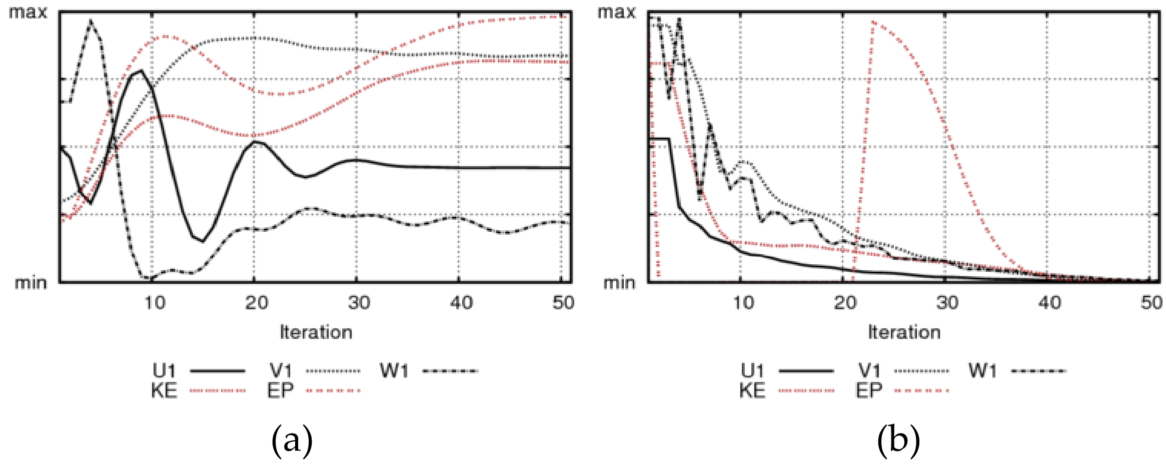


Figure 2.4. (a) Spot value; (b) Residual value for sector 0 degree.

2.4 OBJECT REPRESENTATION

The Objects module serves to position turbines, climatologies, and transferred climatologies within the designated framework. To aid visualization, a diverse array of geometrical objects can be integrated into the 3D terrain model. Alternatively, objects can be sourced from .ows files via the Tools->Import objects menu option. Specific details and properties need to be included within the object file, encompassing visualization files, climatology files, and power curve files. Parameters like hub height, rotor diameter, rotational speed, wind turbine orientation, and coordinate system must be explicitly defined.

Within the park layout feature, the addition of new turbine and climatology files is facilitated. Moreover, adjustments to turbine placement can be made by modifying the x and y coordinates.

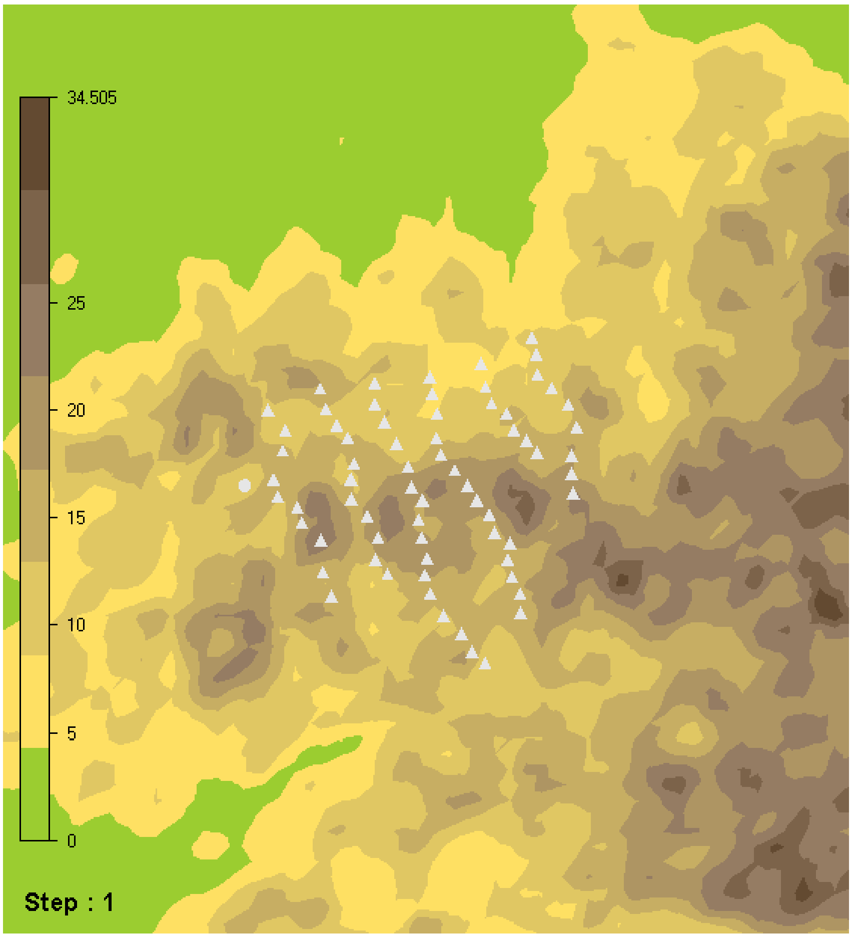


Figure 2.5. Digital terrain model with objects.

2.5 RESULT MODULE

Within the Results module, 2D planes can be generated by extracting variables stored within the wind database. These planes encompass a vertical range extending from ground level up to the specified "Height of reduced wind database" as outlined in the Wind Fields module. The 2D plane is generated at a specified height above the terrain, providing crucial insights into how the terrain influences flow fields. It's essential to emphasize that the Results module primarily functions as a visualization tool for observing wind field simulations. Notably, the wind speeds are not inherently adjusted based on wind measurements; however, non-dimensional, normalized plots are available for analysis [9]. Users can select the desired normalization type through the property grid. Furthermore, the Wind Resources module play a pivotal role in weighting the wind database against climatology data, aiding in comprehensive analysis and evaluation.

Certain properties, including heights and sector angles, are integral components of the plane property. These parameters dictate the heights above ground level at which the results are to be produced. It's important to note that only heights below the specified "Height of reduced wind database" outlined in the Wind Field module are considered valid for result generation. Similarly, the sector angles designated for result generation must align with the angles for which wind field simulations have been executed to be considered valid.

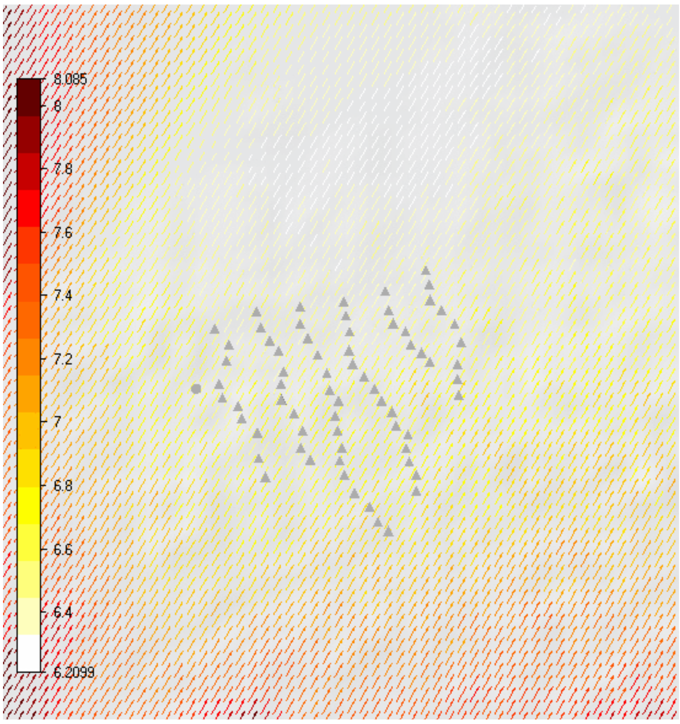


Figure 2.6. Wind velocity 3D (m/s) for sector 210° at 100 m.

2.6 WIND RESOURCES

Prior to running the Wind Resource module, it is required to have at least one climatology established, encompassing all sectors defined within that climatology existing in the wind database. The wind resource map creation involves a weighting process, integrating the wind database with the climatology data. In cases where multiple climatology objects are available, the wind resource map is formulated by employing interpolation techniques based on the inverse distance to these climatology objects.

The Wind Resource module is equipped with a specialized tool for area classification. This tool identifies interconnected regions characterized by high wind speeds, grouping these areas based on both wind speed and size. Additionally, this module estimates the potential power production within these identified areas. There are several properties that needs to be specified such as Wind resource map (wind height, sector interpolation, wake effect models, roughness height etc.).

2.6.1 Sector Interpolation

In the wind database, the wind direction specified for a simulation refers to the wind direction at the inlet. However, due to terrain influences, the wind direction undergoes alterations within the model's interior [9]. To effectively integrate the wind database with a climatology, an interpolation process becomes necessary. This

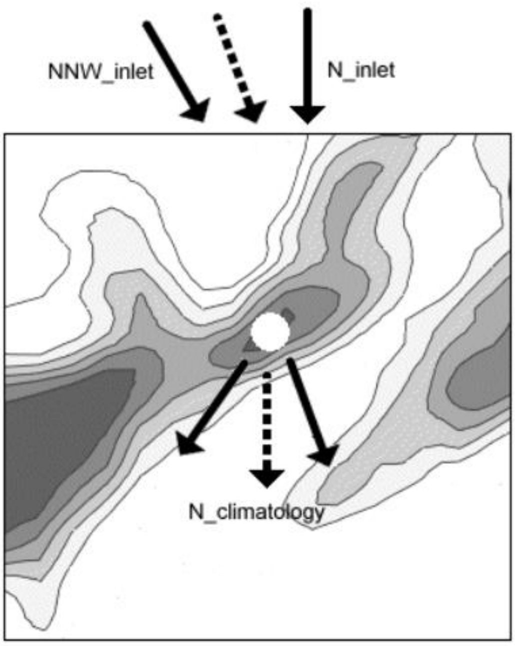


Figure 2.7. Example of sector interpolation, where interpolation of incoming wind from North-northwest and North give wind from North at the climatology location *(from WindSim10.0)*.

interpolation aims to replicate the climatology sectors at their respective positions within the climatology framework, as exemplified in Figure 2.7.

2.6.2 Wake effects

The interplay among wind turbines within a wind farm, commonly termed as the wake effect, describes the phenomenon where one turbine's operation affects others. This effect rises as turbines draw energy from the wind, leading to a reduction in wind speed behind the rotor. Consequently, this alteration induces swirling airflow patterns. Wake effects can be assessed through analytical or Computational Fluid Dynamics (CFD) methodologies. Analytical methods are attractive due to their simplicity and lower computational requirements compared to CFD-based approaches. The following three wake models outlined below belong to the category of analytical models. Each model operates as a single wake model, computing the normalized velocity deficit represented by $\delta V = (U - V) / U$, as depicted in the schematic definition in Figure 2.8. All models exhibit rotational axisymmetric along the x-axis, thereby computing reduced wakes based on hub height.

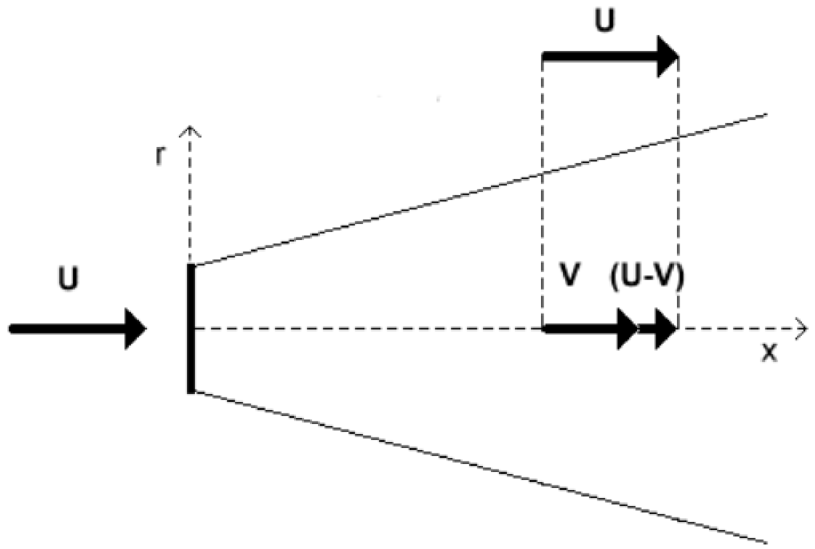


Figure 2.8. Sketch wake effects *(fromWindSim10.0).*

Model 1: Commonly known as the "Jensen model" [11], operates on the principles of momentum deficit theory. This model provides a straightforward linear expansion of the wake, primarily defined by the wake decay factor denoted as 'k'. The wake decay factor exhibits an escalating trend corresponding to higher levels of ambient turbulence, typically falling within a range of 0.04 to 0.075.

Model 2: Often recognized as the "Larsen model," is formulated by drawing from the turbulent boundary layer equations and relies on a similarity assumption [12].

Model 3: This model incorporates a rate of wake expansion that depends on turbulence [13].

2.6.3 Wind Climatology

The wind climatology is represented through a wind rose, illustrating the average wind speed distribution categorized into velocity intervals (bins) and wind directions (sectors) [14]. The initial wind speed data are segmented into 35 bins. However, in the visual depiction of the wind rose, all instances of wind speeds surpassing 16 m/s have been combined. Wind directions are organized into 12 sectors, with the first sector centered on the north direction.

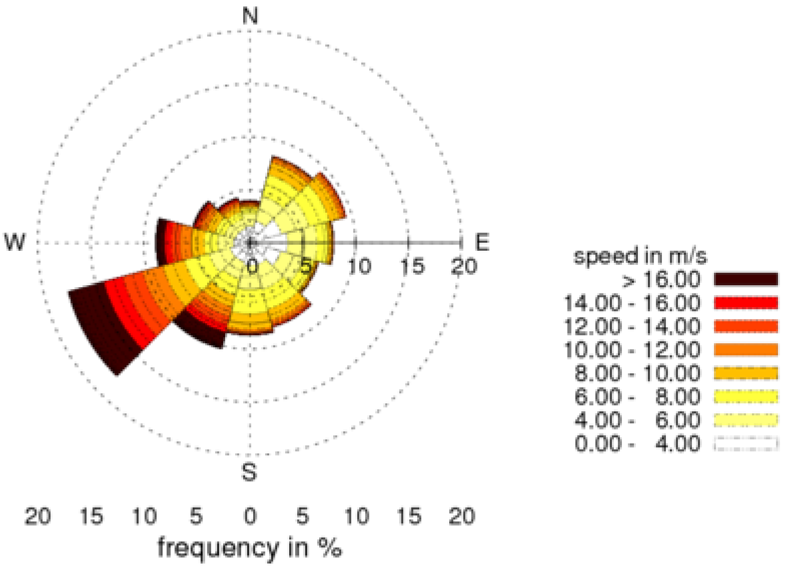


Figure 2.9. Wind Rose.

2.7 ANNUAL ENERGY PRODUCTION (AEP)

The Annual Energy Production (AEP) computation encompasses all visible turbine objects within the study. In scenarios where multiple climatology objects are provided, the AEP calculation is conducted separately for each climatology. This enables the identification and easy access to any disparities among the AEP values derived from different climatologies. A climatology is characterized by its frequency distribution, graphically depicted in the wind rose representation. Moreover, a climatology is also defined by its Weibull distribution. AEP calculations are performed for both representations of climatology.

2.8 COMPLETE WORKING PROCESS

The number of turbines in Smola wind farm in 68 turbines which can produce good amount of energy per year though this wind farm is facing some problems with the wild bird collision. As a result, NINA has conducted a research study how to reduce the number of turbines but producing the same energy output and found a promising solution. This study is based on their strategy to get similar or greater energy output or simply AEP with only 30 turbines of higher capacity(5MW).

At first the terrain file was loaded in the WindSim 10.0 Evaluation software. After the terrain is build, wind fields were specified and different sectors were created. Then the object file was created containing 30(5MW) wind turbines at different locations with a constant hub height of 95m for all the turbines. Two cases are shown in this study where the 30 turbines have different layout depending on different parameters such as elevation or wind flow direction. The wake model was selected and the climatology file was loaded. Now the simulation is complete and the results are ready to be analysed after a simple processing.

This whole process is shown in a flowchart in Figure 2.10

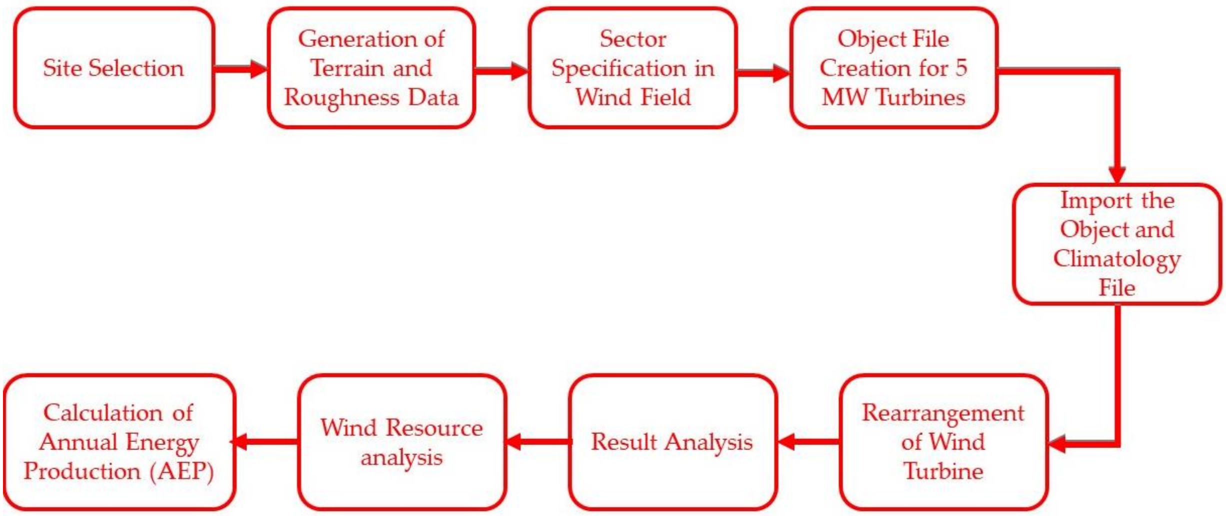


Figure 2.10. Complete working process in flow chart.

3 RESULTS AND DISCUSSIONS

3.1 WIND RESOURCES

A graphical tool that shows data about the wind at a specified area over a predetermined amount of time is called a wind rose. Usually, it offers a graphic depiction of the distribution of wind direction and speed. Figure 3.1 shows the wind rose for the selected location for heights of 95m and Wake Model 1 with 30 sub-sectors and with Wake Decay Factor- set to Automatic.

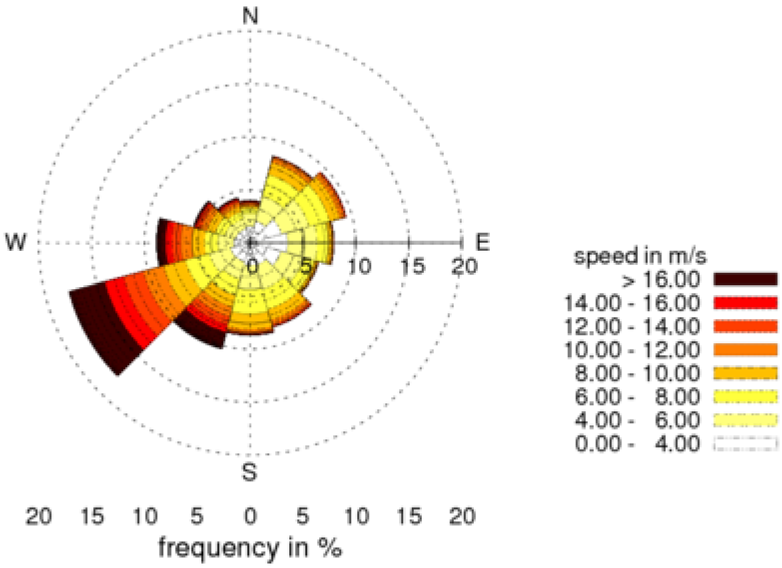


Figure 3.1. Wind Rose for Smola Island.

The figure xx clearly depicts that the air velocity is maximum, along with the frequency or percentage of time the wind comes from that direction at nearly south-west direction, where the velocity can be more than 16 m/s which is well enough for wind energy harvesting. The analysis was based on the climatology data recorded for around four years from August 2016 to January 2019. And considering seasonal wind variation and frequency of wind blowing direction, the two designs were proposed in this study.

The frequency distribution based on numerical calculation in WindSim and Weibull distribution is shown in Figure 3.2.

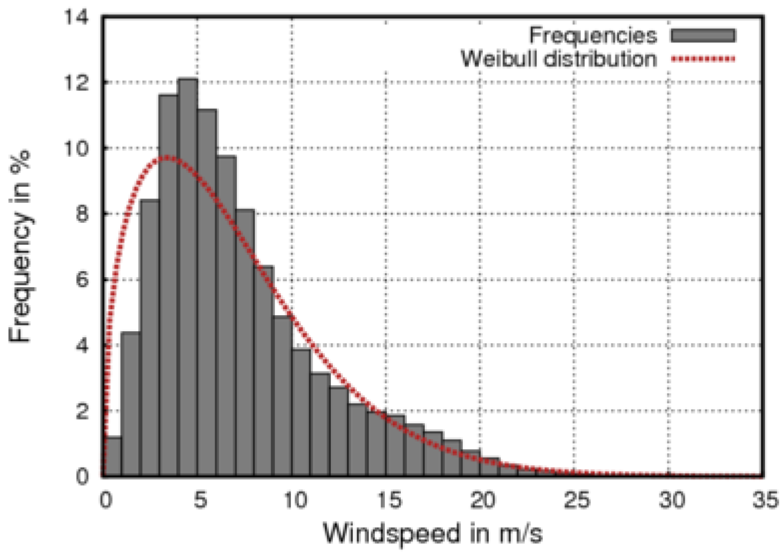


Figure 3.2. Windspeed distribution frequency.

Here on Figure 3.2, it can be seen that the numerical analysis data of frequency doesn’t match with Weibull distribution analysis at low wind velocity. But at higher wind speed; from 10-30 m/s, the frequency data matches with the Weibull distribution curve. The TABLE 3.1 gives the Weibull shape and scale parameters (k, A), accumulated frequency of occurrence and the average wind speed for each sector;

TABLE 3.1. WEIBULL(K,A), FREQUENCY (% RELATED TO ALL SECTORS) AND AVERAGE WIND SPEED (M/S) VS SECTOR.

Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
k	1.32	2.44	2.07	2.08	2.11	2.15	2.45	1.67	2.22	1.93	1.88	1.56
A	5.58	6.67	6.15	5.01	5.04	6.65	6.95	10.28	12.37	10.00	8.13	7.22
Freq.	4.0	8.4	9.4	7.9	6.7	8.2	8.7	10.3	17.7	8.8	5.5	4.4
Mean	5.56	5.91	5.52	4.51	4.53	5.93	6.07	9.36	10.82	8.82	7.20	6.64

This table shows that the average value of "A" is 7.61 and the average value of "K" is 1.45.

3.2 CASE STUDIES

3.2.1 BASE CASE

Existing wind farm in Smola; located in Norway has 68 turbines which were placed in the terrain as shown in Figure 3.3.

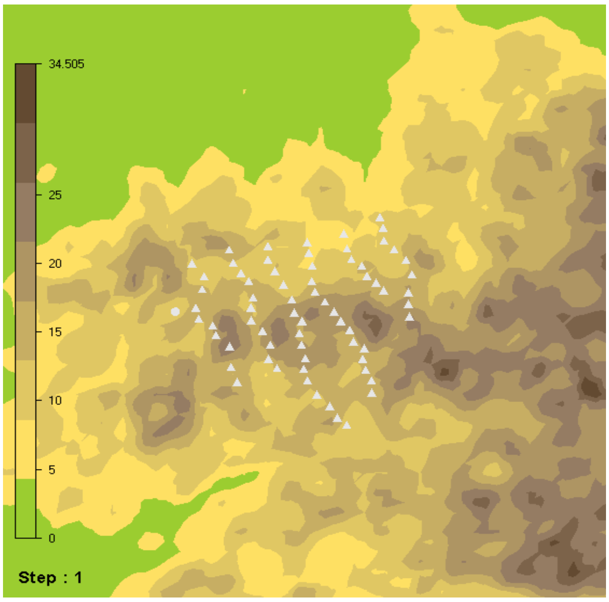
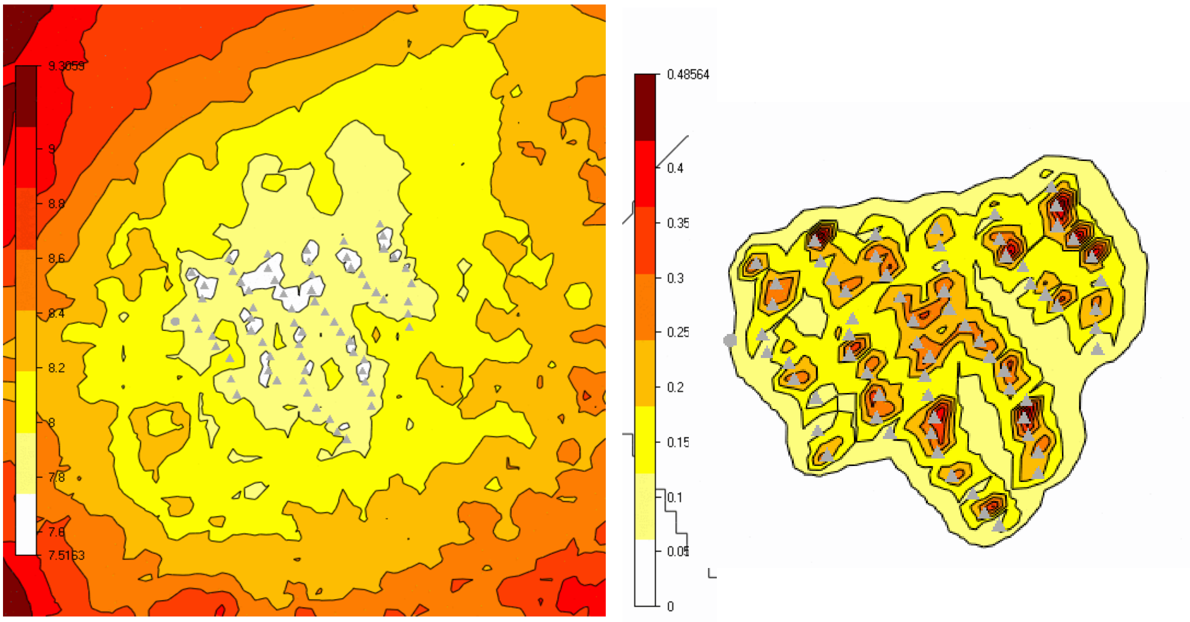


Figure 3.3. Object view of the existing 68 wind turbines of Smola wind farm.



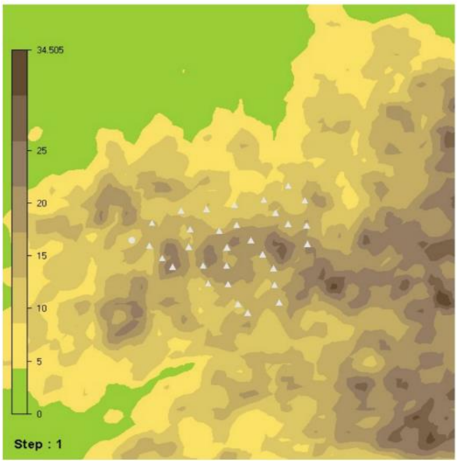
(a) (b)

Figure 3.4. (a)Mean wind speed 2D-wake deficit, (b) Wake deficit (Base Case).

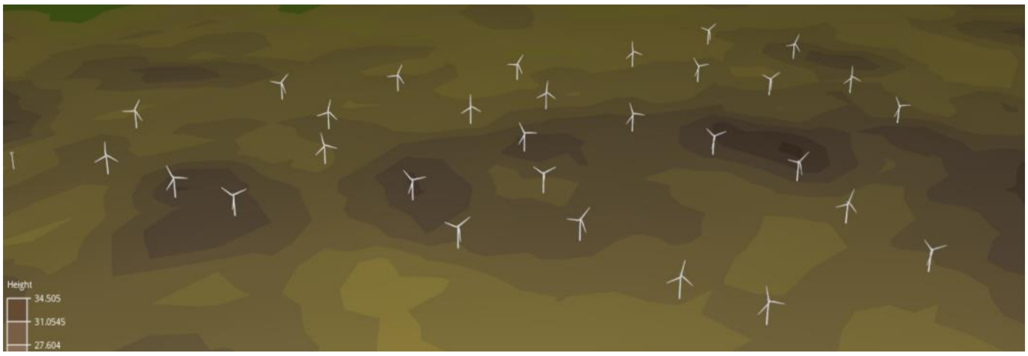
From Figure 3.4 (b), wake regions can be seen creating red zones and affecting other turbines of the same cluster. This layout is a good example chosen to be established due to its high AEP considering the wake loss. Also, turbines are not creating bigger wake regions depending on the direction of wind flow, as a result the wake loss is considerable. Though the existing site is having some issues with the wild birds collision due to the clustering of the turbines and less air space for the birds to fly according to the literature [2]. Also as the number of turbines are more, the more it costs to maintain them in working condition. The AEP for the existing wind farm, from the simulation, authors got 403.99 GWh/y with wake loss of about 5.74%.

3.2.2 CASE 01

In this case 68 wind turbines (2.2 MW & 2,3MW) were replaced with 30, 5MW turbines which is shown in Figure 3.5.



(a)



(b)

Figure 3.5. Wind turbine Park Layout on Smola Island (Case 01), (a) Terrain view, (b) 3D view.

The co-ordinates of the wind turbines are shown in TABLE 3.2. CO-ORDINATES OF TURBINE OBJECTS (CASE 01)from which, different elevation level of the turbines can be noticed for further wind resource and power density analysis.

TABLE 3.2. CO-ORDINATES OF TURBINE OBJECTS (CASE 01)

Turbine Name	x	y	z	Hub height
wecs3	446135.5	7032261.0	8.4	95.0
wecs5	446193.1	7031669.5	15.2	95.0
wecs7	446587.3	7031214.0	18.3	95.0
wecs9	446909.7	7030794.0	19.0	95.0
wecs11	447204.8	7030376.0	17.7	95.0
wecs13	447229.3	7029874.5	13.6	95.0
wecs16	446938.8	7032416.0	11.0	95.0
wecs18	447255.9	7032032.5	12.7	95.0
wecs20	447601.8	7031703.5	15.2	95.0
wecs23	443871.9	7031728.5	13.9	95.0
wecs25	443801.6	7031051.0	14.0	95.0
wecs27	444156.2	7030673.0	18.2	95.0
wecs28	444441.1	7030413.0	23.7	95.0
wecs31	444672.1	7032102.0	12.1	95.0
wecs33	444922.2	7031530.5	14.3	95.0
wecs35	444880.1	7031017.0	14.6	95.0
wecs37	445272.1	7030455.0	19.9	95.0
wecs39	445412.0	7029914.5	13.6	95.0
wecs44	445368.9	7032145.5	11.9	95.0
wecs46	445717.8	7031499.0	14.5	95.0
wecs48	445927.2	7030997.0	19.0	95.0
wecs50	445912.1	7030451.0	17.8	95.0
wecs52	445958.5	7029895.0	17.6	95.0
wecs54	446229.6	7029307.0	12.6	95.0
wecs55	446498.6	7029045.0	13.9	95.0
wecs59	447357.9	7029350.5	15.0	95.0
wecs62	447613.6	7032844.5	9.2	95.0
wecs64	448061.8	7032404.0	13.2	95.0
wecs66	448113.7	7031660.5	17.3	95.0
wecs68	448134.8	7031097.0	21.9	95.0

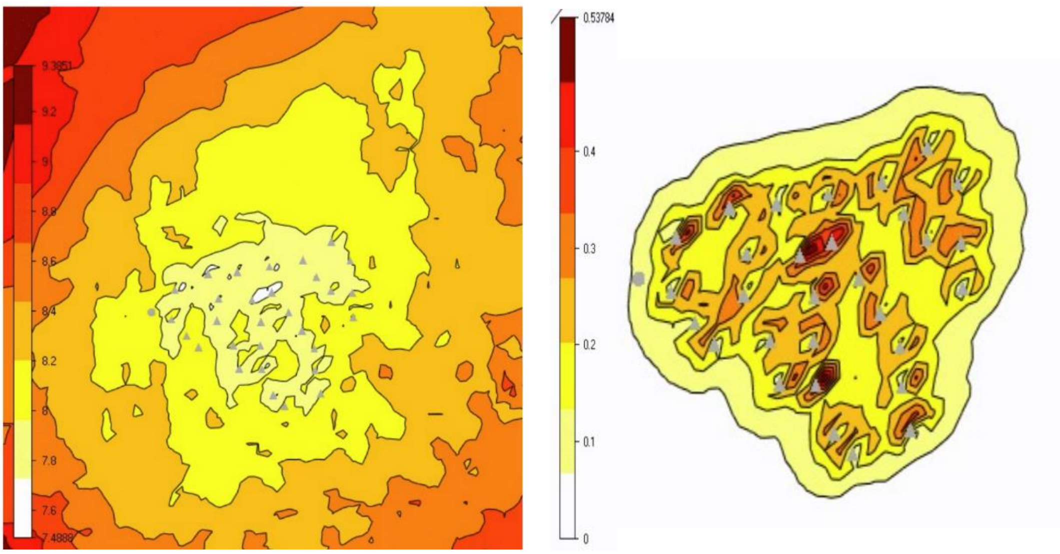


Figure 3.6. (a)Mean wind speed 2D-wake deficit, (b) Wake deficit (Case 01).

Figure 3.1 shows the mean wind speed (2D analysis) and wake deficit due to the flow separation by the wind turbines. This design imitates the existing layout of the wind farm with 30, 5MW wind turbines. According to the wind rose shown in figure xx, the wind frequency is maximum in south-west direction and the design is based on this parameter so that the wake loss can be minimized. Also clustering was mostly avoided. From this Figure 3.6 (a), it can be seen that all the turbines are in a light-yellow zone of wind speed meaning an average wind speed of 8 to 9 m/s. For this wind velocity, the generated wake can be seen on Figure 3.6 (b), where the red zone depicts more wake deficit. Here the effect of clustering can be seen for turbine 5 & 56. Because of the turbulence created by turbine 5, turbine 56 is generating less AEP; to be precise, its generating the minimum energy compared to other 29 turbines. Increasing the distance between 5 and 56th turbines can be a solution for this. The AEP with and without wake loss; Based on frequency analysis, is shown in TABLE 3.3,

TABLE 3.3. THE ANNUAL ENERGY PRODUCTION FOR EACH WIND TURBINE IS BASED ON THE POWER CURVE AND THE SPEED-UP ADJUSTED CLIMATOLOGY.

Name	Power	Hub height	Density	Wind speed	Wind speed including wake losses	Power density	Gross AEP	AEP with wake losses
	(kW)	(m)	(kg/m**3)	(m/s)	(m/s)	(W/m**2)	(MWh/y)	(MWh/y)
wecs3	5000	95.0	1.225	8.00	7.72	751.9	16730.9	15709.8
wecs5	5000	95.0	1.225	8.10	7.72	780.4	17026.1	15592.3
wecs7	5000	95.0	1.225	8.12	7.79	783.3	17138.3	15841.9
wecs9	5000	95.0	1.225	8.12	7.82	778.1	17164.4	15992.8
wecs11	5000	95.0	1.225	8.13	7.85	782.5	17194.1	16084.3
wecs13	5000	95.0	1.225	8.12	7.87	779.0	17140.4	16181.8
wecs16	5000	95.0	1.225	8.07	7.79	765.4	17008.1	15930.4
wecs18	5000	95.0	1.225	8.10	7.77	769.6	17110.4	15853.6
wecs20	5000	95.0	1.225	8.13	7.81	774.9	17253.0	16050.5
wecs23	5000	95.0	1.225	8.11	7.95	800.3	16939.0	16303.4
wecs25	5000	95.0	1.225	8.10	7.94	795.5	16936.1	16335.9
wecs27	5000	95.0	1.225	8.19	7.95	823.5	17163.1	16265.1
wecs28	5000	95.0	1.225	8.28	8.07	847.3	17418.7	16623.4
wecs31	5000	95.0	1.225	8.06	7.83	781.4	16805.3	15989.7
wecs33	5000	95.0	1.225	8.08	7.74	788.0	16877.8	15581.7

wecs35	5000	95.0	1.225	8.04	7.70	775.7	16781.2	15545.3
wecs37	5000	95.0	1.225	8.15	7.85	804.9	17079.2	15916.0
wecs39	5000	95.0	1.225	8.07	7.87	782.3	16870.2	16129.3
wecs44	5000	95.0	1.225	8.05	7.78	772.6	16821.5	15867.4
wecs46	5000	95.0	1.225	8.06	7.65	773.2	16887.0	15345.3
wecs48	5000	95.0	1.225	8.12	7.74	785.5	17091.0	15637.4
wecs50	5000	95.0	1.225	8.11	7.75	788.7	17029.7	15641.5
wecs52	5000	95.0	1.225	8.19	7.92	812.6	17248.8	16198.9
wecs54	5000	95.0	1.225	8.12	7.89	793.4	17058.3	16193.1
wecs55	5000	95.0	1.225	8.16	8.01	802.5	17159.1	16575.0
wecs59	5000	95.0	1.225	8.15	8.02	790.8	17243.3	16741.7
wecs62	5000	95.0	1.225	8.10	7.89	765.5	17177.1	16357.9
wecs64	5000	95.0	1.225	8.16	7.93	782.4	17348.1	16463.7
wecs66	5000	95.0	1.225	8.22	7.95	798.7	17494.0	16482.3
wecs68	5000	95.0	1.225	8.31	8.15	832.7	17677.9	17140.4
All	150000	-	-	-	-	-	512872.1	482571.9
Mean	-	-	1.225	8.12	7.86	788.8	-	-

From TABLE 3.3, it can be seen that the Gross AEP(Annual Energy Production) for the 30 turbines are ranging from 16730 to 17700 MWh/y per turbine; And the AEP with wake loss is ranging from 15.3 to 17 GWh/y per turbine. Therefore, the wake loss is calculated to be 5.91% with total AEP of 482.5GWh/y.

3.2.3 CASE 02

This case is also based on 30, 5MW wind turbines in different formation shown in Figure 3.7. The highest elevation level was prioritized while choosing the locations of the wind turbines, so that there lies no effect of wind velocity loss inside valley areas. Also, the clustering of wind turbines was done so that turbines get the wind blowing from south-west direction, as it is the most frequent wind flow direction according to the wind rose shown in Figure 3.1. The co-ordinates of the wind turbines are shown in TABLE 3.1.

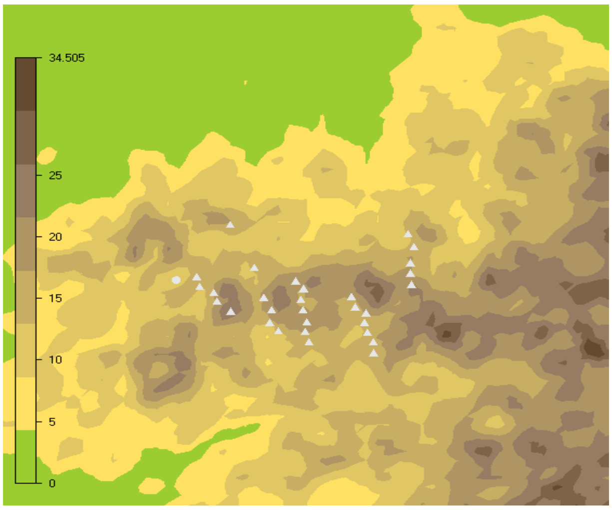


Figure 3.7. Wind turbine Park Layout on Smola Island(Case 02).

The relation between 2D mean wind speed and wake loss is shown in figure xx, where the effect of clustering the wind turbines can be seen clearly.

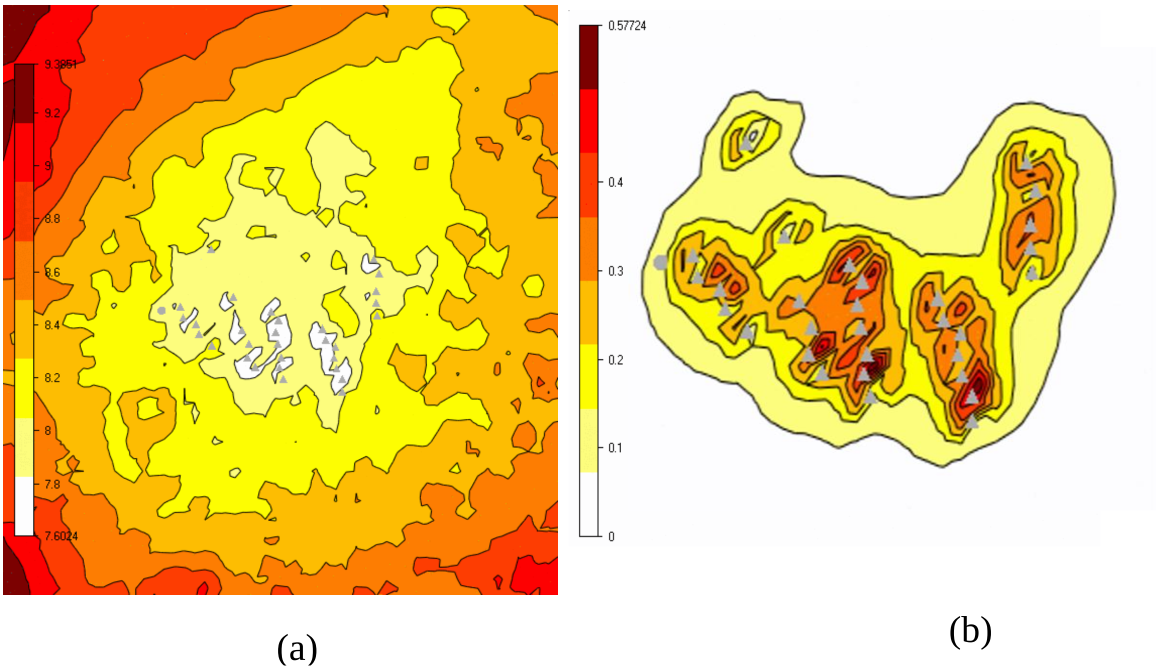


Figure 3.8. (a)Mean wind speed 2D-wake deficit, (b) Wake deficit (Case 02).

It is crystal clear that, this layout is generating more wake regions that case 01. From Figure 3.8 (a), the authors can see more white regions describing more wake loss, as the more white regions, the less wind velocity. From Figure 3.8 (b), it can be seen that, the red zones have increased implying more wake effect and loss of power. The AEP and AEP with wake loss is shown in TABLE 3.5**.**

Table 3.4. CO-ORDINATES OF TURBINE OBJECTS (CASE 02).

Turbine Name	x	y	z	Hub height
wecs9	446909.7	7030794.0	19.0	95.0
wecs10	446987.0	7030530.5	15.8	95.0
wecs11	447204.8	7030376.0	17.7	95.0
wecs12	447172.2	7030127.5	14.3	95.0
wecs13	447229.3	7029874.5	13.6	95.0
wecs24	443745.3	7031303.5	15.4	95.0
wecs25	443801.6	7031051.0	14.0	95.0
wecs26	444092.3	7030901.5	18.2	95.0
wecs27	444156.2	7030673.0	18.2	95.0
wecs28	444441.1	7030413.0	23.7	95.0
wecs34	444876.1	7031307.0	12.7	95.0
wecs36	445113.4	7030769.0	18.3	95.0
wecs37	445272.1	7030455.0	19.9	95.0
wecs38	445238.6	7030132.5	15.5	95.0
wecs39	445412.0	7029914.5	13.6	95.0
wecs41	444428.6	7032638.0	15.4	95.0
wecs47	445763.6	7031188.5	19.5	95.0
wecs49	445869.4	7030714.0	15.9	95.0
wecs50	445912.1	7030451.0	17.8	95.0
wecs51	445992.3	7030136.0	18.6	95.0
wecs52	445958.5	7029895.0	17.6	95.0
wecs53	446036.0	7029635.0	15.1	95.0
wecs54	446229.6	7029307.0	12.6	95.0
wecs58	447356.0	7029631.5	16.5	95.0
wecs59	447357.9	7029350.5	15.0	95.0
wecs64	448061.8	7032404.0	13.2	95.0
wecs65	448181.3	7032069.5	14.2	95.0
wecs66	448113.7	7031660.5	17.3	95.0
wecs67	448109.5	7031390.0	17.5	95.0
wecs68	448134.8	7031097.0	21.9	95.0

TABLE 3.5. THE ANNUAL ENERGY PRODUCTION FOR EACH WIND TURBINE IS BASED ON THE POWER CURVE AND THE SPEED-UP ADJUSTED CLIMATOLOGY (CASE 02).

Turbine Name	Power (kW)	Hub height (m)	Density (kg/m**3)	Wind speed (m/s)	Wind speed including wake losses (m/s)	Power density (W/m**2)	Gross AEP (MWh/y)	AEP with /ake losses (MWh/y)
wecs9	5000	95.0	1.225	8.12	7.69	778.1	17164.4	15518.0
wecs10	5000	95.0	1.225	8.06	7.56	763.3	16985.5	15207.1
wecs11	5000	95.0	1.225	8.13	7.59	782.5	17194.1	15184.4
wecs12	5000	95.0	1.225	8.11	7.59	779.9	17076.4	15111.1
wecs13	5000	95.0	1.225	8.12	7.71	779.0	17140.4	15641.5
wecs24	5000	95.0	1.225	8.15	7.84	813.0	17016.8	15859.1
wecs25	5000	95.0	1.225	8.10	7.82	795.5	16936.1	15997.8
wecs26	5000	95.0	1.225	8.21	7.75	833.7	17211.8	15459.0
wecs27	5000	95.0	1.225	8.19	7.90	823.5	17163.1	16143.8
wecs28	5000	95.0	1.225	8.28	8.05	847.3	17418.7	16555.8
wecs33	5000	95.0	1.225	8.08	7.87	788.0	16877.8	16086.7
wecs36	5000	95.0	1.225	8.11	7.67	792.6	16977.3	15377.4
wecs37	5000	95.0	1.225	8.15	7.63	804.9	17079.2	15153.6
wecs38	5000	95.0	1.225	8.09	7.66	789.0	16891.0	15388.9
wecs39	5000	95.0	1.225	8.07	7.74	782.3	16870.2	15699.4
wecs41	5000	95.0	1.225	8.16	8.08	809.1	17092.2	16788.7
wecs47	5000	95.0	1.225	8.15	7.69	795.6	17159.2	15483.4
wecs48	5000	95.0	1.225	8.12	7.62	785.5	17091.0	15263.9
wecs49	5000	95.0	1.225	8.04	7.43	768.0	16842.6	14561.3
wecs50	5000	95.0	1.225	8.11	7.56	788.7	17029.7	14971.1
wecs51	5000	95.0	1.225	8.18	7.58	809.1	17210.4	15013.7
wecs52	5000	95.0	1.225	8.19	7.66	812.6	17248.8	15190.7
wecs53	5000	95.0	1.225	8.16	7.93	801.0	17166.9	16343.2
wecs58	5000	95.0	1.225	8.19	7.82	798.5	17359.5	15941.2
wecs59	5000	95.0	1.225	8.15	8.01	790.8	17243.3	16763.7
wecs64	5000	95.0	1.225	8.16	7.94	782.4	17348.1	16465.2
wecs65	5000	95.0	1.225	8.15	7.91	777.7	17336.5	16417.8
wecs66	5000	95.0	1.225	8.22	7.85	798.7	17494.0	16130.8
wecs67	5000	95.0	1.225	8.20	7.83	794.0	17448.4	16058.8
wecs68	5000	95.0	1.225	8.31	8.11	832.7	17677.9	17027.5
All	150000	-	-	-	-	-	514751.3	472804.6
Mean	-	-	1.225	8.15	7.77	796.6	-	-

From TABLE 3.6, it can be seen that the Gross AEP(Annual Energy Production) for the 30 turbines are ranging from 16870 to 17677 MWh/y per turbine; And the AEP with wake loss is ranging from 14.5 to 17 GWh/y per turbine. Therefore, the wake loss is calculated to be 8.15% with total AEP of 472.8 GWh/y which is less than that of Case 01. The AEP and wake loss for all cases are shown in TABLE 3.6.

TABLE 3.6. COMPARISON AMONG THREE DIFFERENT CASES BASED ON AEP AND WAKE LOSS.

Cases	**Gross AEP (GWh/y)**	**AEP with Wake Loss (GWh/y)**	**Wake Loss %**
Base Case (69 Turbines)	428.5	403.9	5.74
Case 01 (30 Turbines)	512.8	482.5	5.91
Case 02 (30 Turbines)	514.7	472.8	8.15

From this table, authors can say that the Base case has the lowest wake loss though it has lowest AEP after wake loss is considered. On the other hand, Case 01 has shown more promising AEP despite having slightly bigger wake loss. While Case 02 generates the maximum gross AEP, it also shows maximum wake loss and 2.01% less AEP after considering wake loss than Case 01.

4 CONCLUSION

This study is focused on the simulation and strategic planning, specifically the repowering, of a wind farm employing WindSim software. The investigation focuses on the renowned 'Smøla' wind farm in Norway, comprising 68 wind turbines arranged in 6 rows. This wind farm demonstrates an average annual electricity production of 356 GWh. Constructed in two phases, this farm faces the necessity of repowering: a third of its current turbines require replacement within five years, while the remaining turbines need replacement within a decade.

However, an impediment to the repowering initiative is the high collision risk the wind farm poses to the white-tailed eagles inhabiting the island. A study conducted by the Norwegian Institute of Nature Research (NINA) indicated that repowering the farm with 30 turbines of 5 MW each could curtail collision risks by 68%. Our current task involves the redesign or replanning of the wind farm, utilizing 30 turbines of 5 MW each, aiming to estimate the Annual Energy Production (AEP). This redesign seeks to evaluate and compare wake losses and AEP against the existing layouts.

Concluding Remarks:

- Proposed layouts can produce more AEP than the existing wind Farm.
- Case 01 is more feasible than case 02, because case 02 produces maximum wake loss and about 2.01% less AEP after considering wake deficit.
- Replacing 68 turbines of 2 MW & 2.3 MW with 30 Turbines of 5MW capacity to reduce the bird collision rate while maintaining similar or

greater AEP, is feasible and can be economically profitable, as the maintenance cost reduces with the reduction of total turbines.

Remarks for Future Studies:

- Using more mesh can produce better results. Refining mesh on the edges makes the simulation result more realistic.
- Different combination of the layouts can be simulated for more diverse comparisons.
- A machine learning algorithm with ANN can be developed to determine the best park layout of wind farms with the help of WindSim, making the outcome of the WindSim as the training data for the ANN model.

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