Hochschule Flensburg
University of Applied Science

Wind Energy Technology Institute
Research on wind Energy

Advance Wind Farm Development, WiSe 2024/25

Master’s degree in Wind Engineering, Flensburg, Germany

Submitted by

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Acronyms

E	Easting
N	Northing
UTM	Universal Transverse Mercator
ETRS89	European Terrestrial Reference System 1989
MW	Mega Watt
RD	Rotor Diameter
LCOE	Levelized Cost of Energy
NPV	Net Present Value
IRR	Internal Rate of Return
AEP	Annual Energy Production
WTGs	Wind Turbine Generators
Lidar	Light Detection and Ranging
STATGEN	Stat Generation
MCP	Measure-Correlate-Predict
HH	Hub Height
MWh	Mega Watt hour

1. Introduction and Motivation

This report presents general information on wind farm planning area. The project was developed as part of the exam “Advance Wind Farm Planning” module within the Wind Energy Engineering Master’s Program at the University of Applied Sciences in Flensburg. Wind farm planning is increasing energy production, energy quality as well as reduce structural load. [1]

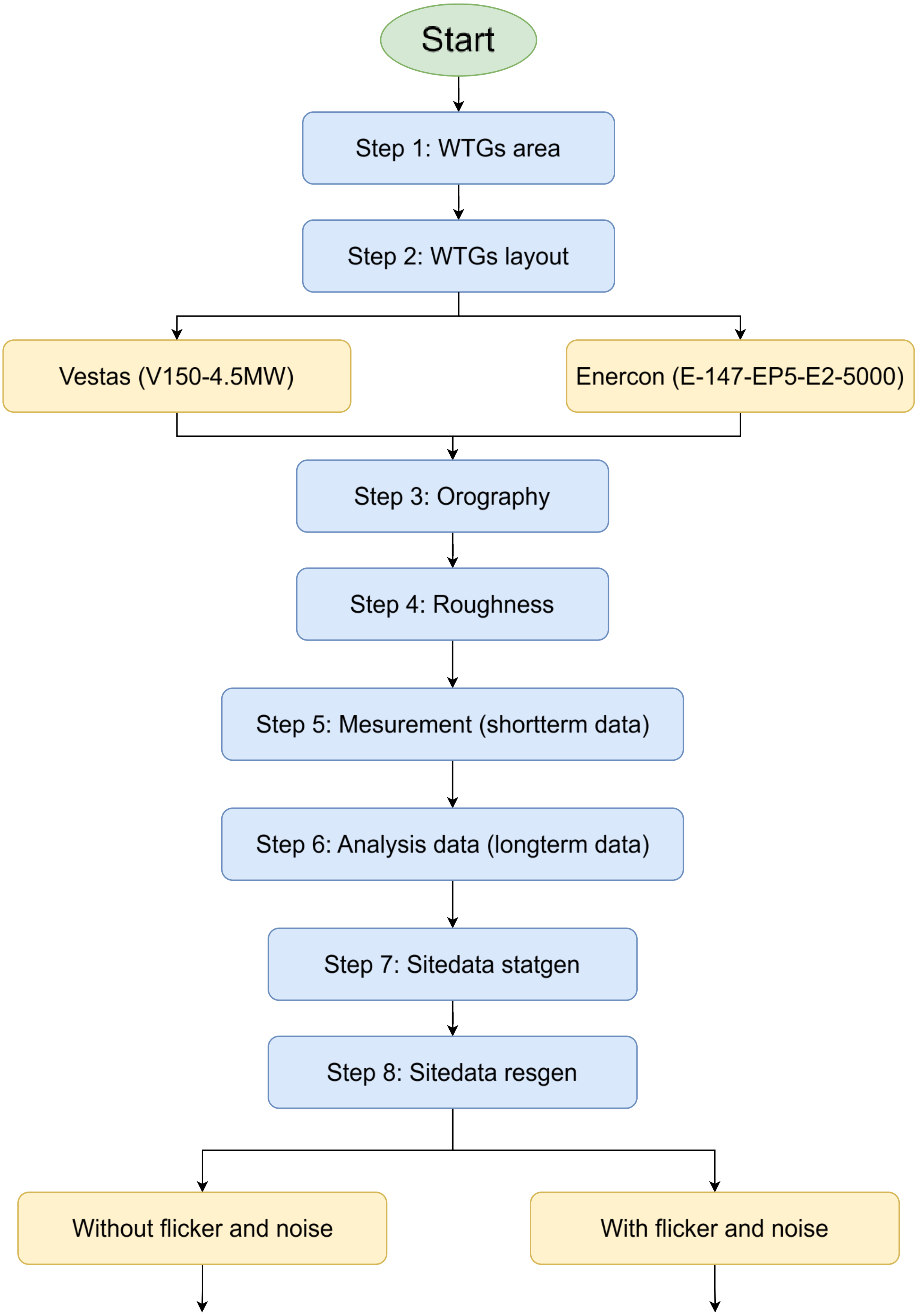
The shapefile already provided into exam, which shows the wind farm area, including all exclusion zones, so no need to consider distances to roads or boundaries. The tip height is limited to **200 meters**. Lidar measurements were taken at coordinates **548207 E, 6061864 N (UTM ETRS89 Z32).** This report presents wind farm layouts for **Vestas V150-4.5MW** and **Enercon E-147 EP5 E2 5000** turbines, considering maximum hub height limit. The layouts follow a minimum spacing of **5 RD** in the main wind direction and **3.5 RD** perpendicular.

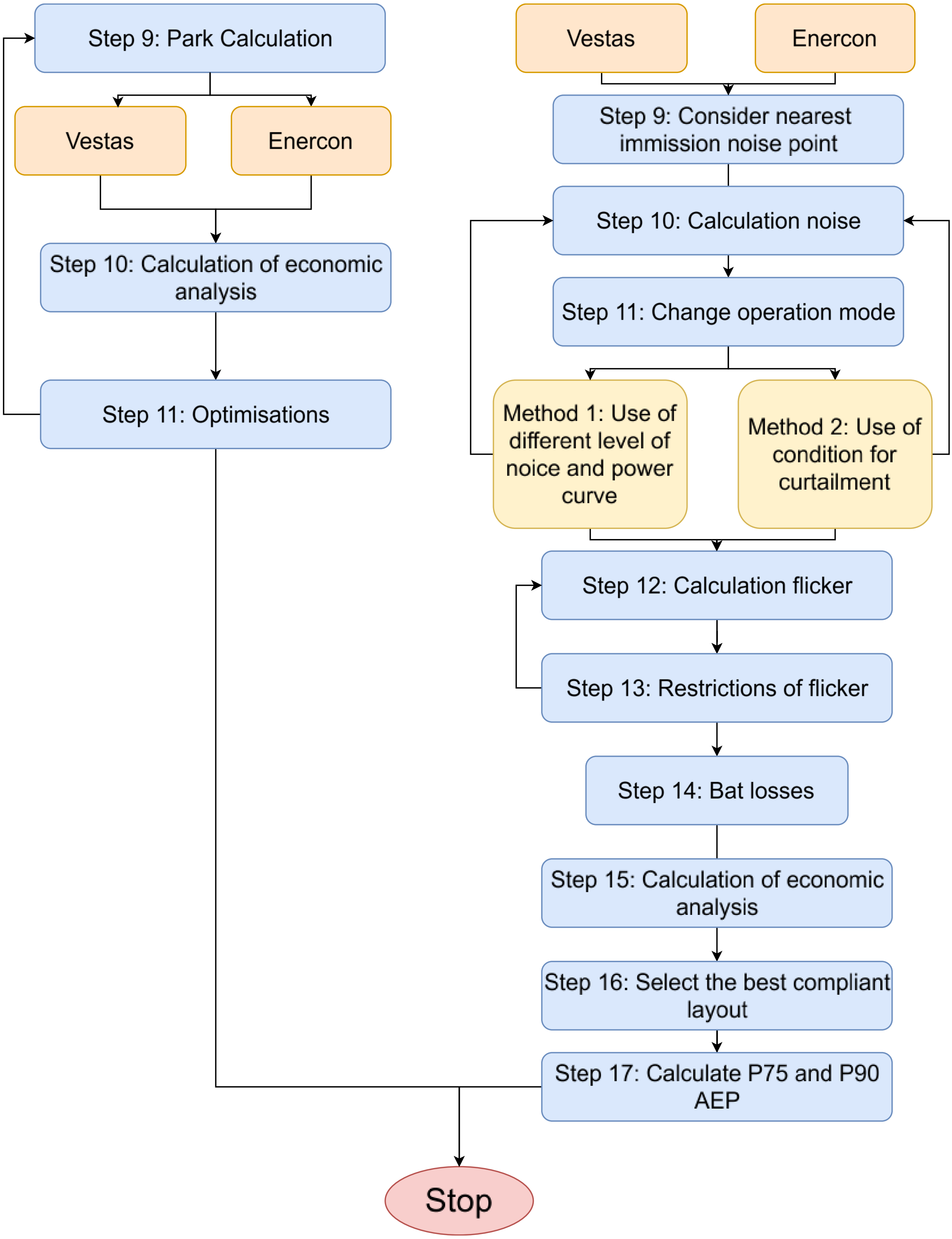
The Objective of this report is to estimate the energy yield for the baseline layout of two turbines, considering losses, without accounting for flicker and noise. The calculations will include the Levelized Cost of Energy (LCOE), Net Present Value (NPV), and Internal Rate of Return (IRR) for each turbine layout. The same calculations will be repeated, this time including flicker, noise, and bat losses. Based on the NPV, the report will identify the best compliant layout. Finally, the **P75** and **P90** Annual Energy Production (AEP) will be calculated for the selected best compliant layout.

Chapter 2 discusses the method used to achieve the objective. Chapter 3 covers our wind farm layout with two types of wind turbines, both with and without requirements as well as presents the results of the report. Chapter 4 discusses how the optimization of the wind farm could be improved if more time was available during the exam.c

To accomplish these tasks, we utilized lecture notes and the WindPro software, which we learned to use during class.

2. Methodology





Step 9: Park Calculation
Vestas
Enercon
Step 10: Calculation of economic analysis
Step 11: Optimisations
Vestas
Enercon
Step 9: Consider nearest immission noise point
Step 10: Calculation noise
Step 11: Change operation mode
Method 1: Use of different level of noice and power curve
Method 2: Use of condition for curtailment
Step 12: Calculation flicker
Step 13: Restrictions of flicker
Step 14: Bat losses
Step 15: Calculation of economic analysis
Step 16: Select the best compliant layout
Step 17: Calculate P75 and P90 AEP
Stop

Reference: [2]

3. Wind Farm Development

The wind area was already provided in the exam, so we directly imported it (see Figure 3.1).

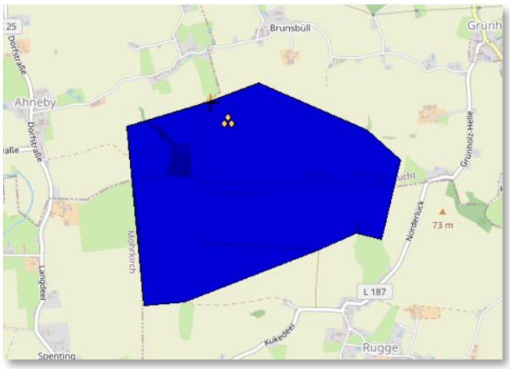


Figure 3. 1: WTGs area

In our calculations, we considered both orography (see Figure 3.2) and roughness (see Figure 3.3), as they are crucial factors. Orography refers to the shape of the terrain, such as mountains and valleys, as well as elevation, which impact wind speed and direction. Roughness relates to the surface texture, including forests, buildings, and water bodies, which affect the wind profile near the ground. These factors play a significant role in accurately assessing wind conditions [3].

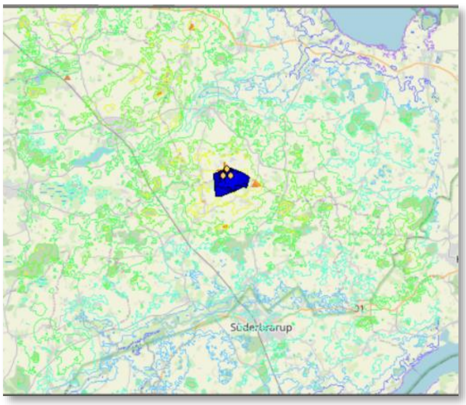


Figure 3. 2: Orography

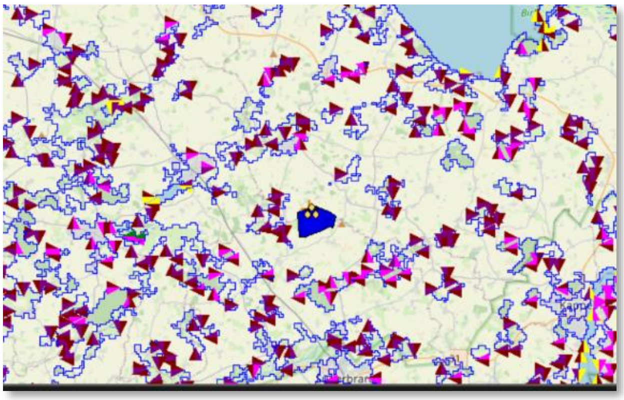


Figure 3. 3: Roughness

The short-term LiDAR data was already provided in the exam, so we imported it into WindPro for further analysis. The long-term wind data was sourced online and imported into WindPro, which is ERA5(T) (See Figure 3.4).

After processing the data, we performed a comparative analysis using MCP (Measure-Correlate-Predict). This method helped in correlating the short-term LiDAR data with the long-term dataset ERA5(T), ensuring accurate wind predictions. The MCP process enhances the reliability of wind resource assessments by adjusting for variations and filling gaps in the data, ultimately improving the accuracy of energy yield estimations. We applied four different models for comparison, but the neural network model showed the closest resemblance to the long-term data (see Figure 3.5). Therefore, we selected this model as the most reliable for our analysis.(Annexture-A: MCP report)

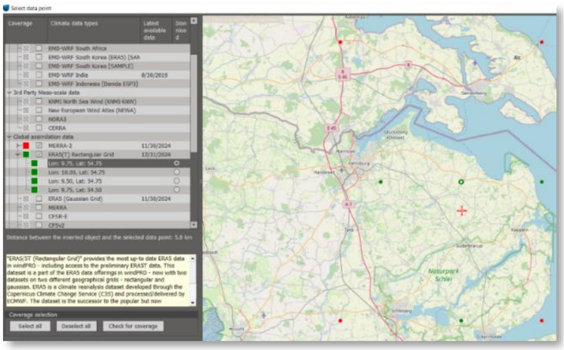


Figure 3. 4: Long term data ERA5(T)

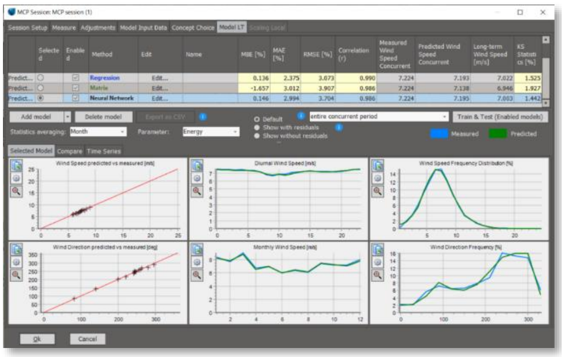


Figure 3. 5: Long term and short term data comparisons

To process and analyze the data, we used site data STATGEN (Annexture-B) to generate site-specific wind statistics and site data RESGEN to create resource grids based on the available data. Then we created a resource map (Annexture-C) using RESGEN data. These steps allowed us to evaluate the wind resource distribution across the study area (see Figure 3.6).

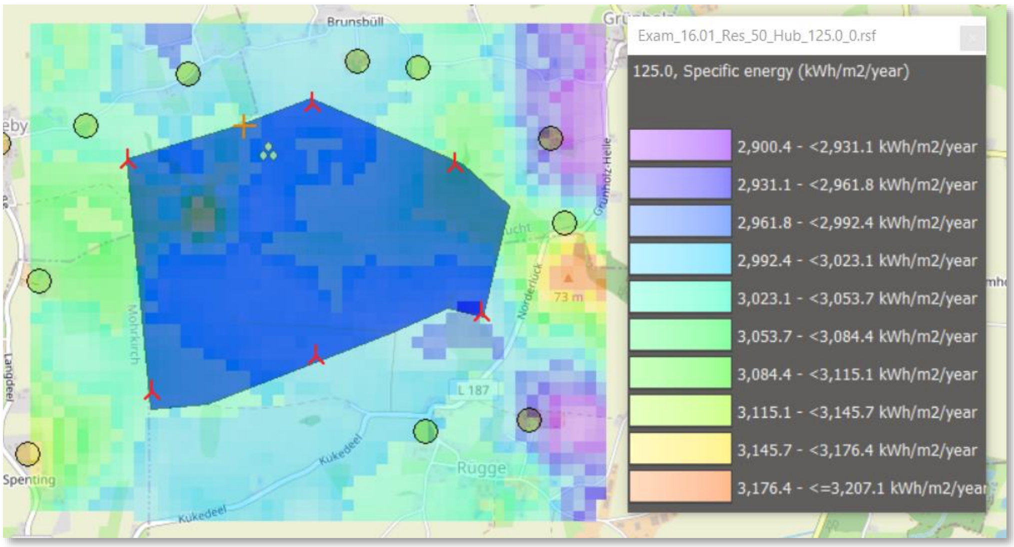


Figure 3. 6 MCP output

3.1 Baseline layout without flicker and noise requirements

Before placing the wind turbines, we considered the wind direction, which is crucial for minimizing wake effects and optimizing energy production. This approach helps increase the Annual Energy Production (AEP) and enhances the overall profitability of the project by ensuring an efficient wind farm layout. As shown in Figure 3.7, the wind rose illustrates the predominant wind directions, and we specifically considered a **240-degree** wind direction for our analysis.

For the wind turbine layout, we considered both wake direction and wake distance to minimize energy losses and optimize efficiency. The wake direction was analyzed using an elliptical shape, where the major direction was set to **5R** and the minor direction to **3.5R** (see Figure 3.8). This approach ensures better spacing between turbines, reducing wake effects and improving overall energy output.

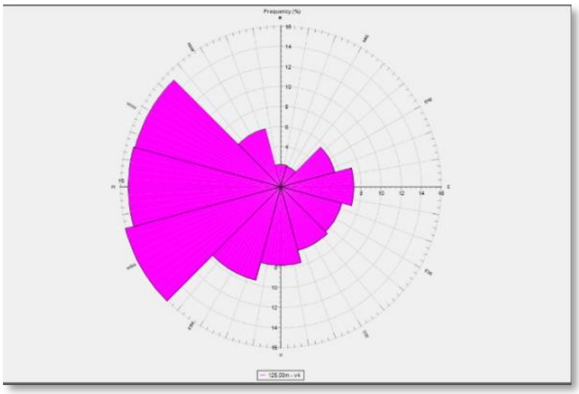


Figure 3. 7: Wind rose

Figure 3. 8: Distance circle for wind turbine

3.1.1 Layouts of Vestas V150-4.5MW HH125

As shown in Figure 3.9, the wind turbine layout features Vestas V150-4.5MW HH125 turbines. In our initial approach, we designed the wind farm layout with a total of six turbines, carefully considering wind direction and wake effects to maximize efficiency.

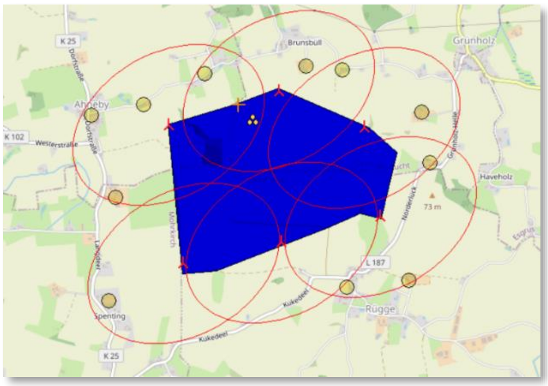


Figure 3. 9: Six wind turbine of Vestas V150 – 4.5MW HH125

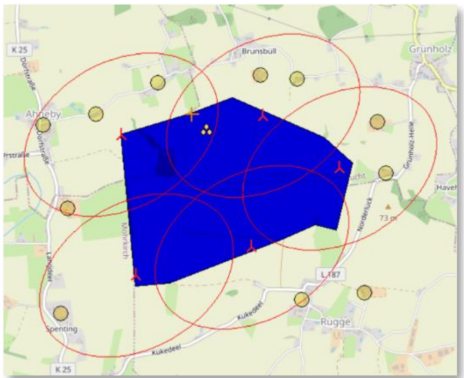


Figure 3. 10: Five wind turbine of Vestas V150 – 4.5MW HH 125

As shown in Figure 3.10, the wind turbine layout features Vestas V150-4.5MW HH125 turbines. In our second approach, we designed the wind farm layout with a total of five turbines, carefully considering wind direction and wake effects to maximize efficiency. The wind turbine layout features Vestas V150-4.5MW HH125 turbines. In our third approach, we designed the wind farm layout with a total of seven turbines.

3.1.2 Comparison of different Layout of Vestas V150-4.5MW HH125

The AEP for the wind farm layout with **five** Vestas V150-4.5MW HH125 turbines is **82,810 MWh/year**, considering **4%** wake losses (see Figure 3.11). The calculated Net Present Value (NPV) is **9,354,499 euros**, and the Internal Rate of Return (IRR) is **14.52%**. The AEP for the wind farm layout with **six** Vestas V150-4.5MW HH 125 turbines is **98,137.1 MWh/year**, considering

5.1% wake losses (see Figure 3.12). The calculated Net Present Value (NPV) is **10,573,478 euros**, and the Internal Rate of Return (IRR) is **14.32%**.

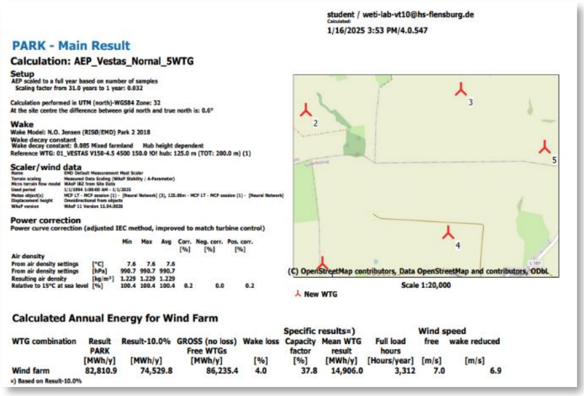


Figure 3. 11: Wind park result for five Vestas wind turbines

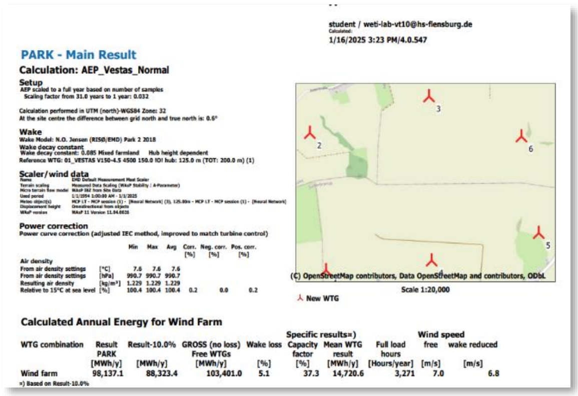


Figure 3. 12: Wind park result for six Vestas wind turbines

The AEP for the wind farm layout with **seven** Vestas V150-4.5MW HH 125 turbines is **112,331.2 MWh/year**, considering **6.8%** wake losses (see Figure 3.13). The calculated Net Present Value (NPV) is **11,187,243 euros**, and the Internal Rate of Return (IRR) is **14.01%**.

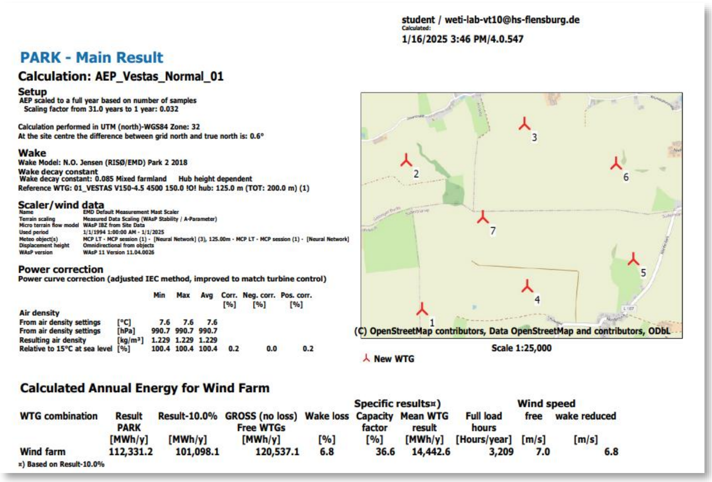


Figure 3. 13: Wind park result for seven Vestas wind turbines

The **seven-turbine** layout has the highest AEP **(112,331.2 MWh/year)** and NPV **(11,187,243 euros)**, but it also has the highest wake losses **(6.8%)** and a lower IRR **(14.01%)**, indicating a reducing over time return on investment.

The **five-turbine** layout has the highest IRR **(14.52%)**, but its NPV **(9,354,499 euros)** and AEP **(82,810 MWh/year)** are the lowest, meaning it generates less revenue overall.

The **six-turbine** layout provides a well-balanced solution, with a high AEP **(98,137.1 MWh/year)**, a competitive NPV **(10,573,478 euros)**, and a solid IRR **(14.32%)**, making it the most financially and technically viable choice. The **six-turbine** layout is the best option because it provides a strong balance between energy production, wake losses, and financial performance.

3.1.3 Layout of Enercon E-147 EP5 E2 5000 HH 126

As shown in Figure 3.14, the wind turbine layout features Enercon E-147 EP5 E2 5000 HH 126 turbines. However, as discussed in the previous chapter, the layout with six wind turbines proved to be the most optimal for maximizing both the NPV and Internal Rate of Return IRR of the project.

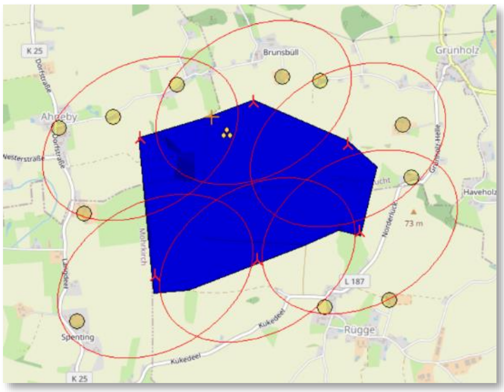


Figure 3. 14: Six wind turbine of Enercon E147 EP5 E2 5000 HH 127

3.1.4 Commercial Evaluation of Wind Farm

Commercial Evaluation of Vestas V150-4.5MW HH125 and Enercon E-147 EP5 E2 5000 HH 126 Wind Farm without Flicker and Noice Requirements

	Vestas	Enercon	Unit
Wind farm installed capacity	27	30	MW
No. of WTGs	6	6	
Lifetime	35	35	Years
Opportunity cost of capital	11	11	%
Remuneration rate	65	65	EUR/MWh
CAPEX			
WTG Capex per MW	1.05	1.05	MEUR/MW
Other Capex per MW	0.35	0.35	MEUR/MW
Total CAPEX	1.4	1.4	MEUR/MW
OPEX			
O&M	80,000	80,000	EUR/WTG/y
Gross AEP	103,401	97246.7	MWh/y
Total Loss	11.6	11.1	%
Cashflows	37,800,000	42,000,000	EUR
NPV	10,573,478	3,502,121	EUR
IRR	14.32	12.00	%
LCOE Calculation			
PV CAPEX	37,800,000	42,000,000	EUR
PV OPEX	4,718,072	4,718,072	EUR
PV AEP	898,656	849,622	MWh
LCOE	47.3	55	EUR/MWh

NET P50 AEP	91,426	86,438	MWh/y
NET P75 AEP	85,301	80,646	MWh/y
NET P90 AEP	79,724	75,374	MWh/y

Table 3. 1: Commercial Evaluation of six Vestas V150-4.5MW HH125 and Enercon E-147 EP5 E2 5000 HH 127 wind turbines

Based on the analysis of the two wind turbine layouts, the Vestas turbine layout **(27 MW)** appears to be the better choice compared to the Enercon layout **(30 MW)**. Although Enercon has a higher installed capacity, Vestas demonstrates a higher Net Present Value (NPV) of **10.57 million euros** compared to **3.50 million euros** for Enercon, along with a higher Internal Rate of Return (IRR) of **14.32%** versus **12.00%** for Enercon. Additionally, Vestas achieves a lower Levelized Cost of Energy (LCOE) of **47.3 euro/MWh**, making it more cost-effective compared to Enercon's **55 euro/MWh**. The superior financial metrics, lower LCOE, and better overall project returns indicate that Vestas is the more favorable choice for maximizing profitability and efficiency.

Note: -

Please find Annexture D (Excel and PDF) for Commercial Evaluation of Vestas V150-4.5MW HH125 Wind Farm without Flicker and Noice Requirements.

Please find Annexture E (Excel and PDF) for Commercial Evaluation of Enercon E-147 EP5 E2 5000 HH 126 Wind Farm without Flicker and Noice Requirements

3.2 Noise and Flicker Compliant Layout

Before evaluating noise and flicker impacts, we identified key areas, such as residential zones, schools, and other critical locations that could be affected by noise. These areas are highlighted as red-colored boxes in Figure 3.15. Defining these zones beforehand allowed us to accurately assess and mitigate potential noise and flicker effects during the planning process.

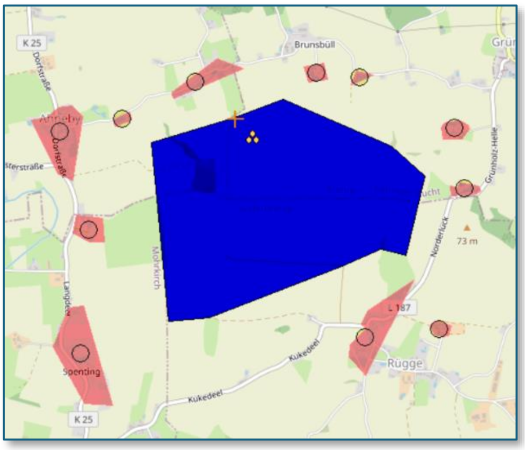


Figure 3. 15: Residencial and other area near to wind farm area

3.2.1 Noise

As shown in Figure 3.15, we identified the nearest emission points and conducted our initial simulation to generate a noise map. The results, presented in Figure 3.16, illustrate different noise zones: black represents areas with a noise sensitivity of **55 dB**, red corresponds to **45 dB**, and yellow indicates **33 dB**.

According to German regulations, the noise limit at night must not exceed **45 dB**. However, in our wind farm, this limit is exceeded at the nearest emission point. Due to the presence of multiple obstacles within the red zone, we implemented two mitigation approaches to address this issue, as outlined below.

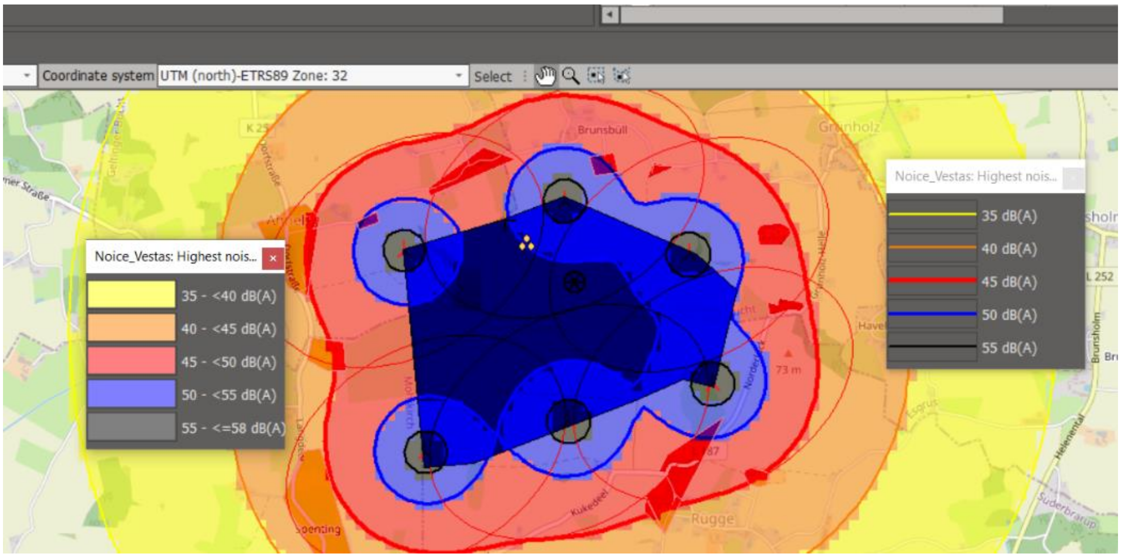


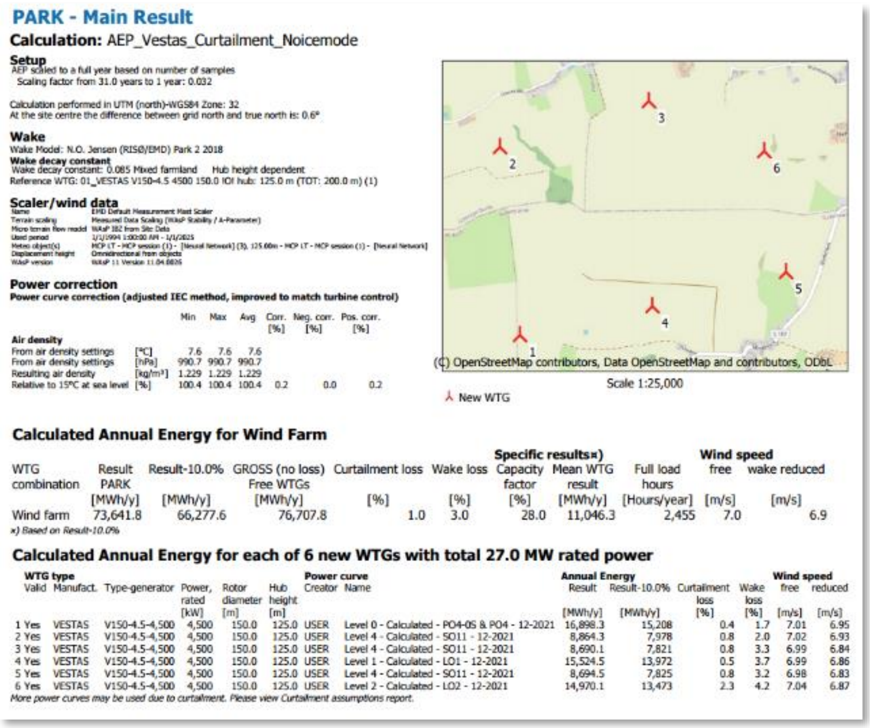
Figure 3. 16: Noice levels Vestas layout

3.2.1.1 Method 1: Use of different modes of operation of wind turbines

In our initial approach, we decided to operate the turbines in a lower mode, particularly those located near residential areas. To achieve this, we experimented with reducing the operational levels.

Vestas V150-4.5MW HH125 Layout

Our wind farm there are six turbines, and we identified that turbines 2, 3, 4, 5 and 6 had emission points classified within the red zone. To mitigate noise emissions, we first set these turbines to a higher level (Full performance) and ran a simulation. We then followed an iterative process with decreasing power modes of operation and adjusting as necessary, to ensure noise emissions remained within acceptable limits. (Annexture-F_First Simulation and Annexture-G_Optimized Map for Vestas)



PARK - Main Result

Calculation: AEP_Vestas_Curtailment_Noicemode

Setup
AEP scaled to a full year based on number of samples
Scaling factor from 31.0 years to 1 year: 0.032

Calculation performed in UTM (north)-WGS84 Zone: 32
At the site centre the difference between grid north and true north is: 0.6°

Wake
Wake Model: N.O. Jensen (RISØ/EMD) Park 2 2018
Wake decay constant
Wake decay constant: 0.085 Mixed farmland Hub height dependent
Reference WTG: 01_VESTAS V150-4.5 4500 150.0 !O! hub: 125.0 m (TOT: 200.0 m) (1)

Scaler/wind data

Name	EMD Default Measurement Mast Scaler
Terrain scaling	Measured Data Scaling (WAsP Stability / A-Parameter)
Micro terrain flow model	WAsP IBZ from Site Data
Used period	1/1/1994 1:00:00 AM - 1/1/2025
Meteo object(s)	MCP LT - MCP session (1) - [Neural Network] (3), 125.00m - MCP LT - MCP session (1) - [Neural Network]
Displacement height	Omnidirectional from objects
WAsP version	WAsP 11 Version 11.04.0026

Power correction
Power curve correction (adjusted IEC method, improved to match turbine control)

		Min	Max	Avg	Corr. [%]	Neg. corr. [%]	Pos. corr. [%]
Air density							
From air density settings	[°C]	7.6	7.6	7.6			
From air density settings	[hPa]	990.7	990.7	990.7			
Resulting air density	[kg/m³]	1.229	1.229	1.229			
Relative to 15°C at sea level	[%]	100.4	100.4	100.4	0.2	0.0	0.2

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	Result-10.0% [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Curtailment loss [%]	Wake loss [%]	Specific results¤) Capacity factor [%]	Specific results¤) Mean WTG result [MWh/y]	Specific results¤) Full load hours [Hours/year]	Wind speed free [m/s]	Wind speed wake reduced [m/s]
Wind farm	73,641.8	66,277.6	76,707.8	1.0	3.0	28.0	11,046.3	2,455	7.0	6.9

¤) Based on Result-10.0%

Calculated Annual Energy for each of 6 new WTGs with total 27.0 MW rated power

	WTG type Valid	Manufact.	Type-generator	Power, rated [kW]	Rotor diameter [m]	Hub height [m]	Power curve Creator	Name	Annual Energy Result [MWh/y]	Result-10.0% [MWh/y]	Curtailment loss [%]	Wake loss [%]	Wind speed free [m/s]	reduced [m/s]
1	Yes	VESTAS	V150-4.5-4,500	4,500	150.0	125.0	USER	Level 0 - Calculated - PO4-0S & PO4 - 12-2021	16,898.3	15,208	0.4	1.7	7.01	6.95
2	Yes	VESTAS	V150-4.5-4,500	4,500	150.0	125.0	USER	Level 4 - Calculated - SO11 - 12-2021	8,864.3	7,978	0.8	2.0	7.02	6.93
3	Yes	VESTAS	V150-4.5-4,500	4,500	150.0	125.0	USER	Level 4 - Calculated - SO11 - 12-2021	8,690.1	7,821	0.8	3.3	6.99	6.84
4	Yes	VESTAS	V150-4.5-4,500	4,500	150.0	125.0	USER	Level 1 - Calculated - LO1 - 12-2021	15,524.5	13,972	0.5	3.7	6.99	6.86
5	Yes	VESTAS	V150-4.5-4,500	4,500	150.0	125.0	USER	Level 4 - Calculated - SO11 - 12-2021	8,694.5	7,825	0.8	3.2	6.98	6.83
6	Yes	VESTAS	V150-4.5-4,500	4,500	150.0	125.0	USER	Level 2 - Calculated - LO2 - 12-2021	14,970.1	13,473	2.3	4.2	7.04	6.87

More power curves may be used due to curtailment. Please view Curtailment assumptions report.

Figure 3. 17 : Vestas Noice mode result

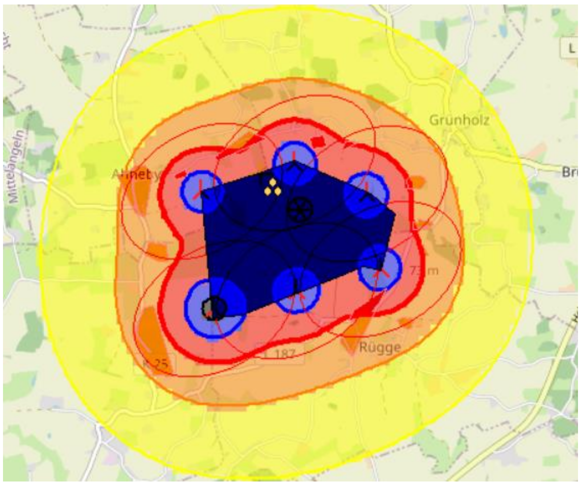


Figure 3. 18 : First Iteration of Operation modes

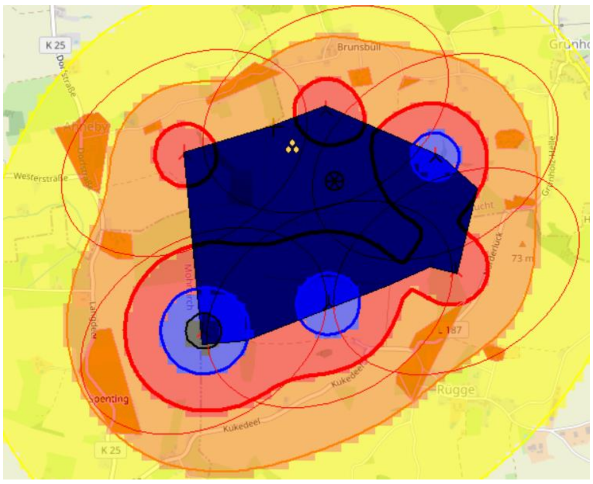
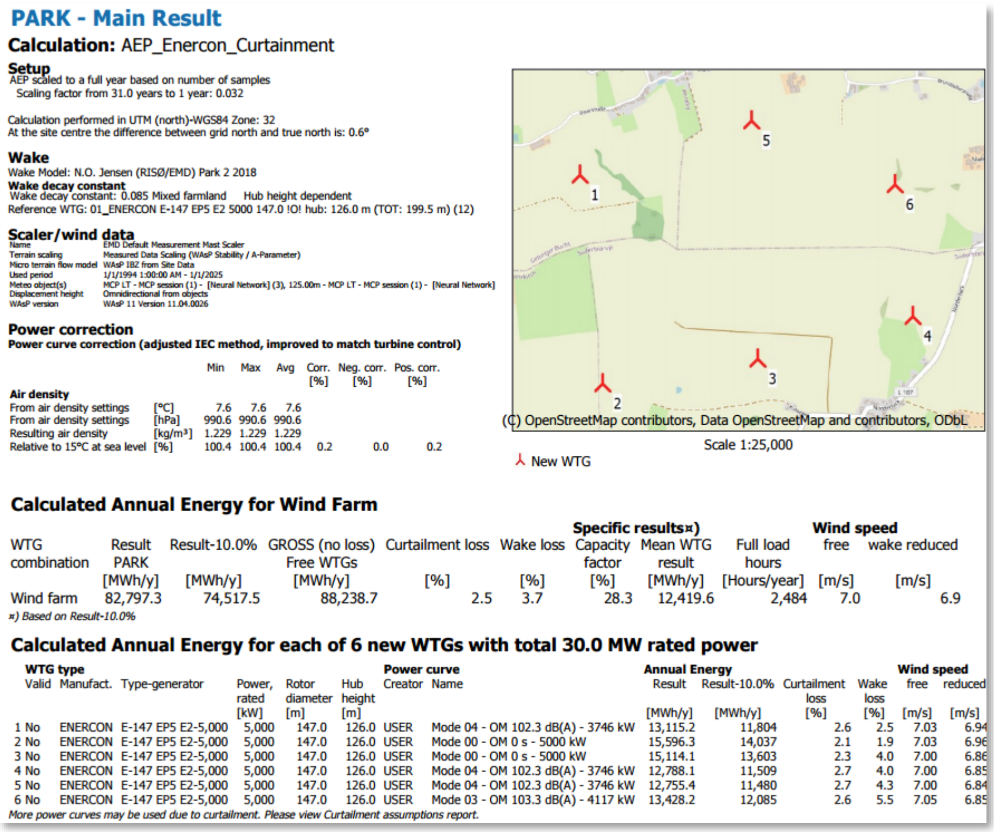


Figure 3. 19 : Final Iteration with optimized result

Enercon E-147 EP5 E2 5000 HH 126 Layout

The same iterative optimization process was applied to the Enercon layout, as illustrated in Figure 3.20. In the Enercon layout, we identified that turbines 1, 4, 5, and 6 had emission points near residential areas. To mitigate this, we operated these turbines in lower power generation modes. (Annexture-H_First Simulation and Annexture-I_Optimized Map for Enercon)



PARK - Main Result

Calculation: AEP_Enercon_Curtainment

Setup
AEP scaled to a full year based on number of samples
Scaling factor from 31.0 years to 1 year: 0.032

Calculation performed in UTM (north)-WGS84 Zone: 32
At the site centre the difference between grid north and true north is: 0.6°

Wake
Wake Model: N.O. Jensen (RISØ/EMD) Park 2 2018
Wake decay constant
Wake decay constant: 0.085 Mixed farmland   Hub height dependent
Reference WTG: 01_ENERCON E-147 EP5 E2 5000 147.0 !O! hub: 126.0 m (TOT: 199.5 m) (12)

Scaler/wind data

Name	EMD Default Measurement Mast Scaler
Terrain scaling	Measured Data Scaling (WAsP Stability / A-Parameter)
Micro terrain flow model	WAsP IBZ from Site Data
Used period	1/1/1994 1:00:00 AM - 1/1/2025
Meteo object(s)	MCP LT - MCP session (1) - [Neural Network] (3), 125.00m - MCP LT - MCP session (1) - [Neural Network]
Displacement height	Omnidirectional from objects
WAsP version	WAsP 11 Version 11.04.0026

Power correction
Power curve correction (adjusted IEC method, improved to match turbine control)

		Min	Max	Avg	Corr. [%]	Neg. corr. [%]	Pos. corr. [%]
Air density							
From air density settings	[°C]	7.6	7.6	7.6			
From air density settings	[hPa]	990.6	990.6	990.6			
Resulting air density	[kg/m³]	1.229	1.229	1.229			
Relative to 15°C at sea level	[%]	100.4	100.4	100.4	0.2	0.0	0.2

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	Result-10.0% [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Curtailment loss [%]	Wake loss [%]	Specific results¤) Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Wind speed free [m/s]	wake reduced [m/s]
Wind farm	82,797.3	74,517.5	88,238.7	2.5	3.7	28.3	12,419.6	2,484	7.0	6.9

¤) Based on Result-10.0%

Calculated Annual Energy for each of 6 new WTGs with total 30.0 MW rated power

	WTG type Valid	Manufact.	Type-generator	Power, rated [kW]	Rotor diameter [m]	Hub height [m]	Power curve Creator	Name	Annual Energy Result [MWh/y]	Result-10.0% [MWh/y]	Curtailment loss [%]	Wake loss [%]	Wind speed free [m/s]	reduced [m/s]
1	No	ENERCON	E-147 EP5 E2-5,000	5,000	147.0	126.0	USER	Mode 04 - OM 102.3 dB(A) - 3746 kW	13,115.2	11,804	2.6	2.5	7.03	6.94
2	No	ENERCON	E-147 EP5 E2-5,000	5,000	147.0	126.0	USER	Mode 00 - OM 0 s - 5000 kW	15,596.3	14,037	2.1	1.9	7.03	6.96
3	No	ENERCON	E-147 EP5 E2-5,000	5,000	147.0	126.0	USER	Mode 00 - OM 0 s - 5000 kW	15,114.1	13,603	2.3	4.0	7.00	6.86
4	No	ENERCON	E-147 EP5 E2-5,000	5,000	147.0	126.0	USER	Mode 04 - OM 102.3 dB(A) - 3746 kW	12,788.1	11,509	2.7	4.0	7.00	6.85
5	No	ENERCON	E-147 EP5 E2-5,000	5,000	147.0	126.0	USER	Mode 04 - OM 102.3 dB(A) - 3746 kW	12,755.4	11,480	2.7	4.3	7.00	6.84
6	No	ENERCON	E-147 EP5 E2-5,000	5,000	147.0	126.0	USER	Mode 03 - OM 103.3 dB(A) - 4117 kW	13,428.2	12,085	2.6	5.5	7.05	6.85

More power curves may be used due to curtailment. Please view Curtailment assumptions report.

Figure 3. 20 : Enercon Noice mode result

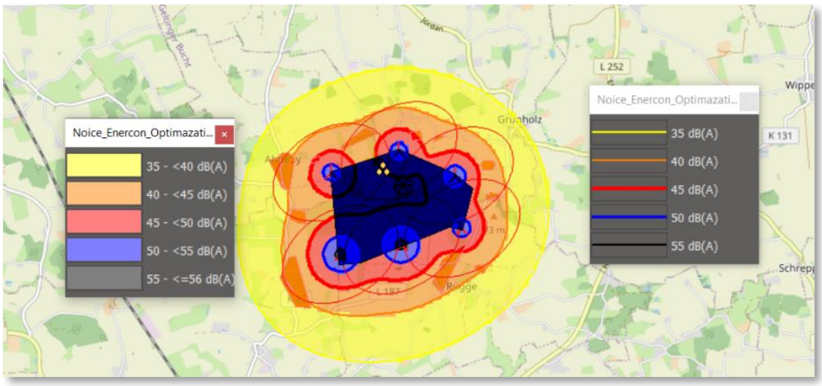


Figure 3. 21: Final Iteration with optimized result for Enercon layout

The impact of the process on AEP will be discussed in the following section 3.3.4.

3.2.1.2 Method 2: Use of condition for curtailment

Another approach to mitigating the noise level issue is shutting down the turbines during nighttime hours, from 22:00 to 06:00. This measure aligns with the legal noise limit of 45 dB, which applies specifically at night when people are asleep. To comply with this regulation, we implemented curtailment on the turbines from January 1 to December 31, restricting their operation during these hours.

The effect of this process on AEP will be examined in Section 3.3.4.

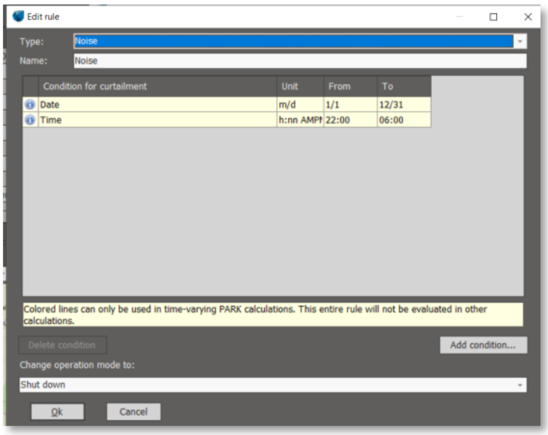


Figure 3. 22 : Noise curtailment

3.2.2 Shadow Flicker

The shadow effect, also referred to as "shadow flicker," happens when the rotating blades of a wind turbine create moving shadows on nearby buildings and properties. This phenomenon, caused by sunlight filtering through the blades, can be a concern for residents living close to wind farms, as it may lead to discomfort, distraction, or even health issues such as headaches or stress in some cases.

Germany enforces stringent regulations to reduce the impact of shadow flicker on nearby residents. The main requirements are as follows:

- **Annual Limit:** Shadow flicker must not surpass **30 hours per year** under worst-case scenarios.
- **Daily Limit:** The effect should not exceed **30 minutes per day** at any affected residence.

Therefore, conducting shadow flicker assessments is crucial, and we have incorporated this process into our wind farm planning, as outlined below.

To implement shadow flicker analysis, we utilized a tool called Shadow Receptor in the WindPro software. Our simulation was performed based on the worst-case scenario, and the results are presented in the figures below.

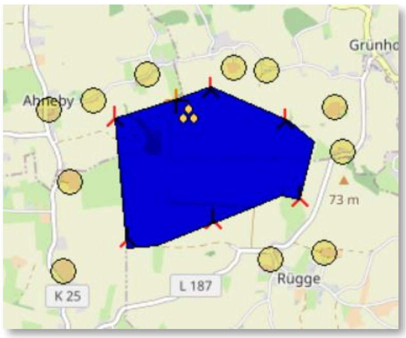


Figure 3. 23 Shadow Flicker

After that, we conducted our simulation and obtained results for both layouts, as shown in Figures 3.24 and 3.25.

Vestas (Annexture-J_ Shadow flicker for Vestas)

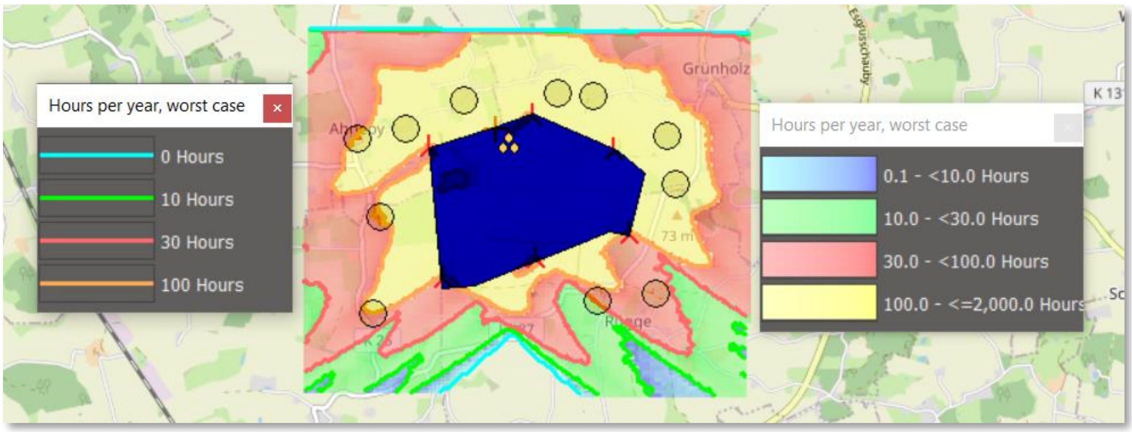


Figure 3. 24 : Shadow flicker for Vestas layout

Enercon (Annexture-K_ Shadow flicker for Vestas)

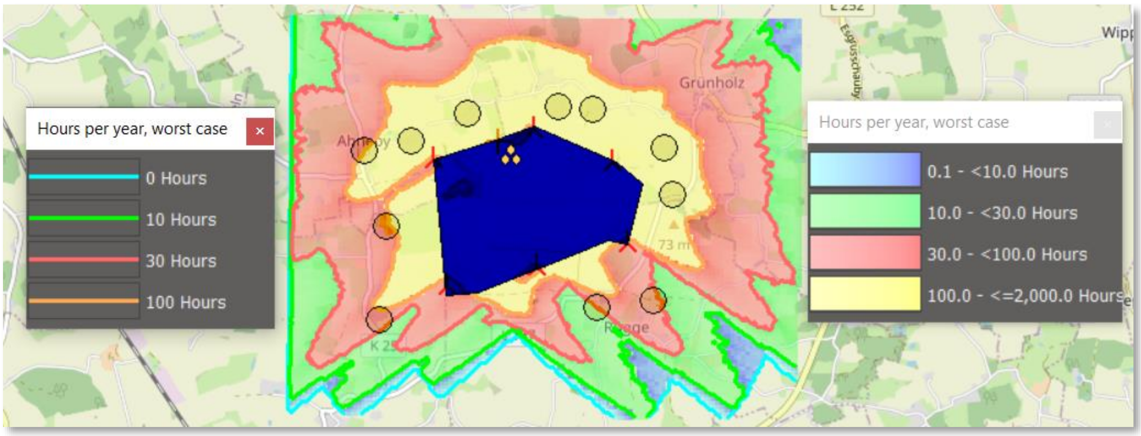


Figure 3. 25: Shadow flicker for Enercon layout

As observed in the flicker map, shadow flickering in both layouts exceeds the **30-hour-per-year** limit. To address this, wind turbine operators must implement mitigation measures, such as automatically shutting down the turbines during critical periods.

However, due to time constraints, we were unable to incorporate this curtailment into the calculations for our layout.

3.3.3 Bats

Curtailment is generally implemented during periods of high bat activity, typically in the spring and autumn migration seasons when bats are more likely to fly near wind turbines. The main concern is the risk of collisions between the turbines and these species, especially during migration times or at specific times of the day when bats are most active. We implemented this curtailment as per the data given in the exam mentioned in Figure 3.24.

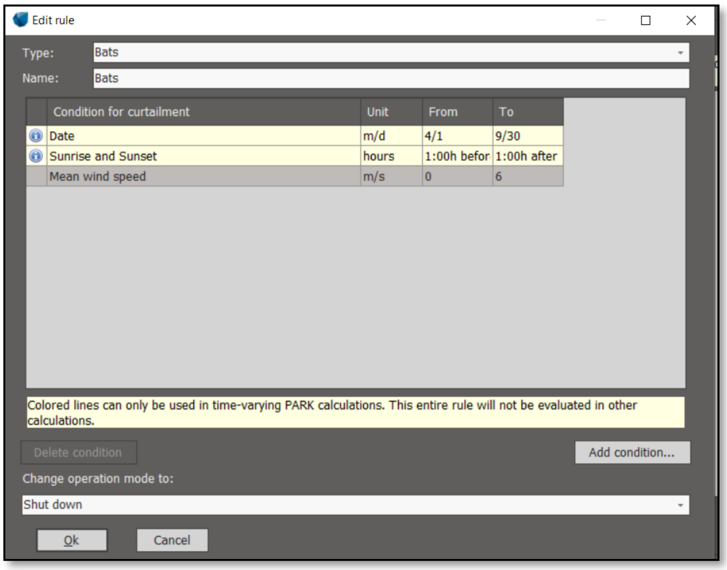


Figure 3. 26 : Implementation of Bat curtailment

3.3.4 Commercial Evaluation of Wind Farm

As mentioned in the previous sections, we carried out calculations for noise and bat curtailment. However, due to time constraints, we were unable to perform calculations for shadow flicker.

First, we will discuss the impact of different turbine operation modes and bat curtailment for both layouts. Then, we will address noise curtailment and bat curtailment, followed by a comparison of the effects of these two approaches on AEP and commercial considerations.

3.3.4.1 Commercial Evaluation based Method 1: Use of different modes of operation of wind turbines and bat curtailment

	Vestas	Enercon	Unit
Wind farm installed capacity	27	30	MW
No. of WTGs	6	6	
Lifetime	35	35	Years
Opportunity cost of capital	11	11	%
Remuneration rate	65	65	EUR/MWh
CAPEX			
WTG Capex per MW	1.05	1.05	MEUR/MW
Other Capex per MW	0.35	0.35	MEUR/MW
Total CAPEX	37.8	42	MEUR/MW
OPEX			
O&M	80,000	80,000	EUR/WTG/y
Gross AEP	76,707.8	88,238.7	MWh/y
Total Loss (Noise + bats)	14.6	23.3	%

Cashflows	37,800,000	42,000,000	EUR
NPV	4,335,342	7,299,220	EUR
IRR	9.59	8.85	%
LCOE Calculation			
PV CAPEX	37,800,000	42,000,000	EUR
PV OPEX	4,718,072	4,718,072	EUR
PV AEP	644,059	665,168	MWh
LCOE	66	70.2	EUR/MWh
NET P50 AEP	65,524	67,672	MWh/y
NET P75 AEP	61,134	63,138	MWh/y
NET P90 AEP	57,137	59.010	MWh/y

Table 3. 2 : Method 1: commercial Evaluation based on Noise modes and bat curtailment

Please find Annexture L (Excel and PDF) for Commercial Evaluation based Method 1: Use of different modes of operation of wind turbines and bat curtailment for Vestas Layout.

Please find Annexture M (Excel and PDF) for Commercial Evaluation based Method 1: Use of different modes of operation of wind turbines and bat curtailment for Enercon Layout.

3.3.4.1 Commercial Evaluation based Method 2: Use of condition for curtailment for Noise and bat

	Vestas	Enercon	Unit
Wind farm installed capacity	27	30	MW
No. of WTGs	6	6	
Lifetime	35	35	Years
Opportunity cost of capital	11	11	%
Remuneration rate	65	65	EUR/MWh
CAPEX			
WTG Capex per MW	1.05	1.05	MEUR/MW
Other Capex per MW	0.35	0.35	MEUR/MW
Total CAPEX	37.8	42	MEUR/MW
OPEX			
O&M	80,000	80,000	EUR/WTG/y
Gross AEP	103,387.3	97,246.7	MWh/y
Total Loss (Noise + bats)	84.2	84.9	%
Cashflows	37,800,000	42,000,000	EUR
NPV	32,645,912	37,793,472	EUR
IRR	-3.11	-4.47	%
LCOE Calculation			
PV CAPEX	37,800,000	42,000,000	EUR
PV OPEX	4,718,072	4,718,072	EUR
PV AEP	160,602	144,420	MWh
LCOE	264.7	323.5	EUR/MWh
NET P50 AEP	15,339	14,693	MWh/y
NET P75 AEP	15,244	13,708	MWh/y

NET P90 AEP	14,248	12,812	MWh/y

Table 3. 3 : Method 2: commercial Evaluation based on Noise and bat curtailment

Please find Annexture-N_ (Excel and PDF) for Commercial Evaluation based on Method 2 Use of condition for curtailment for Noise and bat_Vestas.

Please find Annexture-O_ (Excel and PDF) for Commercial Evaluation based on Method 2 Use of condition for curtailment for Noise and bat_Enercon.

Comparing both commercial evaluations, the first scenario (based on noise modes and bat curtailment) demonstrates a better financial performance than the second scenario (based on noise and bat curtailment). In the first case, the Net Present Value (NPV) is significantly higher for both **Vestas (4.34 million euros)** and **Enercon (7.30 million euros)**, whereas the second scenario shows negative NPV values, indicating financial losses. The Internal Rate of Return (IRR) is also more favorable in the first case (**9.59% for Vestas and 8.85% for Enercon**) compared to negative IRRs in the second scenario (**-3.11% and -4.47%**). Additionally, the Levelized Cost of Energy (LCOE) is significantly lower in the first scenario (**66 euro/MWh for Vestas and 70.2 euro/MWh for Enercon**) compared to much higher values in the second (**264.7 euro/MWh and 323.5 euro/MWh**), making the first approach more cost-effective. Although the Gross AEP is higher in the second scenario, the total losses due to noise and bat curtailment are significantly higher (**84.2% for Vestas and 84.9% for Enercon**) compared to the first scenario (**14.6% and 23.3%**), drastically reducing net energy output and financial viability. Thus, the first approach, which balances noise modes and bat curtailment, proves to be the more economically sustainable option.

4. Recommendations for Future Work

Achieving an optimal design requires repeating this process and adjusting the variables. For example, changing the layout and location and number of wind turbines can lead to different results. However, the software itself also has an optimization option.

In our case, we aimed to achieve a layout with the best economic output within the four-hour exam duration.

For the design where noise, shadow flicker, and bat losses are critical factors, there are more adjustable parameters, such as the adjusting turbine's power mode, defining shutdown hours, and curtailment. Finding the optimal conditions in such cases requires more iteration and, consequently, more time.

5. Conclusion

This study explored various wind farm layouts to optimize energy production while considering economic feasibility and regulatory constraints. Through iterative simulations and adjustments, we evaluated different configurations of Vestas V150-4.5MW and Enercon E-147 EP5 E2 5000 turbines. The results indicated that a six-turbine layout for Vestas achieved the best balance between energy yield, wake losses, and financial performance.

When incorporating constraints such as noise reduction, shadow flicker, and bat curtailment, we found that optimization became significantly more complex, requiring additional adjustments in power modes and operational hours. The financial analysis demonstrated that balancing noise modes and bat curtailment was the most viable approach, whereas excessive curtailment led to reduced profitability.

While our analysis was constrained by the exam's time limit, future studies could refine these results by integrating advanced optimization algorithms and conducting more extensive simulations. Overall, this project highlights the trade-offs between maximizing energy output and complying with environmental and economic considerations in wind farm planning.

6. References

[1] P. D.-I. D. Schlipf and D.-I. R. Steffen, *Wind Farm Control,* Flensburg: Lecture notes, 2024.

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[3] M. C. R. F. Lasse Svenningsen, "Roughness in windPRO," EMD International A/S , Aalborg, 2021.