Formula Sheet

This document outlines the formulas and the main assumptions that were made in the creation of the model.

1. Case Simplification, Design Variables and Bounds

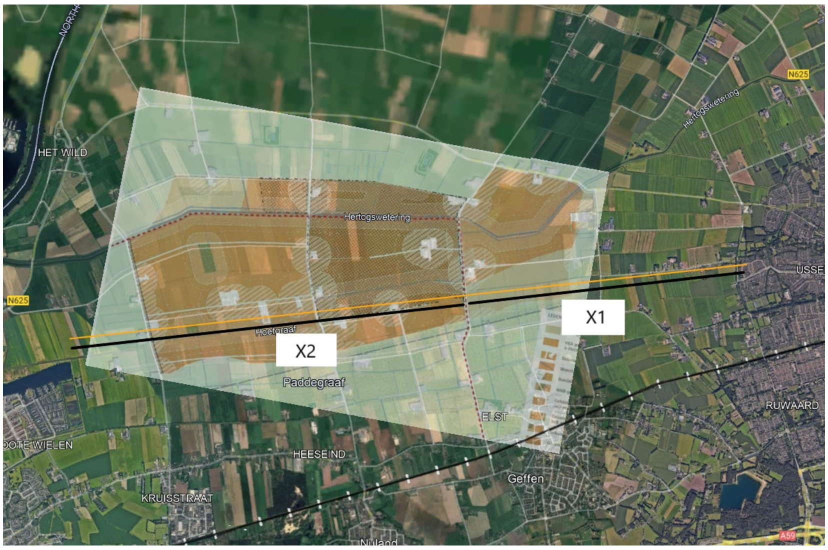

Figure 1 Initial Preferred Alternative in Google Earth, red dotted line is the municipality boundary

The project is represented via the following variables:

- x1 - Distance to the Oss built-up area (km)
- x2 - Distance to the ‘s-Hertogenbosch built-up area (km)
- x3 - Number of wind turbines in the Oss project area
- x4 - Number of wind turbines in the ‘s-Hertogenbosch project area
- x5 - Turbine hub height in the Oss project area (m)
- x6 - Turbine hub height in the ‘s-Hertogenbosch project area (m)

The choice of location of the wind park takes place along a straight line, which is marked in orange in Figure 11. The following bounds apply to the variables:

- 0.1 km ≤ x1 ≤ 3.5 km – geographical restriction
- 0.1 km ≤ x2 ≤ 5 km – geographical restriction
- 1 ≤ x3 ≤ 12 – based on first estimate of wind turbines for Oss
- 1 ≤ x4 ≤ 16 – based on first estimate of wind turbines for den Bosch
- 50 m ≤ x5 ≤ 200 m – based on wind turbine height used in Duurzame Polder documents
- 50 m ≤ x6 ≤ 150 m – based on wind turbine height used in Duurzame Polder documents

These variable boundaries allow to ground the case to the physical and geographical context. At the same time, some variable bounds intentionally ignore some restrictions, such as the minimum distance to built-up areas imposed by the municipalities. This is done to allow the model to consider all options without prejudice and not miss out on potential design variants. However, to make the case modellable within the stated scope it is important to make and outline the key assumptions:

- It is assumed that the Energy Provider is fully financially responsible for the construction but also receives the financial benefits.
- It is assumed that the resulting project can be split into two separate sub-wind parks: one on the Oss side and the other on the 's-Hertogenbosch side.
- The model considers the search for the project location along a straight line.

2. Objective Functions

Objective functions are calculations that indicate the project performance of a certain project configuration. The following list of project performance indicator is set up for this project:

- Net Present Value (NPV). Core stakeholder: Energy Provider.
- Noise Pollution in Oss and 's-Hertogenbosch. Core stakeholders: local residents of Oss and 's-Hertogenbosch, RIVM.
- Bird Mortality. Core stakeholder: Ecologists.
- Particle Pollution. Core stakeholder: RIVM.
- Energy Production of each sub-park. Core stakeholders: Oss and 's-Hertogenbosch municipalities.
- Project Completion Time. Core stakeholders: Oss and 's-Hertogenbosch municipalities.

It is important to note that project time also impacts the NPV indicator. However, the relationship between project time and NPV is not necessarily linear, therefore they are included as separate indicators. Before the calculation of each project performance indicator can be explained in detail, some universal functions used across several objective functions will be established.

2.1. Universal Functions

Due to the nature of the project, both the Oss and 's-Hertogenbosch sub-parks have the same performance indicators and use the same equations, but with different variables. For the sake of conciseness, the logical indicator V, meaning OR, will be used in the expression of these equations.

Firstly, the change of wind speed according to hub height (x5, x6) needs to be set. Wind data is taken for the 10% most windy areas at project location from the Global Wind Atlas (Technical University of Denmark, 2025), which is also used in the Witteveen+Bos assessment report in Appendix II (Witteveen+Bos, 2024).

$$U_{w,Oss \vee Den\ Bosch} = \begin{cases} 6.97\ ms^{-1}, if\ 50m \leq x_{5 \vee 6} \leq 75m \\ 8.16\ ms^{-1}, if\ \ 75m < x_{5 \vee 6} \leq 125m \\ 9.3\ ms^{-1}, if\ \ 125m < x_{5 \vee 6} \leq 175m \\ 10\ ms^{-1}, if\ \ 175m < x_{5 \vee 6} \leq 225m \end{cases} \qquad (1)$$

Secondly, the wind turbine blade diameter calculation, taken directly from Teuber & Wolfert (2024).

$$D_{Oss \vee Den\ Bosch} = 1.3 * \ x_{5 \vee 6} \qquad (m)(2)$$

Swept area of wind turbine blades, from Teuber & Wolfert (2024).

$$A_{Oss \text{ v } Den\ Bosch} = \pi * \left(\frac{D_{Oss \text{ v } Den\ Bosch}}{2}\right)^2 \qquad (m^2)(3)$$

Power capacity per wind turbine, from Teuber & Wolfert (2024). Rho (ρ) is air density and e is wind turbine efficiency in converting wind energy into electricity. Also, total power capacity for the wind park.

$$P_{turbine,\ \ Oss \text{ v } Den\ Bosch} = A_{Oss \text{ v } Den\ Bosch} * \rho * e * U_{w,Oss \text{ v } Den\ Bosch}{}^3 \qquad (W)(4)$$

$$where\ \rho = 1.224\ kgm^{-3}\ and\ e\ = 0.3$$

$$P_{total,\ \ Oss \text{ v } Den\ Bosch} = \frac{P_{turbine,\ \ Oss \text{ v } Den\ Bosch} *\ x_{3 \text{ v } 4}}{10^6} \qquad (MW)(5)$$

Resistance factor, from Teuber & Wolfert (2024).

$$R_{Oss \text{ v } Den\ Bosch} = \frac{x_{5 \text{ v } 6} + U_{w,Oss \text{ v } Den\ Bosch}}{12} \qquad (6)$$

Yearly energy production from the wind park, assuming the capacity factor is 100%.

$$E_{\ Oss \text{ v } Den\ Bosch} = \frac{P_{total,\ \ Oss \text{ v } Den\ Bosch} * 365 * 24}{10^3} \qquad (GWh)(7)$$

Yearly profit from the wind park.

$$Profit_{Oss \text{ v } Den\ Bosch} = E_{\ Oss \text{ v } Den\ Bosch} * EWP - (R_{Oss \text{ v } Den\ Bosch} *\ x_{1 \text{ v } 2} * 365) \qquad (€)(8)$$

2.2. NPV

Setting up an NPV calculation requires establishing a timeline, cash flows at different points of that timeline and the rate of return to be used with the calculation. The timeline is taken from a consultancy report created for the Irish Wind Energy Association (Ionic Consulting, 2019).

Figure 2 Timeline of an onshore wind farm project, adapted from Ionic Consulting (2019) for the Duurzame Polder case

The main difference between what is suggested by Ionic Consulting and what is stated in Figure 12 is the Plan and Permit section. According to the European Union Renewable Energy Directive (Directive 2018/2001), all renewable energy generation projects are to be given the necessary permits within the timeframe of 2 years. However, since delays can occur due to unforeseen aspects such as construction close to Natura 2000 sites, 3 years are taken as the planning and permitting time to be conservative. Total project cradle-to-grave then becomes 31 years. This timeline allows to establish cash flows for every year of project operation. These cash flows are summarized in Table 1.

Table 1 Cash flows for the NPV calculation

Cash Flow Name	When	Amount	Source
Capital Expenditure (CAPEX)	Once, at the end of the Pre-Construction phase	1,600,000 € per MW installed capacity	(Wind Europe, 2022)
Operations and Maintenance (O&M)	Every year of operation	30,722 € per MW per year	(Department for Energy Security and Net Zero, 2023)
Electricity sales revenue	Every year of operation	Formula established below	Formula established below
Decommissioning (DECEX)	Once, at the end of operation	Formula derived from source, see below	(Gück, 2023)

Due to lack of reliable information on wind farm decommissioning costs, a formula was adapted from a conference presentation by Gück (2023).

$$DECEX_{Oss \text{ v } Den\ Bosch} = (0.1 * x_{5 \text{ v } 6} + 31) * P_{total,\ \ Oss \text{ v } Den\ Bosch} * 1000 \qquad (€)(9)$$

As well as that, there are also important constants that must be determined for the NPV calculation. One is the rate of return, since the objective of the Energy Provider is to have a positive NPV, and for that a known rate of return is necessary. For this calculation, the Internal Rate of Return (IRR) is taken to be 4.5% according to a report by Trinomics (2020). It is important to note that this IRR is designed to encourage increased investment, therefore it can reasonably be expected to produce an optimistic NPV.

Another constant is the capacity factor. Capacity factor is a term commonly applied to energy generation facilities and reflects what percentage of the total installed capacity is producing electricity at any given time. According to the report by Wind Europe (2023), the capacity factor for new onshore wind farms is 30-35%. Here it is taken as 30%.

Finally, the electricity sale price is the last parameter needed to calculate the cash flows. Since the energy provider does not sell directly to the customers, but instead sells electricity to grid operator companies, a wholesale price must be considered. According to the European Electricity Wholesale Price Data by Ember (2025), a reasonable wholesale price for the Netherlands can be assumed to be 0.59 cents per kWh. It is assumed that this price stays constant through the project lifecycle, which is a significant limitation of the model.

To summarize, these are the important constants other than those in Table 1:

- IRR = 0.045
- Capacity Factor = 0.3
- Electricity Wholesale Price = 0.059€ per kWh

Another important factor to note when it comes to installation of renewable energy sources is grid resilience, which has been a significant discussion point in the Netherlands in recent years. According to the report on the Exploration (Verkenning in the original) phase of the Duurzame Polder (2020), the two grid operators who consulted the project team, TenneT and Enexis, expressed significant doubts about the grid being able to accommodate a large windfarm. They estimated that for a grid connection of 80 MW to 300 MW a renovation of 3-7 years would be necessary and for a connection of more than 300 MW a renovation of 7-10 years. However, these estimates can be scaled down by 2 years, as it can be assumed that parts of the plan and permit phase can take place in parallel with grid extension operations. To summarize:

- No grid extension is necessary for a wind farm below 80 MW, which means no delay.
- For a wind farm of 80MW to 300 MW a delay of 3 years occurs.
- For a wind farm of more than 300 MW a delay of 6 years occurs.

Applying everything above onto the NPV formula allows to establish the calculation.

$$NPV = \sum_{t=0}^{T+d} \frac{C_t}{(1+NPV)^t};\ T = 31\ years, NPV = 4.5\% \qquad (€)(10)$$

Cash flow number	Calculation
C_{4+d}	$-CAPEX * (P_{total,Oss} + P_{total,Den\ Bosch})$
$C_{6+d} - C_{30+d}$	$Capacity\ Factor * (Profit_{Oss} + Profit_{Den\ Bosch}) - O\&M * (P_{total,Oss} + P_{total,Den\ Bosch})$
C_{31+d}	$-(DECEX_{Oss} + DECEX_{Den\ Bosch})$

$$d = \begin{cases} 0, if\ (P_{total,Oss} + P_{total,Den\ Bosch}) < 80\ MW \\ 3, if\ 80MW \leq (P_{total,Oss} + P_{total,Den\ Bosch}) < 300\ MW \\ 6, if\ (P_{total,Oss} + P_{total,Den\ Bosch}) \geq 300\ MW \end{cases} \qquad (Years)(11)$$

Project delays due to necessary grid extension are applied in the beginning, offsetting the timeline by the delay amount (d).

2.3. Noise Pollution

Noise pollution is taken as the sound pressure level (SPL) at the closest residential area to the wind park. This calculation is taken from Teuber & Wolfert (2024), with slight alterations. The calculation does not account for aspects such as sound reflection and absorption. However, the increase of sound pressure level with source height and wind speed are taken into account for the worst-case scenario. The validity of these aspect is verified by Trikootam and Hornikx (2018) and Scholes and Parkin (1967), since the original work does not provide sources.

Firstly, wind and height adjustments are calculated by accounting for base wind speed ($U_0 = 3ms^{-1}$) and base height ($H_0 = 50m$)

$$AdjW_{Oss\ \mathrm{v}\ Den\ Bosch} = (U_{w,Oss\ \mathrm{v}\ Den\ Bosch} - U_0) * 0.2 \qquad (dB)(12)$$

$$AdjH_{Oss\ \mathrm{v}\ Den\ Bosch} = (x_{5\ \mathrm{v}\ 6} - H_0) \qquad (dB)(13)$$

Then, the sound pressure levels of all wind turbines are combined to be taken as one source in further calculations. The noise from one turbine is taken to be constant 104 dB (L_w).

$$SPL = 10 \log\left(x_{3\ \mathrm{v}\ 4} * 10^{\frac{L_w}{10}}\right) \qquad (dB)(14)$$

SPL at a distance can then be calculated.

$$SPL_{Oss\ \mathrm{v}\ Den\ Bosch} = SPL + AdjW_{Oss\ \mathrm{v}\ Den\ Bosch} + AdjH_{Oss\ \mathrm{v}\ Den\ Bosch} - 20 \log\left(\frac{x_{1\ \mathrm{v}\ 2} * 1000}{1}\right) (dB)(15)$$

2.4. Bird Mortality

Part of the project area contains a nesting ground for small meadow birds, which has recently been a point of concern for the conservation effort in the Netherlands (Vogelbescherming Nederland, 2024).

Bird mortality is challenging to estimate, especially since most gathered data on bird mortality is underestimated due to measurement issues, as laid out by Nilsson et al. (2023). The same article measures the actual mortality rate of meadow birds for a wind park that is located on the migration path. The number provided in the article is 0.62 birds per GWh of energy produced. However, that can only be applied to the actual nesting area. The assumption is made that bird mortality outside of the nesting area is 4 times less, 0.155 birds per GWh of energy produced.

$$Mc_{Oss} = 0.155 \qquad \left(\frac{birds}{GWh}\right) (16)$$

$$Mc_{Den\ Bosch} = \begin{cases} 0.155, if\ x_2 < 3\ km \\ 0.62, if\ 3km \leq x_2 \leq 5km \end{cases} \qquad \left(\frac{birds}{GWh}\right) (17)$$

Since energy production is taken in GWh per year, mortality is also going to indicate bird deaths per year.

$$M = E_{Oss} * Capacity\ Factor * Mc_{Oss} + E_{Den\ Bosch} * Capacity\ Factor * Mc_{Den\ Bosch} (birds/year)(18)$$

2.5. Particle Pollution

In the process of erosion of wind turbine blades, microplastic particles get released into the air, which may have an effect on the health and well-being of both humans and animals in the area (Soldberg et al., 2021). This calculation is taken from Teuber & Wolfert (2024) directly.

$$E_{Oss\ \mathrm{v}\ Den\ Bosch} = U^3_{w,Oss\ \mathrm{v}\ Den\ Bosch} * f * \left(\frac{A_{Oss\ \mathrm{v}\ Den\ Bosch}}{30000}\right); where\ f = 0.001 \qquad (g/day)(19)$$

$$E_{total} = E_{Oss} * x_3 + E_{Den\ Bosch} * x_4 \qquad (g/day)(20)$$

2.6. Energy Production

The energy production formula is already outlined in the Universal Functions section, since it is used in several other functions. At the same time, these other functions have other variable aspects influencing their performance, therefore the Energy Production function can stand on its own. For each municipality the energy production is accounted for separately.

2.7. Project Completion Time

Project completion time stands for the time that has to pass until the wind farms can be in operation, assuming they are started, constructed and finished in parallel. Comparatively to other onshore civil engineering structures, the construction time of a wind park does not have many causes for uncertainty. This can be attributed to such factors as modularity and assembly of prefab parts. The main uncertainties arise with regards to permitting times and whether an adjustment of the surrounding energy infrastructure is required. For this reason, the Project Completion Time function is based on the time until operation shown in Figure 12 and the delay from Equation 11.

$$t_{total} = 5.3 + d \qquad (years)(21)$$

3. Additional Information

This section will feature additional information that can be used in conjunction with the stated formulas to make decisions or shape preference curves.

Noise and dB Levels

Source	Sound Pressure Level *(dB)*
Threshold of Hearing	
Quietest audible sound for persons with excellent hearing under laboratory conditions[2)]	0
Quietest audible sound for persons under normal conditions	
Virtual silence, Barely audible Audio-metric test room	10
Rustling leaves Mosquito	20
Noticeably Quit - Voice, soft whisper	
Quiet whisper (4 ft, 1 m)	30
Home Quiet room Bird call	40
Moderate	
Quiet street Quiet office Whispered speech	50
Loud - Unusual Background, Voice conversation 4 ft, 1 m	
Normal conversation at 4 ft, 1 m	60
Laughter	65
Loud - Voice conversation 1 ft, 0.3 m	
Inside a car Passenger car 80 km/h, 50 mph (50 ft, 15 m) Vacuum cleaner (10 ft, 3 m) Freight Train (100 ft, 30 m) Background conversation restaurant	70
Loud singing Car driven at 105 km/h, 65 mph Washing machine	75
Loud - Intolerable for Phone Use	
Maximum sound up to 8 hour (OSHA criteria - hearing conservation program) Pneumatic tools (50 ft, 15 m) Buses, diesel trucks, motorcycles (50 ft, 15 m) Car wash (20 ft, 6 m) Road with busy traffic	80
Motorcycle (30 ft, 10 m)	88
Food blender (4 ft, 1 m) Maximum sound up to 8 hour (OSHA[1)] criteria - engineering or administrative noise controls) Jackhammer (50 ft, 15 m) Bulldozer (50 ft, 15 m) Noisy factory Newspaper press	90

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