8a OPTIMIZE

8a.1 Introduction

The Classical Optimizer in windPRO was released around year 2000. It has performed well for the tasks it was designed to solve in the youth of the wind energy business. Since then, the development of the wind industry has been fast, and many new requirements and challenges have become relevant. The size of wind farms and the complexity of wind farm areas has increased dramatically. But also, the basis on which decisions are made has matured, so that financial parameters such as costs of developing the farm and even the expectation for future electricity prices should be included already in the windfarm design phase. In addition, new constraining factors emerged that must be considered, such as wake effects from new wind turbines on existing wind turbines.

These developments have led to the need for a new windPRO Optimizer has been released in 2022 in windPRO 3.6. This was just the start of journey towards optimal design and operation of wind farms, and new features have been integrated since into the new windPRO 4.0. Now, in addition to layout optimization, a long-awaited noise curtailment optimization is offered, which is explained in detail in the Noise Curtailment Optimize manual. The journey has not ended here; a wider range of cases will be supported, and more features will be included in windPRO versions to come. If you experience limitations, have wishes or ideas please do not hesitate to reach out and contact us – we are more than happy to listen to your input!

8a.1.1 Offshore Vs Onshore optimization

The New Optimizer in windPRO covers both onshore and offshore optimization. For offshore layouts the geometry is not fixed, for this functionality the user is referred to as the Classical windPRO optimizer. The key differences between onshore and offshore optimizations lie in the setup of the wake decay constant for the annual energy production (AEP) calculation and in the model for calculating the cost of building the wind farm (if costs are included in the objective). Hence, for pure optimizations of AEP there is no difference in the way that the Optimizer operates. However, the performance will of course be guided by the user-provided information such as WTG area and resource, which typically have distinct characteristics offshore and will be reflected in the resulting optimization solutions. A new feature that is particularly useful for offshore applications that came with the release of 4.0 is the integration of cost surfaces. This feature allows to better integrate costs that change over space into the cost analysis. Further details of onshore and offshore cost models are given in section 8a.4.2.

8a.1.2 The GUI tree-structure and its levels: Site>WTG>Size>Run

A flexible graphical user interface (GUI) has been developed for the New Optimizer to accommodate several different scenarios of use (see section 8a.2 for a description of the scenarios). This flexible GUI is represented by a tree located on the left side of the Optimizer window. The tree will be gradually built-up by the user with the required input information and with the different optimization scenarios run by the user. A lot of information needs to be defined and setup prior to running the optimizations. This setup of pre-defined data and pre-calculated information is a prerequisite for gaining sufficiently fast, yet accurate, optimization results.

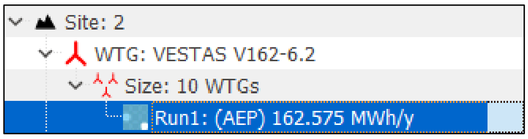

Site: 2
WTG: VESTAS V162-6.2
Size: 10 WTGs
Run1: (AEP) 162.575 MWh/y

Figure 1: *The basic components and levels of the GUI tree: Site, WTG, Size and Run, with Run highlighted.*

Building the tree, setting up and preparing the optimization, different information and decisions must be defined and entered. When a level or item is selected and highlighted in the GUI tree (see Figure 1) the window on the right shows the contents associated to this item, e.g. Site. Adding new levels to build the tree is done using the three buttons below the tree. On the first occasion of adding a level the relevant button is highlighted in green.

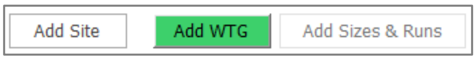


Figure 2: *Building the GUI tree for the optimization and adding levels. Next step is always highlighted in green.*

The following sub-sections go through the setup that needs to be defined at each level of the GUI tree. While setting up and running optimizations the main window of the Optimizer should be on the tab *Setup & run*.

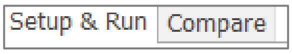


Figure 3: *When setting up and running optimizations the tab of main window should be on 'Setup & run'.*

8a.1.2.1 Site

The Site level is the fundamental level of the optimization, but there can be multiple Sites in the tree to allow studying the effect of different basic assumptions. In the Site, the following information and settings must be defined:

Site Climate/Resources **-** here the pre-calculated wind resource across the site must be defined by selecting an 'rsf' or 'siteres' file. Ideally, the resource has a grid resolution of 0.5 times the turbine rotor diameter or less as this leads to a good balance between resolution and performance.

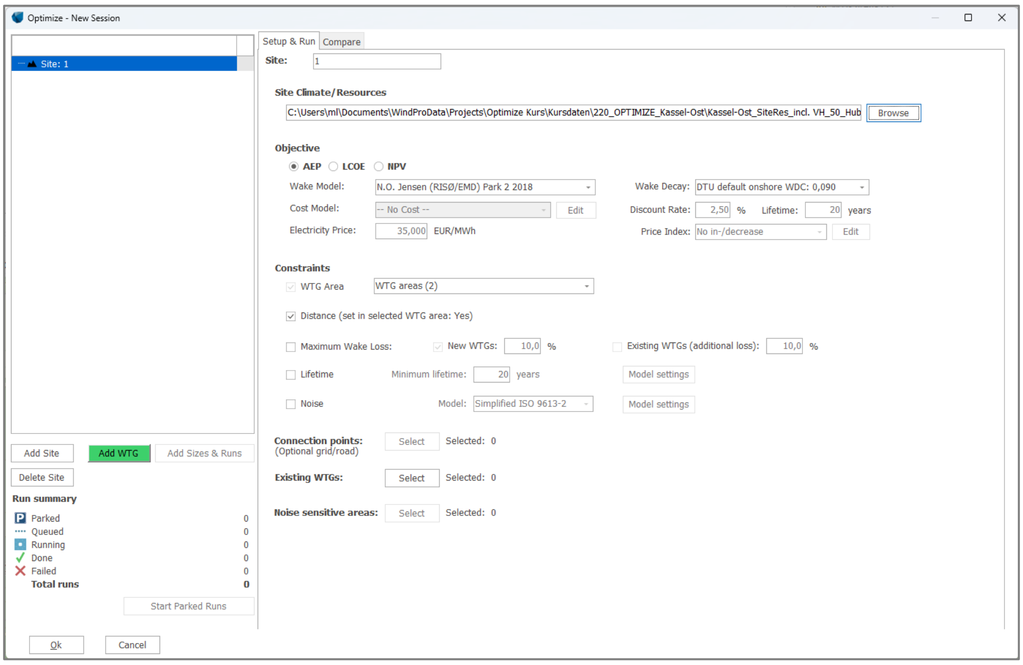
Objective – this is the choice of what the user wants to optimize: AEP (annual energy production), LCOE (cost of electricity) or NPV (profit of project). These are described in detail in section 8a.4. For each choice of objective several associated decisions are required. For instance, *Wake Decay* constant in the PARK calculation (all objectives), setting up a *Cost Model* (LCOE and NPV) or setting the expectation for the future average *Electricity Price.*

Constraints - The particular requirements for the site must be defined and ALWAYS requires definition of a WTG Area. This defines the limits of the site area or sub-areas where turbine placement is allowed, any requirements for minimum and maximum turbine numbers or capacity in each sub-area. It also defines exclusion zones and set-back buffers as well as minimal spacing requirements for turbines in each sub-area. In addition to this the spacing or inter-turbine *Distance* defined in the WTG area may be activated or deactivated. Finally, constraints on turbine component *Lifetime,* turbine noise at noise sensitive areas, and *Wake* constraints for new and existing WTGs may be activated (see section 8a.5 for further details).

Connection points – Objectives which require cost calculation (LCOE and NPV) may include known connection points for external grid and road connection. These points must be pre-defined as Control points and selected here.

Existing WTGs – If there are known turbines in the area from other projects which will create wakes on this project they must be defined as existing WTGs and selected here. Their wake effect on the new turbines will be included and the additional wake that they might experience can be considered.

Noise sensitive areas – If noise constraint is activated one or more noise sensitive area (NSA) points must be selected here.



Site: 1

Site Climate/Resources

C:\Users\ml\Documents\WindProData\Projects\Optimize Kurs\Kursdaten\220_OPTIMIZE_Kassel-Ost\Kassel-Ost_SiteRes_incl. VH_50_Hub

Objective

● AEP ○ LCOE ○ NPV

Wake Model: N.O. Jensen (RISØ/EMD) Park 2 2018

Wake Decay: DTU default onshore WDC: 0,090

Cost Model: -- No Cost --

Discount Rate: 2,50 %

Lifetime: 20 years

Electricity Price: 35,000 EUR/MWh

Price Index: No in-/decrease

Constraints

☑ WTG Area: WTG areas (2)

☑ Distance (set in selected WTG area: Yes)

□ Maximum Wake Loss: ☑ New WTGs: 10,0 % □ Existing WTGs (additional loss): 10,0 %

□ Lifetime Minimum lifetime: 20 years

□ Noise Model: Simplified ISO 9613-2

Connection points: (Optional grid/road) Selected: 0

Existing WTGs: Selected: 0

Noise sensitive areas: Selected: 0

Run summary

Parked	0
Queued	0
Running	0
✓ Done	0
✗ Failed	0
Total runs	**0**

Figure 4: *Setting up the Site level of an optimization and building the GUI tree.*

8a.1.2.2 WTG

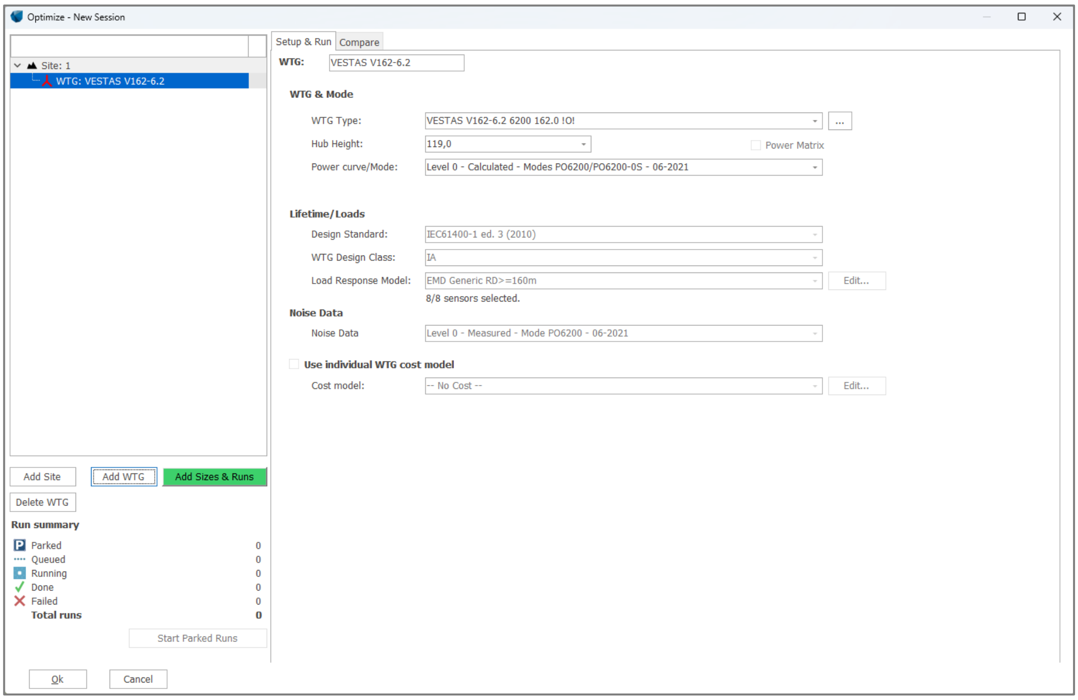
At the WTG level the required data must be defined for the objective and constraints selected on the Site level. All new turbines in optimizations in this branch of the tree will use the selected turbine and data.

WTG & Mode - Any optimization requires the selection of a turbine model from windPRO's WTG catalogue, a *Hub height,* and the *Power curve/Mode* for that turbine model. This is the basis for the AEP and wake loss calculations. For traditional power curve data the appropriate power curve is selected and for Power Matrix data the operation mode is also selected.

Lifetime/Loads – If lifetime constraint is activated the turbine *Design Standard* and *Design Class* must be defined as well as the *Load Response Model* for use in the calculation of loads and lifetime.

Noise Data – When noise constraint has been activated, the noise data must be selected from the Noise curves provided in the WTG catalogue. For Power Matrix the noise data are pre-defined via the selected mode.

Use individual WTG cost model - When multiple WTG types are defined for the same Site, it might be relevant to define different cost models for each WTG type individually. In that case this option must be activated and the cost model for the current WTG type defined here. This will override the cost model selected on the Site level.


Optimize - New Session

Site: 1
WTG: VESTAS V162-6.2

WTG: VESTAS V162-6.2

WTG & Mode

WTG Type: VESTAS V162-6.2 6200 162.0 !O!
Hub Height: 119,0
□ Power Matrix
Power curve/Mode: Level 0 - Calculated - Modes PO6200/PO6200-0S - 06-2021

Lifetime/Loads

Design Standard: IEC61400-1 ed. 3 (2010)
WTG Design Class: IA
Load Response Model: EMD Generic RD>=160m
8/8 sensors selected.

Noise Data

Noise Data: Level 0 - Measured - Mode PO6200 - 06-2021

□ **Use individual WTG cost model**

Cost model: -- No Cost --

Run summary

Parked	0
Queued	0
Running	0
Done	0
Failed	0
Total runs	**0**

Figure 5: *Setting up the WTG level of an optimization.*

8a.1.2.3 Size (and 'Add Sizes & Runs' button)

The Size level has no setting up on the window to the right. Instead, it is created in a single step together with at least one Run at it its sub-level (child). This is done via the *Add Sizes & Runs* button (see green highlight in Figure 5).

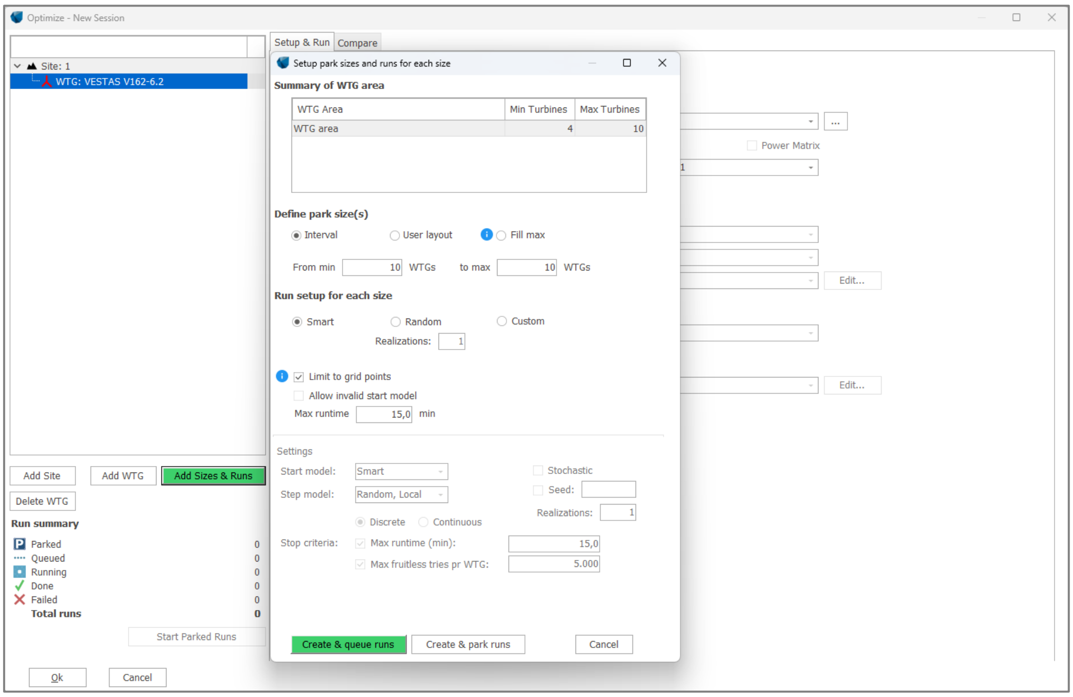
Once the Sizes and Runs have been created this window shows an overview of all the runs for this size. In this regard a run is simply an optimization for the park size in question and subject to optimization settings.

The benefit from adding Sizes & Runs in a single step is mainly efficiency, so that more park sizes can be created at once with identical optimization settings without further effort.

Define Park size(s) - Here the user can define the park sizes of interest. Note that ALL sizes *from minimum* through *to maximum* will be created once the button *Create & queue runs* is pressed after which a separate optimization will be run for each size. It is therefore recommended to limit the range of sizes such that it results in a reasonable number of optimizations. The table above the size selection summarizes the requirements for minimum and maximum turbine numbers in the WTG area. Limits on capacity are automatically converted to turbine numbers given the selected WTG. Alternatives, to defining a range of sizes are either to define a *User layout* where the user must select the initial positions for the optimization or *Fill max* which will seek to fill the maximum number of turbine units (see section 8a.3 for further details).

Run setup for each Size – This setup defines the optimization strategy for each created optimization run. Default is *Smart* with the alternatives *Random* and *Custom*. The latter unlocks the lower section of the window unleashing the full flexibility of the optimization solution (see section 8a.3 for details). The *Realizations* setting available for *Random* simply defines how many times to repeat the experiment of starting an optimization run from a random initial layout. Setting realizations to, for example, five will yield five different random runs for each size.

When setup is done in the Setup & Run window the optimizations can either be put in the queue directly by pressing *Create & queue runs* or be parked for now to be run later by pressing *Create & park runs.*



Run summary

Parked	0
Queued	0
Running	0
Done	0
Failed	0
Total runs	**0**

Summary of WTG area

WTG Area	Min Turbines	Max Turbines
WTG area	4	10

Define park size(s)

● Interval ○ User layout ○ Fill max

From min 10 WTGs to max 10 WTGs

Run setup for each size

● Smart ○ Random ○ Custom

Realizations: 1

☑ Limit to grid points

□ Allow invalid start model

Max runtime 15,0 min

Settings

Start model: Smart

Step model: Random, Local

● Discrete ○ Continuous

Stop criteria: ☑ Max runtime (min): 15,0

☑ Max fruitless tries pr WTG: 5.000

□ Stochastic

□ Seed:

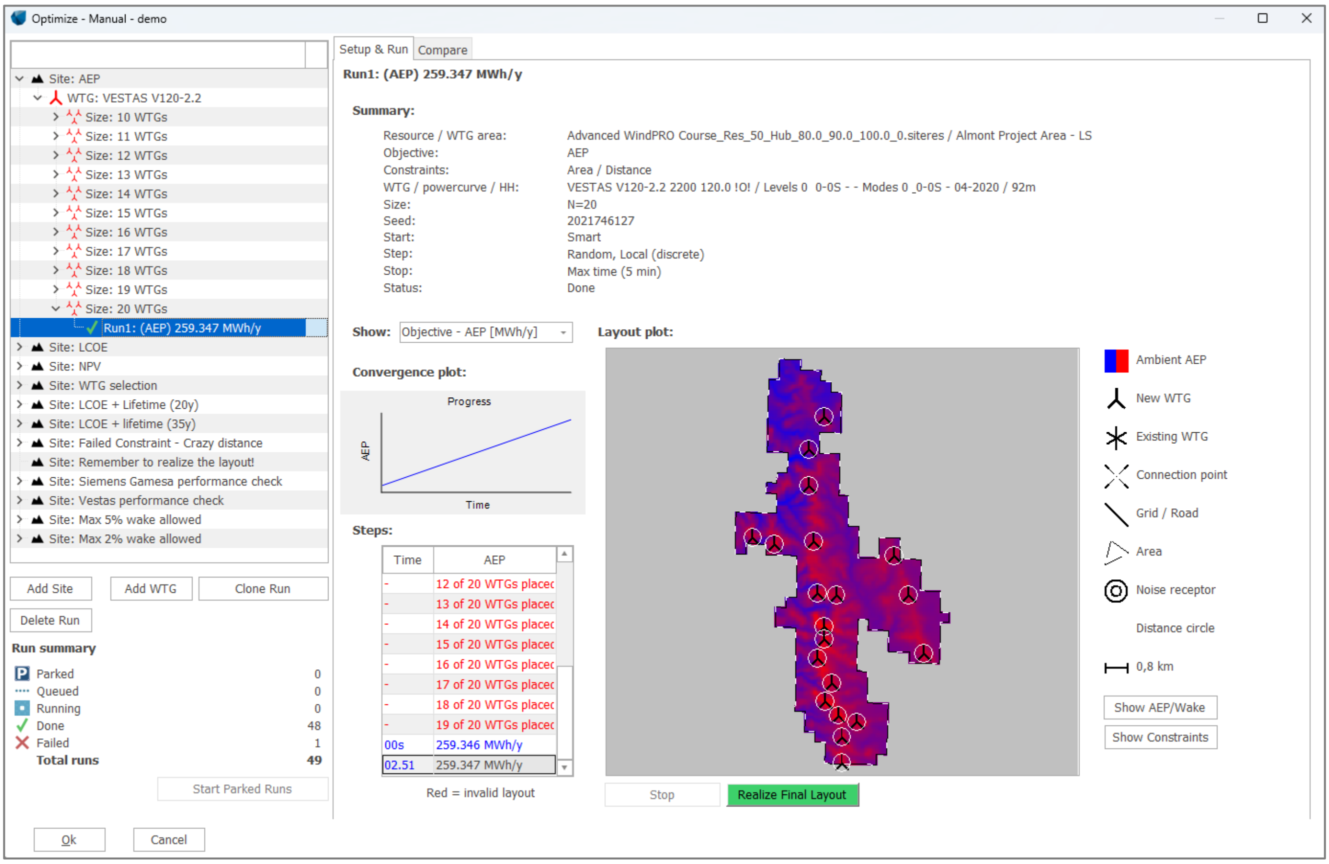
Realizations: 1

Figure 6: *Setting up the Size and Run level in one go via the button ‘Add Sizes & Runs’.*

8a.1.2.4 Run

The deepest level of the GUI tree is the *Run* level. At this level each optimization run is presented and when they are completed a resulting optimized layout can be created in the windPRO object list and map window by pressing *Realize Final Layout*. Through the course of the optimization the positions of WTGs at the current step of the optimization run are visible and updated in the *Layout plot.* Similarly, the *Steps* list will show the current and history of the Objective. Alternatively, the Wake loss (available for all objective) or AEP, Wake loss or Cost[1] are plotted (only available for LCOE and NPV objectives. This information is also available in the *Convergence plot.* At the top of the view is a detailed summary of the settings for the run, including a *Status* indication whether it is running, done or failed.

Details of constraints and/or individual turbine production and wake loss information may be viewed via the buttons *Show AEP/Wake* and *Show Constraints* to the lower left of the Optimizer window.


Optimize - Manual - demo

- Site: AEP
  - WTG: VESTAS V120-2.2
    - Size: 10 WTGs
    - Size: 11 WTGs
    - Size: 12 WTGs
    - Size: 13 WTGs
    - Size: 14 WTGs
    - Size: 15 WTGs
    - Size: 16 WTGs
    - Size: 17 WTGs
    - Size: 18 WTGs
    - Size: 19 WTGs
    - Size: 20 WTGs
      - ✓ Run1: (AEP) 259.347 MWh/y
- Site: LCOE
- Site: NPV
- Site: WTG selection
- Site: LCOE + Lifetime (20y)
- Site: LCOE + lifetime (35y)
- Site: Failed Constraint - Crazy distance
- Site: Remember to realize the layout!
- Site: Siemens Gamesa performance check
- Site: Vestas performance check
- Site: Max 5% wake allowed
- Site: Max 2% wake allowed

Run summary

Parked	0
Queued	0
Running	0
✓ Done	48
✗ Failed	1
Total runs	**49**

Run1: (AEP) 259.347 MWh/y

Summary:

Resource / WTG area:	Advanced WindPRO Course_Res_50_Hub_80.0_90.0_100.0_0.siteres / Almont Project Area - LS
Objective:	AEP
Constraints:	Area / Distance
WTG / powercurve / HH:	VESTAS V120-2.2 2200 120.0 !O! / Levels 0 0-0S - - Modes 0 _0-0S - 04-2020 / 92m
Size:	N=20
Seed:	2021746127
Start:	Smart
Step:	Random, Local (discrete)
Stop:	Max time (5 min)
Status:	Done

Show: Objective - AEP [MWh/y]

Steps:

Time	AEP
-	12 of 20 WTGs placec
-	13 of 20 WTGs placec
-	14 of 20 WTGs placec
-	15 of 20 WTGs placec
-	16 of 20 WTGs placec
-	17 of 20 WTGs placec
-	18 of 20 WTGs placec
-	19 of 20 WTGs placec
00s	259.346 MWh/y
02.51	259.347 MWh/y

Red = invalid layout

Figure 7: *The Run level of the GUI tree. This documents the course the optimization run selected in the tree.*

The current status of a run is indicated in the *Status* line in the *Summary* when the run is selected in the tree. The status is also in the tree itself on the level of the run and via the icons shown to the left on that line. The legend for these icons and a summary status of all current runs within the tree are shown just below the tree (see **Figure 7**).

[1] Note that shown cost values are not discounted only index corrected (if set) and summed over the lifetime.

8a.2 Which decision to optimize?

Many important decisions need to be taken when developing a wind farm. Several of these decisions can benefit from an optimization approach but may not fit well into a traditional optimization setup. In some of the cases the variables on which the decisions are based on (the objective) such as AEP, or financial metrics as cost-of-energy (COE) may not be suitable or sufficiently sensitive to the decisions in question. One such example is the size of a wind farm. The relation between the number of WTGs in the farm and the associated AEP, is simply an increase with the number of WTGs. COE on the other hand typically decreases smoothly with the number of WTGs. This makes AEP and COE unsuitable for determining the optimal size of a wind farm on their own [1]. To accommodate these additional and important decisions in the optimization setup, but not directly in the actual algorithmic optimization process, the decision of these variables is supported by the structure of the GUI. The main use-scenarios are described in the following and includes the following key decisions in wind farm development:

- Design of a layout
- Number of WTGs in the park
- Choice of turbine model
- Fulfillment of constraints

Section 8a.1.2 has described how to establish the tree with a Site, WTG and one or more optimization runs and the settings and inputs needed at each level of the GUI tree. All these settings are done on the *Setup & Run* tab (cf. Figure 8), which basically is the action mode of the Optimizer, where optimizations can be added and setup and details can be viewed.

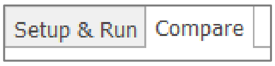
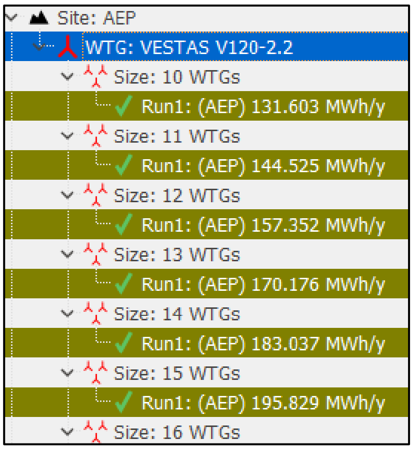


Figure 8: *The Compare and Setup & Run tabs. Here Compare is selected.*

To compare multiple finalized optimizations the Optimizer has a ‘comparison mode’ which is available via the *Compare* tab (cf. Figure 8). In compare mode, the GUI allows for easy comparison across results for different WTGs, sizes and runs mainly showing the results and some overall settings. Once in compare mode (i.e. on the Compare tab) the GUI tree will behave slightly differently as it will start highlighting the runs which are being compared in mustard color (cf. Figure 9). The highlight shows the level selected by the user below which runs will be compared. When a site is selected results will be compared for WTGs defined for that site. For each WTG the best run across all sizes will be chosen and highlighted in mustard color. When selecting a WTG all sizes below that level will be compared, for each size the best run will be chosen if there is more than one run. Selecting a size will simply compare all runs for that size.

At the current stage it is not possible to compare across sites, as they may have different objectives and constraints which cannot easily be compared.



Site: AEP
WTG: VESTAS V120-2.2
Size: 10 WTGs
Run1: (AEP) 131.603 MWh/y
Size: 11 WTGs
Run1: (AEP) 144.525 MWh/y
Size: 12 WTGs
Run1: (AEP) 157.352 MWh/y
Size: 13 WTGs
Run1: (AEP) 170.176 MWh/y
Size: 14 WTGs
Run1: (AEP) 183.037 MWh/y
Size: 15 WTGs
Run1: (AEP) 195.829 MWh/y
Size: 16 WTGs

Figure 9: *Appearance of the GUI-tree when in compare mode.*

8a.2.1 Design of layout (given park size)

Designing a layout with a single fixed number of WTGs is the basic and simplest mode of use for the Optimizer. Just one optimization needs to be set up and run once the data and settings on the Site and WTG levels have been defined. The flexibility of the GUI tree helps to compare different strategies for the optimization, described in further detail in section 8a.3. Such strategies could include the default, which is called *Smart,* a user defined initial layout (via *User Layout*), or perhaps relying more on stochasticity by including random runs. In the last case, several random runs can be started via *Realizations*.

Once a single run has been added for the park size in question more runs can be added by selecting the size in the tree and pressing the button *Add Runs,* which in this case has replaced the Add Sizes & Runs button (shown when the WTG level is selected). If, on the other hand, a particular run in the tree is selected, then the button renames to *Clone Run* – this will allow to use the result of that run at starting point for another run. This can be useful for continuing an optimization or doing an optimization with multiple stages. The three variants of the '*Add…*' button are shown in Figure 10.

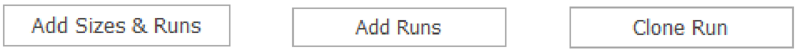
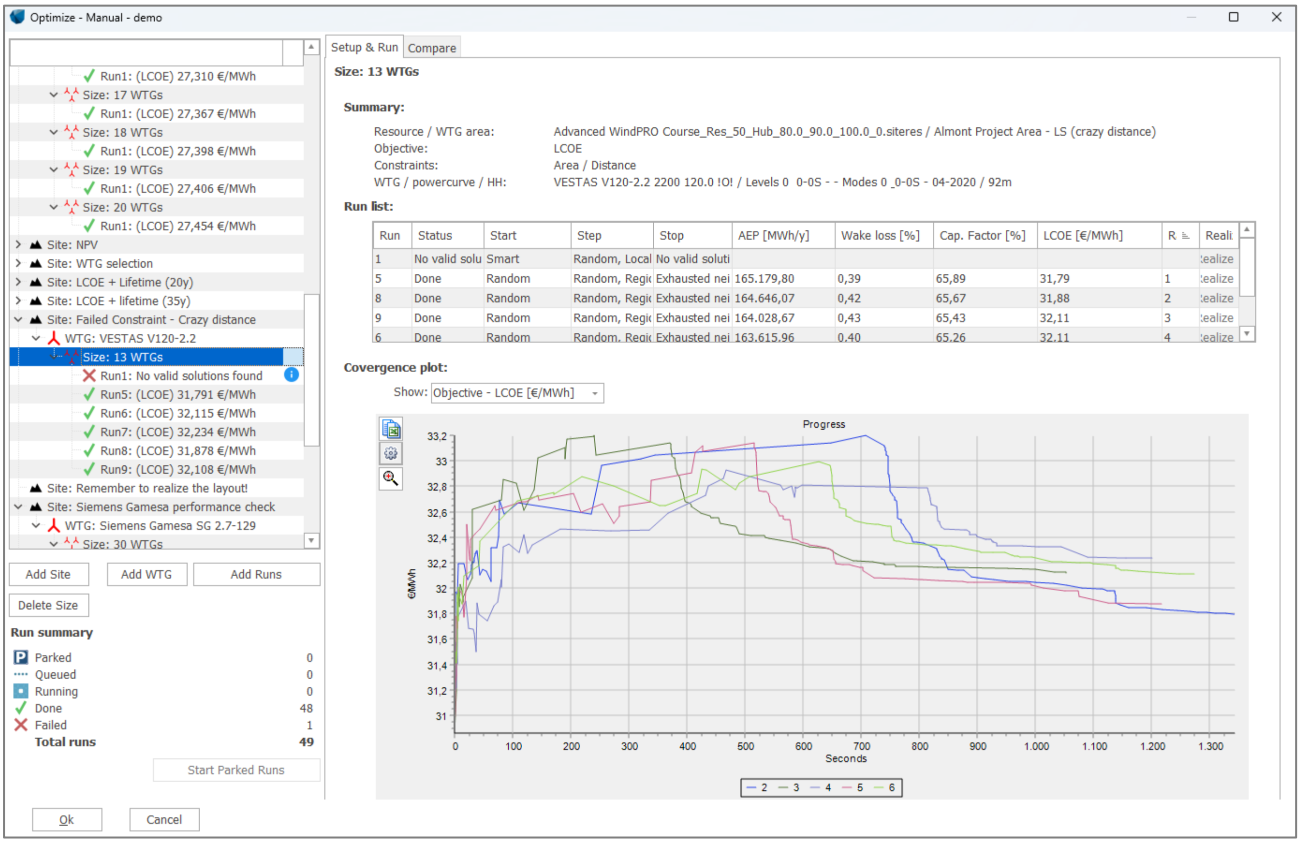


Figure 10: *Different variants of the 'Add…' button. The variant Add Sizes & Runs occurs when a WTG is selected in the tree, Add Runs when a Size is selected and Clone Run when an existing finalized run is selected.*

An example of a size with several runs is demonstrated in Figure 11 showing the view on *Setup & Run* tab. Figure 12 shows the view on the *Compare* tab, which is more focused on comparing the objective for the final layout across the runs.



Optimize - Manual - demo

- Run1: (LCOE) 27,310 €/MWh
- Size: 17 WTGs
  - Run1: (LCOE) 27,367 €/MWh
- Size: 18 WTGs
  - Run1: (LCOE) 27,398 €/MWh
- Size: 19 WTGs
  - Run1: (LCOE) 27,406 €/MWh
- Size: 20 WTGs
  - Run1: (LCOE) 27,454 €/MWh
- Site: NPV
- Site: WTG selection
- Site: LCOE + Lifetime (20y)
- Site: LCOE + lifetime (35y)
- Site: Failed Constraint - Crazy distance
  - WTG: VESTAS V120-2.2
    - Size: 13 WTGs
      - Run1: No valid solutions found
      - Run5: (LCOE) 31,791 €/MWh
      - Run6: (LCOE) 32,115 €/MWh
      - Run7: (LCOE) 32,234 €/MWh
      - Run8: (LCOE) 31,878 €/MWh
      - Run9: (LCOE) 32,108 €/MWh
- Site: Remember to realize the layout!
- Site: Siemens Gamesa performance check
  - WTG: Siemens Gamesa SG 2.7-129
    - Size: 30 WTGs

Add Site | Add WTG | Add Runs | Delete Size

Run summary

Parked	0
Queued	0
Running	0
Done	48
Failed	1
Total runs	**49**

Start Parked Runs

Ok | Cancel

Setup & Run | Compare

Size: 13 WTGs

Summary:

Resource / WTG area: Advanced WindPRO Course_Res_50_Hub_80.0_90.0_100.0_0.siteres / Almont Project Area - LS (crazy distance)
Objective: LCOE
Constraints: Area / Distance
WTG / powercurve / HH: VESTAS V120-2.2 2200 120.0 !O! / Levels 0 0-0S - - Modes 0 _0-0S - 04-2020 / 92m

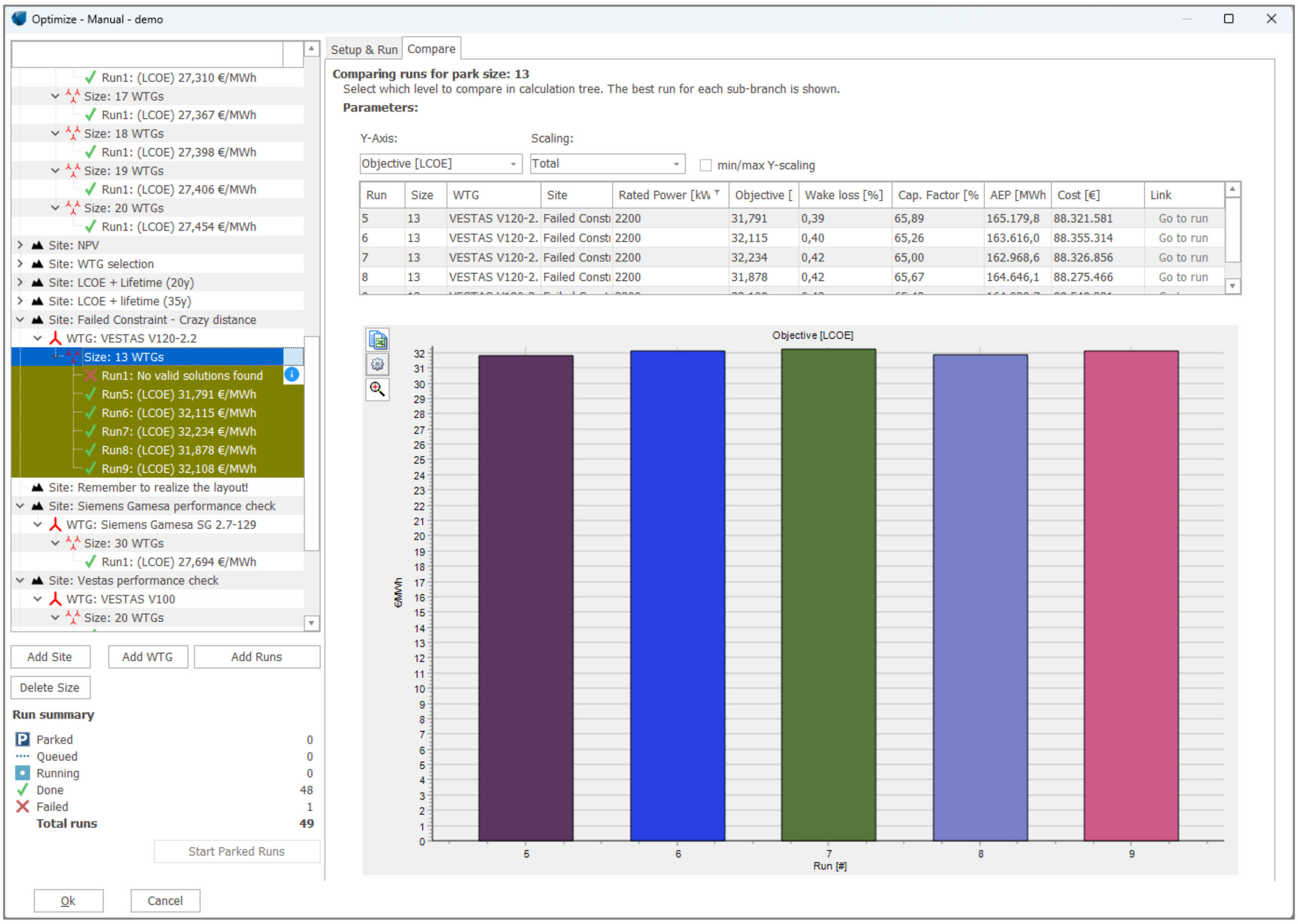
Run list:

Run	Status	Start	Step	Stop	AEP [MWh/y]	Wake loss [%]	Cap. Factor [%]	LCOE [€/MWh]	R	Reali
1	No valid solu	Smart	Random, Local	No valid soluti						ealize
5	Done	Random	Random, Regi	Exhausted nei	165.179,80	0,39	65,89	31,79	1	ealize
8	Done	Random	Random, Regi	Exhausted nei	164.646,07	0,42	65,67	31,88	2	ealize
9	Done	Random	Random, Regi	Exhausted nei	164.028,67	0,43	65,43	32,11	3	ealize
6	Done	Random	Random, Regi	Exhausted nei	163.615,96	0,40	65,26	32,11	4	ealize

Covergence plot:

Show: Objective - LCOE [€/MWh]

Figure 11: *Setup & Run tab for a park size (10 WTGs) with several runs. See Figure 12 for Compare tab.*



Optimize - Manual - demo

- ✓ Run1: (LCOE) 27,310 €/MWh
- Size: 17 WTGs
  - ✓ Run1: (LCOE) 27,367 €/MWh
- Size: 18 WTGs
  - ✓ Run1: (LCOE) 27,398 €/MWh
- Size: 19 WTGs
  - ✓ Run1: (LCOE) 27,406 €/MWh
- Size: 20 WTGs
  - ✓ Run1: (LCOE) 27,454 €/MWh
- Site: NPV
- Site: WTG selection
- Site: LCOE + Lifetime (20y)
- Site: LCOE + lifetime (35y)
- Site: Failed Constraint - Crazy distance
  - WTG: VESTAS V120-2.2
    - Size: 13 WTGs
      - ✗ Run1: No valid solutions found
      - ✓ Run5: (LCOE) 31,791 €/MWh
      - ✓ Run6: (LCOE) 32,115 €/MWh
      - ✓ Run7: (LCOE) 32,234 €/MWh
      - ✓ Run8: (LCOE) 31,878 €/MWh
      - ✓ Run9: (LCOE) 32,108 €/MWh
- Site: Remember to realize the layout!
- Site: Siemens Gamesa performance check
  - WTG: Siemens Gamesa SG 2.7-129
    - Size: 30 WTGs
      - ✓ Run1: (LCOE) 27,694 €/MWh
- Site: Vestas performance check
  - WTG: VESTAS V100
    - Size: 20 WTGs

Add Site | Add WTG | Add Runs | Delete Size

Run summary

Parked	0
Queued	0
Running	0
Done	48
Failed	1
Total runs	**49**

Start Parked Runs

Ok | Cancel

Setup & Run | Compare

Comparing runs for park size: 13

Select which level to compare in calculation tree. The best run for each sub-branch is shown.

Parameters:

Y-Axis: Objective [LCOE]

Scaling: Total

☐ min/max Y-scaling

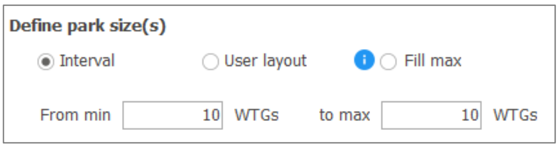
Run	Size	WTG	Site	Rated Power [kW	Objective [	Wake loss [%]	Cap. Factor [%	AEP [MWh	Cost [€]	Link
5	13	VESTAS V120-2.	Failed Consti	2200	31,791	0,39	65,89	165.179,8	88.321.581	Go to run
6	13	VESTAS V120-2.	Failed Consti	2200	32,115	0,40	65,26	163.616,0	88.355.314	Go to run
7	13	VESTAS V120-2.	Failed Consti	2200	32,234	0,42	65,00	162.968,6	88.326.856	Go to run
8	13	VESTAS V120-2.	Failed Consti	2200	31,878	0,42	65,67	164.646,1	88.275.466	Go to run

Figure 12: *Compare tab showing several runs for the same size (10 WTGs) also shown in Figure 11.*

8a.2.2 Number of WTGs (park size)

The New Optimizer can be used to analyze parks with different sizes, but it does not optimize for the number of turbines since the objectives are not well suited to optimize the park size: If the objective is to maximize the AEP, it is generally best to place as many wind turbines as possible into the park. In such case the *Fill max* option can be used. On the contrary, if the objective is to minimize the costs, it would be optimal to place none. In practice, the problem is often to find the wind turbine positions that are optimal for the specified objective with a given park size, and it is more useful to analyse different set-ups per park size and for different park sizes.

To analyze the park size, simply set the appropriate range of sizes from min to max in the *Add Sizes & Runs* setup as shown in Figure 13. Then choose the preferred setup of the runs which will be created for each size (see section 8a.1.2.3 for further details). The Optimizer uses parallelization so several runs will start and run simultaneously to speed-up performance.



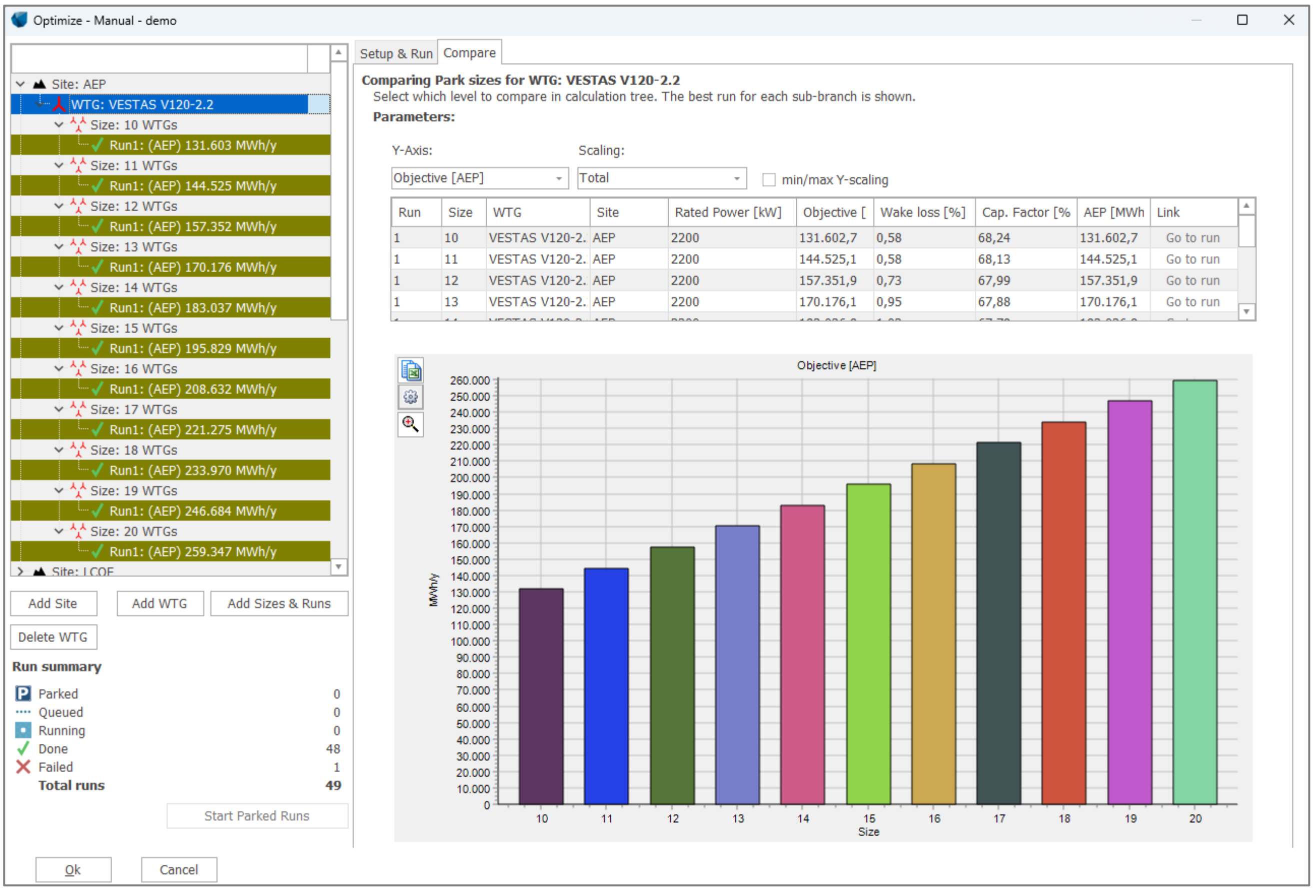
Define park size(s)

● Interval ○ User layout ○ Fill max

From min 10 WTGs to max 10 WTGs

Figure 13: *Setting a range of park sizes in the Add Sizes & Runs window. An optimization run (or more via Realizations) will be created for each size.*

Once completed, the results can be visualized and analyzed on the *Compare* tab and by selecting the relevant WTG in the tree.



Optimize - Manual - demo

- Site: AEP
  - WTG: VESTAS V120-2.2
    - Size: 10 WTGs
      - ✓ Run1: (AEP) 131.603 MWh/y
    - Size: 11 WTGs
      - ✓ Run1: (AEP) 144.525 MWh/y
    - Size: 12 WTGs
      - ✓ Run1: (AEP) 157.352 MWh/y
    - Size: 13 WTGs
      - ✓ Run1: (AEP) 170.176 MWh/y
    - Size: 14 WTGs
      - ✓ Run1: (AEP) 183.037 MWh/y
    - Size: 15 WTGs
      - ✓ Run1: (AEP) 195.829 MWh/y
    - Size: 16 WTGs
      - ✓ Run1: (AEP) 208.632 MWh/y
    - Size: 17 WTGs
      - ✓ Run1: (AEP) 221.275 MWh/y
    - Size: 18 WTGs
      - ✓ Run1: (AEP) 233.970 MWh/y
    - Size: 19 WTGs
      - ✓ Run1: (AEP) 246.684 MWh/y
    - Size: 20 WTGs
      - ✓ Run1: (AEP) 259.347 MWh/y
- Site: LCOE

Run summary

Parked	0
Queued	0
Running	0
✓ Done	48
✗ Failed	1
Total runs	**49**

Comparing Park sizes for WTG: VESTAS V120-2.2
Select which level to compare in calculation tree. The best run for each sub-branch is shown.
Parameters:

Y-Axis: Objective [AEP]
Scaling: Total
□ min/max Y-scaling

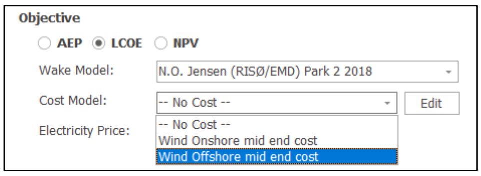
Run	Size	WTG	Site	Rated Power [kW]	Objective [	Wake loss [%]	Cap. Factor [%	AEP [MWh	Link
1	10	VESTAS V120-2.	AEP	2200	131.602,7	0,58	68,24	131.602,7	Go to run
1	11	VESTAS V120-2.	AEP	2200	144.525,1	0,58	68,13	144.525,1	Go to run
1	12	VESTAS V120-2.	AEP	2200	157.351,9	0,73	67,99	157.351,9	Go to run
1	13	VESTAS V120-2.	AEP	2200	170.176,1	0,95	67,88	170.176,1	Go to run

Figure 14: *Example Compare view for a range of sizes. The optimizations are run using LCOE objective.*

In some cases, the runs for the largest park sizes will fail before all turbines could be placed by the start model. This can indicate the maximum number of turbines which is possible to place, but care must be taken as several factors influence this outcome. One thing is making sure that the grid resolution is not too coarse, generally around 0.5 RD ensures good performance. Another possibility is that the default start model (*Smart*) places turbines according to the objective – but that the maximum is determined by a constraint, hence placement may not be ideal regarding minimizing constraint exceedance. Section 8a.2.4 describes a procedure that improves chances of finding a valid layout in such cases.

8a.2.3 Choice of turbine model

To analyze the choice of WTG model, simply add all the relevant WTG models to the Site. In such cases setting the maximum allowed capacity of the grid in the WTG area is beneficial as this will automatically influence the maximum number of turbines for each model, given its capacity. It may also be relevant to set individual cost models for each WTG if detailed cost information is available. However, this is not required as the default cost model will automatically account for the difference in rotor size and generator capacity of each WTG type.

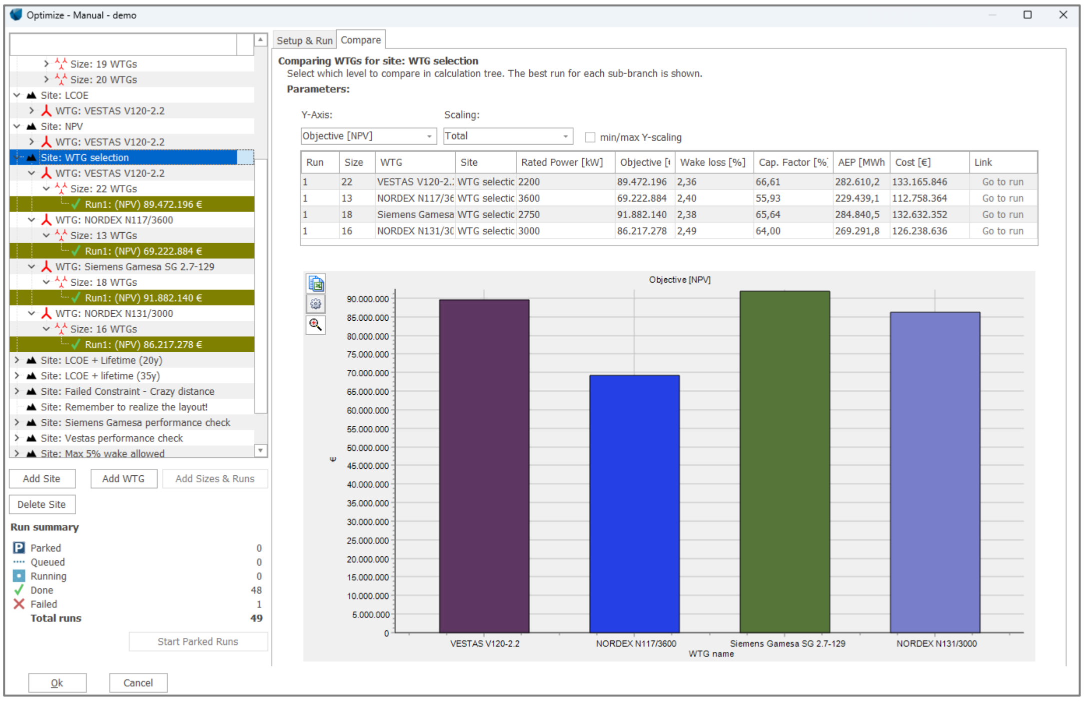


Objective
○ AEP ● LCOE ○ NPV
Wake Model: N.O. Jensen (RISØ/EMD) Park 2 2018
Cost Model: -- No Cost --
Electricity Price:

-- No Cost --
Wind Onshore mid end cost
Wind Offshore mid end cost

Figure 15: *Setting individual cost models for each WTG type.*

The results across the WTGs may be compared on the *Compare* tab by selecting the relevant site in the tree. If there are more sizes and runs for each WTG the best run (with regard to the selected objective) is chosen to represent each WTG type. Figure 16 shows an example of comparing NPV optimizations across three turbine types.


Optimize - Manual - demo

- Size: 19 WTGs
- Size: 20 WTGs
- Site: LCOE
  - WTG: VESTAS V120-2.2
- Site: NPV
  - WTG: VESTAS V120-2.2
- Site: WTG selection
  - WTG: VESTAS V120-2.2
    - Size: 22 WTGs
      - Run1: (NPV) 89.472.196 €
  - WTG: NORDEX N117/3600
    - Size: 13 WTGs
      - Run1: (NPV) 69.222.884 €
  - WTG: Siemens Gamesa SG 2.7-129
    - Size: 18 WTGs
      - Run1: (NPV) 91.882.140 €
  - WTG: NORDEX N131/3000
    - Size: 16 WTGs
      - Run1: (NPV) 86.217.278 €
- Site: LCOE + Lifetime (20y)
- Site: LCOE + lifetime (35y)
- Site: Failed Constraint - Crazy distance
- Site: Remember to realize the layout!
- Site: Siemens Gamesa performance check
- Site: Vestas performance check
- Site: Max 5% wake allowed

Add Site | Add WTG | Add Sizes & Runs | Delete Site

Run summary

Parked	0
Queued	0
Running	0
Done	48
Failed	1
Total runs	**49**

Start Parked Runs

Ok | Cancel

Setup & Run | Compare

Comparing WTGs for site: WTG selection

Select which level to compare in calculation tree. The best run for each sub-branch is shown.

Parameters:

Y-Axis: Objective [NPV]

Scaling: Total

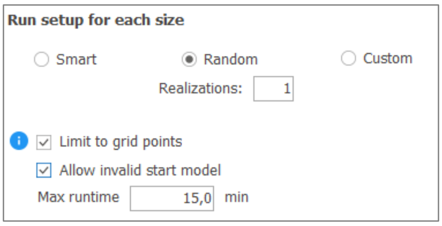
□ min/max Y-scaling

Run	Size	WTG	Site	Rated Power [kW]	Objective [(	Wake loss [%]	Cap. Factor [%]	AEP [MWh	Cost [€]	Link
1	22	VESTAS V120-2.:	WTG selectic	2200	89.472.196	2,36	66,61	282.610,2	133.165.846	Go to run
1	13	NORDEX N117/36	WTG selectic	3600	69.222.884	2,40	55,93	229.439,1	112.758.364	Go to run
1	18	Siemens Gamesa	WTG selectic	2750	91.882.140	2,38	65,64	284.840,5	132.632.352	Go to run
1	16	NORDEX N131/30	WTG selectic	3000	86.217.278	2,49	64,00	269.291,8	126.238.636	Go to run

Figure 16: *Compare tab showing results for three different WTG models for a site.*

8a.2.4 Fulfillment of constraints (spacing, noise, lifetime, wake)

In some cases, the optimization is more driven by the constraints (noise or loads) than by the objective (AEP, LCOE or NPV). This does not mean that the objective is irrelevant, but rather that the design space is very difficult to navigate in for the Optimizer because large parts are invalid due to the constraints. In some cases, this may lead to runs failing for particular sizes because the start model cannot generate a valid layout, i.e. place all turbines without violating the constraints. If this happens it can be beneficial to add several runs with the *Random* run setup for a failed size and with the setting *Allow invalid start model* activated. This will allow the start model to place all the required turbines but disregard the constraints (except the WTG area). The step model will then seek to minimize the constraint exceedance first, and if that succeeds then optimize the objective function.


Run setup for each size

○ Smart ● Random ○ Custom

Realizations: 1

☑ Limit to grid points

☑ Allow invalid start model

Max runtime 15,0 min

Figure 17: *Setup of a run showing how Allow invalid start model is activated. This option is only supported for Random start models.*

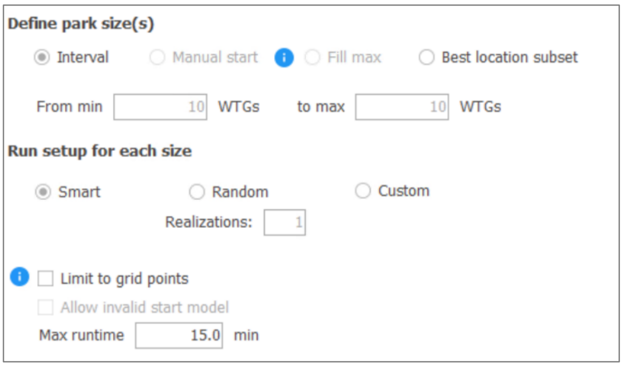
8a.3 Optimization algorithm

The wind farm optimization problem is a difficult problem mainly due to the occurrence of several local minima and so-called non-linearity and interaction in the objective functions, chiefly arising from the turbine wake interaction. If one turbine is moved the optimum position for all other turbines in the park may change or they may exceed a constraint they did not before. These effects may be accentuated by too coarse a resource grid and too coarse a directional resolution in the wake model or simply by multi-directional wind roses. When constraints are included, these may also prevent otherwise beneficial layout changes and effectively split the solution space into many smaller un-connected “islands” (in a high dimensional sense), which are extremely difficult to navigate for an optimization algorithm. The supported objectives and constraints are described in section 0.

The structure of the New Optimizer reflects the structure of the underlying solution approach, which is a classical iterative search, but with many built-in smart features that improve its performance and efficiency. In this framework, an optimization needs a *Start model*, an initial ‘first guess’ and then a *Step model* that subsequently seeks to make iterative, incremental improvements to further improve and optimize the Start model. As the final optimal model is not known a priori, one or more *Stop criteria* are needed to decide when to halt the search of the Step model. This could be once a maximum time or a maximum number of fruitless attempts to take a new step improvement have been tried.

The better the initial Start model the more focused the iterative Step model can perform its search. In fact, the wind farm optimization problem is so complex that with many turbines it is very difficult for an iterative solution to find a good optimum. Increasing the likelihood of ending up in an only modestly good local optimum. In this sense the old saying “*Well begun is half done”* is extremely pertinent and the reason for the development of the *Smart* Start models described in section 8a.3.1.

Figure 18 shows the basic options available for setting up optimization runs. The Optimizer includes multiple options both for the Start model, Step model and Stop criteria and is quite flexible in this sense. However, the basic options shown represent the main recommended combinations of Start and Step models.



Define park size(s)

● Interval ○ Manual start ○ Fill max ○ Best location subset

From min 10 WTGs to max 10 WTGs

Run setup for each size

● Smart ○ Random ○ Custom

Realizations: 1

□ Limit to grid points

□ Allow invalid start model

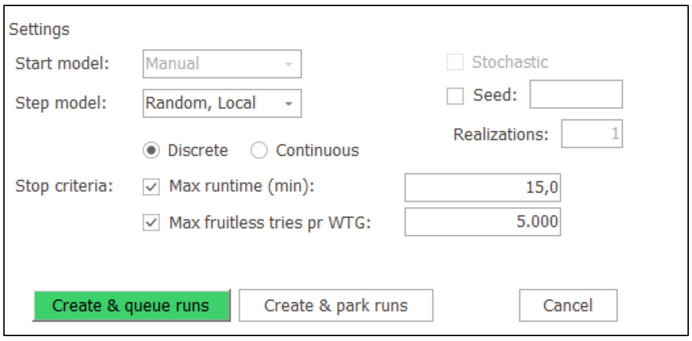
Max runtime 15.0 min

Figure 18: *The basic setup options for optimization runs.*

The full flexibility is available when choosing the *Custom* option where all the Start, Step and Stop options become available. These options are summarized in the bullet points below including the two additional options, *Seed* and *Realization*, which are explained in their respective parentheses.

- **Custom**
  - Start: Fill; Manual; Resource Greedy; Random; Smart
  - Step: Random, Local; Random, Regional; Random, Global
    - Resolution: Discrete (Limit to grid points), Continuous
  - Stop: Max runtime, Max fruitless tries, (exhausted neighborhood)
  - Stochastic (use of random numbers)
  - Seed (to ensure reproducibility of stochastic methods)
  - Realizations (how many runs to generate for a stochastic method)

The last listed Stop criterion, *exhausted neighborhood,* is in parentheses as it is never selectable for the end-user and always applied when the optimization runs with the *Discrete* resolution setting, where turbine positions are limited to the grid points in the resource grid. This Resolution setting with options *Discrete* or *Continuous* is a property of the step model as it is referred to as *Limit to grid points* in the basic options setup (i.e. not *Custom)*.



Settings

Start model: Manual

Step model: Random, Local

● Discrete ○ Continuous

□ Stochastic

□ Seed:

Realizations: 1

Stop criteria: ☑ Max runtime (min): 15,0

☑ Max fruitless tries pr WTG: 5.000

Figure 19: *The detailed setup options available when choosing the Custom option.*

To keep the GUI user-friendly, we have pre-defined combinations of Start model and Step model (cf. Figure 18) that are known to perform well together. Above all the *Smart* option which is the default option will perform the best in the majority of cases. The pre-defined (default) combinations are listed below indicating the Start and Step models

- **User Layout**
  - Start: Manual (i.e., user defined)
  - Step: Random, Regional
- **Fill max**
  - Start: Fill
  - Step: Random, Local
- **Best location subset**
  - Start: Fill
  - Step: Random, Local
- **Smart**
  - Start: Manual (i.e., user defined)
  - Step: None
- **Random**
  - Start: Random
  - Step: Random, Regional

The following sections describe the Start, Step and Stop options in further detail.

8a.3.1 Start model

The purpose of the Start model is to define the initial guess of the optimization solution and to make that guess as good as possible. As described earlier, for complex optimization problems "*well begun really is half done*", and most likely much more than just half done. A poor starting model will be more likely to end up in modest local optimal solutions. All the start models operate strictly on the resource grid. If this grid is excessively coarse relative to the rotor diameter of the turbine model, that is to say >1RD, the performance of the Start models may deteriorate, in particular the more advanced ones like the *Smart* Start model. The optimal trade-off between speed and resolution lies around 0.5RD for the resource grid spacing relative to the turbine rotor diameter.

Unless the *Allow invalid start model* is activated the Start model will respect all activated constraints. The option can only be activated for the *Random* start model. See section 8a.2.4 for further information.

The *Smart* Start model picks the optimal position (approximately) for each new WTG it places, regarding the actual chosen objective and the effects of already-placed turbines. If stochastic is activated a measure of randomness is added in the placement of each individual turbine.

The *Random* Start model is fully stochastic and picks the positions at random across the entire grid. More than one *Realization* is recommended for this model, typically 7-8 or more, which simply means doing several similar runs with different sets of random numbers. This model can be beneficial particularly if the optimization is strongly influenced by restrictive constraints. A fixed *Seed* may be set to exactly reproduce random numbers as this seed is used both for the start and step models to ensure full consistency. A fixed seed cannot be used with multiple realizations.

The *Resource Greedy* option is mainly included for historic reasons and for comparisons with the Classical windPRO Optimizer. It picks each turbine position according to the best available resource position disregarding wake effects and any objective function. This option performs well for sites with strong resource variation (e.g. a ridge) using the AEP objective.

The *Fill* Start model will simply disregard the resource and start filling turbines from one corner only respecting the constraints until the required number have been placed. If selected via the *Fill max* option, the filling will continue until no more turbines can be placed due to the constraints – this option is particularly vulnerable to too coarse a resource grid.

The *Manual* Start model is defined by the user who selects the turbine’s starting positions.

The *Best location subset* Model is new in windPRO 4.1 and allows the user to identify the optimal subset of locations from a defined set of turbine locations.

8a.3.2 Step model

The Step model iteratively seeks to improve the Start model until a Stop criterion is met. All the Step models are stochastic, which means that they rely on random numbers. This means that both a turbine is selected at random and that a new position for that turbine is selected at random. The main difference between the Step models is the pool of positions from which these new positions are drawn.

The *Random, Local* Step model assumes that the current layout and turbine positions are relatively close to the optimum. The assumption is typically valid for Smart Start models and *Manual* user defined Start models. The local step model draws random positions from a local area around the turbine.

The *Random, Regional* Step model draws the random positions from a relatively large region around the turbine, expecting improvements to be found further away, and the optimum position is not in the direct neighborhood.

The *Random, Global* Step model draws new positions from the entire domain. It is not utilized in any of the standard options as convergence is inefficient. However, as a first broad search phase it can be useful followed by a *Random, Regional* step model initiated via a Clone run, for example.

When grid spacing is finer than the expected optimal trade-off at around 0.5D, the default option is *Limit to grid points (Discrete)*. When grid spacing exceeds 0.5D, the default option is *Continuous*, which will allow turbines to move away from grid points and prevent local optima due to a grid that is too coarse which is important. The drawback is that the most natural Stop criterion cannot be used as will be described in the next section.

The main difference between the local, regional, and global set-up is the areas around the turbines considered for steps. In a local step, the local area is 5D at the start of the optimization run and becomes iteratively smaller until it reaches 1D at the end of the run in the discrete case or 0.5D in the continuous case. The distance that defines the regional area is a square root of the vertical and horizontal distance of the whole WTG area, but at least 5D in case of small WTG areas, at the start of the optimization run. It also ends up at 1D in the discrete case and 0.5D in the continuous case. In the global step, the whole area is constantly considered during the run.

8a.3.3 Stop criteria

The purpose of the Stop criteria is to detect if an optimization is converged or so close to being converged that further improvement will be insignificant. Another purpose is to give the user a chance to set a maximum waiting time (with the risk of stopping prematurely far from an optimum).

Max runtime is the maximum time Step model is allowed to run. When the time is up the optimization is stopped. The time to generate the starting model is not included in the timing.

Max fruitless tries simply defines the maximum number of unsuccessful attempts to take a step which accepted before stopping. Both invalid steps (i.e., failed constraints) and steps without improved objective values are counted.

Exhausted neighborhood is an option hidden from the user which is the most efficient stopping criterion. It can only be used for runs with the resolution set to *Limit to grid points (Discrete)*. It is a memory that tests if all possible positions in the search neighborhood for all turbines have been tried in vain – and if so, the current layout is by definition an optimum and the run is stopped. For continuous runs the search neighborhood is always infinite no matter how small it is, and this Stop criterion cannot be employed.

8a.3.4 Objective & Constraints

Put simply, the *Objective* of an optimization is what we seek to optimize. The design variables are the degrees of freedom given to the Optimizer, which are allowed to be modified to find the best possible objective. In this Optimizer only the turbine positions, their X and Y coordinates are explicit design variables. The number of turbines and the turbine models are implicit design variables which the user can analyze and optimize via the flexible structure of the GUI-tree. The choice of objective may differ for different users, the supported objectives are described in next section.

Constraints are known limitations which must be fulfilled for a solution to be accepted, hence, we call a solution which fulfills all constraints *Valid*. A solution where at least one constraint is violated is *Invalid* (and will not be accepted).

8a.4 Objectives

An optimization needs a quantity that must be optimized, the *Objective*, given a set of design variables that may be varied. For some objectives optimization implies maximization, which is the case when wind farm production (AEP) or project profit is the objective. For other objectives optimization implies minimization, which is the case for cost-of-energy optimization.

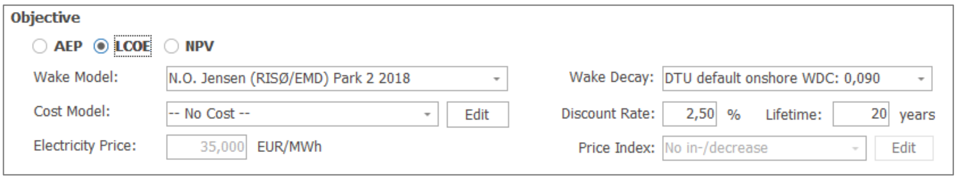
8a.4.1 AEP

AEP is simply the Annual Energy Production including wake losses. The AEP calculation is based on the resource data in the selected .rsf or .siteres file, containing sector-wise Weibull parameters (A and k) and frequencies (f). Wake effects are calculated using the PARK2 wake model and the user-defined wake decay constant.

Wind farm layout optimizations using AEP as the objective have a drawback, particularly if the available WTG area is large: The optimization may lead to very spread-out layouts that would incur excessive costs for building roads and grid connection. This is the main motivation for choosing other objectives, in particular, objectives which include the costs of building the wind farm.

8a.4.2 Costs

Costs are not included as an objective on its own in the New Optimizer, at least not directly. However, the estimation of costs is an important input to financial objectives such as cost-of-energy (COE) or profit (NPV), to account for the balance between the created value (i.e., AEP) and the expected costs required to realize that potential. Costs in the New Optimizer are estimated using the windPRO Cost tool. This tool estimates costs using parameterized formulas fitted to a large amount of real historic costs and based on extensive literature reviews. As an example, turbine costs scale with generator capacity (MW), specific capacity (MW/m^2), rotor size (m^2) and hub height (m) via an elaborate regression expression. The cost tool comes with six predefined cost models, three price levels ‘high’, ‘mid’ and ‘low’ for onshore and offshore, respectively.



Objective

○ AEP ● LCOE ○ NPV

Wake Model: N.O. Jensen (RISØ/EMD) Park 2 2018

Wake Decay: DTU default onshore WDC: 0,090

Cost Model: -- No Cost -- Edit

Discount Rate: 2,50 %

Lifetime: 20 years

Electricity Price: 35,000 EUR/MWh

Price Index: No in-/decrease Edit

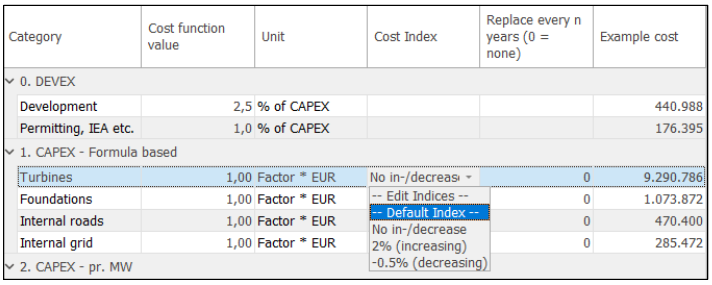
Figure 20: *Selection of the cost model showing the two default cost models for onshore and offshore respectively.*

In the cost tool, the costs are divided into four main categories as listed below.

- Devex: development expenditure
- Capex: capital expenditure
- Opex: operational expenditure
- Abex: abandonment expenditure

Development expenditures (Devex) quantify the cost associated with developing the project, getting permissions to build the wind farm etc. Capital expenditures (Capex) represent the main investment of building the wind farm. Operational expenditures (Opex) represent the costs of keeping the wind farm running through its lifetime, and abandonment expenditures (Abex) quantify the estimated amount of money to eventually remove the wind park. Capex is the only cost category which depends on the actual design of the layout via the costs for the internal grid connection between the turbines (and roads for onshore).

For each cost a *Cost Index* may be defined to account for expected future trends in the price development. This index should exclude the effect of the general baseline inflation.



Category	Cost function value	Unit	Cost Index	Replace every n years (0 = none)	Example cost
0. DEVEX					
Development	2,5	% of CAPEX			440.988
Permitting, IEA etc.	1,0	% of CAPEX			176.395
1. CAPEX - Formula based					
Turbines	1,00	Factor * EUR	No in-/decreas	0	9.290.786
Foundations	1,00	Factor * EUR		0	1.073.872
Internal roads	1,00	Factor * EUR		0	470.400
Internal grid	1,00	Factor * EUR		0	285.472
2. CAPEX - pr. MW					

Figure 21: *Extract from the Cost tool showing the possibility to enter Price Indices for each cost component, but also the possibility to include replacement costs, e.g. for gearboxes.*

In Figure 21 please note the possibility to insert adjustments to the baseline costs via entries in the table column *Cost function value*. It is via values in this column that the high and low alternative cost models are defined, by an increase or decrease of these factors.

In the Optimizer the wind farm is assumed to be built and put into operation the year after the current year, which for 2023 would be 2024. Devex is assumed to occur the year before the installation, i.e. the current year. When the reference year defined in the cost tool deviates from the year that a cost occurs the price index (if set) will be used to adjust the costs accordingly. The default cost index is zero through the lifetime.

Note that the total cost values shown in the optimizer are not discounted only index corrected (if set by the user) and summed over the lifetime.

For the grid (offshore and onshore) and road connection costs (onshore only) an additional sub-optimization is solved for finding the shortest possible way to connect the turbines in the layout. Either to each other or to any of the *Connection points* if defined for the *Site.* The resulting inter-connection distance is what enters the cost calculation. The solution to this sub-optimization relies on graph theory and the optimization problem is referred to as the minimum spanning tree. The connections of the minimum spanning tree are visualized in the *Layout plot* for each run as the black connection lines between the WTGs (and connection points, if any).

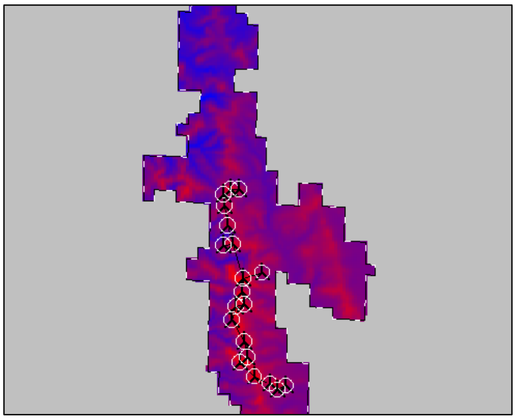


Figure 22: *Layout plot from for a run with LCOE optimization showing the black connection lines.*

As a final remark it is important to stress that the cost model is deliberately kept relatively simple with a minimum of assumptions which are calibrated against actual project costs. Hence, the user does not need, in fact cannot, set a large range of particular cost items such as the cost of crossing a stream or railway. Although that degree of flexibility might appear beneficial, if the input quantities are not known the values will be associated with a very large uncertainty, as will the resulting overall cost estimates.

The current cost tool seeks to strike an ideal balance between accuracy and detail/flexibility, but with a preference for accuracy over detail. In the end what is important is getting the right order of magnitude of costs as input to the financial objectives described in the following sections.

8a.4.2.1 Offshore Vs Onshore costs

The onshore and offshore cost setups share many cost components, and both include costs for the internal grid connection, but with very different price constants. A main difference is that the onshore cost model includes the cost of connecting roads where the offshore model includes the cost of a main grid connection (to the shore). Also, the foundation and area are calculated differently. See the manual for the Cost tool for further details (windPRO BASIS manual, chapter 2 section 18).

8a.4.3 LCOE

Levelized cost of energy (LCOE) is often preferred as an objective in optimizations, as on the one hand it includes the effect of costs, in particular Capex, the cost of building the wind farm project. On the other hand, LCOE does not require further assumptions of uncertain quantities such as the future development of the electricity price. In addition, a *discount rate* must also be assumed for the costs to calculate LCOE, to discount future costs to present day values. The discount rate is a baseline interest rate often representing the average interest rate for secure investments such as bonds or set as the baseline return of investment in a company. windPRO uses the so-called *real discount rate*, which is corrected for the general inflation (i.e., it excludes inflation). Hence, future costs in the windPRO cost tool should not account for inflation.

In LCOE the future AEP is discounted similarly, which might seem counter-intuitive. However, the AEP of each year through the lifetime will lead to a cash flow via the sale of the produced electricity. In this regard the AEP produced next year is worth more than AEP produced in say 15 years (for positive discount rates), assuming a constant electricity price. Thus, LCOE accounts for the discount effect of both future costs and future sale of electricity and calculates the average cost of electricity from these, as expressed in the equation below (e.g. [2] or [3]):

$$LCOE = \frac{NPV_{TotalCost}}{NPV_{Yield}} = \frac{\sum_j \frac{Costs_j}{(1+d)^j}}{\sum_i \frac{AEP_i}{(1+d)^i}}$$

In the above expression, costs are condensed to a single sum for each year. In practical terms, the Capex will occur in year zero, the installation year, and the Opex occurs in all the following years until end of lifetime, possibly increasing over time if the user has set a cost index for the future years.

The LCOE has the drawback in that it tends to increase (i.e., deteriorate) with increasing size of a wind farm, as the best resource positions get taken first and wake effects tend to increase with park size. The total profit of the project on the other hand would typically increase with the size of the wind farm. Hence, LCOE will generally lead to too small a wind farm if used as an objective to determine the wind farm size. When comparing wind farms of equal capacity LCOE does not suffer from this shortcoming.

8a.4.4 NPV

The Net Present Value (NPV) for a wind farm project is simply put the **total profit of the wind farm** through its lifetime converted to present day value. NPV bares many similarities with the LCOE, and addresses the main drawback of LCOE, that it under evaluates the value of larger projects. Still NPV includes the penalizing effect of Capex costs for spread-out layouts. The main difference between NPV and LCOE is the fact that the AEP in future years is explicitly converted to a cash flow. This requires the assumption of a future electricity price (P) in addition to the discount rate (d), which by default is constant, but may include future projections via a *price index* similar to the cost components. The equation below summarizes the calculation of NPV (e.g. [3]).

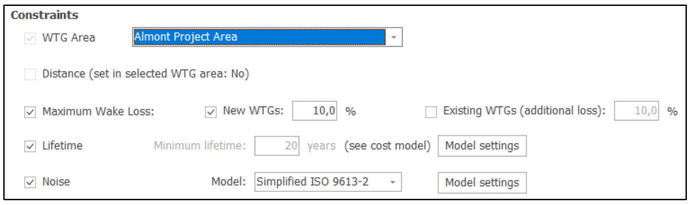
$$NPV = NPV_{TotalCashflow} = \sum_i \frac{P_i \cdot AEP_i - Costs_i}{(1+d)^i}$$

NPV is the most flexible objective function of the three objectives supported in the Optimizer. In fact, NPV can give similar results to both AEP optimizations and LCOE optimizations. The performance is controlled by the trade-off between costs and AEP, which is defined by the assumed electricity price. For very high electricity prices, costs lose importance and the NPV objective approaches the AEP objective. For very low electricity prices AEP loses its importance and the optimization will be driven mainly by costs to minimize expenses. If the electricity price is set to be equal to the LCOE from another optimization, then the performance of the NPV objective will yield results very similar to the LCOE optimization.

The NPV has several advantages compared to AEP and LCOE and addresses their shortcomings. NPV also works well as an objective for determining the size of a wind farm as it will seek to maximize the lifetime profit of the project. But as profit in absolute terms tend to grow with project size, the optimal size will often be the maximum allowed park size, as is the case for AEP. The main drawback when using NPV as an objective is that an assumption of a future electricity price is required, and that this assumption is associated with a large or even very large uncertainty. At the same time the assumed electricity price may significantly influence the performance of the NPV objective as described above.

8a.5 Constraints

The following sections describe the constraints supported by the New Optimizer. The supported constraints are shown in Figure 23. Note that including *Lifetime* or *Noise* constraints are subject to additional windPRO license requirements as they draw on calculation functionality in the LOAD RESPONSE and DECIBEL modules, respectively.



Constraints

☑ WTG Area: Almont Project Area

□ Distance (set in selected WTG area: No)

☑ Maximum Wake Loss: ☑ New WTGs: 10,0 % □ Existing WTGs (additional loss): 10,0 %

☑ Lifetime Minimum lifetime: 20 years (see cost model)

☑ Noise Model: Simplified ISO 9613-2

***Figure 23:** Constraint options.*

8a.5.1 Area & distance (sub-areas)

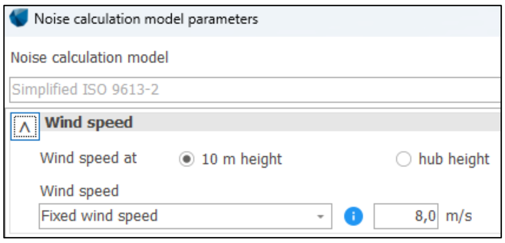
Defining a *WTG area* object is a prerequisite for all optimizations. The WTG area object serves the purpose to define the area limitations for turbine placement. A site may be split into arbitrarily many sub-areas and each sub-area may have individual limitations on minimum and maximum numbers of turbines or installed capacities. Sub-areas may also have individual requirements for turbine spacing typically defined as an elliptical constraint in terms of rotor diameters oriented along the prevalent wind direction. The Optimizer will always adhere to the areal requirements defined in the selected WTG area, whereas minimum requirements for inter-turbine distances must be separately activated via the *Distance* constraint. Even if no distance constraint is activated the Optimizer will not accept a turbine spacing below 1D. Some tips and considerations to the WTG area import are available in section 8a.6.2, and detailed information about the WTG area object is available at Appendix 8 OPTIMIZE Classic in section 8.0.1.5.

8a.5.2 Wake loss

The maximum wake loss constraint is a new feature in windPRO 4.0 (cf. Figure 23). It allows to define maximum wake losses for both new WTG and existing WTG objects; the maximum wake losses can be specified independently from each other.

8a.5.3 Noise

The noise constraint requires an activated license for the DECIBEL module. The calculation is a stripped-down version of the ISO 9613-2 standard. The noise constraint is defined for a single wind speed selected in the *Model settings* for the noise requirement (Figure 24). Noise sensitive areas must be selected on the Site level (Figure 25) and WTG source noise data on the WTG level (Figure 26).



Noise calculation model parameters

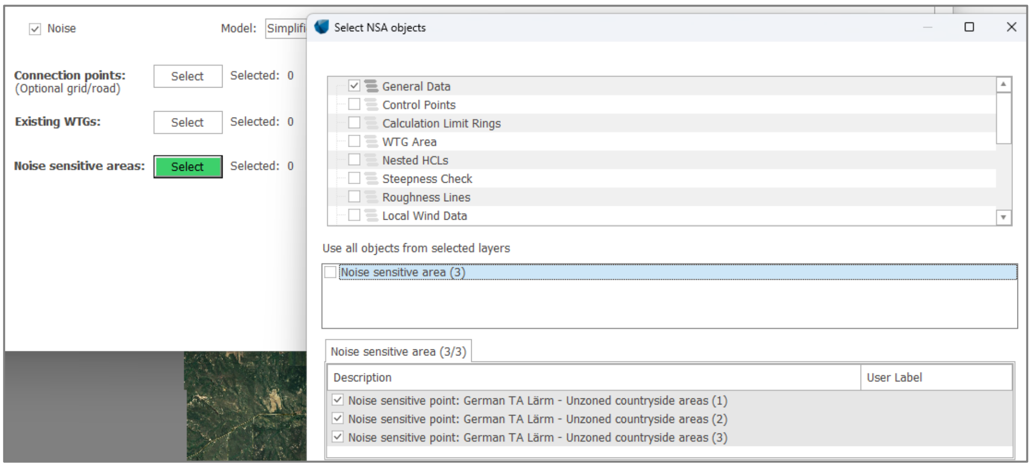
Noise calculation model: Simplified ISO 9613-2

Wind speed

Wind speed at: ● 10 m height ○ hub height

Wind speed: Fixed wind speed 8,0 m/s

***Figure 24:** Model settings for the Noise constraint (Site level), showing the selection of wind speed.*



☑ Noise Model: Simplifi

Connection points: (Optional grid/road) Select Selected: 0

Existing WTGs: Select Selected: 0

Noise sensitive areas: Select Selected: 0

Select NSA objects

- ☑ General Data
- ☐ Control Points
- ☐ Calculation Limit Rings
- ☐ WTG Area
- ☐ Nested HCLs
- ☐ Steepness Check
- ☐ Roughness Lines
- ☐ Local Wind Data

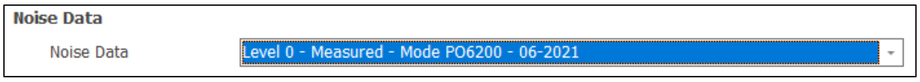
Use all objects from selected layers

☐ Noise sensitive area (3)

Noise sensitive area (3/3)

Description	User Label
☑ Noise sensitive point: German TA Lärm - Unzoned countryside areas (1)	
☑ Noise sensitive point: German TA Lärm - Unzoned countryside areas (2)	
☑ Noise sensitive point: German TA Lärm - Unzoned countryside areas (3)	

Figure 25: *Selection of noise sensitive areas (NSAs) on the Site level in the tree.*



Noise Data

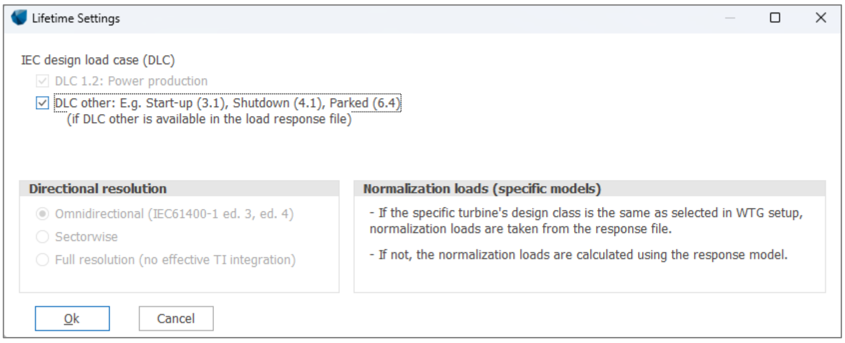
Noise Data: Level 0 - Measured - Mode PO6200 - 06-2021

Figure 26: *Selection of noise data on the WTG level in tree.*

8a.5.4 Component Lifetime (loads)

The lifetime constraint requires an active license for the LOAD RESPONSE module and sets a constraint on required minimum lifetimes for selected turbine components for each WTG position.

The calculation of lifetimes and activation of the lifetime constraint requires a resource file including all the siting parameters for fatigue calculation, i.e., a *.siteres* file. Such a file may be calculated using the RESOURCE calculation in windPRO drawing upon the IEC61400-1 ed. 4 calculation functionality in SITE COMPLIANCE, or can be downloaded from the free online GASP dataset. The calculation options are a stripped-down version of LOAD RESPONSE as can been from the *Model settings* in Figure 27.



Lifetime Settings

IEC design load case (DLC)

☑ DLC 1.2: Power production

☑ DLC other: E.g. Start-up (3.1), Shutdown (4.1), Parked (6.4)
(if DLC other is available in the load response file)

Directional resolution

- ● Omnidirectional (IEC61400-1 ed. 3, ed. 4)
- ○ Sectorwise
- ○ Full resolution (no effective TI integration)

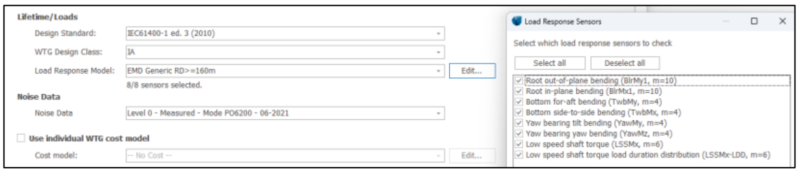
Normalization loads (specific models)

- If the specific turbine's design class is the same as selected in WTG setup, normalization loads are taken from the response file.
- If not, the normalization loads are calculated using the response model.

Ok Cancel

Figure 27: *Model Settings for the Lifetime constraint accessed on the Site level.*

The lifetime calculation also requires the setup of the wind turbine *Design Standard* and *Class* as well as selection of the *Load Response Model* which can be either a generic model or a specific model provided by a manufacturer. For the response model, a set of sensors must be selected for the constraint, here it is recommended to focus on the key components such as blade root and tower bottom, and perhaps low speed shaft (LDD).



Lifetime/Loads

Design Standard: IEC61400-1 ed. 3 (2010)

WTG Design Class: IA

Load Response Model: EMD Generic RD>=160m Edit...

8/8 sensors selected.

Noise Data

Noise Data: Level 0 - Measured - Mode PO6200 - 06-2021

☐ Use individual WTG cost model

Cost model: -- No Cost -- Edit...

Load Response Sensors

Select which load response sensors to check

Select all Deselect all

- ☑ Root out-of-plane bending (BlrMy1, m=10)
- ☑ Root in-plane bending (BlrMx1, m=10)
- ☑ Bottom for-aft bending (TwbMy, m=4)
- ☑ Bottom side-to-side bending (TwbMx, m=4)
- ☑ Yaw bearing tilt bending (YawMy, m=4)
- ☑ Yaw bearing yaw bending (YawMz, m=4)
- ☑ Low speed shaft torque (LSSMx, m=6)
- ☑ Low speed shaft torque load duration distribution (LSSMx-LDD, m=6)

Figure 28: *Turbine design class and response model selection on WTG level.*

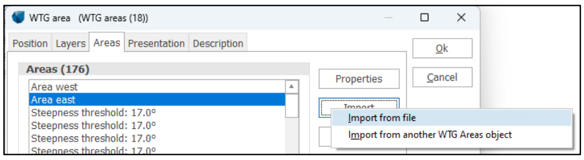
8a.6 Practical recommendations

8a.6.1 Run settings

- As a default, *Smart start* is recommended.
- For sites where it is difficult to allocate the desired number of turbines with only distance constraints, *Fill max* is recommended.
- For sites where it is difficult to allocate the desired number of turbines with noise, wake or lifetime constraints in addition to noise constraints, multiple realizations of a *Random* start model are recommended with the option *Allow invalid start model* enabled. The *Fill max* algorithm is not designed to handle other constraints than distance constraints.
- When the computation times are long due to either large WTG areas and/or many turbines to be placed, it is recommended to apply the option *Limit to grid points*. This often yields a good starting point in much shorter time, and the solutions can then be further optimized in a consequent step, e.g. using Mnaual startik.

8a.6.2 WTG Area import

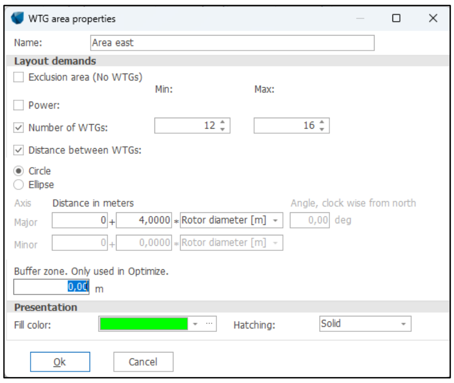
A convenient approach is to import pre-defined WTG Areas (cf. Figure 29**:** WTG area Import from file.) as shapefile format (*.shp*). Each feature of the shapefile a WTG area is handled separately for which properties can be defined, e.g., whether the area is an exclusion zone or a WTG area, the minimum and maximum number of WTGs to be placed, the minimum distance between WTG (cf. Figure 29). Moreover, a buffer zone can be specified (cf. Figure 30) for the optimization.


WTG area (WTG areas (18))

Areas (176)

Area west
Area east
Steepness threshold: 17.0°
Steepness threshold: 17.0°
Steepness threshold: 17.0°
Steepness threshold: 17.0°

Figure 29: *WTG area Import from file.*


WTG area properties

Name: Area east

Layout demands

□ Exclusion area (No WTGs)

	Min:	Max:
□ Power:		
☑ Number of WTGs:	12	16

☑ Distance between WTGs:

● Circle
○ Ellipse

Axis	Distance in meters			Angle, clock wise from north
Major	0 +	4,0000 *	Rotor diameter [m]	0,00 deg
Minor	0 +	0,0000 *	Rotor diameter [m]	

Buffer zone. Only used in Optimize.
0,00 m

Presentation

Fill color: 🟩 Hatching: Solid

Figure 30: *WTG area settings.*

The WTG area object handling is quite strict. In windPRO 4.0, WTG area intersections are not allowed, neither are features within features (so-called islands). If such features must be imported, it is necessary to use Geoinformation Systems to cut a part of the outer ring of the polygon feature (cf. Figure 31). An enhanced and user-friendly version of WTG area import is planned for future versions.

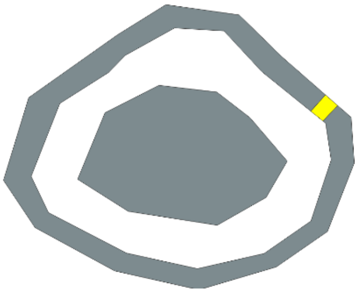


Figure 31: Feature within feature (island). The yellow part of the feature has been cut out of the outer ring and is handled as a third WTG area object. This prevents an intersection error message in the optimization.

8a.6.3 Example projects

Three sample projects are provided to show the range of utilities of the optimizer tool: a sample on-shore project, a sample off-shore project, and a sample project for the new noise curtailment optimizer.

The onshore sample project *Aparados da Serra.w41p* provides a variety of optimization scenarios. These include runs with AEP, LCOE and NPV objectives, runs with different constraints and on different WTG area structures. Lastly, it shows a performance comparison for different turbine types and a performance comparison for different optimization configurations.

The offshore sample *Cost model offshore.w41p* showcases the new option of including cost maps in the cost set-up that can be used to represent a whole variety of costs, e.g., bathymetry-based costs, soil structure foundation costs, or travel costs.

The noise curtailment *Curtailment optimizer demo project.w41p* shows how a non-compliant wind farm layout can be made compliant with noise regulations while still obtaining the maximum possible energy yield from optimal curtailment strategies.

8a.7 References

[1] A. P. J. Stanley, O. Roberts, J. King, and C. J. Bay, “Objective and algorithm considerations when optimizing the number and placement of turbines in a wind power plant,” *Wind Energy Sci.*, vol. 6, no. 5, pp. 1143–1167, 2021, doi: 10.5194/wes-6-1143-2021.

[2] T. Rubert, D. McMillan, and P. Niewczas, “A decision support tool to assist with lifetime extension of wind turbines,” *Renew. Energy*, vol. 120, pp. 423–433, 2018, doi: 10.1016/j.renene.2017.12.064.

[3] W. Short, D. J. Packey, and T. Holt, “A manual for the economic evaluation of energy efficiency and renewable energy technologies,” 1995. doi: NREL/TP-462-5173.