Add-on Module:

Blockage Effect

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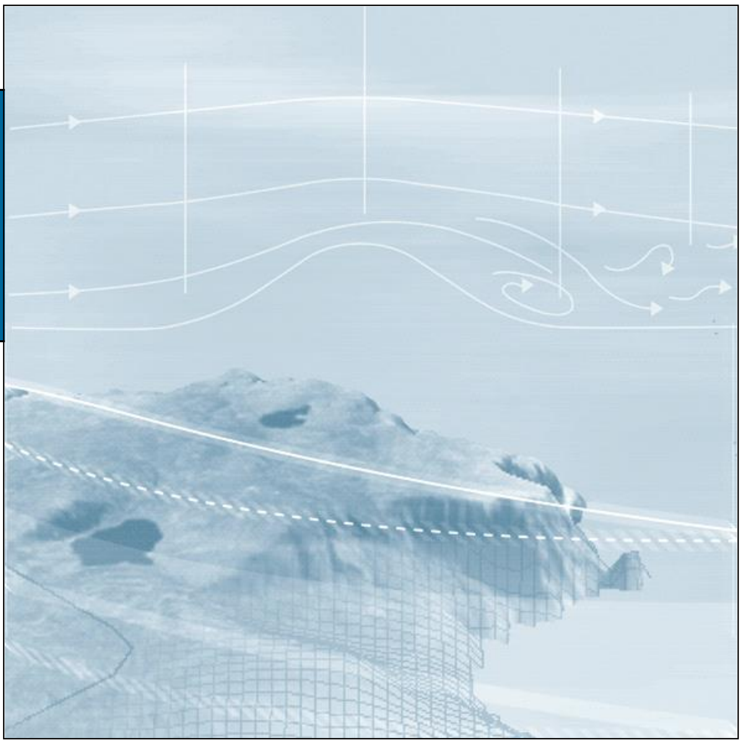

WindSim | Blockage Effect

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WindSim 11

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With *WindSim* 11 we provide the possibility to account for the interaction between turbines of a wind farm and the surrounding wind field. With the new implementation this interaction is not only considered downstream in terms of wakes but also upstream where it is expected to find a loss in windspeed due to the existence of the wind farm itself. This collective effect of blockage in front of the wind farm has been investigated in *WindSim* extensively. In order to take these effects into account a model embedded in *WindSim's* Wind Resources and Energy module was developed. On the one hand a lowering of the complete wind speed within the blocked area is expected but on the other hand a speed up is assumed in the regime lateral to the wind farm. Both effects can be described with the *WindSim* software.

The whole calculation is based on the so-called actuator disc (AD) model, where the turbine is modeled as a porous obstacle in the CFD simulation. The introduction of actuator discs therefore provides the inclusion of turbine-wind field as well as wind farm-wind field interaction. One main difficulty here is that these effects are highly dependent on the incoming windspeed level, which is solved via interpolation based on two wind speed simulations.

Additionally, *WindSim* developed a combined model where the blockage effect is deducted from the actuator disc calculation but the wake is taken into account via one of the three analytical wake models available in *WindSim*. In this way it is possible to obtain an estimation for the bias of the corresponding wakes-only model and the extent of the blockage effect at once. The procedure to obtain best possible predictions for available Wind Resources and AEP's can be split into two parts, the setup in which the underlying input data for the *Blockage Effect* calculation is prepared and the evaluation part where the *Blockage Model* can be applied to the Wind Resources or the Energy module separately.

Setup

The setup part is based on four separate wind field projects, two freestream calculations (without AD) and two calculations including the AD, with a high and a low wind speed scenario for both.

These four projects have to be based on one common grid determined by the AD calculation. Due to the need of resolving the rotor area properly, the actuator disc model automatically generates a refined grid that should be used also for the default *WindSim* projects without AD. In order to present the *WindSim* output for the blockage effect calculation an example calculation is used throughout this document. The exemplary windfarm consists of an extremely dense layout with 6x6 turbines (Figure 1).

In order to set up the grid for the AD calculation the objects file (**.ows*) defining the turbine positions and some other turbine characteristics is needed. This file can also be exported from the Objects module of a usual *WindSim* project (*Tools → Export Objects (.ows)…).* In the AD calculation this file has to be reloaded in the Terrain module in order to create a refined grid in the area where the turbines are located (see Figure 1).

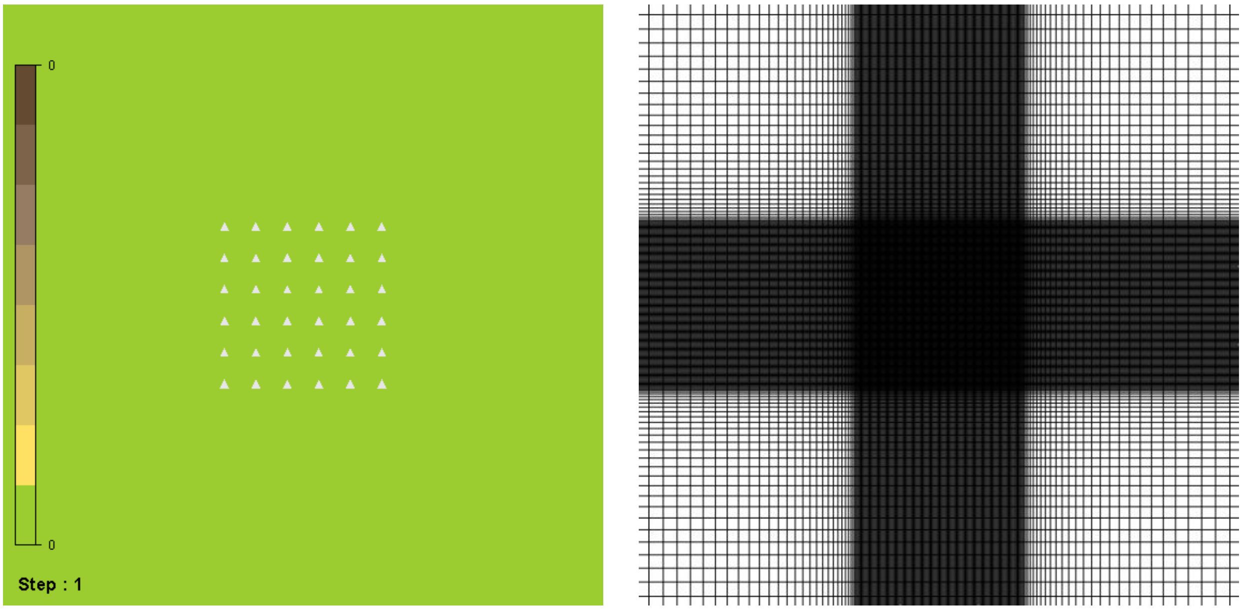


Figure 1: Shown is an exemplary Wind farm on the left hand side and the corresponding grid. In the area where the turbines are located the grid is refines automatically for the AD calculation.

After running the Terrain module for the AD you can find the blockage file *actuator_discs.bws* in the dtm folder of your project. This file defines the underlying refined grid and has to be used as *refinement file* in the Terrain module of the default calculations without AD as well. In this step we recommend to rename the file *actuator_discs.bws,* e.g. *refinement.bws.*

After the Terrain module is finished for both cases (with and without AD) you can make a copy of both projects to end up with four *WindSim* projects representing the following simulations:

1. Default project with high wind speed
2. Default project with low wind speed
3. Actuator Disc project with high wind speed
4. Actuator Disc project with low wind speed

For that you have to choose two wind speed representatives for a high and a low wind speed regime which are used as input (*speed above boundary layer height*) in the *Wind Field* calculation of *WindSim*. For example 20 and 7m/s at 500m boundary layer height leading to approximately 17 and 6m/s wind speed at hub height level (120m).

So in the first step these four *WindSim* projects for the *Terrain* and the *Wind Fields* module has to be created and run. Make sure that all projects in the *Wind Fields* calculation have exactly the same input parameters except for the speed above boundary layer height.

For the blockage effect calculation affecting only the *Wind Resources* and the *Energy* module one then has to choose a working project. This project has to be a project without AD and can be either one of the two from above or an additional one with intermediate wind speed. Here one can create an extra Layout for the *Blockage Effect* calculation, since the working project can contain Layouts including the *Blockage Effect Model as well as default Layouts concurrently.* Afterwards the *Objects* module should be run. The turbines can be added with the *objects file* from above (*Tools* → *Import Objects (.ows)…).* The available climatologies can be loaded as usual.

In order to initiate the blockage calculation one has to specify the path of the four underlying projects that has been already prepared. That is simply done by creating a text file called *blockage_effect.log* which contains the corresponding paths in the order as shown in Figure 2. Remember to always keep the right order since *WindSim* can only differentiate between the files due to this order. Remember to always end your path with a backslash otherwise an error will appear.

Figure 2: In order to initiate the Blockage Effect calculation a file as shown here has to be added to the log folder of the Layout where the calculation should be run. Note to keep the right order here.

Once the *blockage_effect.log* file is placed in the log folder of your Layout (*\log\blockage_effect.log*) the blockage calculation is automatically initialized.

Implementation

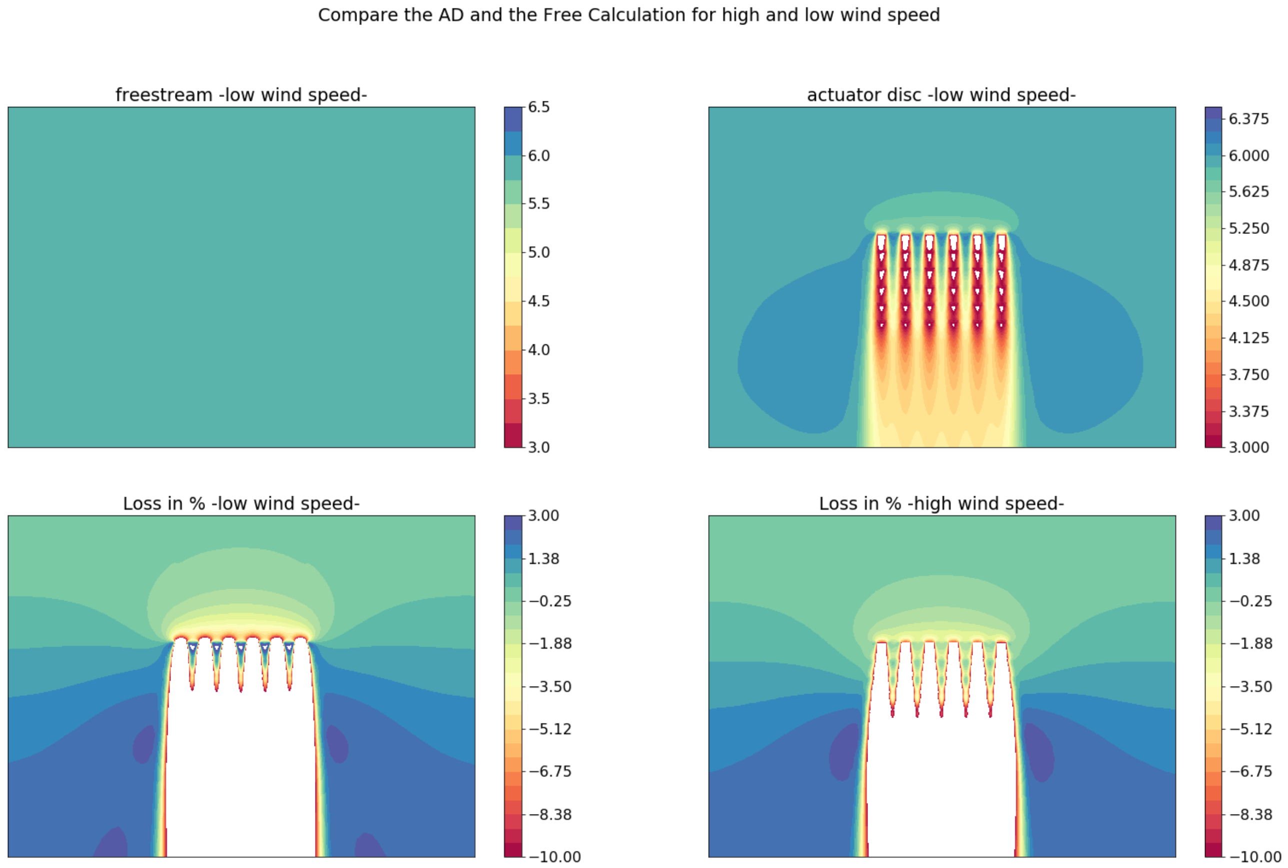
In the current implementation the blockage effect calculation in *WindSim* provides results based on an actuator disc approach as well as a combined approach where the wake is taken into account by an analytical wake model (Model A and B below).

From the basic projects (1-4) the influence of the existing turbines on the wind field is approximated. This is done by investigating the percentage change of the wind field as shown in Figure 3. In the upper left picture the absolute value of the 2d wind speed at hub height level v_{free} is shown for the free calculation without AD. On the upper right picture the equivalent results for the AD calculation v_{AD} is shown. Both calculations are based on a low wind speed above boundary layer (e.g. 7m/s above 500m).

In the lower left plot the resulting percentage wind speed loss

$$D = (v_{AD} - v_{free})/v_{free}$$

is depicted for the low wind speed scenario whereas the right plot shows the equivalent result for the high speed case (e.g. 20m/s above 500m).



and a low speed (lower left) consideration the speed loss can be included depending on the incoming wind speed.

As one can see from Figure 3, the reduced wind speed area in front of the wind farm, making the blockage effect visible, is highly dependent on the incoming wind speed level. With the consideration of two different wind speed levels it is therefore possible to perform an interpolation and take the speed dependence of the blockage effect into account.

In this context a simple linear interpolation is applied as shown in Figure 4. Instead of calculating the resulting percentage speed loss for every speed bin, an interpolation between the low and the high wind speed is done.

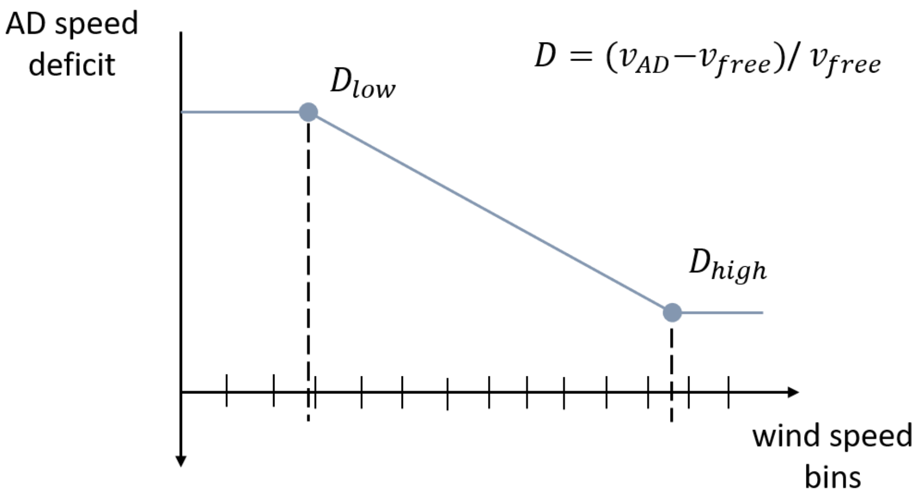


Figure 4: Represented is a sketch of the interpolation scheme applied to the speed deficit of an AD calculation compared to a default run.

Based on the results of your working project (without AD) these speed deficit factors are applied to correct the speeds due to the *Blockage Effect* as well as wake effects (only for Model A). This is done in two ways in *WindSim:*

A. Combine the AD calculation with freestream results
B. Combine the AD calculation with freestream results to estimate the blockage effect and apply wakes by an analytical wake model

The first possibility extracts the blockage as well as the wake effects from the actuator disc calculation, whereas the second approach employs the blockage effect from the actuator disc calculation but still applies an analytical wake model to the reduced wind field at turbine position. In particular, this is interesting in comparison to a calculation without *Blockage Effect* correction. The difference in these results serves as a measure for the extent of the *Blockage Effect*.

The basis of both models is a freestream calculation that is used to scale the wind field against present climatologies. The blockage and wake effects are taken into account in terms of the speed reuction factors as shown above.

Upfront Parameter

For the energy production and the analytical wake models the speed deficit as described is especially important at the positions of the turbines. Here, one runs into a problem regarding the actuator disc approach on which the *Blockage Effect* calculation is based. The wind speed at turbine position cannot be used as a representative input to the power curve in this approach. This is because the actuator disc is now representing a real obstacle, directly interacting with the wind field and highly influencing it. The *WindSim* software solves this problem by using the wind speed somewhat in front of the turbine instead of directly at the turbine position. This approach is connected to a parameter d_{up} that specifies the distance between the turbine position and the location where the wind speed is extracted from (see Figure 5).

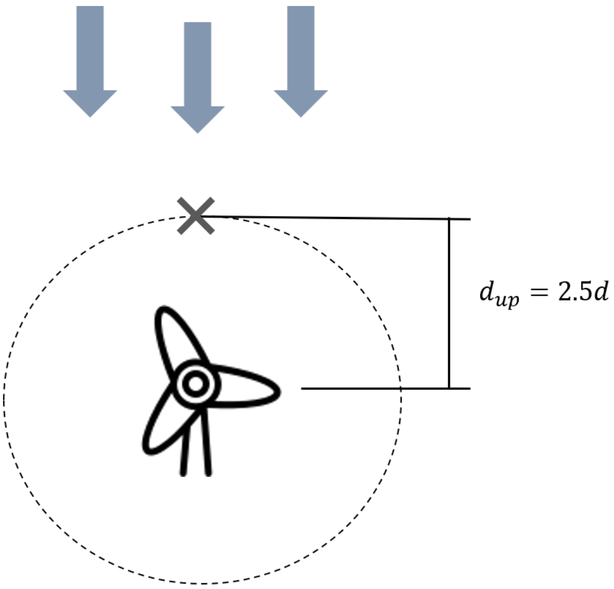


Figure 5: The location where the windspeed is evaluated is shown.

In the current implementation this upfront value is set to $d_{up} = 2.5d$ by default with d being the rotor diameter of the turbine. The introduction of d_{up} therefore overcomes the shortcomings of the AD model.

Considering a turbine in isolation, the reduced wind field in front of this turbine is mostly already taken into account by the power curve. With an appropriate upfront parameter one can therefore avoid to overestimate the *Blockage Effect* in the resulting AEP's. The upfront parameter can therefore be used in order to evaluate the wind speed at the same location as where the power curve has been measured, here a distance of $2.5d$ is recommended (IEC 61400-12-1:2005-12).

In fact, when the wind speed at the turbine position is needed for the calculation we evaluate the wind speed $2.5d$ upfront. This is also the case for the interpolated wind speed reduction described in the last section.

By adding a line in the *blockage_effect.log* file with the keyword 'upfront parameter' and a colon in column 20 as usual for WindSim parameters this upfront parameter is accessible for the user. For instance with the additional line “upfront parameter : 1.5” the upfront parameter can be set to 1.5 rotor diameters. This can make sense in special cases but is generally not recommended.

Two Approaches including the Blockage Effect

The basis of both Model A and Model B is a wind speed reduction table containing the interpolated results of the wind speed loss $(v_{free} - v_{AD})/v_{free}$ at the positions d_{up} in front of the turbines.

Model A

For Model A this table is stored in the file *object_4_‘wec’_AD_int_‘clim’.blws* in the object folder of the corresponding Layout for every turbine ‘*wec’ and every climatology ‘clim’.* As in every standard *WindSim* project a sector interpolation is done for every climatology in order to obtain a sector representation at the climatology point (see *WindSim* description pages). This interpolation is done for the speed reduction as well for which reason there is also one speed reduction file per climatology *clim*. These factors are applied to the normal speed from the working project as shown in the figure below. They include blockage as well as wake effects. Note that this procedure is done for all sectors and all speed bins.

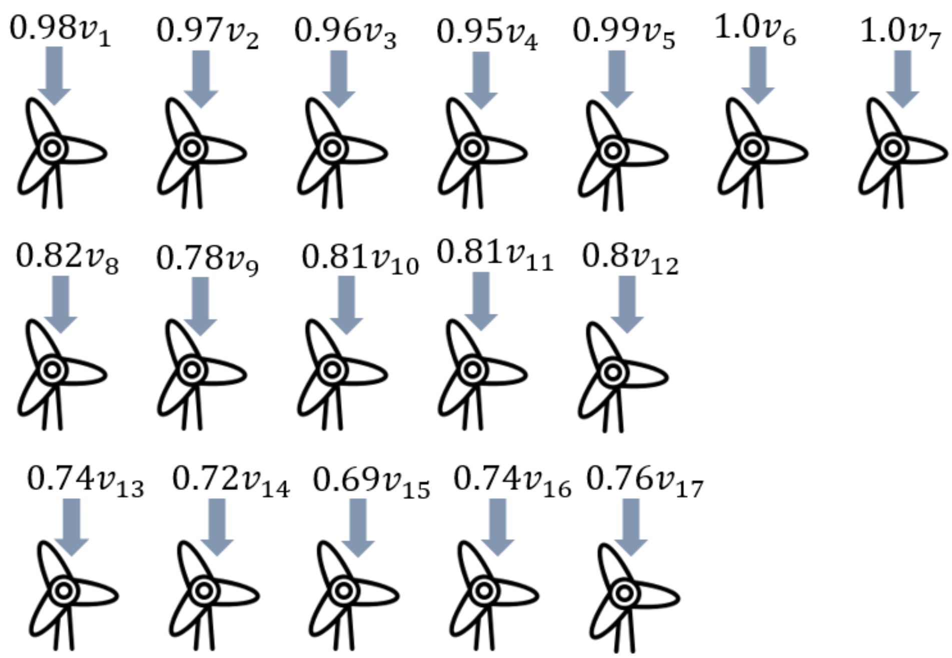


Figure 6: Shown is an example of how the reduced incoming wind is taken into aacount in Model A.

Model B

In contrary to Model A the speed reduction within Model B is handled in a different way. The idea is to decouple the blockage effect from the wake effects of the actuator disc calculation and apply an analytical wake model.

For the following procedure one has to decide which turbines are waking and which turbines are waked. This is already based on the analytical wake model you have chosen in the *WindSim* GUI. The wind speed reduction for turbines that are not waked but waking (blockage turbines in green) are used to calculate an average blockage reduction since they are not affected by wake. This average value is then applied to the inner turbines (marked as yellow in the Figure 7).

The resulting wind speed reduction only including the *Blockage Effect* is analogically written to the file *object_4_'wec'_all_int_'clim'.blws* in the objects folder of your project Layout for every turbine 'wec' and climatology 'clim'. The data therein is additionally sector as well as bin dependent.

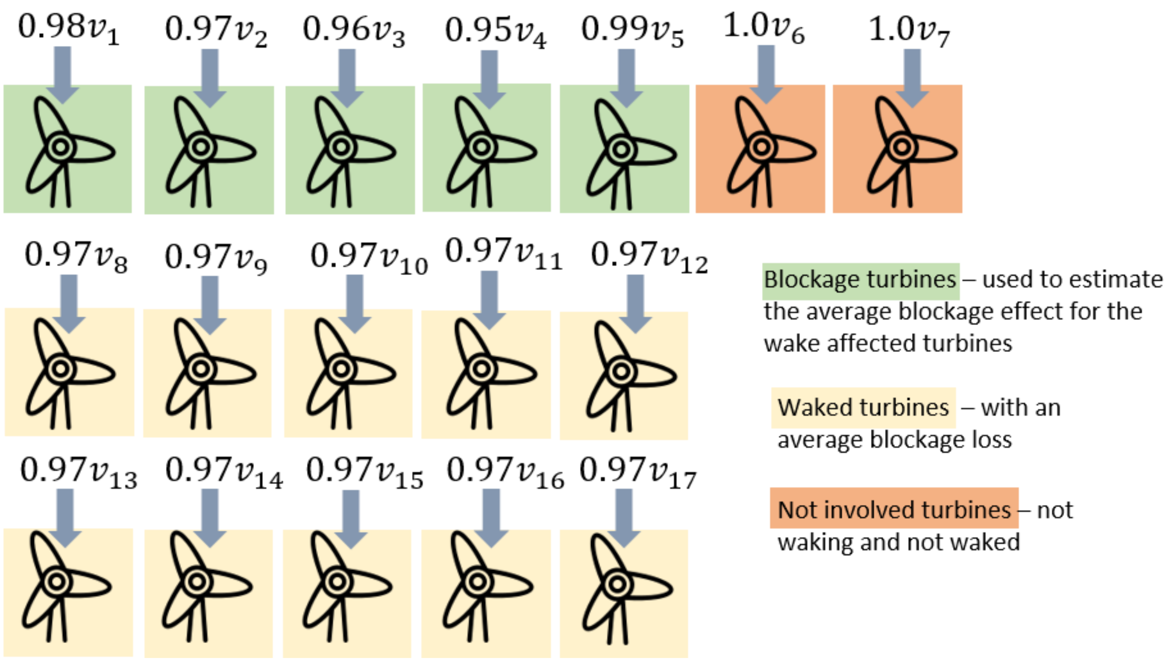


Figure 7: Shown is how the wind speed reduction factor is applied in Model B in order to take an collective Blockage Effect into account but exclude wake effects. In order to decouple the blockage effect and add an analytical wake model it is decided which turbine is waking but not waked (green). On the basis of the speed deficit for those turbines an average loss is determined for the turbines in the center of the wind farm (yellow).

Since we do not assume any wake for the front turbines, the reduced wind speed factors for the blockage turbines remain the same (compare Figure 6 and Figure 7). This reduced wind speeds are finally used as input for the analytical wake calculation that is now set on top of the consideration of Model B. The blockage effect for not involved turbines (not waking and not waked) is assumed to be zero why the corresponding weighting factors are set to 1 in Figure 7.

Eventually we end up with two models for the energy production, both including blockage and wake effects. In contrast to Model A, Model B is suitable to compare with a calculation where the wind speed reduction factors are set to zero (=no reduction), which is equivalent to a standard wake calculation with *WindSim*. The difference finally gives access to the bias of a wakes-only consideration due to the *Blockage Effect*.

Evaluation

Results Module

In the Results module everything works quite the same as in a standard *WindSim* project except for the fact that *WindSim* automatically produces additional plots showing the basis of the blockage effect calculation. Here two kind of pictures are generated showing the speed reduction loss $D = (v_{AD} - v_{free})/v_{free}$ in percent for the high and the low level input speed. These images are represented by the *WindSim* gui as shown in Figure 8 for the low speed level case.

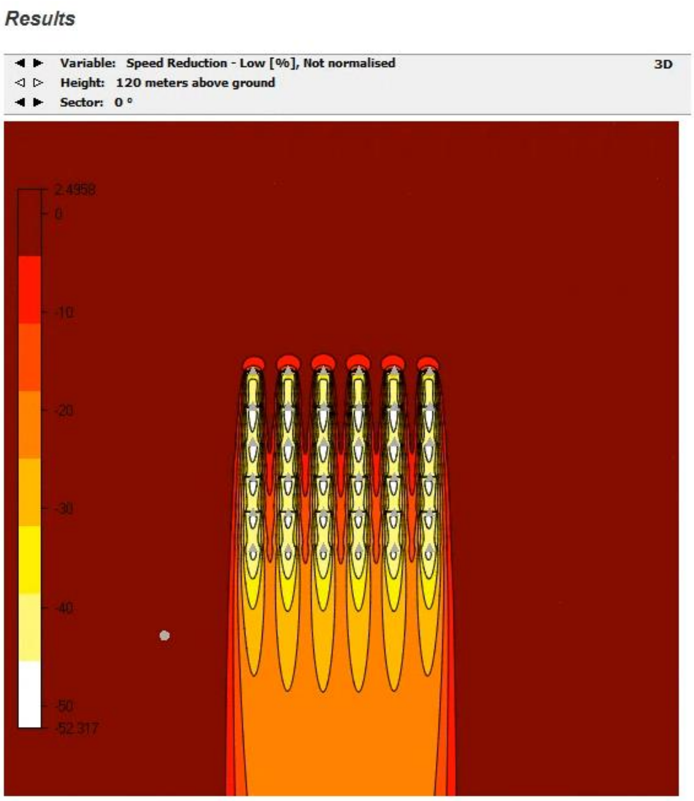


Figure 8: Shown is the Speed Reduction in percent for the low speed level as generated in the Results module by the WindSim gui.

Wind Resources Module

In the Wind Resources module the output of the Mean wind speed 2D, the Power density as well as the Mean ambient Turbulence Intensity is connected to your current working project. Currently, only the *Wake deficit* and the *Mean wind Speed 2D – wake deficit* output is connected to the *Blockage Effect* calculation of Model A. The wake deficit that is shown here include the blockage as well as wake deficits as calculated with the AD in Model A. It could be interpreted as the wakes seen by the actuator disc and interpolated to every wind speed bin.

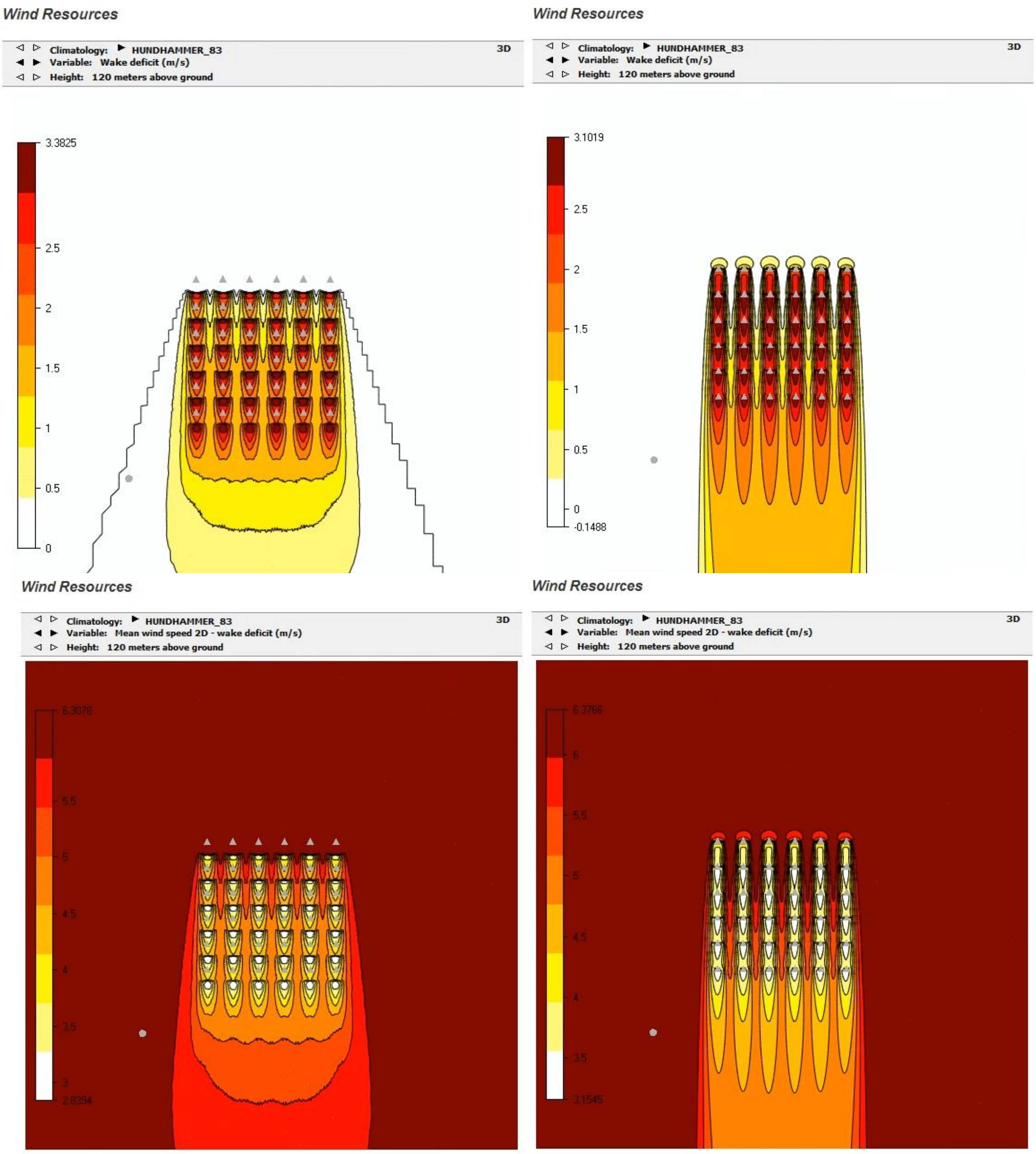


Figure 9: On the right hand side the wake deficit and the (mean speed-wake deficit) are shown as they are obtained in the Blockage Effect calculation of WindSim. For comparison the same results are represented on the left hand side for an default WindSim project (Wake Model 1).

The resulting images taken from the example project of the JIP are represented on the right hand of Figure 9. On the left hand side the corresponding results of the underlying working project are shown without *Blockage Effect* calculation. These results are obtained if the file *blockage_effect.log* is not present in the log folder and the Blockage Effect calculation is consequently not initialized.

Note that for simplicity a test climatology was used that only includes wind coming from the north (see Figure 10).

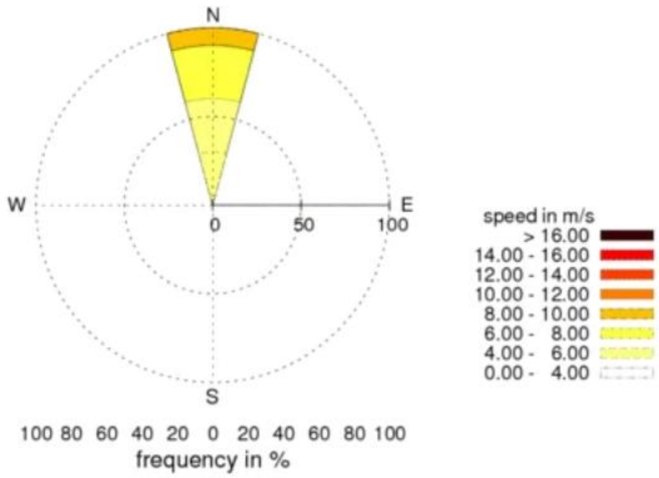


Figure 10: For simplicity the climatology on which the Wind Resources of Figure 9 are based only includes wind speeds for sector 0.

This climatology is chosen to make the comparison and the understanding of the images shown in the *Wind Resources* module easier (Figure 9). On the other hand it has to be mentioned that it represents an artificial extreme case where the output does not represent realistic circumstances, this is the same regarding the *Energy* module.

Energy Module

The current implementation of the *Blockage Effect* calculation will result in three different numbers for the AEP, as shown in Figure 11.

Once you have initialized the blockage effect calculation you will automatically obtain the wake losses based on three different models, the first column *Wake Loss %* gives the analytical wake loss. This is just the same as you would have for a default *WindSim* project and corresponds to the result of your underlying working project.

The second column *Wake loss including blockage effect %* corresponds to Model B and contains the wake loss which is calculated by the analytical wake model when it sees a decrease in wind speed in the first row of the turbines and assumes an average decrease for the following rows due to a blocking by the wind farm. Note that the choice of the analytical wake model can differ for the *Wind Resources* and the *Energy* module. The wake calculations are executed separately for every module.

The last column *Wake loss calculated by the actuator disc %* is referring to the procedure from Model A.

In contrary to the other results, the result from Model A does not include an analytical wake model at all. The advantage of the other models is that they can be compared reasonably and therefore give the possibility to quantify the impact of the blockage effect. It is important to understand that the number given as *Wake Loss %* is equal to the number of *Wake loss including blockage effect %* for the case that all speed reduction factors as depicted in Figure 6 and Figure 7 are equal to zero. The difference of these two numbers therefore provides a measure for the influence of the *Blockage Effect to the AEP.*

By the combination of actuator disc (AD) calculations with analytical wake models it is therefore possible to decouple the influence of the blockage effect.

Annual Energy Production AEP

Energy production has been calculated for the following climatologies:

Climatology	Distribution	AEP with wake losses	Wake loss %	Wake loss including blockage effect %	Wake loss calculated by actuator disc %
TestClimatolog..	Frequency table	**43.8573**	71.52	73.08	73.99
TestClimatolog..	Weibull distribution	**48.7583**	67.32	69.08	69.67

Table 1. Energy production in GWh/y based on climatology represented as frequency table, Weibull distribution and time series (time series are calculated only if power history and IEC classification are active, note that missing values in the time series are treated as 0 speed values in the production calculation).

Air density (kg/m^3)	Wake model	Multi-wakes model	Roughness (m)	Amb. Turb. Int. (%)	Sub-sectors	Influence range (Rotor diameter)
No correction	1	2	Variable	-	30	1.0 - 50.0

Table 2. Site and wake characteristics.

Figure 11: Represented is an example output of the energy module in WindSim. If the blockage calculation was properly executed, three numbers connected to the AEP's are given. The first column is identical to the AEP output of your working project.

Due to the artificial climatology and dense layout we obtain unrealistic high wake losses and the difference in the three calculation procedures is emphasized.