



1st WindSim Americas User Meeting

4 December 2014, Orlando

AEP Optimization

PRESENTED BY: ARNE R. GRAVDAHL, CTO

windsim

Content

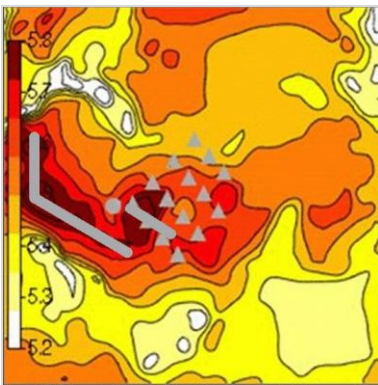
- Introduction
 - Value proposition
 - Software used
 - Optimization teaser – Winddoku
- Park Optimizer
 - How it works
 - Example – Optimization of Net Present Value (NPV)
- Downscaling reanalysis data
 - Downscaling MERRA
 - Downscaling Virtual Met Masts
 - Summary
- AEP optimization based on reanalysis data
 - Sites and setup
 - Optimization results
 - Summary

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Value proposition – Designing profitable wind farms

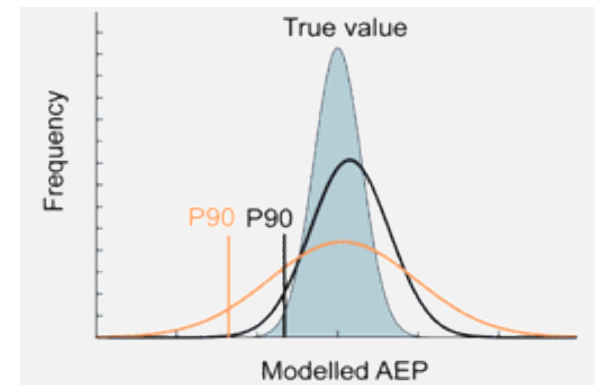
- To increase the power production from wind turbines through optimal placement and operation by means of wind modeling
 - Increased Annual Energy Production, AEP
 - Reduced maintenance costs
 - Better financing, higher P90



10% AEP increase (Torrild, Denmark, 2002)

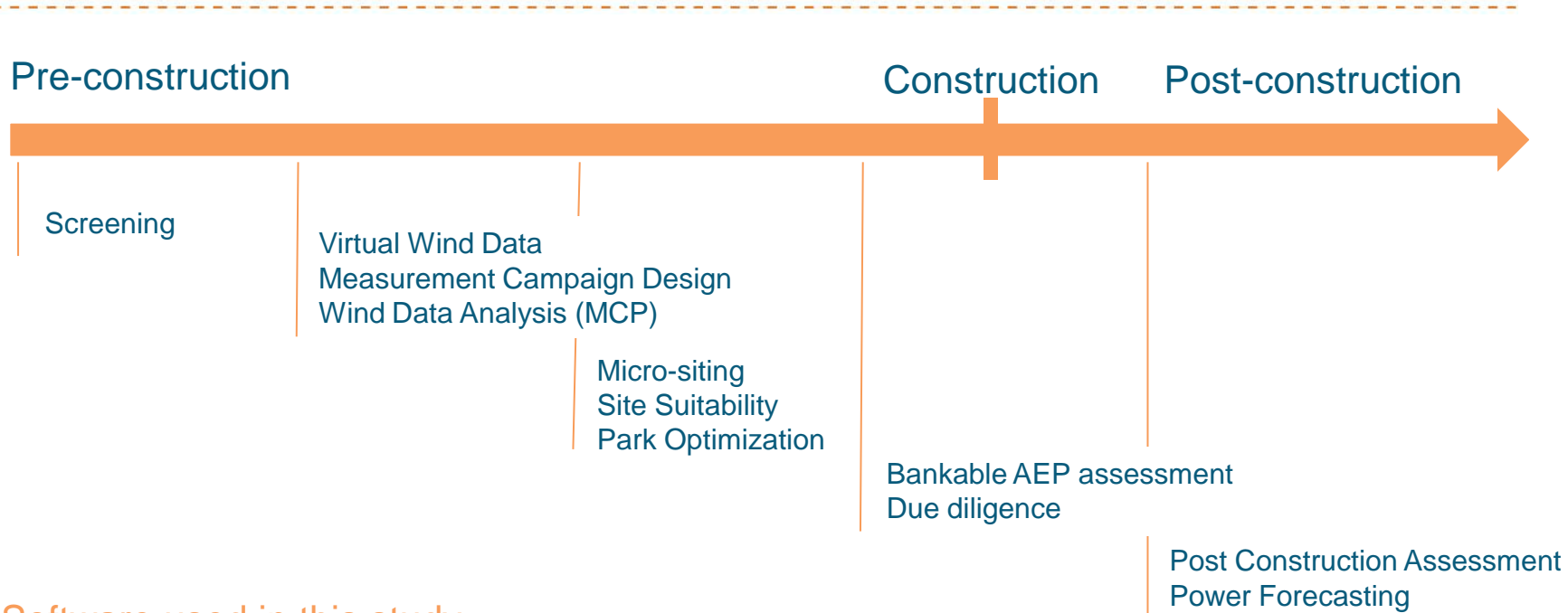
Name	Inflow in %	Turbulence in %	Inflow in m ³	Slip inflow in %	Slip turbulence in %
100000000_100	17.8	18.8	-8.9	2.8	2.8
100000000_200	17.8	18.8	-8.4	2.8	1.8
100000000_300	20.7	22.7	-8.9	3.5	1.8
100000000_400	20.8	23.1	-7.1	2.8	2.3
100000000_500	18.2	14.1	-8.7	3.4	1.1
100000000_600	16.2	16.1	-11.1	2.7	4.8
100000000_700	19.2	19.1	5.8	4.0	4.8
100000000_800	4.3	41.1	1.3	3.8	2.8
100000000_900	17.1	15.8	-3.8	1.9	2.1
100000000_1000	14.8	16.4	-8.2	2.8	1.1
100000000_1100	18.8	22.7	8.7	4.0	8.7
100000000_1200	18.3	22.2	8.9	3.4	1.8
100000000_1300	18.8	22.7	7.3	2.2	1.8
100000000_1400	18.8	21.8	6.1	1.8	1.1
100000000_1500	18.4	21.8	4.8	6.8	1.1
100000000_1600	18.8	21.4	7.7	1.2	1.8
100000000_1700	18.8	21.8	4.1	1.3	1.4
100000000_1800	18.8	21.1	4.8	1.4	1.8
100000000_1900	18.4	20.1	8.8	1.7	8.8

Correlations; Production log – inflow and turbulence (Chieti, Italy, 2005)

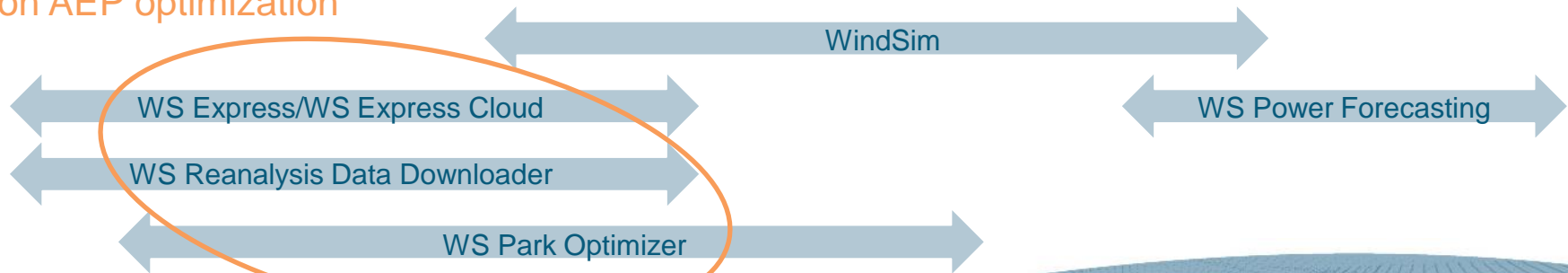


Financiers might ask for CFD, but in general the uncertainties is set by consultants according to their experience

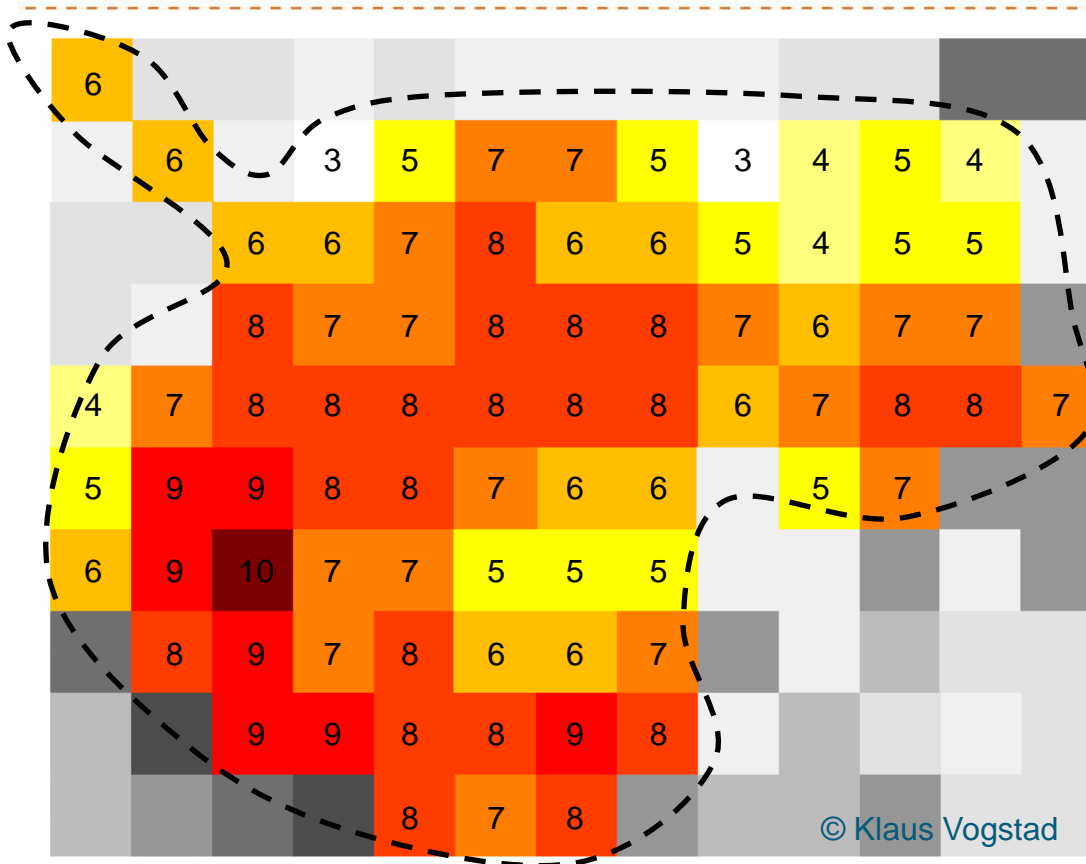
Software Suite – Wind project time span



Software used in this study on AEP optimization



Park Optimization: Design the most profitable layout



The wind varies within the wind farm area due to terrain and roughness variations.

Your task is to position 10 turbines in order to maximize the wind farm production.

To reduce the wake effects, the turbines must be separated by a minimum distance of two cells in the horizontal, vertical and diagonal directions.

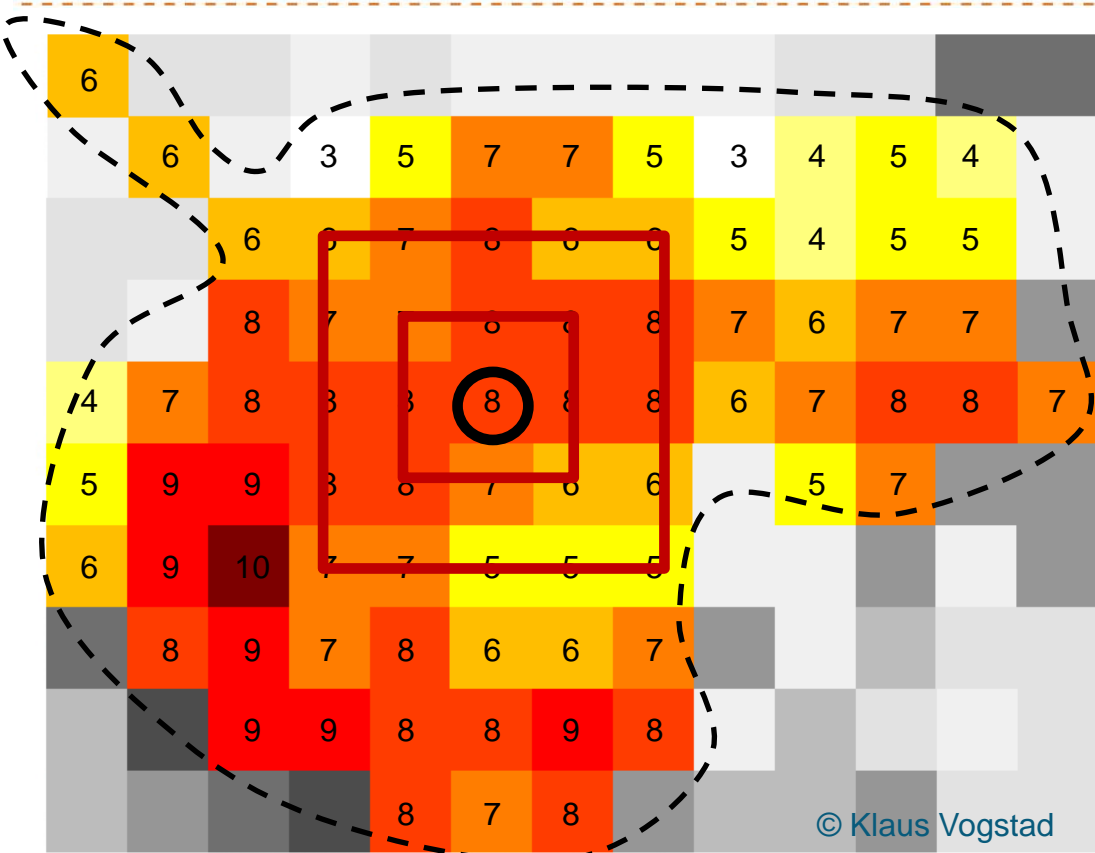
Try different locations to maximize your total score.

Wind resource map with annual mean wind speeds (m/s)

Turbine	1	2	3	4	5	6	7	8	9	10	Total
Wind speed											

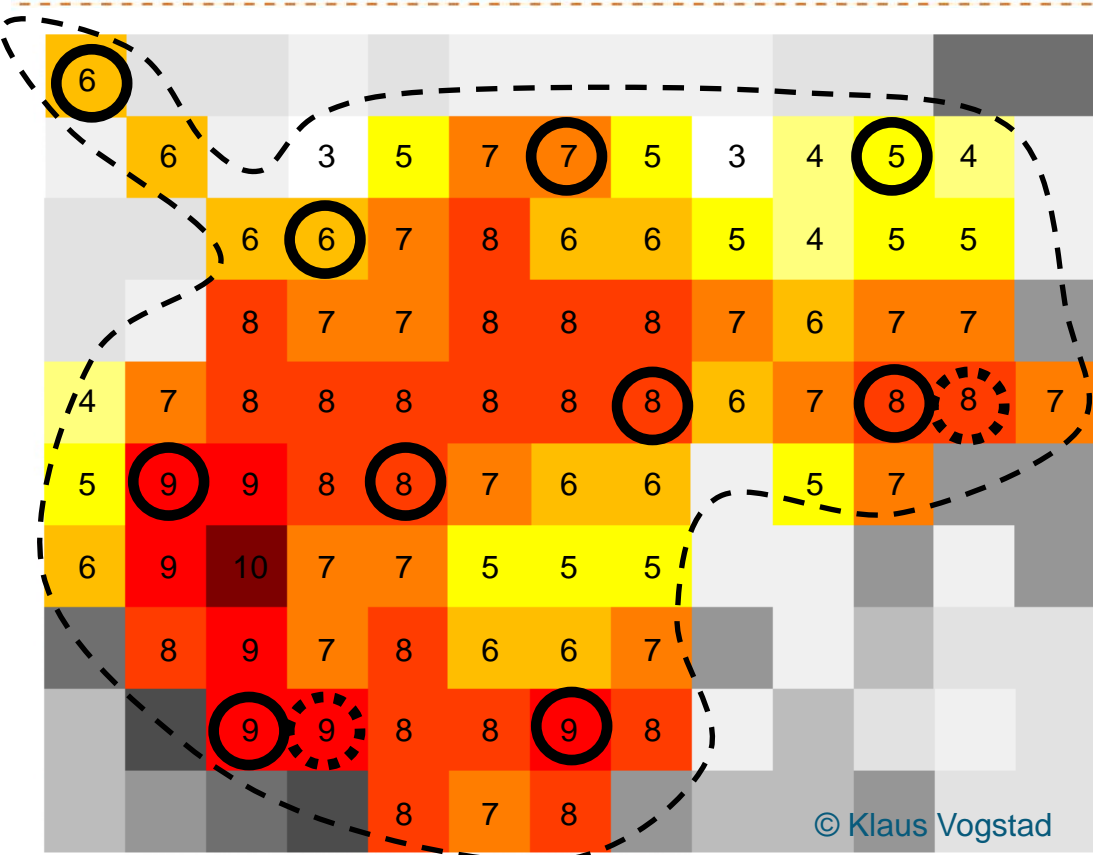
Courtesy of Klaus Vogstad

Park Optimization: Invalid positions



Wind resource map with annual mean wind speeds (m/s)

Park Optimization: Best score -75 points



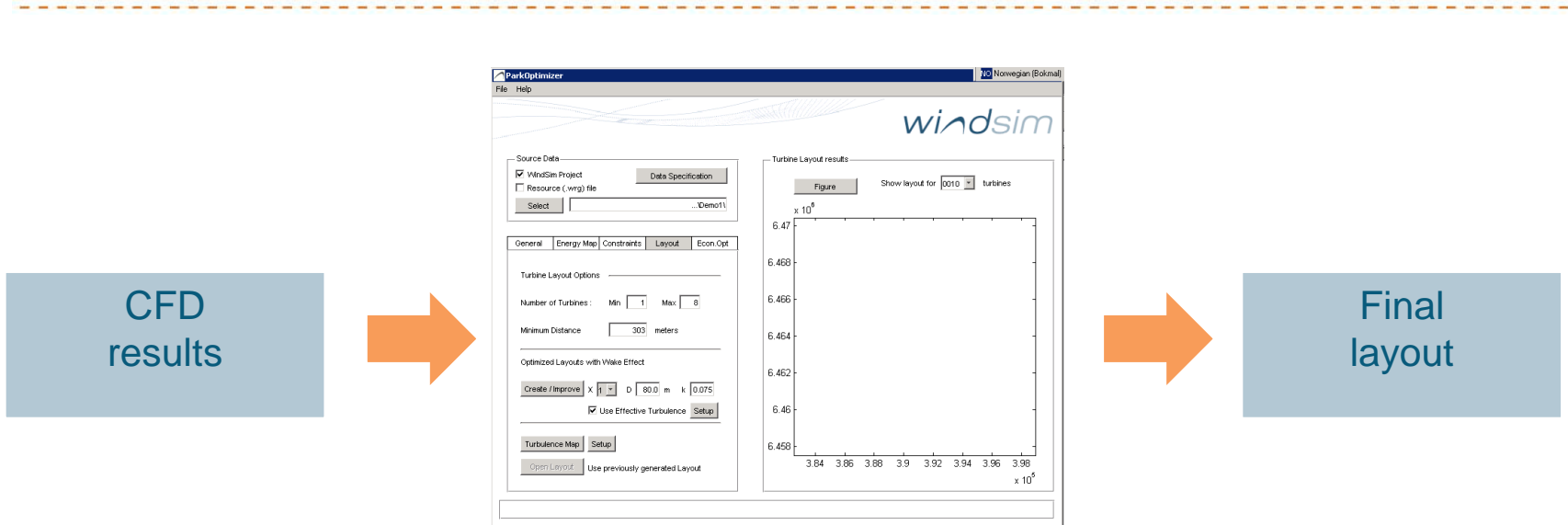
Wind resource map with annual mean wind speeds (m/s)

Turbine	1	2	3	4	5	6	7	8	9	10	Total
Wind speed	5	6	6	7	8	8	8	8	9	9	75

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Layout Optimization: Park Optimizer



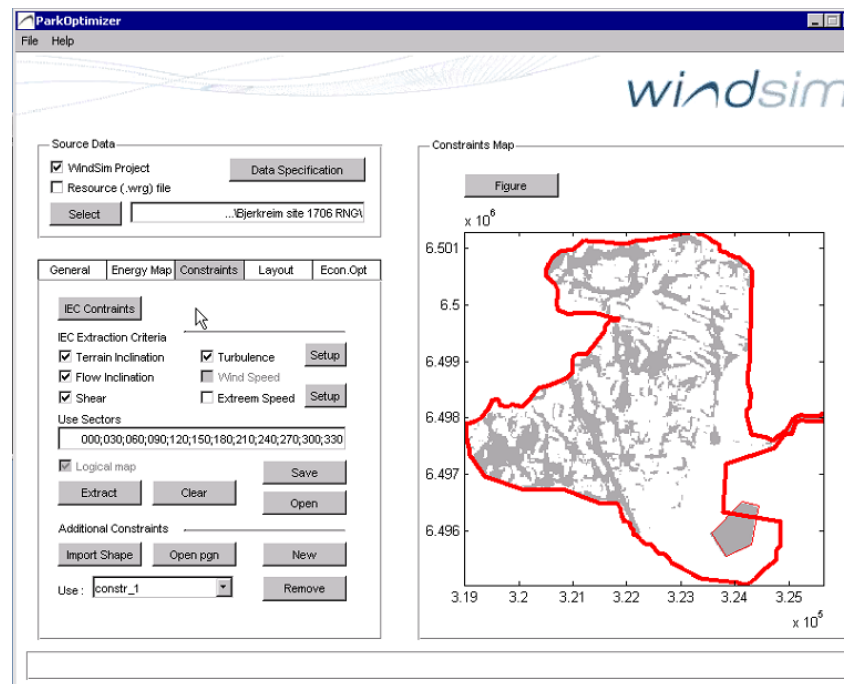
- 1 Project constraints
- 2 IEC compliance
- 3 Optimize turbine layout
- 4 Optimize size

Webinar recording Park Optimizer: <https://www.youtube.com/watch?v=0gsMszUEXaUC>

Layout Optimization: Project constraints

1) Project constraints:

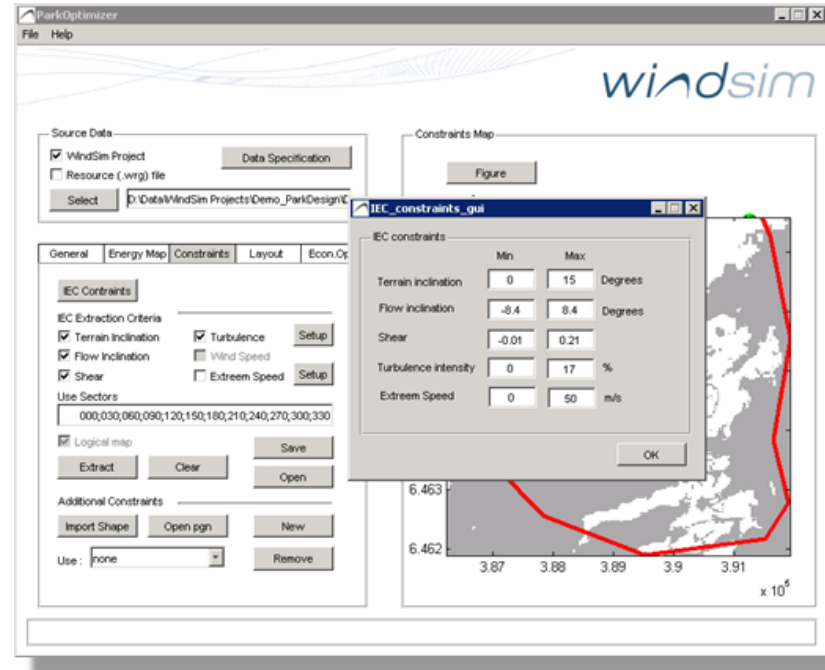
Exclusion of areas where it is not possible to set up turbines e.g. natural reserves, roads etc. Easy definition via shape files which can be loaded into the PO



Layout Optimization: IEC compliance

2) IEC Compliance:

- Shear
- Flow inclination
- Turbulence
- Extreme wind
- Terrain inclination



Layout Optimization: IEC compliance

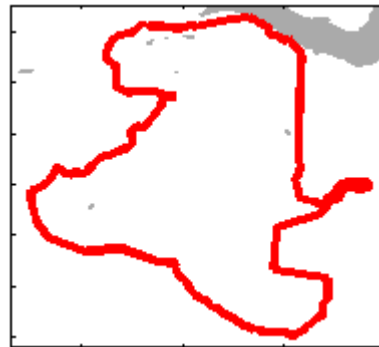
Terrain inclination



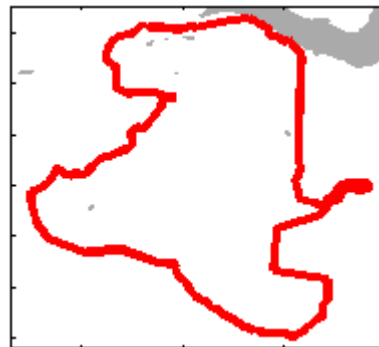
Shear



Flow Inclination



Extreme wind



TI

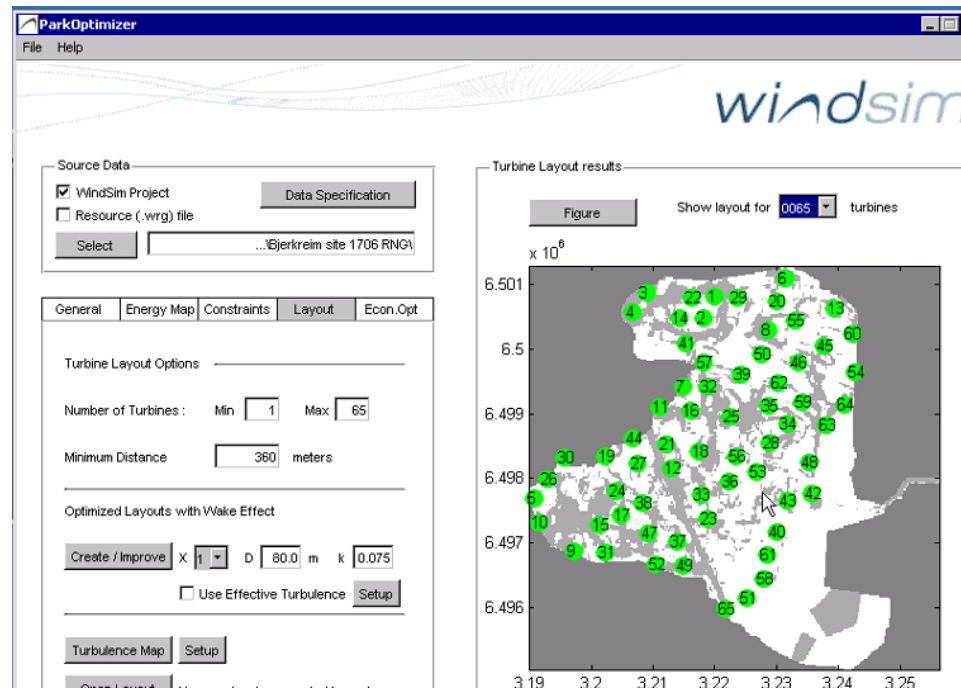


Total



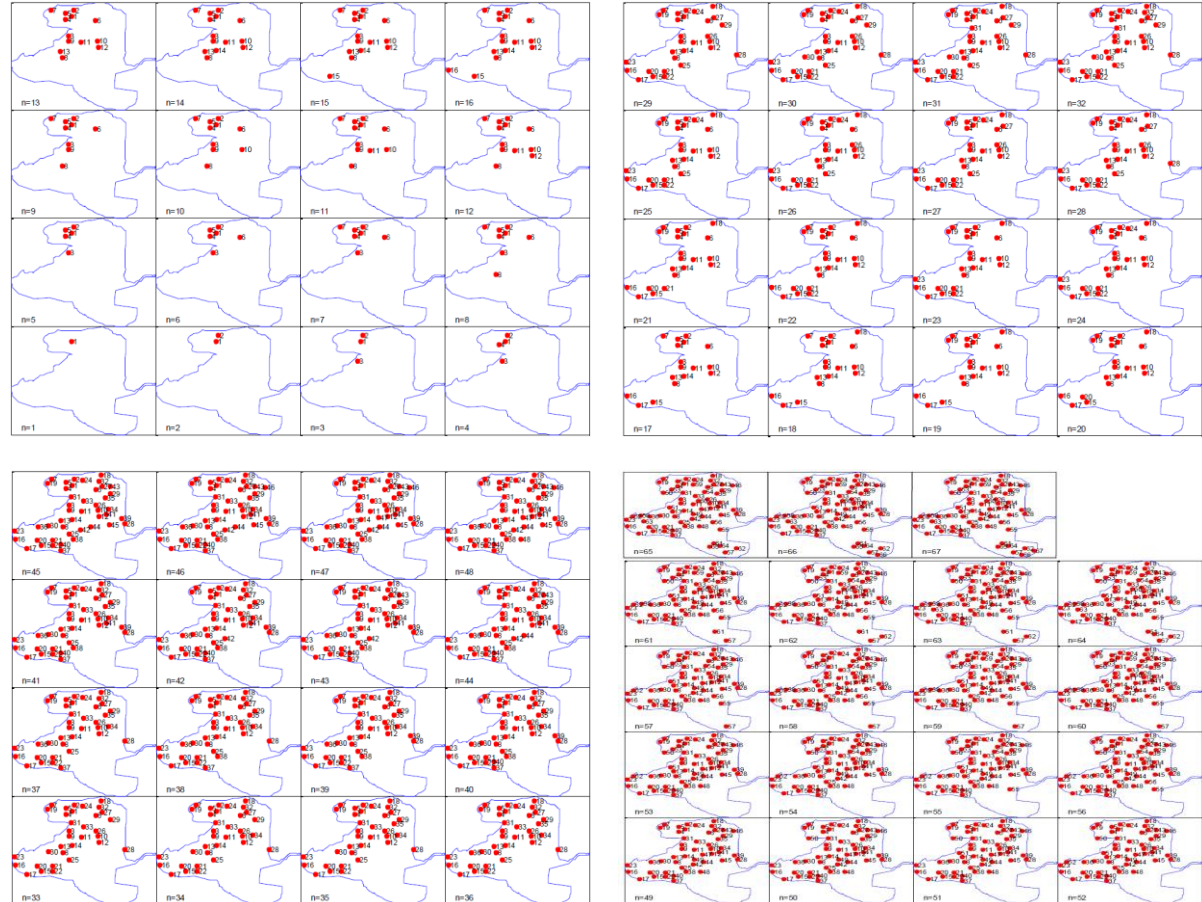
Layout Optimization: Optimize turbine layout

3) Optimize turbine layout:



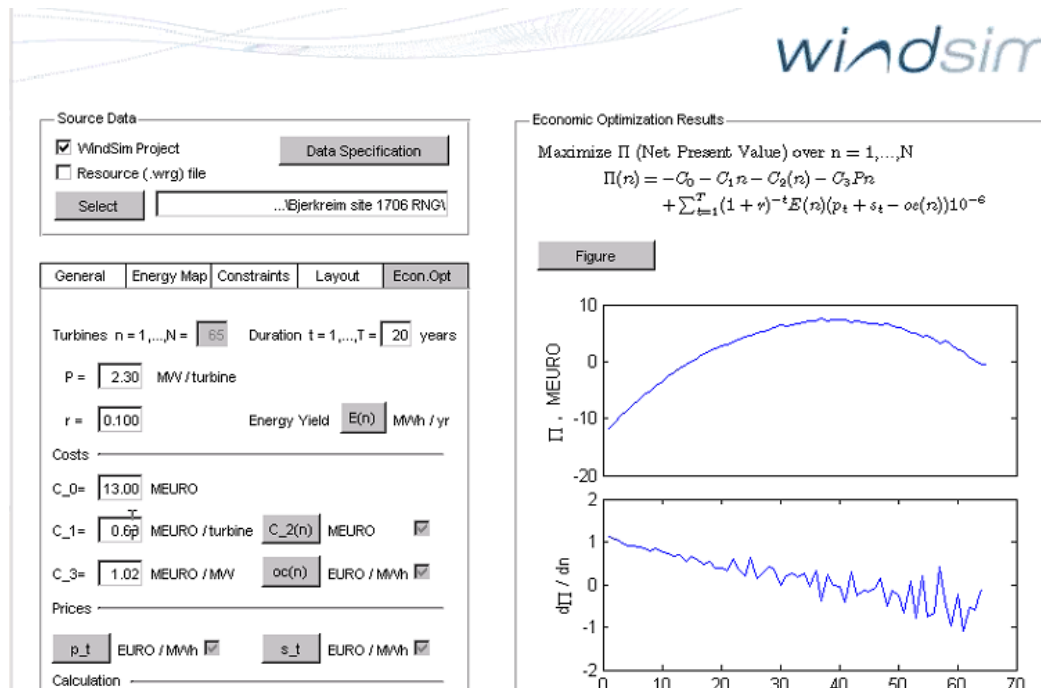
Layout Optimization: Optimize turbine layout

In principle all turbine positions might change when adding one more turbine. Hence a project with N turbines will generate N layouts as seen in the right he example where $N=65$



Layout Optimization: Optimize size

4) Optimize size:



Source Data

WindSim Project Resource (.wrg) file

Select ...Ejerkreim site 1706 RNg\

General Energy Map Constraints Layout Econ.Opt

Turbines $n = 1, \dots, N =$ 65 Duration $t = 1, \dots, T =$ 20 years

$P =$ 2.30 MW / turbine

$r =$ 0.100 Energy Yield $E(n)$ MWh / yr

Costs

$C_0 =$ 13.00 MEURO

$C_1 =$ 0.6p MEURO / turbine $C_2(n)$ MEURO

$C_3 =$ 1.02 MEURO / MW $oc(n)$ EURO / MWh

Prices

p_1 EURO / MWh s_1 EURO / MWh

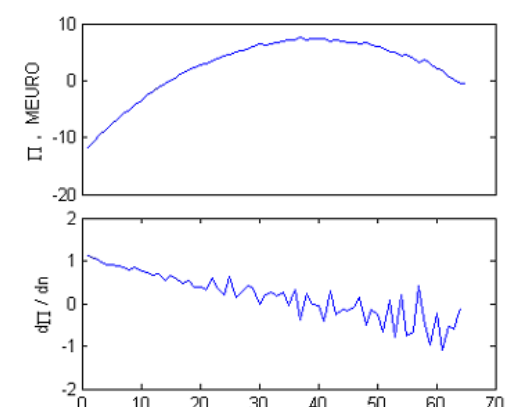
Calculation

Economic Optimization Results

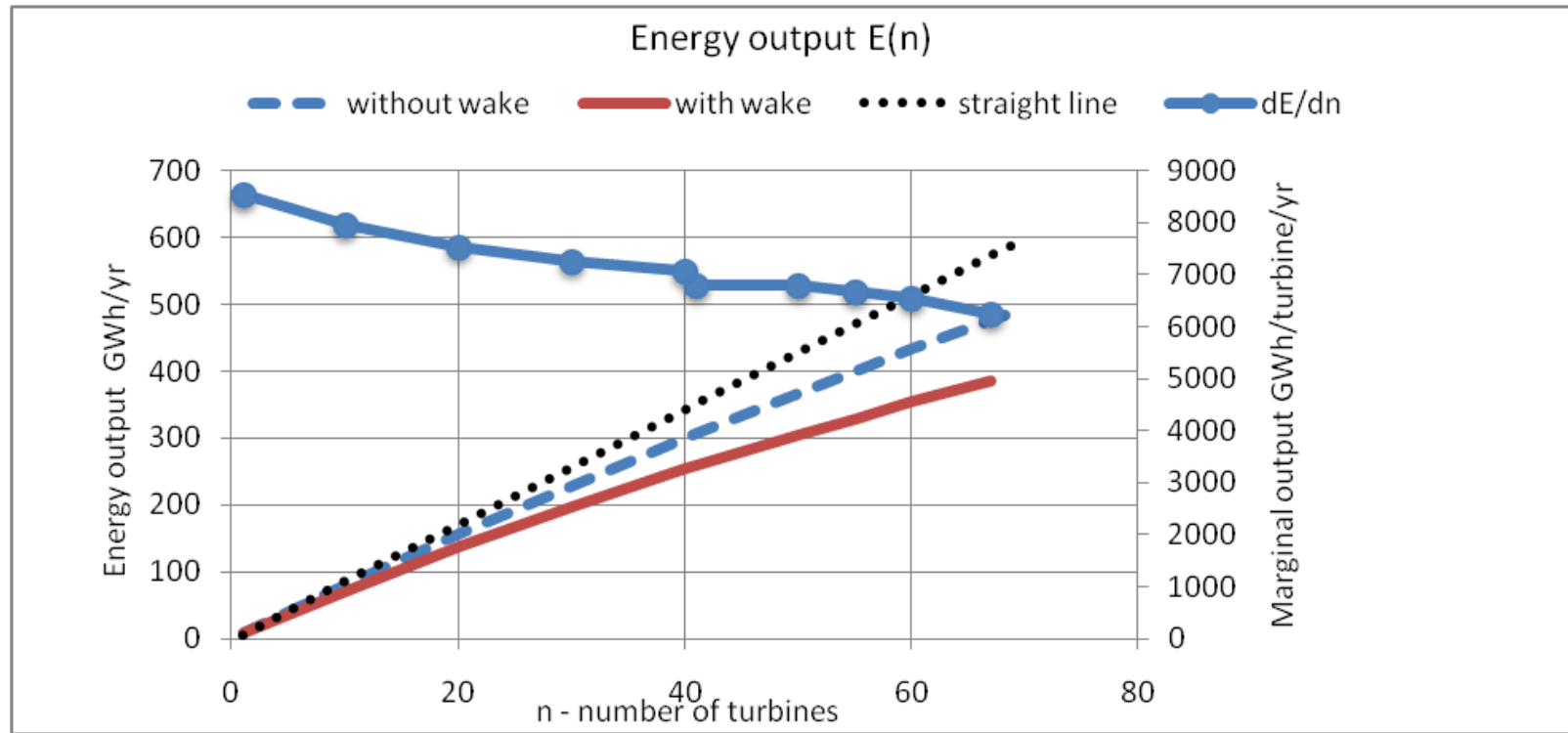
Maximize Π (Net Present Value) over $n = 1, \dots, N$

$$\Pi(r) = -C_0 - C_1 r - C_2(r) - C_3 P r + \sum_{t=1}^T (1+r)^{-t} E(r)(p_1 + s_1 - oc(r)) 10^{-6}$$

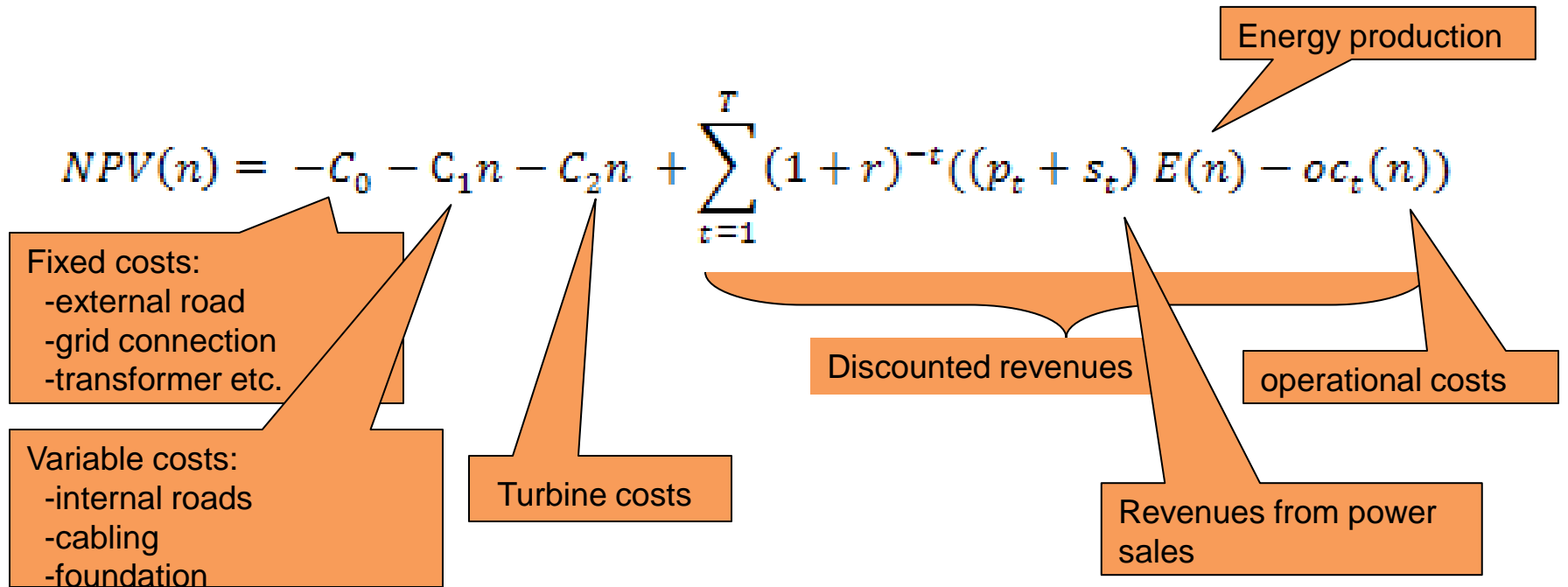
Figure



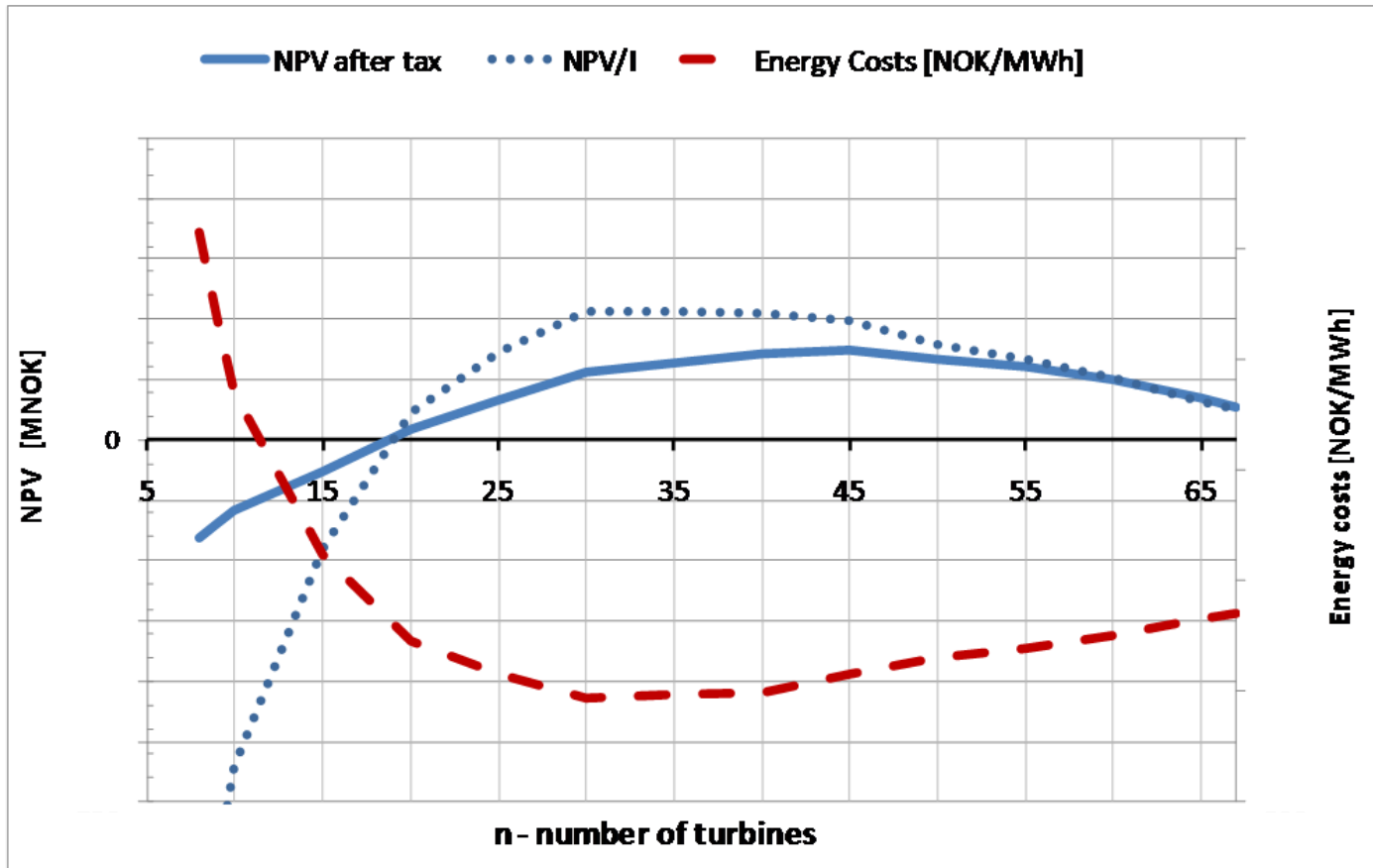
Layout Optimization: Optimize size



Layout Optimization: Profitability Curve



Layout Optimization: Profitability Curve



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 - Summary

Reanalysis data – Advantages & Application

- Despite the inherent challenges involved (i.e., coarse resolution, model sensitivities to physical parameterizations, etc.), incorporation of mesoscale reanalysis data into the wind resource assessment process offers a number of unique advantages and opportunities for application

Advantages:

- Provides decades worth of quality controlled, historical meteorological data (i.e. wind, temperature, moisture, etc.)
- Provides realistic wind speed and direction time series for any location on the globe and at any height if downscaled properly
- Reduces dependency on expensive measurement campaigns

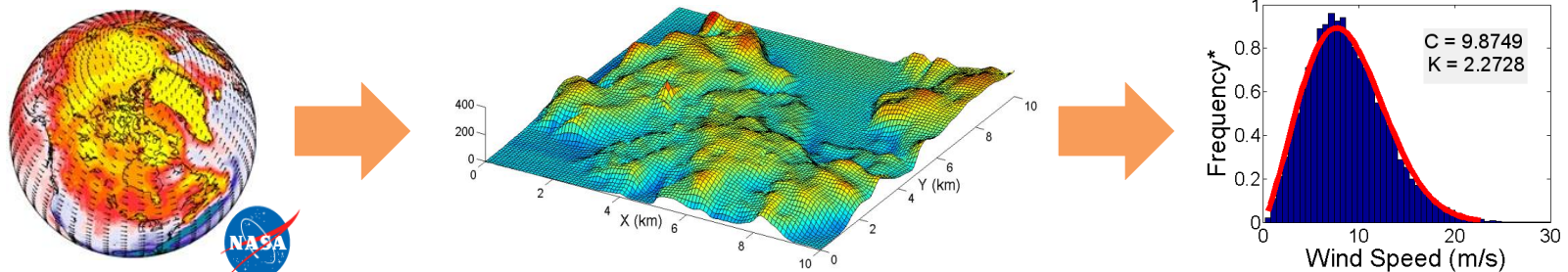
Application:

- Early identification of potential site for wind farm projects
- Reference dataset for long term correction (MCP)
- Help measurement campaign design, lower the investment risks of tall and well instrumented met mast
- **Early optimization of the layout and other early stage wind farm planning**

Downscaling MERRA data using CFD

• In this study, modeled meteorological data from NASA's "*Modern-Era Retrospective analysis for Research and Applications*" (MERRA) reanalysis dataset was used to scale CFD simulations carried out by the WindSim model. The major components of the downscaling procedure are:

- Multiple MERRA grid points are utilized
- An in-house height correction is applied to each MERRA grid point to improve wind speed representativeness
- A horizontally stretched grid is required in the region close to each MERRA point to minimize erroneous terrain speed-up near climatology point



Downscaling meso-scale wind data; MERRA, CFD, Virtual climatology at turbine position

Sites and accuracy

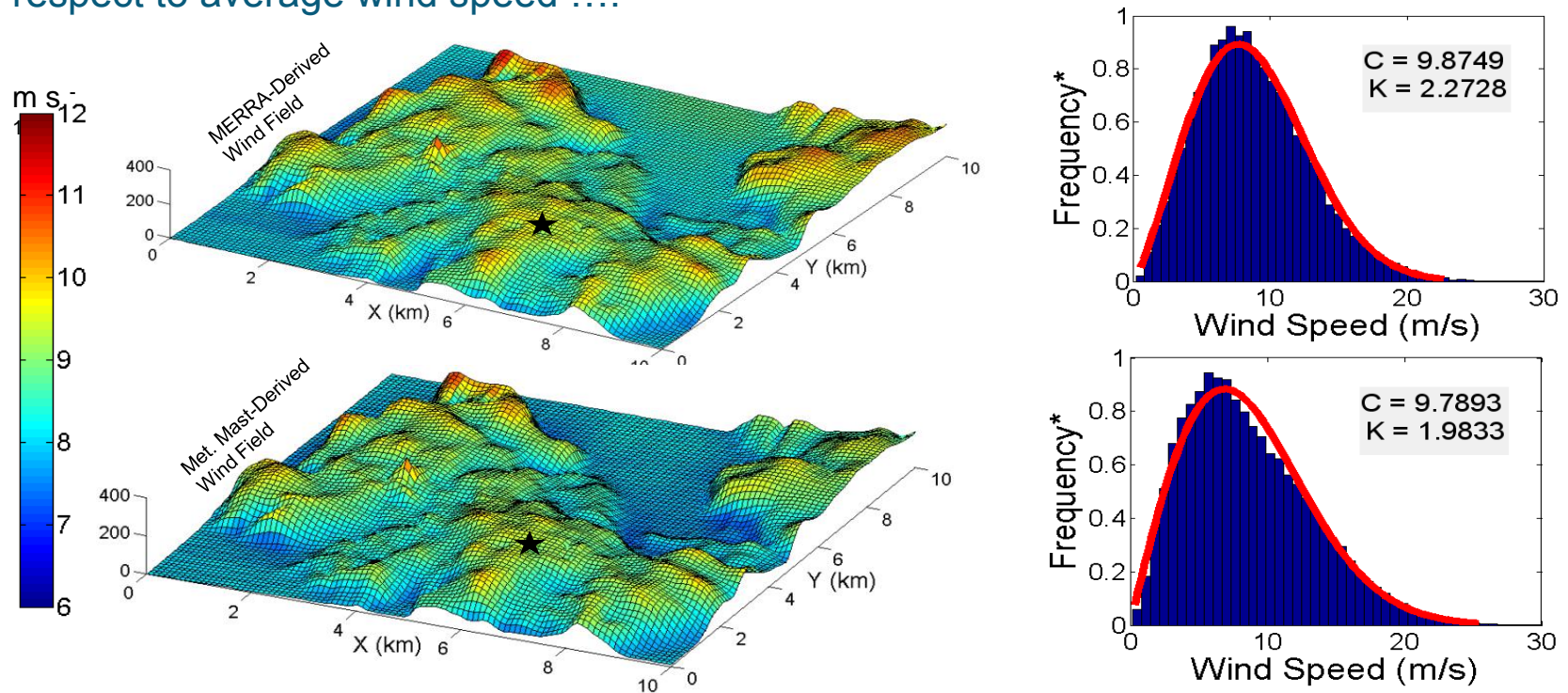
The validity of the downscaling methodology was verified against 7 sites of varying atmospheric stability and terrain characteristics. At each site, virtual climatologies were compared to measured wind climatologies with respect to vertical profile, speed and direction distribution, and time series. At sites where energy production data were available, AEP validations were carried out.

Case	Surface Characteristics	Stability % (Neutral/Stable/Unstable)			Mean Wind Speed % Error*
1	Complex-Coastal/Smooth	16	73	11	+2.51
2	Flat/Forested	8	59	33	+4.90
3	Very Rugged/Forested + Fields	21	51	26	+15.86
4	Small Hills/Smooth	28	36	36	+6.24
5	Small Hills/Forest + Grassland	21	50	29	-10.83
6	Small Trenches/Low vegetation	12	49	39	-6.72
7	Offshore	22	54	24	-1.33

*Description of cases and percent errors of virtual climatology versus met mast mean wind speed measurement. *Heights of wind speed validation are respective of sensor height*

Wind validation I

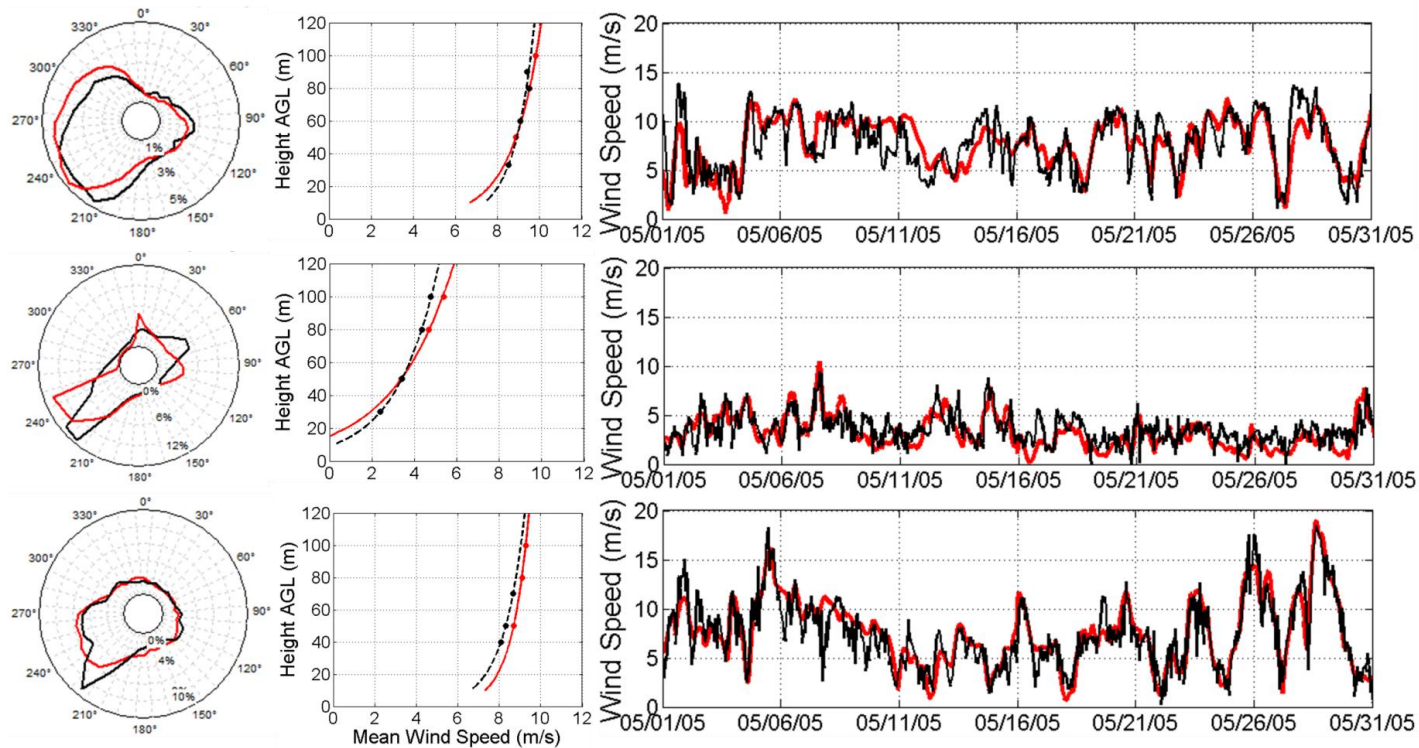
At each site, virtual climatologies were compared to measured wind climatologies with respect to average wind speed



Simulated mean wind speed for Case 1 scaled by measured (bottom left) and virtual climatology (top left) time series. Also, corresponding wind speed frequency distribution for the measurement location, as denoted by the black star, extracted from the model solutions scaled by the measured (bottom right) and virtual (top right) climatology time series

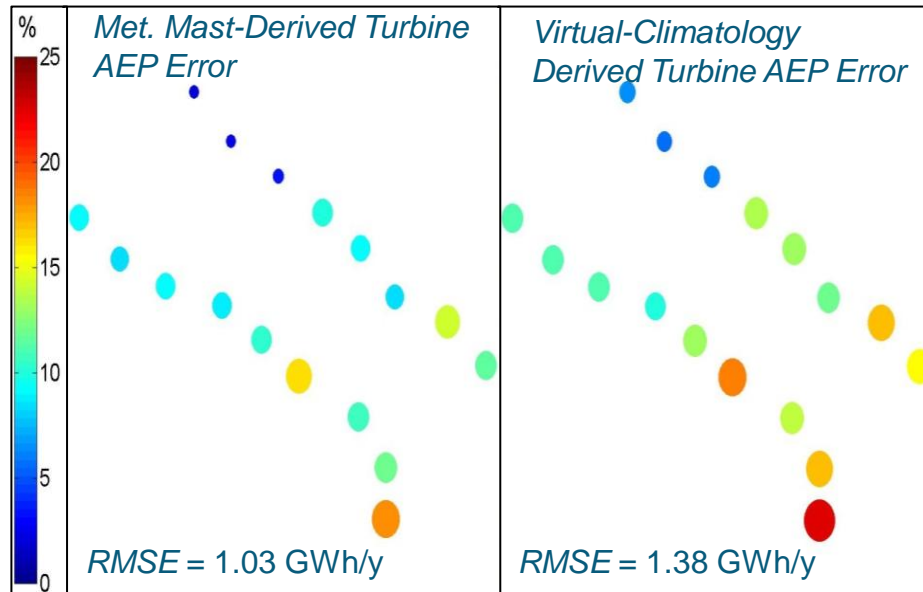
Wind validation II

... and with respect to wind rose, vertical profiles and time series



Comparison of wind rose (left column), mean wind speed profile (middle column), and sample 50m wind speed time series (right column) for met mast location. Red represents virtual climatology and black represents measurements. The three rows correspond to cases 7, 2, and 4 (in order from top to bottom)

Energy validation



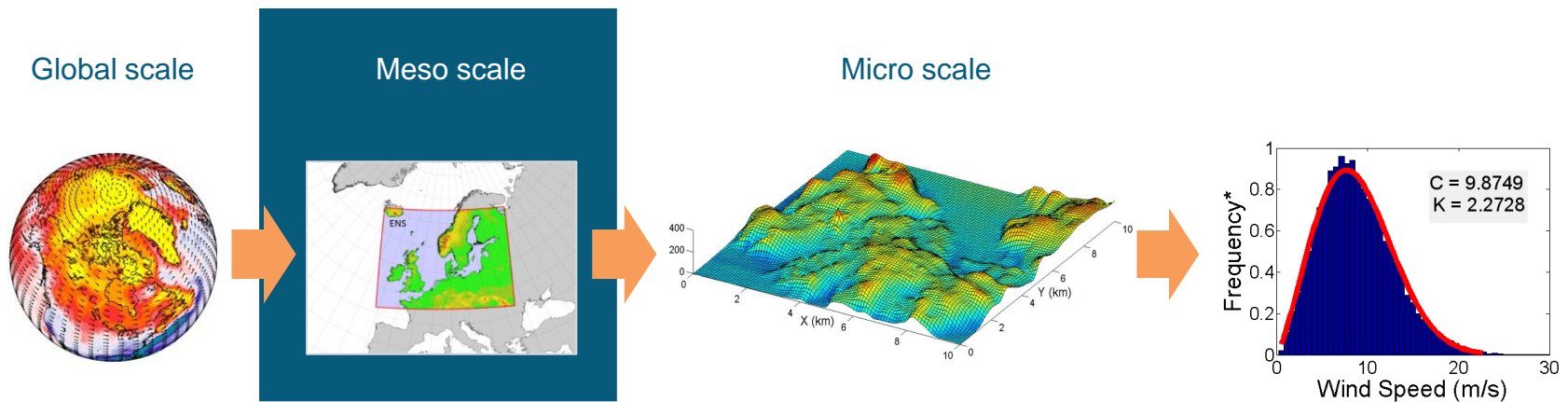
Total Farm Avg. AEP for Case 1	Met. Mast-Derived AEP (GWh/y)	Virtual-Climatology-Derived AEP (GWh/y)
WM 1	165	171
WM 2	170	177
WM 3	165	170

Turbine specific, AEP error of Case 1 when CFD simulation is scaled by 50m met mast measurements (left) and virtual climatology (right). RMSE is computed using historical power production data as truth.

AEP estimates for Case 1 with respect to Wake Model (WM). Observed AEP was approx. 150 GWh/y.

Downscaling Virtual Met Masts (VMM[®] MetOffice) using CFD

- As opposed to the MERRA data download where the Meso scale was skipped, the downscaling with VMM includes the Meso scale

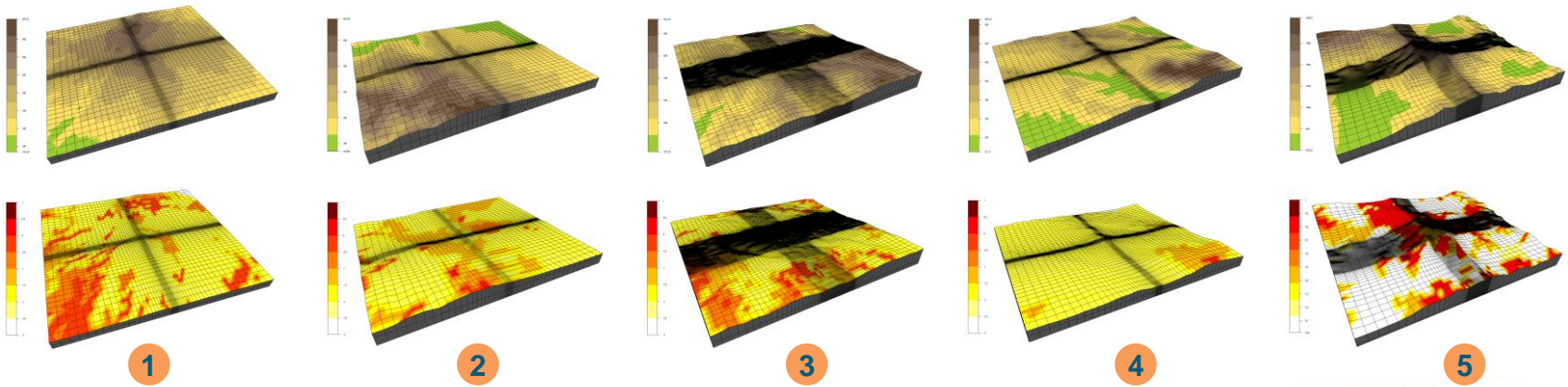


Downscaling meso-scale wind data; VMM, CFD, Virtual climatology at turbine position

Sites

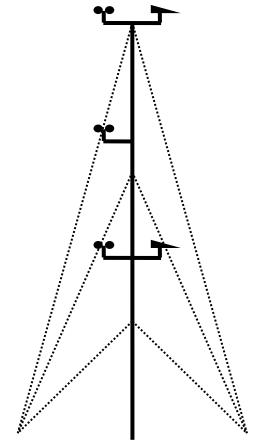


5 sites in complex terrain and complex climatology driven by thermal effects. Elevation difference up to 900m and terrain inclination up to 36 degrees



Wind measurements available – Validation

- 11 met masts ranging from 40m to 70m
- Calibrated cup anemometers
- Only top sensor used
- Hourly wind speed and direction values from 10 minutes averages
- More than 21 years of cumulative data



Preliminary analysis shows that CFD downscaling brings to a reduction of 0.4 m/s in standard deviation of errors (uncertainty) and 0.12 m/s in average (bias)

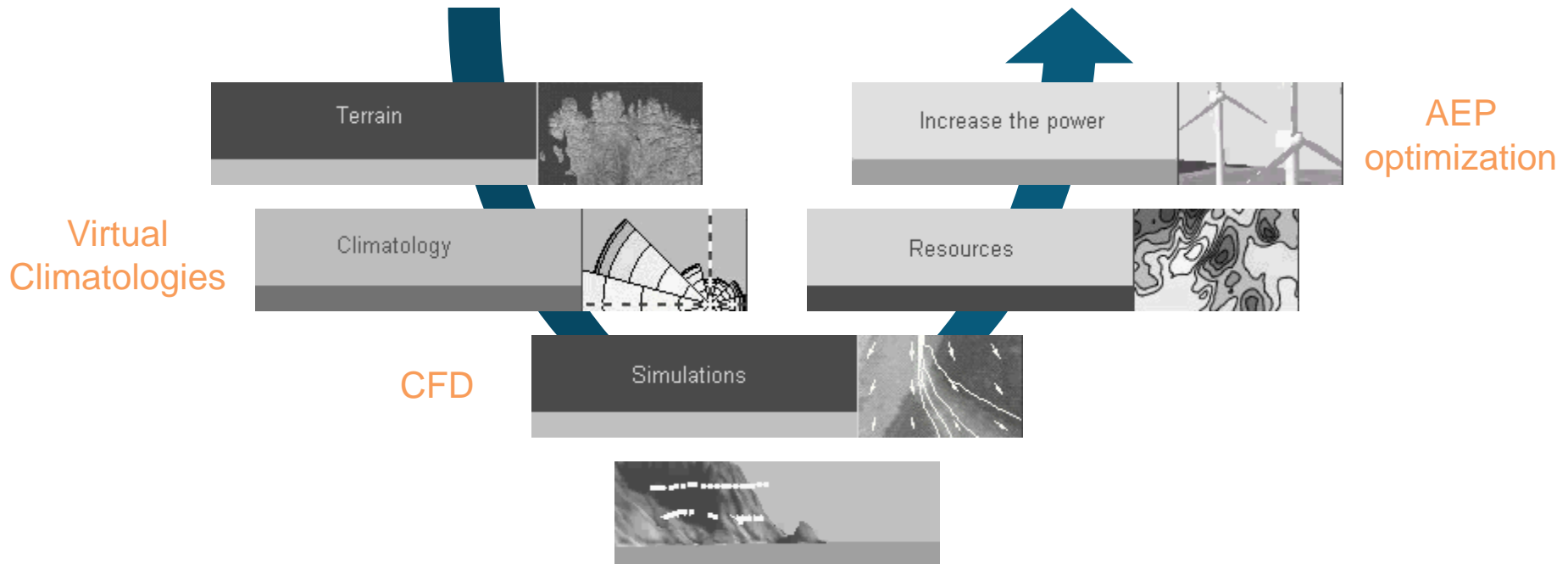
Summary – Downscaling meso-scale wind data using CFD

- We have developed a methodology for generating high-resolution, virtual wind climatologies (i.e., speed and direction time series) for any location around the world and for any height within the surface layer
- The downscaling can be made based on MERRA or with intermediate meso-scale steps like the method of VMMs (Virtual Met Masts)

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Micro-siting procedure – Early AEP optimization



The micro-siting procedure consists of five steps; Terrain, Climatology, Simulation, Resources and AEP optimization

- Layout changes can be difficult after completion of the permit process
- Early AEP optimization of the layout

AEP optimization based on reanalysis data

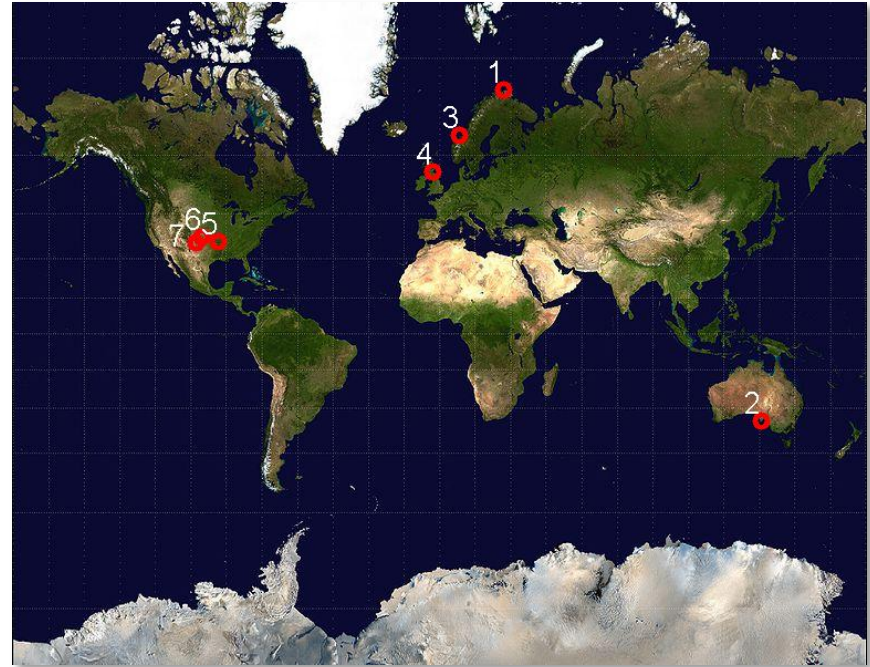
- Check the potential AEP increase in existing wind farms by changing the layout
 - Calculate a reference AEP based on the existing layout and reanalysis data
 - Calculate a hypothetical AEP based on an optimized layout and reanalysis data
 - Find the increased AEP ($AEP_{\text{hypothetical}} - AEP_{\text{reference}}$)
- As an alternative to the conventional technique of deploying multiple tall met masts and waiting one or several years for this data, we propose the use of mesoscale reanalysis model output statistically and dynamically downscaled using computational fluid dynamics (CFD)

Sites – AEP optimization based on reanalysis data

- In this presentation we comment on the importance of optimizing turbine positions while quantifying potential AEP improvements for a number of existing wind farms

- The wind energy development over the past two decades has been accelerated by the abundance of locations with promising wind resources. These locations have been aggressively sought-out due to their low-risk of inefficiency; nevertheless, future development depends on the exploration of areas with higher-risk wind resource

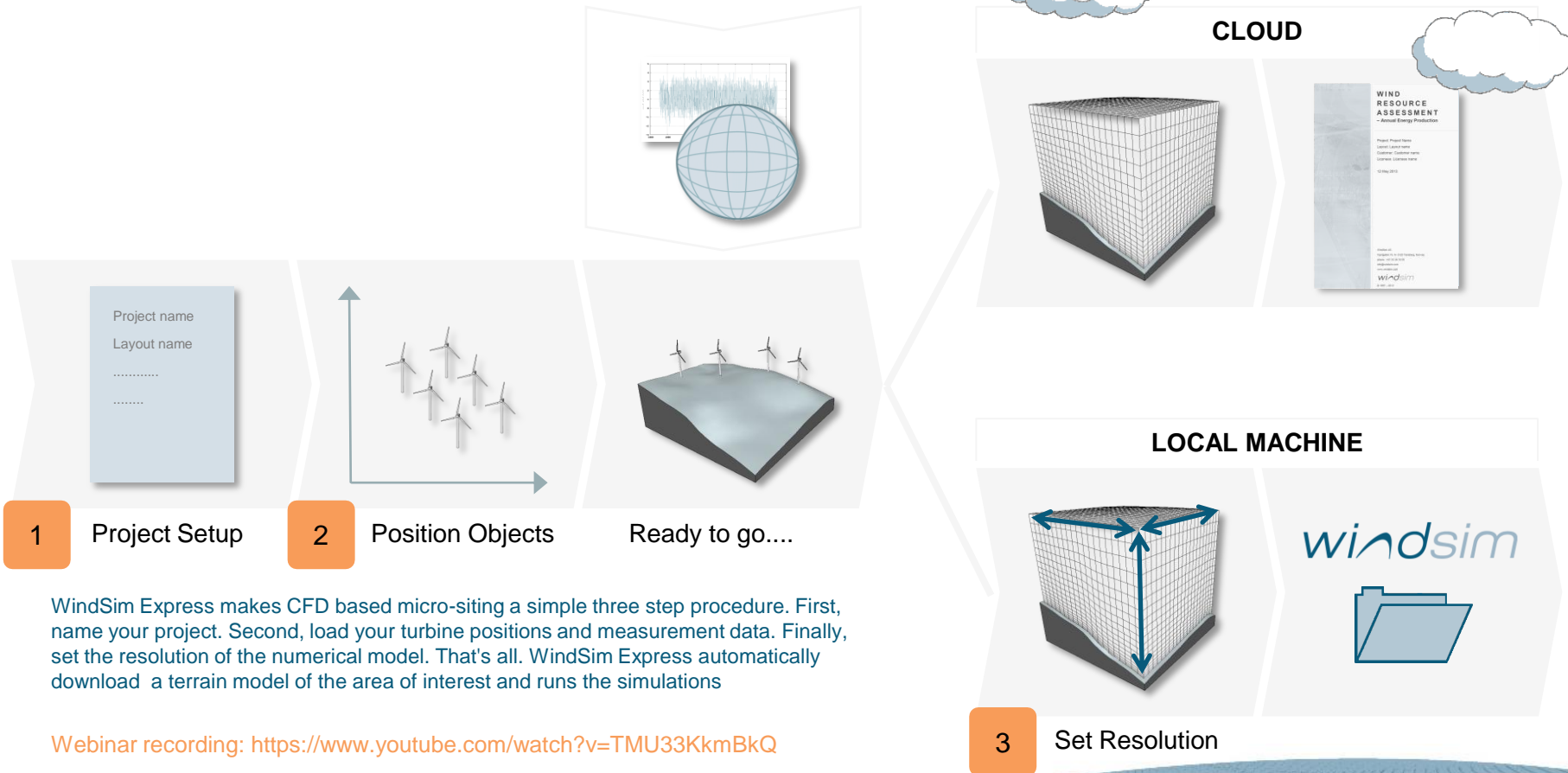
- These higher-risk sites are inevitably much more sensitive to pre-construction technical decisions (i.e. turbine layout, hub height, turbine selection, etc.) and accurate wind resource characterization



Locations of the seven sites used in this study

Tools: Wind Simulations – WS Express/WS Express Cloud

- WindSim Express (Cloud) addresses the early stage market



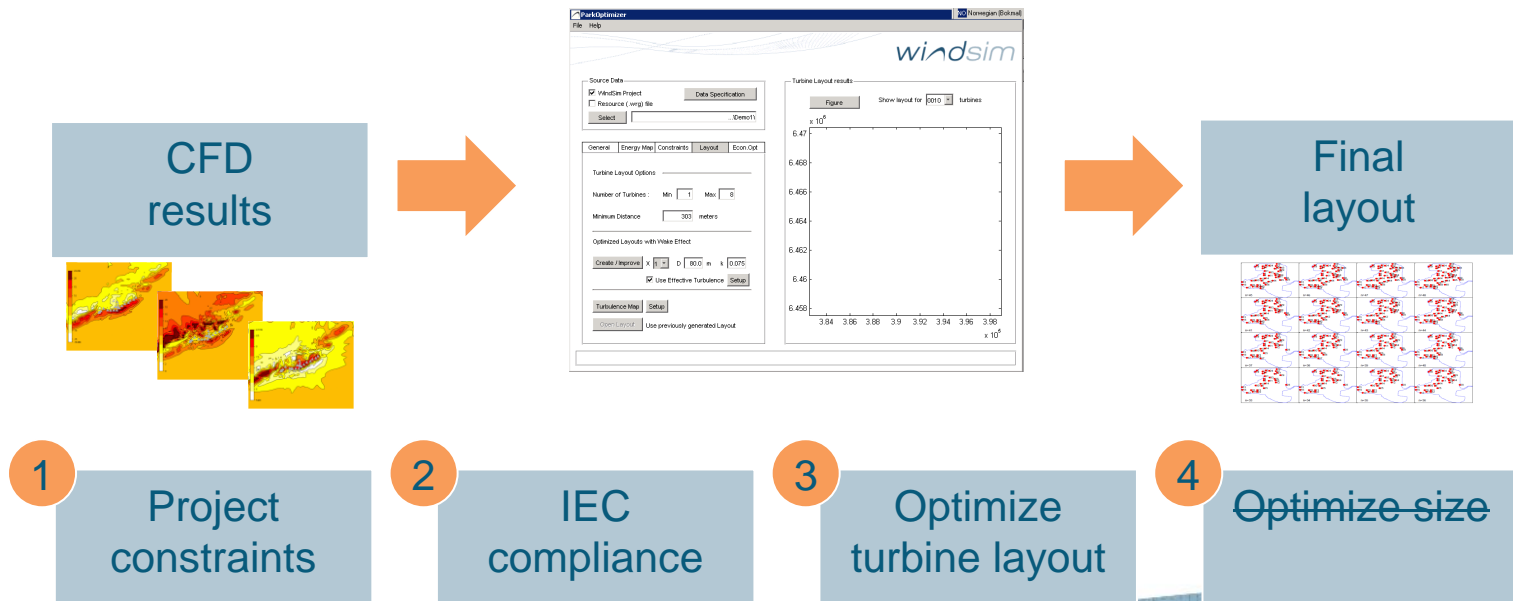
WindSim Express makes CFD based micro-siting a simple three step procedure. First, name your project. Second, load your turbine positions and measurement data. Finally, set the resolution of the numerical model. That's all. WindSim Express automatically download a terrain model of the area of interest and runs the simulations

Webinar recording: <https://www.youtube.com/watch?v=TMU33KkmBkQ>

Tools: Park Optimization – simplified approach

• Based on simulated wind conditions an optimized layout is found taking into account the following constraints:

- Projects constraints – Rectangular area enclosing all turbines
- IEC compliance
- Optimize turbine layouts – Not changing the original number of turbines
- ~~Optimize wind farm size~~



Optimization details

- The optimized layout of each wind park was constrained by the IEC standards
- The hub heights corresponded to the real hub heights of each wind farm (i.e. 42 – 82 m above ground level)
- A standard turbine power curve and rotor diameter was used for all cases
- CFD simulations were scaled using virtual climatology data derived from MERRA reanalysis

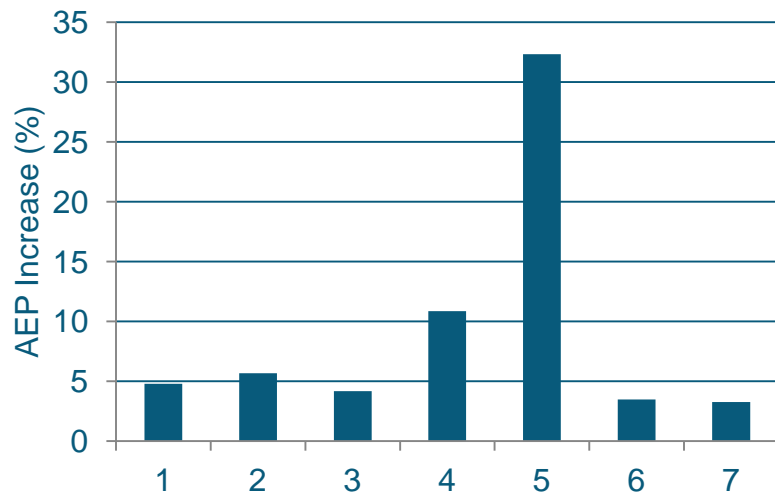
Optimization results

Case	Site	Location	# of Turbines	Original AEP (GWh/y)	Original Wake Loss (%)	Optimized AEP (GWh/y)	Optimized Wake Loss (%)	AEP Increase (%)
1	Kjøllefjord	Northern Norway	17	146	5.13	153	1.85	4.79
2	Cathedral Rocks	Southern Coast of Australia	33	229	4.63	242	3.02	5.68
3	Hitra	West Coast of Norway	23	120	4.01	125	2.55	4.17
4	Black Hill	Eastern Scotland	22	138	10.47	153	3.70	10.87
5	U.S. WF 1	Mississippi River Valley	60	133	2.76	176	2.53	32.33
6	U.S. WF 2	U.S. Great Plains	162	952	2.63	985	3.28	3.47
7	Wildorado	Northern Texas	70	489	5.54	505	3.19	3.27

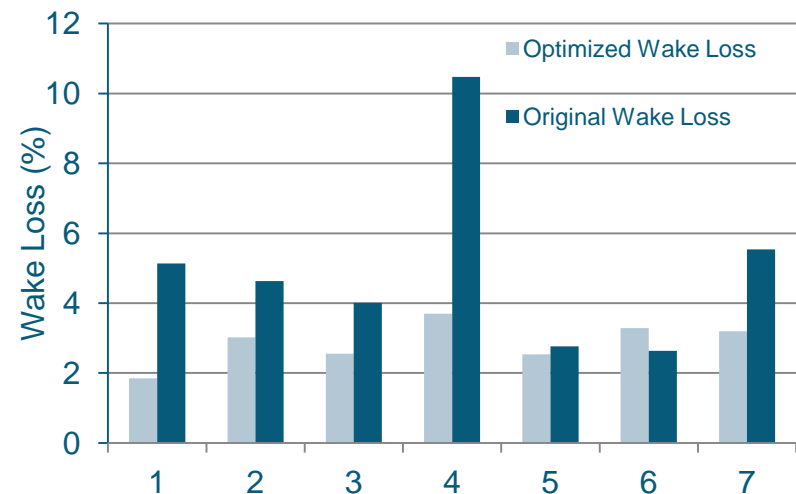
Summary of the cases and comparison of the power statistics from the original and optimized turbine layouts

Optimization results

- Demonstrated a methodology based on the use of a global reanalysis dataset (MERRA) which has proven capable of delivering realistic wind fields also in complex terrain
- For the cases investigated, we have found optimized AEP increases ranging from 3% to 32% and wake loss decreases up to 7%



Increase in annual energy production (AEP) after park optimization for each case



Original and optimized wake losses for each case

Optimization results – Case 2

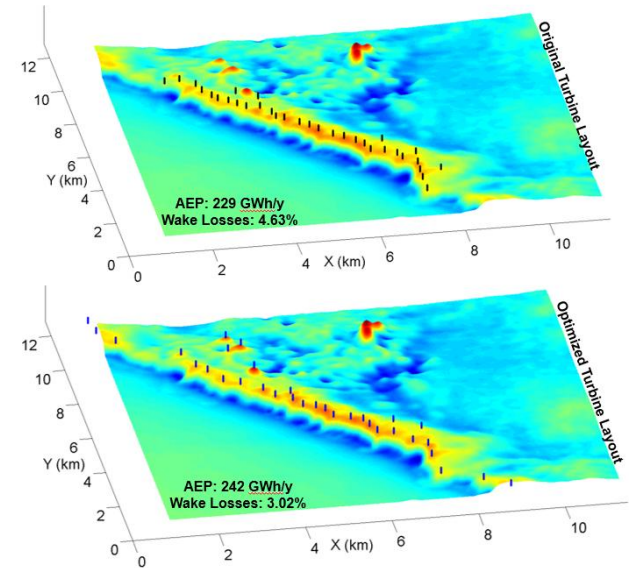
- As an example of the functionality of the park optimizer, we will highlight results from case 2 which corresponded to the Cathedral Rocks wind farm on the southern coast of Australia
- Cathedral Rocks wind farm is positioned very near a precipitous cliff at the land-sea interface. The orientation of the cliff adjacent to the wind farm helps to amplify the ambient surface layer wind speed due to orographic speed-up when the wind impinges directly onto the cliff face



*Cathedral Rocks wind farm on the southern coast of Australia .Image credit: Energy Australia
(<http://www.energyaustralia.com.au/about-us/what-we-do/generationassets/cathedral-rocks-wind-farm>)*

Optimization results – Case 2

- The simulated mean wind speed at the hub height is shown along with the original and optimized layouts
- It seems clear that the original park developers were focused on capitalizing on the narrow band of high mean wind speed associated with the bluff cliff land mass adjacent to the land-sea cliff.
- By creating an original park layout in a linear-type orientation parallel to the cliff, the wind farm was able to achieve an estimated AEP of 229 GWh/y with wake losses of 4.63 %
- After using the WindSim-based park optimization module with the simulated wind field, the 33 turbine locations were modified and the AEP was increased to 242 GWh/y. At the same time, wake losses decreased to 3.02 %
- The optimized park layout still follows the elongated structure adjacent to the coastline; however, the turbines are more spread out and push towards the edges of the prescribed optimization bounds. Also, a few turbines migrate towards the isolated mean wind speed peaks slightly away from the main strip of high winds



Mean wind speed (warm colors are high wind speed and cool colors are slow wind speed) at hub height (60m AGL) for Case 2 overlaid with original layout (top) and optimized layout (bottom).

Summary – AEP optimization based on reanalysis data

- AEP increases of primarily 3 to 10% were achievable through the park optimization process; however, there was an outlier of 32% for Case 5 mainly due to the large area that the original park occupied.
- Wake loss decreases of up to 7% were found; however, for one case (6) wake losses increased slightly despite the fact that overall AEP increased.
- Overall, the magnitude which a wind park can be optimized is closely related to the size of the land area available; in other words, expanding the boundaries of the wind park slightly can significantly improve power production for most cases
- In addition, it was found that the capacity of the park optimizer to produce valuable park layouts strongly depends on the accurate prescription of all relevant geologic, technical, and financial constraints

Authors – Acknowledgements

This presentation is partly based on two papers published at EWEA 2014

Downscaling MERRA Mesoscale Data for the Generation Microscale Wind Fields Using CFD

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¹North Carolina State University; Raleigh NC, U.S.A.

²WindSim AS; Tønsberg, Norway

From reanalysis data to park optimization

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¹North Carolina State University; Raleigh NC, U.S.A.

²WindSim AS; Tønsberg, Norway

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