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Abstract

In the framework of the FP7 project EERA DTOC: Design Tool for Offshore wind farm Cluster, a new software supporting the planning of offshore wind farms was developed, based on state-of-the-art approaches from large scale wind potential to economic benchmarking. The model portfolio includes WAsP, FUGA, WRF, Net-Op, LCoE model, CorWind, FarmFlow, EeFarm and grid code compliance calculations. The development is done by members from European Energy Research Alliance (EERA) and guided by several industrial partners. A commercial spin-off from the project is the tool 'Wind & Economy'. The software has been compared and validated to a wide extent. Around 10 wake models have been compared to SCADA data from the Horns Rev 1 offshore wind farm in the North Sea, and the Lillgrund and Rødsand-2 wind farms in the Baltic Sea. The Rødsand-2 wind farm is located nearby the Nysted-1 wind farm, thus an investigation of the wake influence between dual operation twin farms was possible. Furthermore both micro- and mesoscale wake models have been compared to satellite-based wind farm wake data in the North Sea. Regarding the planning of the electrical grid, both inter-array and long-distance cables were modelled by the software and several tests were performed. The calculations include the smoothing effect on produced energy between wind farms located in different regional wind zones and the short time scales relevant for assessing balancing power. The grid code compliance was tested for several cases and the results are useful for wind farm planning of the grid and necessary components and controls.

1. Introduction

The EERA partners together with valuable industry partners across Europe formed a consortium to enable the cost reduction of energy by building a new, integrated design tool for offshore wind farm and cluster planning. The consortium proposed the project Design Tools for Offshore Wind Farm Clusters (DTOC) to the FP7 call on "Development of design tools for Offshore Wind farm clusters". This resulted in the successful 3.5-year long project coordinated by DTU Wind Energy in collaboration with 21 partners (www.eera-dtoc.eu). Collaboration took place with the parallel project ClusterDesign (https://www.cluster-design.eu/).

The overall project aim of the EERA DTOC project was to develop 'A robust, efficient, easy to use and flexible tool created to facilitate the optimised design of individual and clusters of offshore wind farms'.

This should help developers, strategic planners and other stakeholders in the offshore wind energy business to improve planning of offshore wind farms at cluster scale. The new design tool focuses on wind farm wake losses and wind farm electrical cabling. The project objective

was to deliver an integrated tool for the design of individual wind farms and clusters of wind farms. The tool is composed of existing models from the EERA science partners. Major industry partners in the project guided the effort of the project to ensure maximum benefit also from the industrial perspective. In this way the project enabled a move from science to business.

2. Wake analysis and coupling from micro- to meso-scale

Within the EERA DTOC project one completed major task was the comparison between more than 10 wake models and SCADA data, in conjunction with the IEA Wind Task 31 WAKEBENCH. The wake models range from engineering models, to fast parametrized models, to CFD and mesoscale models. SCADA data was kindly provided from the wind farms Horns Rev 1 in the North Sea, and Lillgrund and Rødsand-2 in the Baltic Sea. The Rødsand-2 is located nearby the Nysted-1 wind farm, thus the investigation of the wake influence between dual operation wind farms was possible. Table 1 lists the wake models and wind farms. Ship-based wind lidar data observed near the FINO-1 meteorological mast and the Alpha Ventus wind farm in the North Sea and scanning lidar data were collected and compared to the wake models. High-resolution satellite remote sensing images showing long wind farm wakes and these were qualitatively compared to the micro- and mesoscale wake model results.

Table 1. List of wake models and wind farms. The models in yellow are engineering models, in brown fast parametrized models, in green CFD model and in blue mesoscale models. See Appendix A for further information on the wake models.

Models	Affiliation	Horns Rev WF	Lillgrund WF	Rødsand II WF	Rødsand II/Nysted WF
SCADA/BA	DTU Wind Energy/K.S.Hansen	x	x	x	(x)
NOJ/BA	DTU Wind Energy/misc		x		
NOJ/GU	DTU Wind Energy/misc		x	x	
NOJ/BA	DTU Wind Energy/A. Pena	x	x	x	
WASP/NOJ	Indiana Uni/RB	x			
GCL/BA	DTU Wind Energy/misc		x		
GCL/GU	DTU Wind Energy/misc	x	x		
GCL(GU)	CENER/JS.Rodrigo	x	x		
FUGA/SO	DTU Wind Energy/S. Ott	x	x	x	
DMW	DTU Wind Energy/TJ.Larsen	x			
AD/RANS	UPORTO/J.L. Palma	x		x	x
CRESflowNS	CRES/ J. Prospathopoulos	x	x	x	
FarmFlow	ECN Wind Energy/J.G Scheepers	x	x	x	x
CFDWake	CENER/B.G. Hevia	x		x	
RANS/f_PC	DTU Wind Energy/P.vd Laan			x	x
Ainslie	RES-LTD/T.Young	x	x		
WRF/UPM	Ciemat/A.Palomares			x	
Mesoscale	DTU Wind Energy/P.Volker			x	

The engineering wake models are widely used. During the project a new way of averaging results from engineering wake model using post-processing to propagate the assumed wind directional uncertainty was presented [1, 2]. It is here called the Gaussian uncertainty (GU) method. The Gaussian uncertainty method appears very useful in particular for narrow wind direction bins. The bin averaging (BA) method is without post-processing. The effect of atmospheric stability in engineering wake models when modelling large wind farm was investigated [3]. One engineering wake model was compared to observations at Sexbierum [4]. In the project there was much focus on very large wind farms. The results on using an engineering wake model and assuming an infinite offshore wind farm were presented [5]. It is clear that such results cannot be evaluated against measurements as such large wind farms do not exist.

The need for using new methods for benchmark evaluation between SCADA data and wake models was addressed [6, 7] and in particular the 360° wind farm efficiency was seen as a highly relevant method. As example we show the result from Horns Rev 1 and Rødsand 2 assuming wind speeds between 8±0.5 m/s. The results are presented in Fig. 1. It is noted that for Rødsand 2 the upwind wind farm Nysted 1 influences to a high degree the park efficiency. The SCADA data used for comparison have to be analysed carefully. The uncertainty (e.g. one standard deviation) on SCADA is not shown in Fig.1 but the uncertainty has been investigated in this project [8]. It is important to consider this uncertainty before conclusions can be drawn on specific wake model performance [8]. The major learnings from the analysis were that most wake models capture the wind farm efficiency well and that the uncertainty on SCADA data has to be addressed [9].

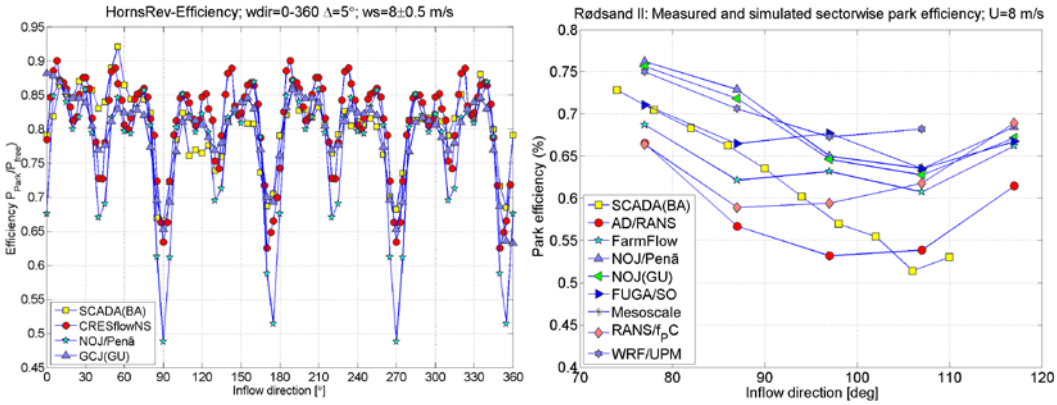

Fig. 1. Wind farm wake observed from SCADA data and wake models results at Horns Rev 1 for 360° and for Rødsand 2 for 41° in the eastern sector where SCADA data was available.

The computation of very detailed wind farm wake structures is possible from CFD models [10] and the CFD results compare well in qualitative terms to the wind farm wake structures seen in the well-known photo from Horns Rev 1 where interestingly the winds are near cut-in wind speeds and only few turbines produce power. Most studies on wake consider winds in the speed range from above cut-in wind speed to rated wind speed. Comparison results from CFD models in this project include results from CRES flow [11, 12] and Ventos [13].

Meso-scale wake model comparison to SCADA data was performed [14, 15, 16, 17]. One advantage of mesoscale models is the possibility to include synoptic conditions and the constantly evolving diurnal winds in the modelling. This was very interesting for the interpretation of very long wind farm wakes up to 70 km observed from high-resolution satellite Synthetic Aperture Radar images [18, 19]. Here it may be noted that satellite winds are observed at 10 m while the maximum wake deficit is expected near hub-height. Therefore the comparison results are only qualitative. A new method for extrapolation of wind climate statistics based on the satellite data to hub-height was developed, the so-called lifting method [20]. This has particular importance for energy yield and wind resource assessment (see next section). Finally, a major experimental campaign near FINO-1 and the Alpha Ventus wind farm with ship-based and scanning lidar took place and comparison was made [21].

3. Energy yield

The energy yield estimation consists of providing means to produce an accurate assessment of the expected net energy yield from wind farms and clusters of wind farms as well as the associated uncertainty by integrating results from wakes models and electrical losses models. To analyse the different gross energy estimation techniques in a homogeneous way the FINO-1 site was selected as test case. With FINO-1 measured data at different height levels and a power curve as input, the project participants calculated mean wind speed, data coverage and wind frequency distribution after filtering; long term wind speed distribution; hub height (120 m) wind speed distribution; long-term predicted gross energy (P50) and the estimated uncertainty

of the long term predicted gross energy yield. To obtain net annual energy production from gross annual energy production different losses must be estimated. Participant's results were independently compared and contrasted with one another.

According to the steps analysed in the FINO-1 gross energy estimation (see Figure 2) some critical points were detected:

- Filtering: the large deviations in the data recovery after filtering, mainly due to the mast shadowing effect show the need to have clear rules on filtering erroneous data.
- Long term: a great variety of reference data and long term correlation methods are used, in each case and depending on the quality of the available data an exhaustive long term analysis should be done including validation and uncertainty assessment.
- Vertical extrapolation: everybody has used the Hellmann exponential law that has good results for annual mean values but not when profiles are classified in terms of the observed atmospheric stability, where the wind shear is overestimated during unstable conditions and underestimated in stable conditions.

The conclusion obtained is that there is a need for clear and common methodologies and standards to perform the wind energy yield assessment in offshore wind farms [22].

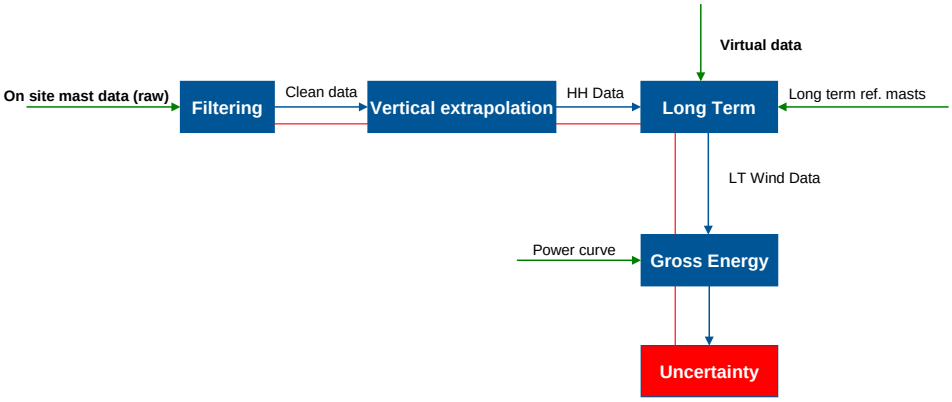

Figure 2. Flowchart of the FINO 1 test case composed of a series of modules (blocks), input data (in green) and exchanged variables (black text on blue arrows). The uncertainty estimation followed up all the process (red lines)

4. Electrical infrastructure

The electrical infrastructure, from each turbine to the onshore grid connection points, makes up a significant part of the overall cost of offshore wind energy. Optimisation of grid design is therefore crucial. With larger and farther from shore wind farms, the design of the high voltage inter-array grid that connects offshore substations to shore becomes increasingly complex. The Net-Op tool [23] addresses this optimisation problem with a mixed integer linear programming approach that takes into account the investment costs as well as the variability of wind power production, power prices or demand [24] at a number of potential onshore connection points, and the value of power trade over the same infrastructure. The result gives the most socio-economic offshore grid topology: Which substations should be connected, number of cables and transmission capacity.

The number of possible grid topologies becomes extremely large even with a relatively small number of nodes (substations and connection points). For example, 10 nodes gives 10^{13} possible topologies. For this reason, Net-Op includes a first step where it clusters substations and selects which connections to include, thereby dramatically reducing the size of the optimisation problem. Net-Op is useful to quickly generate economically sound grid topologies in a strategic planning or early development phase of a wind farm cluster. By running the

optimisation multiple times with varying parameter values, a set of topologies may be generated, indicating the sensitivity to the choice of parameters, and providing starting points for more detailed analyses.

The inter-array grid may be calculated with EeFarm [25], the power fluctuation and system reserves requirements with CorWind [26] and forecasting and control active and reactive power with the Wind Farm Cluster Management System (WCMS) [27].

5. Verification of grid code compliance for far future wind clusters

The high penetration levels of wind power force grid codes to apply new constrains on wind power plants. This report investigates the ability of offshore wind clusters, which are connected via HVDC corridors, to fulfil the grid code constrains, especially those related to voltage stability. The impact of connecting three wind farms clusters, in the North Sea, to three onshore grids; UK, European and Nordic grids is investigated. The ability of these wind clusters to match grid code requirements during severe and mild events is examined. The tool compares between several methods of connection, namely, AC, HVDC or Hybrid, and suggests the best choice based on economic studies. The tool is composed from different sub-tools, for example, EeFarm and Net-Op. The Net-Op tool provides an optimized topology for the connection of wind clusters to the grid. The meteorological and technical data, as well as the chronological dominant energy prices in the markets which will be connected to the wind farms clusters are prerequisites for the mentioned tools.

The benchmark system represents the major regions (UK, Europe presented by the German and Dutch aggregate grids, and Norway) which will be connected directly or indirectly to three wind clusters with an overall capacity of 3.6 GW as shown in Fig 3a. This report utilizes the output of Net-Op tool to prepare a dynamic model to simulate the 15-bus benchmark system using PSS®E as shown in Fig 3b. The annual average load demand at each bus is integrated according to real chronological hourly data.

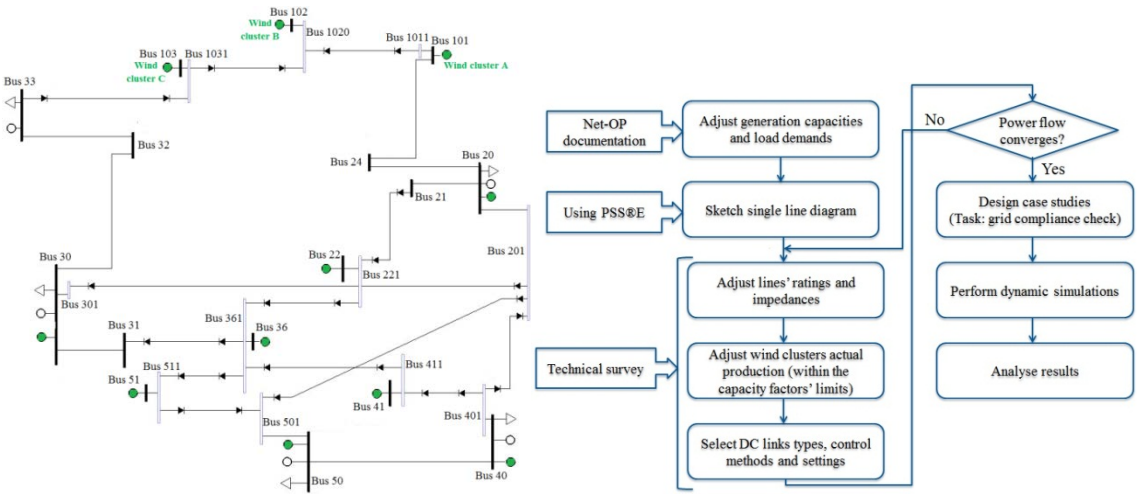

Figure 3. a) Benchmark system single line diagram. b) Flow chart for the applied procedure to build the system model in PSS®E based on Net-Op tool outcomes.

Applied case studies examine the stability of the grid during and after severe and moderate disturbances, and assure that the grid codes are complied with. Two methods are applied to impose faults to the benchmark system, namely the PSS®E fault routine, and the integration of user models. Case studies investigate the impact of three-phase solid faults at different buses, phase deviations, and force major bus to follow certain grid code (through the integrated user model). E.On and Nord grid codes are implemented. The capacity factors of all wind clusters are assumed to be 55%.

Results are encouraging and confirm that wind clusters respond to faults and disturbances as desired by grid codes. The four PSS®E fault routine cases proved to be coping with the grid codes. The offshore wind clusters are connected through HVDC corridors. Thus, the reactive capability mainly depends on the reactive limits of the HVDC link power converters not on the wind clusters. The converters of HVDC failed in some cases to provide the required reactive current to the nearby faulted bus because the converters' embedded models in PSS®E are not equipped with the suitable control algorithms. Advanced user models could be integrated to provide make the converters capable of supporting voltage stability during dips.

6. Design tool for offshore wind farm clusters software

The EERA DTOC integrated software manages input of meteorological data, wind turbine data, and other static information, and support the user to optimize the cluster lay-out and electrical infrastructure including grid code compliance (grid). The output of this process is a number of different farm and infrastructure variants, benchmarked by the economic measure of LCOE (Levelized Cost of Energy). The software integration is built upon a combination of tools on his/her DTOC server, i.e. software operated directly from the user, and services, i.e. software operated remotely either due to high computational demands or complex model input/output. An overview is given in Figure 5. Figure 6 shows the user interface of the DTOC software which is typically running on a company server. The tool is accessible from any browser and supports a true multi-user access protected by user rights management.

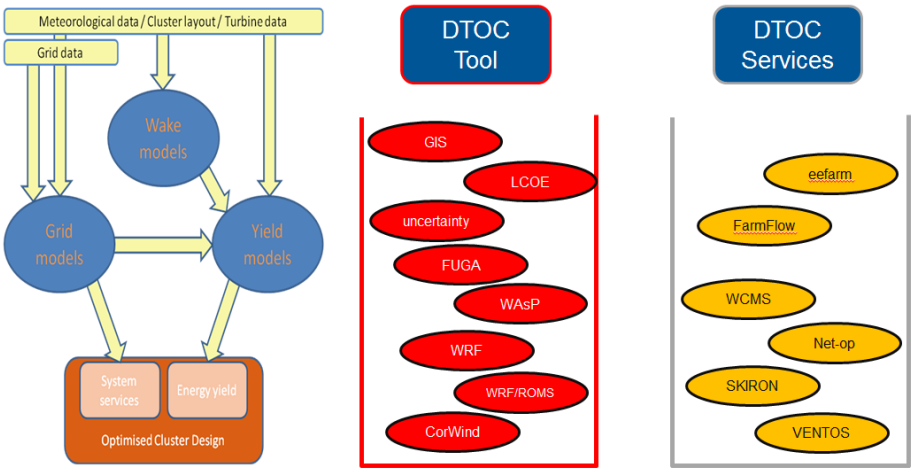

Figure 5. Conceptual overview of the DesignTool of Offshore wind farm Clusters (DTOC) and the tools and services provided.

Additionally, the input/output to the Geographical Information System (GIS) is locally installed as well. The static background data like bathymetry, other existing wind farms in the area, information about the wind potential or a complete wind atlas are stored in data bases and are represented as shape files to the GIS. The results for selected lay-out variants are shown on-line and in Excel format.

The tool has been tested extensively as a final stage of the DTOC project. Several industrial users from the project as well as many scientific partners have tested the various components and the interactions of the software. Being new to the software, the testers reported a steep learning curve and an overall good functioning of the software. Within the project we defined three so-called scenarios for which we applied the software for hypothetical planning of clusters of wind farms. The base scenario was near the UK coast and involved 5 MW wind turbines. The near-future scenario was in the middle of the North Sea and involved 10 MW wind turbines while the far-future scenario for year 2030 was in the northern part of the North Sea and

involved several clusters of large wind farms [28]. The decision parameter used to compare the design options is the Levelized Cost of Energy (LCoE). It is straightforward to calculate very many scenarios with minor and/or major changes and thereafter in well-documented way keep track of all the results. These are stored in the database. Therefore other domain experts in a major company may use the exact same data for their specific calculations. The cost output can be read into more advanced financial software for further assessment.

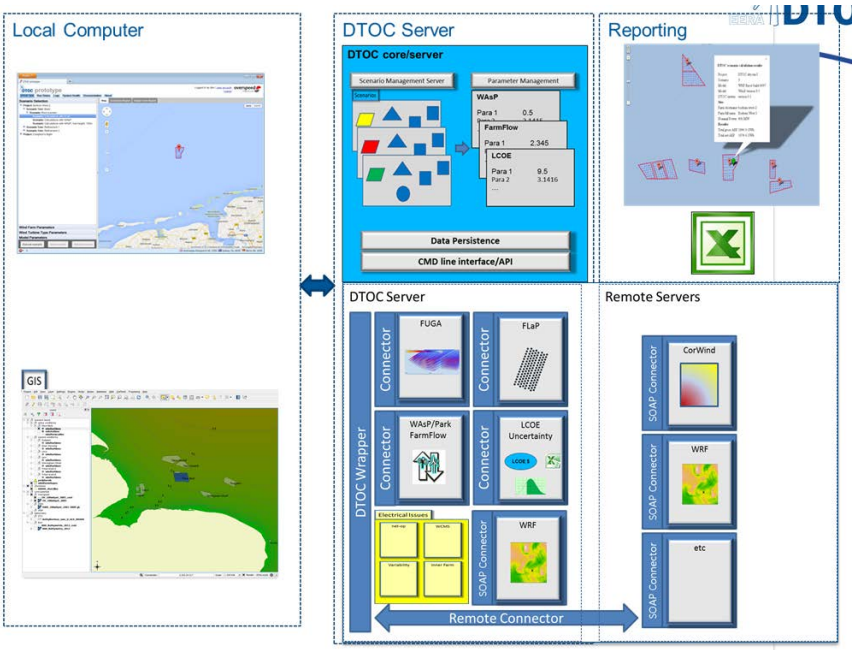

Figure 6. The Design Tool for Offshore wind farm Clusters (DTOC) overview.

7. Discussion

The cost reduction possibly achieved by using an integrated design tool for offshore wind farm cluster planning arises from the fact that many major issues can be combined. It is truly difficult to optimize in “one go” all components such as the wind farm lay-out, the wake loss, the wind farm load, the energy yield, the wind variability at short and longer time scales, the foundations, the operation and maintenance, the electrical infrastructure, etc. The DTOC tool includes, for some of the components, the best practice level while other aspects are only addressed in a limited way through the possibility of input of own cost estimates, e.g. for foundations. The choices we made in this project to develop the DTOC tool were based mainly on the interest of major wind farm developers and partly on suggestions from strategic planners. The overall evaluation of the business potential for the tool was positive. Therefore the company Overspeed has decided to market the tool under the name “Wind&Economy” Strategic Optimization http://wind-and-economy.com/home/

8. Conclusion

The main project output, the ‘Wind & Economy’ software, provides a new frame for planning offshore wind farm clusters. By seamless integration of state-of-the-art models from the scientific development by the EERA members, which have been compared and validated by the research community and end-users, provides a significant potential for cost reductions. The rapid development of offshore wind farms in the Northern European Seas with major clusters planned in many countries makes the release of this novel tool available with due diligence. The testing and validation of the tool is based on in-depth comparison analysis to observations at several major offshore wind farms.

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Appendix A

NOJ is a mass-conserving engineering wake model with a known thrust coefficient, rotor radius and wake decay coefficient [29] combined with the PARK wind farm flow model [3].
GCL is a superposition model based on a parabolic type of model, which combines wake deficits successively [30].
FUGA is a linearized flow solver based on the steady-state RANS equations. It uses a simple eddy viscosity turbulence closure and the Actuator Disk (AD) approach [31].
DMW is the dynamic wake meandering model that includes a stochastic model of the dynamics of the meandering frame of reference and added wake turbulence is included [32].
AD/RANS represents the VENTOS®/2 code [33, 34] with the momentum drag of a wind turbine is done implicitly using a uniformly loaded Actuator Disk model [13].
CRESflowNS [35] is a full 3D Navier–Stokes solver and using the reference velocity for thrust calculation, a parabolic procedure is applied [36].
FarmFlow is based on the UPMwake [37]. Atmospheric stability through the Monin-Obukhov length and the rotor is modelled as an actuator disc characterized by the thrust curve [38].
CFDWake is an elliptic CFD wind farm model, implemented in OpenFOAM, which allows simulating wake effects inside big wind farms through the actuator disc concept [39, 40].
RANS/fPC is based on the flow solver EllipSys3D [41] improved with RANS equations and turbulence modeled with the k-ε-fP [42] and include Coriolis force on wind turbine wake [43].
Ainslie model is based on the eddy viscosity model including both the turbulent mixing due to the turbulence generated by shear and the ambient turbulence [44].
WRF/UPM is based on WRF [45] and it is coupled to the CFD model UPMPARK [46] and thereby describes the diffusion of multiple wakes in the atmospheric surface layer.
Mesoscale (WRF) is combined with an explicit wake parametrization where wind turbine is treated as a drag device and cause only additional turbulence due to shear [17].

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