Executive Summary:
In line with the targets of the European Strategic Energy Technology Plan (SET Plan) of the European Commission, the project ClusterDesign was co-funded by the European Union. Six partners in four countries formed a consortium in order to build on three ideas:

• To give accurate projections of the energy production and the fatigue-life consumption of offshore wind farm clusters
• To account for the wind shadows caused by nearby wind farms, and control each farm with the aim of maximising production of the cluster of wind farms.
• To put wakes to advantage by carefully distributing wake losses over the wind farm.

The consortium has been developing or improving specific models since December 2011, and has integrated these into a ToolBox for Integrated Wind Farm Design, comprising:

• Meso-scale wind and stability atlas for the North Sea comprising a 20 year WRF simulation at 2 km² resolution
Advanced and fast wind farm wake models yielding the ambient conditions at each turbine location
- Turbine load response database (private)
- Electrical collection and grid connection models yielding a distribution of CAPEX and OPEX costs for a given layout considering a range of cabling topographies for and evaluation of virtual power plant (VPP) capabilities
- Wind farm control strategies (ECN’s active wake control)
- An IT infrastructure allowing easy integration of new models through definition of an API for that model
- A user-friendly graphical user interface and infrastructure to link all simulation outputs and present absolute and comparative simulation costs/outputs.

These models have been validated by:
- An extensive offshore measurement campaign comprising load measurements, met mast measurements, nacelle mounted 3D scanning lidar measurements and corresponding SCADA data.
- Performing testing of the ECN Active wake control concept on an onshore wind farm.

Users can test the demo available at www.cluster-design.eu.

The major outcomes of this project are:
- That the North Sea atmosphere is consistently more stable that that over the immediately surrounding land,
- That the load reduction of Active wake Control is very limited and well within design safety margins,
- That active wake control is only useful if turbines are placed quite close together, meaning that designers should take such control strategies into account at design phase, and
- A high quality offshore flow dataset which can be used for model evaluation for offshore wake models.

Project Context and Objectives:
The ClusterDesign project saw the development of a toolbox for integrated offshore wind farm cluster design combining different offshore wind farm design tools allowing the integration of the intelligent control of offshore wind farm clusters at the planning stage. These tools are intended for wind farm developers and manufacturers to assist in designing cost effective wind farm and cluster topologies, electrical connection configurations and topologies, as well as wind turbine and wind farm control strategies. The toolbox facilitates finding solutions that meet multiple criteria:
- maximising energy extraction
- reducing uncertainty of energy yield predictions,
- maximising income to cost ratios, and
- maximising power system support capability.

To achieve these goals the project concept consists of the following main elements:
- Modelling – Further development of existing models that each aim at optimizing major wind farm functionalities related to design and control in offshore applications: namely power production – loads – power system support (ancillary services). The set of models consists of advanced wake models, wind
power system support (ancillary services). The set of models consists of advanced wake models, wind farm electrical connection models, virtual power plant operation models, load and performance models and the related wind farm control concepts and models.

- Integration – Combination of the aforementioned models in a toolbox for integrated wind farm cluster design.
- Validation and improvement of the models and toolbox results against on-site measured data in an operating large offshore wind farm in the North Sea. Control concepts are applied as well in the same wind farm.
- Valorisation – Transforming the results into industrial applicable solution, thus, ensuring significant impact of the developed solutions.

Project Results:
The ClusterDesign project delivered important contributions that will support the further development of the exploitation of offshore wind energy resources as required by the European Strategic Energy Technology Plan. Particularly, the project will impact the reduction in the LCOE for offshore wind in the following ways:

Improved control of offshore clusters
- Development of wind farm cluster controller: Cluster Design focuses on the overall approach to combine different design optimization tools, grid interconnection models and grid connection designs with intelligent mechanisms for wind turbine, farm and cluster control. Within this project RWE Innogy was mainly involved in the conceptual design and the definition of requirements for a Wind Cluster Control System as well as the implementation and testing of ECN’s Active Wake Control Concept at the Goole Fields onshore wind farm.

Considering the impact of Cluster Design one can clearly state that the integrated offshore wind farm cluster design is the most promising approach in reducing the LCOE as one of the major challenges in offshore wind farm engineering is to offer energy at reasonable and cost competitive prices.

- Testing of ECN’s Active Wake Control Concept: This concept promises a net increase in power output and the reduction of loads and thus increasing the lifetime of the wind turbines. If this improvement of performance can be validated, ECN’s Active Wake Control Concept can directly impact the LCOE. As the cluster control is further enhanced, offshore wind farms can be operated as virtual power plants in the long term and therefore securing the energy supply through an increase in flexibility of power production. Having this in mind, the future economic impact of the Cluster Design project can be very relevant.

- Apart from the economic, the academic impact should also be regarded. Scientifically speaking, the implementation and testing of the Wake Control Concept displays a great opportunity to confirm theoretical ideas and push forward science and research. As mentioned, these ideas have great potential to reduce LCOE in the long term. This project paved the way for the first full-scale trial of this concept.

Reduced wind energy modelling costs
- PALM / Flex5 coupling: An important aspect of the ClusterDesign project that laid the basis for other current or future activities of the University of Oldenburg was the development of a coupling between the large eddy simulation model PALM and the aeroelastic code Flex5. Within the ClusterDesign project
Based on the experiences with the coupling from the large-eddy simulation side, the corresponding algorithms have been further developed in the framework of the national project CompactWind, where PALM has been coupled with the publicly available aeroelastic code FAST. In the currently running national project WIMS-Cluster it is one of the objectives to further develop the coupling algorithm. E.g. it is attempted to allow different time steps in the large-eddy simulation model and the aeroelastic code in order to save computational time. Moreover, the coupling should be extended from the actuator line model implemented in PALM to the enhanced actuator disc model with rotation implemented in PALM. Such a coupling would result in a significant reduction of the computational time required for the coupling of a turbulence-resolving flow model and an aeroelastic code. Recently, ForWind – University of Oldenburg has also applied for a new national research project, in which the coupled flow and aeroelastic models will be used in order to simulate the flow conditions in huge offshore wind farms. In this new project the results of the coupled flow and aeroelastic models should serve as a reference for simplified flow models, whose computational requirements are in a better agreement with the computational resources that are available to the industry. Once thoroughly validated a main application of the PALM-Flex5 building will therefore be to create data bases for controlled environmental (atmospheric) conditions that due to its low degree of parameterization allows for a better understanding of the physics of the interaction between the atmospheric boundary layer and wind energy converters and can afterwards be used to further develop cheaper engineering models. The main benefit of the coupled approach is that it can fully account for the dynamics of the wake. Another possible application of the coupling between the large-eddy simulations model and aeroelastic code are cases where engineering models obviously fail. The coupled models will help to understand why the engineering models are failing in these specific situations.

- Flap speed improvement: Effort has been spent to further enhance the speed of the FLaP model with in the ClusterDesign project.

- FLaP model development: An analytical wind farm wake model has been implemented into the wake model FLaP. In comparisons with measured data reported in literature this analytical wind farm wake model showed a convincing performance. Thus, FLaP can now be used to calculate the flow conditions in and energy output of wind farms that are in the wake of other wind farms, i.e. FLaP has been further developed to a wind farm cluster model. In several benchmarks for wake models during the project it could be shown that the very fast wake model FLaP, which is based on an Ainslie-approach, can deliver results that are in good agreement with much more complex, but considerably slower wake models. Thus, it can be justified to use FLaP to evaluate a huge number of different layouts of a wind farm in order to select a number of very promising ones. The application of the new binary output format NetCDF assures that even the output of a very huge number of simulations with FLaP can still easily be handed. The selected, most promising layouts of a wind farm can then be further analyzed with the means of a more complex wake model such as the model FarmFlow that has also been further developed in the framework of the ClusterDesign project to further reduce the uncertainties of the calculations. The combination of slower and faster wake models might contribute to the reduction of computational time required for the optimization of a wind farm layout.

Improved understanding of wake interaction:

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• Within the ClusterDesign project a unique LiDAR data set, several months of measurements of the flow conditions inside a wind farm, has been generated by applying a long-range LiDAR system of ForWind – University of Oldenburg. This dataset offers 4-D views on the structure of the flow within waked and unwaked regions allowing a leap forward in the understanding of these flows. Such datasets are to date rare in the field. The value of this data set has already been shown in the framework of the ClusterDesign project by further improving the wake models of ECN and FarmFlow on the basis of this data. However, so far only a small amount of the data could be been analyzed in the framework of the ClusterDesign project. It is expected that the full analysis of the data, which has high priority at several project partners of the ClusterDesign project even after the project has ended, will lead to further improvements of wake models.

Improved load modelling estimates
• FLaP output extended: Development of the model FLaP in the framework of the ClusterDesign project also included providing an interface to load modelling. The horizontal and vertical shear over the rotor layer is output by FLaP is now available as standard output, as well as the turbulence intensity at each turbine location. This additional information contributes to improved load calculations. Reduced uncertainties of load calculations might offer the possibility to adjust the design of wind turbines and finally to a reduction of the cost of offshore wind turbines. In the end this will contribute to a reduction of the levelized costs of offshore wind energy.

Improved resource estimates
• WASA stability: The wind and stability atlas derived in the framework of the ClusterDesign project points out that the atmospheric stability conditions over the North Sea are much different from those over the land. Unstable conditions occur more often over the sea than over the land. This might make offshore wind farms more attractive as under unstable conditions smaller wake effects can be expected. The higher attractiveness indicated by the wind and stability atlas might in the end lead to better financial conditions for new offshore wind farm projects and thus lower levelised costs of offshore wind energy.

• WRF model parameterization: Within the ClusterDesign project it as shown that the quality of data provided in the wind and stability atlas (WASA) which was derived from WRF mesoscale simulations has some advantages in comparison with data sets published before the ClusterDesign project. Due to an optimized set up of the parameters of the mesoscale simulations, from which the most important ones are the planetary boundary layer model, the nudging options and the high spatial resolution of 2 km, as well as sea-surface data, e.g. the root-mean square error could be reduced considerably compared to earlier studies.
• WASA timescale: Another advantage of the WASA generated in the ClusterDesign project that contributes to a better knowledge on the atmospheric conditions over the North Sea is the long period of twenty years that is covered by the wind atlas. Wind atlases typically cover periods up to 10 years, but it has been shown within the framework of the ClusterDesign project that data from such long periods is required in order to achieve a high accuracy of the wind estimates.

• WASA structure: Another advantage of the wind and stability atlas is that it offers time series instead of statistics. This makes the data very easy to use by wake models and preserves real combinations of several atmospheric parameters. The wind and stability atlas is also unique in the number of parameters that it offers, e.g. also atmospheric stability, turbulence intensity and shear. All of these parameters are key factors for improved energy yield and load calculations for new wind farms.

Reduction of LCOE

Supporting reduced-carbon economy: Towards the general public, one always has the obligation to offer benefits for society. As RWE Innogy might be able to lower the LCOE with the help the outcomes of the Cluster Design project, offshore wind energy becomes more competitive to conventional energy production. Offering a carbon free and stable power production, wind energy can experience a rising acceptance in the society.

All these activities would not have been possible without the results achieved in the ClusterDesign project.

Potential Impact:
The ClusterDesign project delivered important contributions that will support the further development of the exploitation of offshore wind energy resources as required by the European Strategic Energy Technology Plan. Particularly, the project will impact the reduction in the LCOE for offshore wind in the following ways:

Reduced modelling costs
• PALM / Flex5 coupling: An important aspect of the ClusterDesign project that laid the basis for other current or future activities of the University of Oldenburg was the development of a coupling between the large-eddy simulation model PALM and the aeroelastic code Flex5. Within the ClusterDesign project based on the experiences with the coupling from the large-eddy simulation side, the corresponding algorithms have been further developed in the framework of the national project CompactWind, where PALM has been coupled with the publicly available aeroelastic code FAST. In the currently running national project WIMS-Cluster it is one of the objectives to further develop the coupling algorithm. E.g. it is attempted to allow different time steps in the large-eddy simulation model and the aeroelastic code in order to save computational time. Moreover, the coupling should be extended from the actuator line model implemented in PALM to the enhanced actuator disc model with rotation implemented in PALM. Such a coupling would result in a significant reduction of the computational time required for the coupling of a turbulence-resolving flow model and an aeroelastic code. Recently, ForWind – University of Oldenburg has also applied for a new national research project, in which the coupled flow and aeroelastic models will be used in order to simulate the flow conditions in huge offshore wind farms. In this new project the results of the coupled flow and aeroelastic models should serve as a reference for simplified flow models, whose computational requirements are in a better agreement with the computational resources that are available.
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• Flap speed improvement: Effort has been spent to further enhance the speed of the FLaP model in the ClusterDesign project. The model is already fast, but further speed improvements along with quality improvements can lead to this model being chosen in favour of other models by park/cluster designers, thus bringing commercial exploitation to ForWind.

• FLaP model development: An analytical wind farm wake model has been implemented into the wake model FLaP. In comparisons with measured data reported in literature this analytical wind farm wake model showed a convincing performance. Thus, FLaP can now be used to calculate the flow conditions in and energy output of wind farms that are in the wake of other wind farms, i.e. FLaP has been further developed to a wind farm cluster model. In several benchmarks for wake models during the project it could be shown that the very fast wake model FLaP, which is based on an Ainslie-approach, can deliver results that are in good agreement with much more complex, but considerably slower wake models. Thus, it can be justified to use FLaP to evaluate a huge number of different layouts of a wind farm in order to select a number of very promising ones. The application of the new binary output format NetCDF assures that even the output of a very huge number of simulations with FLaP can still easily be handed. The selected, most promising layouts of a wind farm can then be further analyzed with the means of a more complex wake model such as the model FarmFlow that has also been further developed in the framework of the ClusterDesign project to further reduce the uncertainties of the calculations. The combination of slower and faster wake models might contribute to the reduction of computational time required for the optimization of a wind farm layout. These quality improvements can lead to this model being chosen in favour of other models by park/cluster designers, thus bringing commercial exploitation to ForWind.

Improved understanding of wake interaction:
• Flap developed to allow turbine control: The speed of the FLaP model and the fact that the model has been coupled with the mesoscale model WRF in the framework of the ClusterDesign project opens the possibility to use the wake model FLaP also for the purpose of controlling a wind farm during its operation. The model can now be easily fed with data from a numerical weather prediction model and with the achievements of the ClusterDesign project even the status of the wind turbine can be taken into account in the calculations. By running the model for different operational modes of the wind farm the optimal solution for a certain expected weather situation can be determined. This is another contribution to the optimization of power production by offshore wind farms achieved in the ClusterDesign project. This additional functionality of Flap increases the use cases and applicability of the model, thereby increasing its effectiveness in exploitation.
• Within the ClusterDesign project a unique LiDAR data set, several months of measurements of the flow conditions inside a wind farm, has been generated by applying a long-range LiDAR system of ForWind – University of Oldenburg. This dataset offers 4-D views on the structure of the flow within waked and unwaked regions allowing a leap forward in the understanding of these flows. Such datasets are to date rare in the field. The value of this dataset has already been shown in the framework of the ClusterDesign project by further improving the wake models of ECN and ForWind – University of Oldenburg on the basis of this data. However, so far only it has only been possible to analyze a small amount of the data in the framework of the ClusterDesign project. It is expected that the full analysis of the data, which has high priority for several project partners of the ClusterDesign project even after the project has ended, will lead to further improvements of wake models. Improvement of wake models will allow improved design of on and offshore parks, reducing the LCOE for these parks. The dataset itself may also be sold in the future to interested parties.

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Improved resource estimates
• WASA stability: The wind and stability atlas derived in the framework of the ClusterDesign project points out that the atmospheric stability conditions over the North Sea are much different from those over the land. Unstable conditions occur more often over the sea than over the land. This might make offshore wind farms more attractive as under unstable conditions smaller wake effects can be expected. The higher attractiveness indicated by the wind and stability atlas might in the end lead to better financial conditions for new offshore wind farm projects and thus lower levelised costs of offshore wind energy. This can be exploited by direct sale of the dataset, as well as by inclusion in offers for commercial sales of the ClusterDesign ToolBox.

• WRF model parameterization: Within the ClusterDesign project it has been shown that the quality of data provided in the wind and stability atlas (WASA) which was derived from WRF mesoscale simulations has some advantages in comparison with data sets published before the ClusterDesign project. Due to an optimized set up of the parameters of the mesoscale simulations, from which the most important ones are the planetary boundary layer model, the nudging options and the high spatial resolution of 2 km, as well as sea-surface data, e.g. the root-mean square error could be reduced considerably compared to earlier studies.

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Improved virtual power plant capabilities
• Delecto electrical model: The electrical tool allows evaluation of the Virtual Power Plant capabilities for each electrical design alternative considering the outputs from other tools as wind resource, the site and wind turbine characteristics. In addition the VPP module of the electrical tool is the starting point for the wind farm cluster control tool which enables running offshore wind farms by a central control entity in order to increase the offshore system flexibility. This could be exploited by including the tool in offshore control mechanisms either as part of or separately to, the ClusterController developed within the ClusterDesign project.

The electrical modelling tool allows foreseeing the required wind power plant capabilities in line with current and future grid codes. This feature is essential in order to increase power system reliability for high levels of wind penetration in the electrical power system. From a technical point of view, the design of offshore wind farm clusters for operating in virtual power plants in combination with the control tool contributes to an increase in overall power system efficiency due to a reduction of losses in the electrical system.

Offshore topology cost reduction
• Delecto electrical model: The electrical tool contributes to the reduction in LCOE of offshore wind by considering the cost and reliability of the electrical components of each evaluated alternative and their impact in the expected energy curtailed during the life of the offshore wind farm. The cost benefit analysis between reduced CAPEX and increased OPEX estimates the long term cost associated with a range of topologies. Combined with the output of the resource, wake and prodduction estimate models, this permits the overall optimisation of the entire wind farm as part of a cluster, reducing the lifetime cost of energy. This tool will be exploited as part of the ClusterDesign ToolBox; this ields unique selling point to the ToolBox.

• Corrective control: The electrical design tool in the present is based in the philosophy that against specific disturbances the system security is ensured primarily through redundancy in assets. This results in a higher investment and low utilisation of network assets. Given the recent developments in ICT and control technologies, decision making can be moved much closer to real-time thus enabling a shift towards a corrective control paradigm. By relying on post fault corrective measures, operators can drive the system closer to its limit without unduly restricting its operation to ensure recoverability in the event of a fault. This ability would result in significant savings in network infrastructure investment. This can be exploited in the
ability would result in significant savings in network infrastructure investment. This can be exploited in the future after further research on this topic.

All of these impacts, both commercially exploitable now and in the future as well as scientific in nature would not have been possible without the benefit of the ClusterDesign project.

List of Websites:
www.cluster-design.eu
Contact
Achim Woyte
AWO@3e.eu

Related documents

[Link]

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