EUDP

Final report

General information (delete this section)

*Depending of project type, project size and project complexity the **number of pages** in the final report may vary. For smaller **development and demonstration** projects, the final report normally should not be more than 20 pages plus possible relevant appendices. For larger **research, development and demonstration** projects, the final report should not be more than 50 pages.*

The final report will be used for dissemination purposes and the information stated in the final report should be suitable for dissemination. The final report will be published at www.energiteknologi.dk.

*The guidance text (in italic) should be deleted, so the application form **only** contains numbered headings as well as relevant text from the applicant.*

1. Project details

Project title	Large Scale Offshore Wake Impact on the Danish Power System (OffshoreWake)
File no.	EUDP/ForskEL 64017-0017/12521
Name of the funding scheme	EUDP
Project managing company / institution	DTU
CVR number (central business register)	30 06 09 46
Project partners	Vattenfall
Submission date	27 September 2022

2. Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future.

The short description should be in two versions:

- *English version*
- *Danish version*

Each version should be brief, no more than 2000 characters (including spaces).

English version:

This project aims at improving the operation of the Danish power system, through building a more accurate wind to power calculation system by taking into account of the large wind farm wake effect, as well as the sea conditions.

The obtained results include a comprehensive modelling system in which key model components are coupled, including wind, wave, wake and power balancing. The system uses WRF for atmospheric modelling, with the wind farm wake effect calculated using the Explicit Wake Parameterization (EWP) and Wind Farm Parameterization (Fitch) schemes. The WRF model is coupled to the wave model SWAN and ocean model ROMS, and provides input to the power balancing model CORres.

This modelling system was built with and tested with cases and input data from the North Sea region and Denmark for power balancing. Though the modelling system can be applied to any regions. In the future, we envision it to be applied in larger regions than Denmark, e.g. for all North Europe. Part of the modelling system can and have also been used for multiple purposes. For instance, for offshore forecasting for O&M, our wind and wave coupled modelling (WRF-SWAN) can provide simultaneous wind and wave parameters. For estimating resource and planning, WRF with EWP and Fitch schemes are being extensively used, where both real and future wind farm scenarios are examined. The hindcast from the various combinations of these model components can be used to study long tern trend and climatological impact on e.g. wave field, wind field and power systems.

Dansk

Formålet med dette projekt er at forbedre driften af det danske elsystem gennem udviklingen af et modelkompleks som inkluderer skyggeeffekten mellem havmølleparker og strømningsforholdene i en integreret beregning af effekten fra havmølleparker og dens betydning for balanceringen af det danske elsystem.

Resultatet af projektet er først og fremmest et omfattende modelkompleks som kobler modeller for vindfluktuationer, bølger, skyggevirkninger, konvertering til effekt og endelig en model for balancering af det danske elsystem. Vindfluktuationerne beregnes vha. WRF atmosfæriske modeller mens skyggevirkningen tilføjes vha. Explicit Wake Parameterization (EWP) og Wind Farm Parameterization (Fitch) skemaer. WRF modellen er koblet sammen med bølgemodellen SWAN and havmodellen ROMS, og giver vindhastighedstidsserier til beregning af tidsserier for effektfluktuationer og effektprognoser med CorRES, som derefter anvendes til simulering af balanceringen i det danske elsystem.

Modelkomplekset er udviklet og verificeret med forskellige eksempler i Nordsøen, hvor effekten fra havmølleparkerne indgår i simuleringen af balanceringen af det danske elsystem. Men modelkomplekset kan også anvendes i andre regioner. Fremadrettet forestiller vi os at modelkomplekset anvendes til simulering af balancering i større områder, f.eks. hele Nordeuropa incl. Nordsøen og Østersøen. Dele af modelkomplekset kan desuden anvendes til en række andre formål. F.eks. kan kan koblingen af vind (WRF) og bølgemodeller (SWAN) anvendes til at planlægge vedligehold af havmølleparker, mens kombinationen af WRF, EWP opg Fitch kan anvendes til at undersøge scenarier for udbygningen med offshore havmølleparker. Modelkomplekset kan desuden anvendes til langtidsforudsigelser af klimaforandringer og deres indvirkning på elforsyningen.

3. Project objectives

- *What was the objective of the project?*
- *Which energy technology has been developed and demonstrated?*

We would like to draw the readers' attention that this project was originally a ForskEL project, not EUDP project, so that the focus has been research and development. EUDP took over the coordination in 2017 when ForskEL does not exist any longer. This leads to that this current report is rather brief and we direct the readers to Appendix-A, which is the complete technical report of this project.

The overall objective of this project is to make the operation of the Danish power system more effective through a more accurate estimation of the time varying offshore wind power modelling. The primary objective is to take into account the large scale wakes from neighbouring wind farms in the current wind-to-power calculation system. A secondary objective is to advance the offshore wind farm wake calculation by providing more accurate sea surface conditions through coupling an ocean wave model to the wind and wake models.

We developed and advanced the wind energy technology in the following aspects: the modeling ability in including the wind farm wake effect into the wind resource and power balancing calculation; the modeling ability in including the interaction effects between wind, waves and wakes; the extraction and post-processing of the weather model output for the power balancing calculation. A series of cost-efficient and effective methods are developed and test to obtain long-term, climatologically representativeness of the effects. Please refer to Appendix-A for the details.

4. Project implementation

- *How did the project evolve?*
- *Describe the risks associated with conducting the project.*
- *Did the project implementation develop as foreseen and according to milestones agreed upon?*
- *Did the project experience problems not expected?*

The project started as expected. Project members were engaged and the project progresses. We have a monthly meeting (last Monday of each month), where people report progress and challenges, and discuss solutions and make plans.

However, this project has been challenged by a long list of risks. Within the first year, three personals left the project, due to various reasons. The colleague at Vattenfall was sick and left Vattenfall. Our key scientists, one post doc and one researcher, both left Denmark for their home countries because of family reasons. Additional members left DTU in the following years due to the status of their contract and they found jobs elsewhere. In 2020, we all suffered from COVID. At DTU, one colleague accidently deleted a lot of our data from the super computer that are related to this project. At the same year, yet another colleague became ill.

The solutions to these challenges have been to involve all members in the team, relocate tasks and recourses, recruit new members and coordinate with EUDP to adjust time lines and budget. With extension of 14 months, we are relieved and proud to deliver the project.

The above mentioned challenges slowed down our process, but it did not change the path of the development of the project. We were able to develop the implementation as planned and according to milestones agreed upon.

In our proposal the expected risks include the commitment of the partner, data shortage, technical difficulties in developing the modelling system and implementing the codes to software. Among these, only data shortage was encountered, and our solution is to introducing data from other wind farms, which will support the project the same way as the originally designed dataset. It is however unexpected that so many of our colleagues for so many “life-related” reasons have to leave the project. It is also unexpected that someone deleted our data by accident. It is of course also unexpected COVID would hit us all.

5. Project results

- *Was the original objective of the project obtained? If not, explain which obstacles that caused it and which changes that were made to project plan to mitigate the obstacles.*
- *Describe the obtained technological results. Did the project produce results not expected?*
- *Describe the obtained commercial results. Did the project produce results not expected?*
- *Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.*
- *Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.*

The original objectives of the project was obtained.

The obtained technological results are all expected and they include:

- The coupling of wind model, wake model and wave model (The WWW model)
- The coupling of WWW model to the power balancing system
- The development of methods for assessing long term effect of winds, waves and wakes
  - Representative-year method
  - Selective dynamical downscaling
  - Classes of wind conditions
- The fully coupled modelling system including wind, wave, wake and power balancing

As explained earlier, this project was originally a forskEL project, therefore there are no commercial development involved.

The end users include

- Transmission System Operators (TSO)
- Energy planners
- Wind farm owners/developers
- Commercial wind power forecasters
- Academic institutes

The project has been disseminated in a variety channels, including

- Conferences:
  - EGU (European Geophysical Union),
  - WESC (Wind Energy Science Conference),
  - EMS (European Meteorological Society),
  - Deepwind,
  - ICEM (International Conference of Energy and Meteorology)
  - WindEurope
- Workshops:

    - 18th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Dublin, 2019;
    - EERA JP wind 2021;
    - MMC-sponsored Industry Workshop: Atmospheric Science Challenges for the Wind Energy Industry 2020;
    - International workshop on the specific issues of Taiwan offshore wind farm
- Journals:
    - Geosci. Model Dev.;
    - Boundary-Layer Meteorol.;
    - Quarterly Journal of the Royal Meteorological Society;
    - Wind Energy Science;
    - Frontiers for energy.

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*
- *Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.*
    - *Did the project so far lead to increased turnover, exports, employment and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment and additional private investments?*
- *Describe the competitive situation in the market you expect to enter.*
    - *Are there competing solutions on the market? Specify who the main competitors are and describe their solutions.*
- *Describe entry or sales barriers and how these are expected to be overcome.*
- *How does the project results contribute to realise energy policy objectives?*
- *If Ph.D.'s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities.*

As explained earlier, it is originally a ForskEL project, and there are no "commercial results" proposed the first place and it is not relevant for competitive situation, sales.

Here we will only address the "technological results", and the future use and by whom:

- The more accurate power prediction, is useful for Transmission System Operators (TSO), such as Energinet.dk
- The tools from this project to improve regional cost estimate, and to pre-calculate the wake losses of existing wind farms when tendering out new adjacent areas for wind farms, are useful for Energy planners, such as the Danish Energy Agency
- The tools from this project to obtain better financing and better ability to trade electricity on the market is useful for wind farm owners/developers, such as Vattenfall, Ørsted and Eqinor
- Some of our model modules are useful for commercial wind power forecasters, such as ENFOR. They would be interested in including these into their systems. Some companies find the wind-wave coupled modelling system for providing the simultaneous wind and wave field attractive for offshore O&M activities, and particularly for the development of floating wind
- The scientific and technological development regarding the studies of physics and numerical modelling are attractive for academic institutes. Several of them have contacted us for that.

For the original ForskEL project, we coupled one existing PhD project to this project and supported 20% of the work. The work includes several parts: 1) extensive tests of wind farm setups and investigation of its effect 2) implementation of EWP scheme in a new atmospheric model, the flex mesh global model MPAS, in comparison with WRF model. The studies have been disseminated at a number of conferences, included in the PhD thesis and now under development of a journal paper.

7. Project conclusion and perspective

- *State the conclusions made in the project.*
- *What are the next steps for the developed technology?*
- *Put into perspective how the project results may influence future development*

The conclusions made in the project include:

- About the modelling system:
  - The coupling of modelling components is successful.
  - The modelling system is robust and yet flexible. The calculation is efficient even taking all components into account, including wind, wave, wake and power balancing. The flexibility is in the use of different pieces of the modelling system, being wind-wake, wind-wave, wind-wave-wake and their combination with power balancing
  - The modelling system is useful for long-term, climatological, studies
  - The modelling system is useful for focused, case specific studies when we try to understand specific physics and feedback in the model.
  - The modelling system can be used for a variety of purposes, with examples given in section 6.

- About the wakes
  - The wind farm wake effects are not negligible and they need to be taken into consideration when calculating the resources
  - The wind farm wake effect needs to be taken into consideration when balancing the power
  - The wind farm wake effects are affected by the farm displacement, turbine type, density and distance to and upwind wind conditions to the neighbouring wind farms
  - The wind farm wake can extend to a few to hundreds of meters, depending on the stability conditions and wind farm (turbine) characteristics

- About the interaction between wind, wave and wakes
  - The impact on the winds at hub height is secondary, compared to the wake effect, within the operational wind speed range
  - The effect of wakes on the wave field can be of a few percentage, which is not negligible
  - The simultaneous information about wind, wave and wake from a physics-consistent modelling system is useful for a wide range of offshore applications, including O&M, floating wind etc.

The next step for the developed technology can be in two main directions. One is application and one is for further research. For application, we need to reach out to various end users. For further research, there are still more that can be improved. One is to improve the wake parameterization. The situation is that we created a lot of model results, but the validation part is rather week due to lack of measurements. Thus to obtain the detailed spatial and temporal variation of the wind field in the presence of wakes, we still need more measurements to understand it, before improving the modelling. The wave modelling also needs strengthening for a few conditions, including swell and coastal. Since the wake effects are most predominate during stable conditions, the air-sea exchange of not only momentum, but also heat needs further investigation, in order to improve the model credibility.

This project is a pioneer in this field. We set an example that it is doable and how to do it.

8. Appendices

- *Add link to relevant documents, publications, home pages etc.*

The project link is www.offshorewake.dk

The technical details of this project is documented in Appendix A: Large Scale Offshore Wake Impact on the Danish Power System. The complete publication list is in Chap 11, which can also be found from https://www.offshorewake.dk/publications

Appendix B is a zip file that includes all deliverables from this project.