Reducing LCoE from offshore wind by multiscale wake modeling

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Acronyms and Abbreviations

CF	Capacity Factor
Consortium	The National Offshore Wind Research and Development Consortium
DTU	Danish Technical University
ERA5	A climate reanalysis dataset from the European Center for Medium-Range Weather Forecasts
EWP	Explicit wake parameterization (New, alternative wind farm parameterization, not standard in WRF)
Fitch	Wind farm wake parametrization by Anna Fitch for use in WRF
FUGA	A wake model for wind farms
HPC	High performance computing
kWh	kiloWatt hours
LCoE	Levelized Cost of Energy
LLJ	low-level jet
ms^{-1}	meters per second
MW	megawatts
NOJ	Niels Otto Jensen parameterization used as the baseline in the microscale modeling
NOWRDC	National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
PARK	Also known as the Jensen model for wakes within wind farms
W	Watts
WRF	Weather and Research Forecasting Model

Executive Summary

The aim of this research was to quantify atmospheric flow characteristics and within wind farm and between wind farm wake losses to provide sufficient technical detail about the US offshore environment to simulate both the impact of turbine layouts and multiple wind farms on the levelized cost of energy.

High resolution WRF simulations of wind turbine wakes in and behind the US East coast lease areas using both the Fitch and EWP wind farm parameterizations were undertaken. Simulations of 11 representative 5-day periods with representative atmospheric conditions have been performed for 4 different layouts: (i) control (uniform spacing of 1.85 km in the south-north and east-west directions, approx. installed capacity density of 4.3 $MWkm^{-2}$), (ii) corridor (every 6th north-south column from (i) removed), (iii) half density (approx. installed capacity density of 2.1 $MWkm^{-2}$) and (iv) a higher density (approx. installed capacity density of 6 $MWkm^{-2}$) layout. Power losses due to wakes in the control layout are around 35% of total power. Wakes defined as a 5% normalized velocity deficit are shown to extend over very large distances – in some cases over 90 km.

Extensive microscale modeling using NOJ and FUGA parameterizations has been undertaken. Six wind turbine layouts were initially simulated for the 16 east coast lease areas: Control (1.85 km spacing), maritime corridors, double and half densities (i.e. layouts (i)-(iv) used in the mesoscale modeling), plus two layouts that are rotations of the control spacing where the layouts are rotated about a central point by 30° and by 60°. Initial results suggest limited benefit to changing row orientation (i.e. the rotation) in terms of annual energy production for the NY lease area. This prompted selection of the 6 $MWkm^{-2}$ installed capacity density as the final simulation with WRF using both EWP and Fitch wind farm parameterizations. This provides more detail for a wider range of turbine densities similar to those used in European offshore wind farms. A levelized cost of energy model was developed. Simulations for NY show that in general NOJ generates higher AEP than FUGA and the levelized cost of energy model results are consistent with this.

In terms of the configuration of wind farms the results are more sensitive to the installed capacity density than to the row orientation. However it is also clear that the uncertainty in the long-term direction distribution is critical. Further, there may be environmental or other benefits from particular configurations e.g. using a maritime corridor.

In addition to outreach and collaboration with other institutions working on related topics, results from the model simulations were published in high quality journals and presented at conferences and seminars.

Advisory Board

- Nicolai Nygaard (Ørsted)
- Nick Smith (Shell Offshore)
- Cedric Dall'Ozzo (EDF)
- Shannon Davis (DOE)
- Ben Hallissy (DOE)
- Mike Robinson (NREL)

1 Task 0: Project Management And Progress Reporting

1.1 Project team

In addition to the two principal investigators we had a full-time postdoctoral fellow Tristan Shepherd working on the project and a graduate student; Jeanie Aird (who is supported financially by a National Science Foundation Graduate Fellowship).

1.2 Project meetings

Regular quarterly meetings with the Consortium staff, DoE, the Advisory Board and the PI's were held via zoom. Presentations were submitted and a short report of each meeting given in the quarterly reports.

1.3 Outreach

The project was presented at the National Offshore Wind R&D Symposium 2020 and 2021.

RB and SP also participated in Resource Characterization and Siting for the future of Offshore Wind Energy Discussion Agenda Roundtable led by Shannon Davis of DoE for the Congressional Report on Offshore Wind Energy 24 March 2021.

Our project was featured as the National Offshore Wind Research & Development Consortium project of the week 12 March 2021. Link here!

The project PIs have held discussions to enable knowledge sharing and collaboration with other NOWRDC projects (listed by lead organization and title of project) and other interested parties:

- General Electric (PI: Jing Le, NREL lead: Eliot Quon): Impact of Low Level Jets on Atlantic Coast Offshore Wind Farm Performance. Meeting date: March 31 2021. The overarching objective of the meeting was to examine potential overlap/symbioses in terms of modeling strategies.
- On June 16 2021 the Cornell team met with the NREL teams on the NOWRDC projects: Wind Farm Control and Layout Optimization for U.S. Offshore Wind Farm (PI: Paul Fleming, NREL) and A Validated National Offshore Wind Resource Dataset with Uncertainty Quantification (PI: Mike Optis, NREL). Note: RJB and SCP are co-PI's on the first award. The collaboration continued through 2022.
- We visited and held discussions at Ørsted Denmark with Marjin Veraat (and Jakob Kronberg remotely) 28 June 2021.
- Through summer 2021 and 2022 we held a number of meetings and discussions on wakes and wake modeling at the Danish Technical University (DTU) including:
    - with the Resource Modeling Head of Section Jake Badger and Marc Imberger to discuss DTU's Agora study (see details of our comparative analyses in Pryor et al. (2021) Joule).
    - with the WRF expert Andrea Hahmann and her graduate student Oscar Manuel Garcia Santiago

- with members of the WAsP team Rogier Floors and Morten Nielsen
- with member of the FUGA team including Gunner Larsen
- with members of the py-wake team including Mads Mølgaard Pedersen**.**

A framework website for reporting was made: Web site http://www.geo.cornell.edu/eas/PeoplePlaces/Faculty/spryor/OffshoreWakes/index.html

The project was featured at Cornell: https://www.eas.cornell.edu/news/harnessing-vast-offshore-wind-energy-resource and https://cals.cornell.edu/news/grant-supports-development-efficient-offshore-wind-farms and in the Cornell Chronicle 10/13/2020 https://cals.cornell.edu/news/grant-supports-development-efficient-offshore-wind-farms

A synthesis of research under this award for a trade magazine WindTech International was published in the May/June 2022 issue. This is part of our efforts to make this research more directly accessible to those working in the wind energy industry. The article is entitled 'Wind, waves and wakes for the U.S. east coast offshore lease areas'(Barthelmie et al. 2022a). It briefly summarizes; extreme wind and wave conditions, low-level jets and wakes analyses for the US East coast lease areas.

1.4 Papers and presentations

International reviewed papers published:

Barthelmie, R.J., Letson, F., Aird, J.A. and Pryor, S.C. 2022: Wind, Waves and Wakes for the US East Coast Offshore Lease Areas, *WindTech International*, May/June 2022. https://www.windtech-international.com/editorial-features/wind-waves-and-wakes-for-the-us-east-coast-offshore-lease-areas

Pryor, S.C.; Barthelmie, R.J.; Shepherd, T.J.; Hahmann, A.N.; Garcia Santiago, O.M. Wakes in and between very large offshore arrays. *Journal of Physics: Conference Series* 2022, *2265*, 022037, doi:10.1088/1742-6596/2265/2/022037.

Barthelmie, R.J.; Larsen, G.C.; Mølgaard Pedersen, M.; Pryor, S.C. Microscale modelling of wind turbines in the New York offshore lease area. *Journal of Physics: Conference Series* 2022, *2265*, 022040, doi:10.1088/1742-6596/2265/2/022040.

Aird, J.A.; Quon, E.W.; Barthelmie, R.J.; Pryor, S.C. Region-based convolutional neural network for wind turbine wake characterization from scanning lidars. *Journal of Physics: Conference Series* 2022, *2265*, 032077, doi:10.1088/1742-6596/2265/3/032077.

Aird, J.A., Barthelmie, R.J., Shepherd, T.J. and Pryor, S.C. 2022: Occurrence of Low-Level Jets over the Eastern US Coastal Zone at Heights Relevant to Wind Energy, Energies, *Energies,* 15*, 445.*

Pryor, S.C., Barthelmie, R.J. and Shepherd, T. 2021: "Wind power production from the U.S. east coast offshore lease areas", *Joule*, 5, 2663–2686.

Aird, J.A., Quon, E., Barthelmie, R.J., Debnath, M., Doubrawa, P. and Pryor, S.C. 2021: Region-Based Convolutional Neural Network for Wind Turbine Wake Characterization in Complex Terrain, *Remote Sensing*, 13(21), 4438.

Pryor S.C. and Barthelmie R.J. (2021): A global assessment of extreme wind speeds for wind energy applications. *Nature Energy* **6** 268-276 doi: 10.1038/s41560-020-00773-7.

Barthelmie R.J., Dantuono K., Renner E., Letson F.W. and Pryor S.C. (2021): Extreme wind and waves in U.S. east coast offshore wind energy lease areas. *Energies* 14 1053 doi: 10.3390/en14041053.

Presentations:

Pryor, S.C. and Barthelmie, R.J. 2023: Inter- and Intra-Array Wake Losses for the US East Coast Offshore Lease Areas. *Wind Energy Science Conference, 23-26 May 2023, Glasgow, UK.*

Hallgren, C., Aird, J.A. Ivanell, S., Körnich, S.H., Vakkari, V., Barthelmie, R.J., Pryor, S.C., Sahlée, E. 2023: Machine Learning Methods to Improve Offshore Low-Level Jet Predictions by ERA5, *Wind Energy Science Conference, 23-26 May 2023, Glasgow, UK.*

Foody, R., Barthelmie, R.J., Coburn, J.J. and Pryor, S.C. 2022: Wind Resources and Operating Conditions in the New York Bight Offshore Lease Areas. *AGU Fall Meeting 2022*.

Barthelmie, R.J., Larsen, G.C., Mølgaard Pedersen, M. and Pryor, S.C. 2022: Microscale modeling of wind turbines in the New York offshore lease area, S*cience of Making Torque from Wind*, Delft, 1-3 June 2022.

Pryor, S.C., Barthelmie, R.J., Shepherd, T.J., Hahmann, A.N. and Garcia Santiago, O.M. 2022: Wakes in and between very large offshore arrays, S*cience of Making Torque from Wind*, Delft, 1-3 June 2022.

Aird, J.A., Quon, E., Barthelmie, R.J. and Pryor, S.C. 2022: Region-Based Convolutional Neural Network for Wind Turbine Wake Characterization from Scanning Wind Lidars, S*cience of Making Torque from Wind*, Delft, 1-3 June 2022.

Pryor, S.C. and Barthelmie, R.J. 2022: Extreme wind and wave conditions, *Air-Sea interactions and implications for offshore wind energy*. 10-11th February 2022.

Barthelmie, R.J. and Pryor, S.C. 2022: Wind turbine wakes offshore, *Air-Sea interactions and implications for offshore wind energy*. 10-11th February 2022.

Pryor, S.C., Barthelmie, R.J. and Shepherd, T.J 2022: Power and Wakes in the U.S. East Coast Offshore Lease Areas, *American Meteorological Society Annual Conference*, 25 January 2022.

Pryor, S.C., Shepherd, T.J. and Barthelmie, R.J. 2021: Wind power production from the U.S. east coast offshore lease areas. *AGU Fall Meeting*. December 2021. ID# 901943.

Pryor, S.C. and Barthelmie, R.J. 2021: *Reducing LCoE from offshore wind by multiscale wake modelling*, at the NOWRDC Seminar, 9 November 2021 (Held virtually).

Pryor, S.C. and Barthelmie, R.J. 2021: Reducing LCoE from offshore wind by multiscale wake modelling, *Seminar at the Danish Technical University* and via zoom, 1 July 2021.

Barthelmie, R.J., Shepherd, T.J. and Pryor, S.C. 2021: Offshore wakes in the US East coast lease areas. *Wind Energy Science Conference*, 25-28 May 2021.

Pryor, S.C., Barthelmie, R.J., Shepherd, T.J. and 2021: 20% of US electricity from onshore wind: Impacts on wakes, system efficiency and regional climate, *Wind Energy Science Conference*, 25-28 May 2021.

Aird, J.A., Quon, E.W., Barthelmie, R.J., Debnath, M., Doubrawa, P.D., Pryor, S.C. 2021: Region-Based Convolutional Neural Network for Wind Turbine Wake Characterization in Complex Terrain**,** *Wind Energy Science Conference*, 25-28 May 2021.

Aird, J.A., Barthelmie, R.J., Pryor, S.C. and Shepherd, T.J. 2021: Coastal Low-Level Jets over the Northeastern US Atlantic: Implications for Offshore Wind Resources, *Wind Energy Science Conference*, 25-28 May 2021.

Shepherd, T.J., Barthelmie, R.J. and S.C. Pryor 2021: Sensitivity of wind turbine wake effects and array-array interactions to wind farm parameterization and model resolution, *Wind Energy Science Conference*, 25-28 May 2021.

Aird, J.A., Barthelmie, R.J., Pryor, S.C. and Shepherd, T.J. 2021: Coastal Low-Level Jets over the Northeastern US Atlantic: Implications for Offshore Wind Resources, *Wind Energy Science Conference*, 25-28 May 2021.

Shepherd, T.J., Barthelmie, R.J. and S.C. Pryor 2021: Sensitivity of wind turbine wake effects and array-array interactions to wind farm parameterization and model resolution, *Wind Energy Science Conference*, 25-28 May 2021.

2 Task 1: Macroscale Flow Conditions

To provide high-performance computing for the project a series of proposals had to be written and submitted to XSEDE. These were authored by Professor Pryor. The obtained resources were substantial but still required intensive management to meet the project needs. This was mainly due to the high-resolution (temporal and spatial) simulations undertaken over an extensive domain. Management focused on how to utilize these resources to enable both (1) analysis of existing model output from (a) output from our high-resolution (1.33 km by 1.33 km) WRF simulations (July 2009-June 2011) and (b) the ERA5 reanalysis/other data sets and (2) conduct new WRF simulations of wind farm wakes.

We compiled sources for other offshore data sets that could potentially be used for validation such as reanalysis data, satellite and in situ observations. Data have been obtained and code has been written to access and process these datasets including NCDC offshore buoys and NYSERDA/Ørsted buoy lidar (Figure 2.1). We've downloaded wind and wave data from ERA5 for the offshore lease areas for the period 1979-2018 that can be utilized to describe the wind climate and identify representative scenarios. Analysis of ERA5 reanalysis output and in situ/remote sensing observations was used to characterize extreme wind and wave climates in the lease areas. A paper was published in the journal Energies that quantifies expected the extreme (50-year return period) wind speed at/near hub-height and the 50 and 1 year return period maximum and significant wave heights in the 16 offshore wind energy lease areas along the US east coast (Barthelmie et al. 2021). Global estimates of the fifty-year return period wind speed at a nominal height of 100-m a.g.l. were published. The entire digital atlas is available for download from ZENODO doi: 10.5281/zenodo.4306822 and are described in full in: Pryor S.C. and Barthelmie R.J. (2021): A global assessment of extreme wind speeds for wind energy applications. *Nature Energy* **6** 268-276 doi: 10.1038/s41560-020-00773-7 (Pryor and Barthelmie 2021).

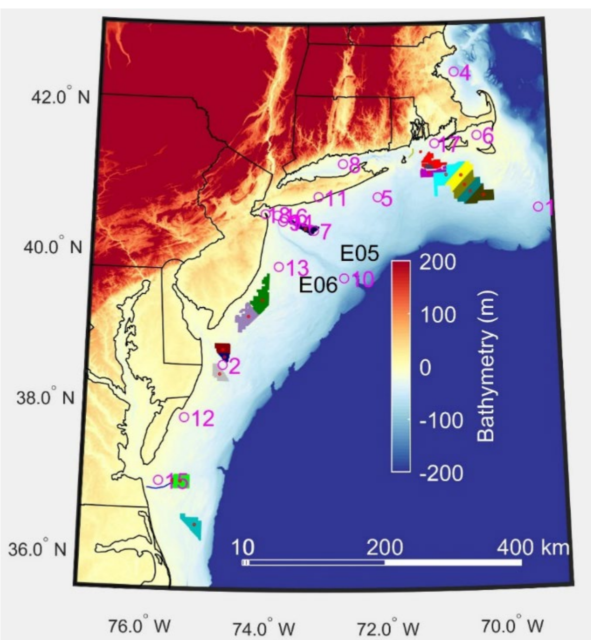

Figure 2.1. Locations of the NCDC buoys (magenta) and NYSERDA lidar buoys (black) data obtained for evaluation of Cornell's WRF simulations

Analyses of high-resolution (1.33 km by 1.33 km grid spacing) output from our WRF simulations (2 calendar years) to characterize flow conditions over the offshore lease areas have also continued. We have compared wind speeds and directions at the different lease areas from the two years of WRF simulations with data from other sources including wind and wave data from ERA5 for the offshore lease areas for the period 1979-2018. Analysis of the occurrence of low-level jets (LLJ) across the rotor plane in the 16 lease areas is underway and indicates that the occurrence of LLJ is much less frequent than over land areas such as Iowa (Aird et al. 2020) and is strongly seasonal with very low occurrence of LLJ over winter (Aird et al. 2022). Analysis of spatial gradients to compare with similar analysis over land in the US (Barthelmie et al. 2020) were presented in a technical report to NYSERDA

We developed a process to select flow conditions and specific periods for the Weather Research and Forecasting model (WRF) simulation of wind farm wakes. Selection of the flow cases is based on forty years of ERA5 data wind speed and wind direction from 100 m height from the NY lease area and is predicated on the idea that the primary drivers of wind farm wake intensity are wind speed (via the wind turbine thrust coefficients), ambient turbulence and atmospheric stability (since the ability of the atmosphere to erode the wake is dictated by these factors). The procedure for selection of the flow scenarios is as follows: 3 wind speed classes are defined based on typical thrust curves and wake intensities; 4-10 ms^{-1} (intense wakes due to high thrust coefficients), 10-16 ms^{-1} (moderate) and 16-25 ms^{-1} (low). In the 40 years of ERA5 output 14% of hours exhibit wind speeds below 4 ms^{-1} and much less than 1% of hours exhibit wind speeds at 100 m above 25 ms^{-1}. The wind rose is initially described in 10° sectors and then degraded (coarsened) into four directional sectors that are expected to have very different turbulence intensity based on over-water fetch and prevailing atmospheric stability. The northeasterly flow sector has long over water fetch, the southeast also has a long sea fetch, southwesterly flow has a moderate sea fetch and northwest has a shorter average sea fetch. The frequency of hourly wind speeds and directions in each flow class (i.e. combined wind speed and direction) are then summarized (Table 2.1) and used to define the flow scenarios needed to capture 75% of all hours. This results in 10 flow cases but we separate the most frequent flow scenario (NW with wind speeds at 100 m of 4-10 ms^{-1}) into two to capture this flow scenario once under cold season (stable stratification) and warm season (unstable conditions). As shown in Table 2.1 and Figure 2.2, performing simulations of these flow scenarios will provide information on ~75% of conditions occurring offshore.

Table 2.1. Defining the scenarios and determining their frequency (given in %). The number in brackets indicates the scenario number. These scenarios are modes of atmospheric flow and are used to select the periods used in the WRF-wake simulations

WD (°)/WS (ms^{-1})	WS<4	WS 4-10	WS 10-16	WS 16-25	Description
NE 0-90		9.6(4)	4.6(7)	0.9(12)	Long offshore fetch
SE 90-180		7.5(6)	2.3(8)		Long offshore fetch
SW 180-240		12.5 (2)	9.1(5)	1.6(9)	Most frequent
SSW 240-270					
NE 270-360		15.7 (1,10)	11.0 (3)	1.4(11)	Frequent/flow from land
Frequency (%)	14	51.0	29.6	4.9	Total #=350640

To identify the 5-day simulation periods, the ERA5 dataset was examined if it met the wind speed and direction criteria at lease area 8. The data were examined in rolling 24 hour periods calculating the largest number of hours meeting the criteria. The five day periods with the largest number of criteria hours were identified. The data periods were examined within the matrix of the scenarios to ensure that the scenarios were distributed over the year rather than being grouped in any particular season (Figure 2.2). This was undertaken to ensure that varying stability was accounted for in the wake simulations.

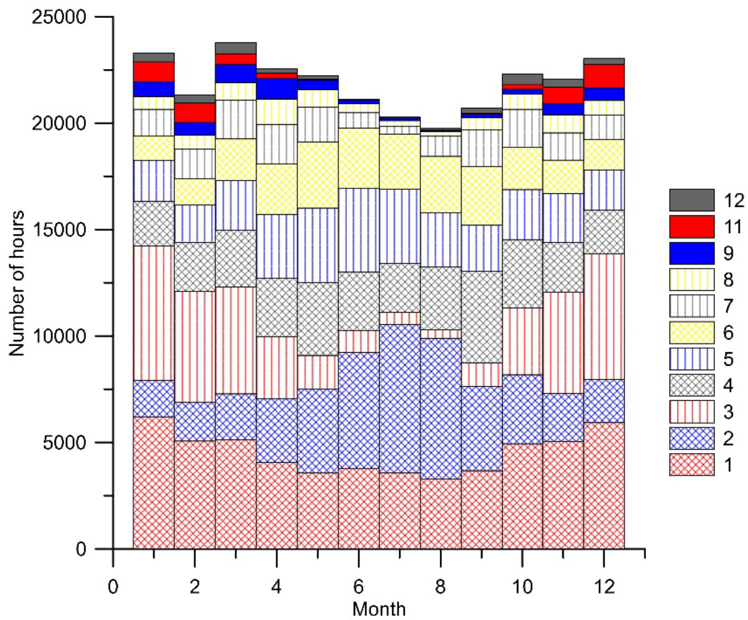

Figure 2.2 The number of hours in each scenario. Red = direction NW 270-360°, blue = SW 180-240°, gray =NE 0-90°, yellow = SE 90-180°. Hatching is for low wind speeds 4-10 ms^{-1}, vertical stripes are moderate wind speeds 10-16ms^{-1} and solid shading indicates high wind speeds 16-25 ms^{-1} .

3 Task 2: Mesoscale Wakes

Once the 5-day periods that represent each of the 11 flow scenarios had been identified in Task 1, the process of downloading boundary-conditions from ERA5 for each of the WRF simulations was initialized and the five-day simulations begun. The WRF simulations are being performed for a triple nested domain wherein the inner-most domain is computed twice; once without the action of wind turbines (domain 3) and once with wind turbines present (domain 4). The velocity deficit at wind turbine hub-height (150 m) is used as a metric of wake intensity and extent. This velocity deficit is determined from the wind field with no turbines operating (i.e. output from domain 3) minus the wind field with the turbines operating (domain 4), normalized by the no-turbine wind field. For these simulations the lease areas are fully occupied with a spacing of 1.85 km with 15 MW IEA reference wind turbines. The power and thrust curves are shown in Figure 3.1.

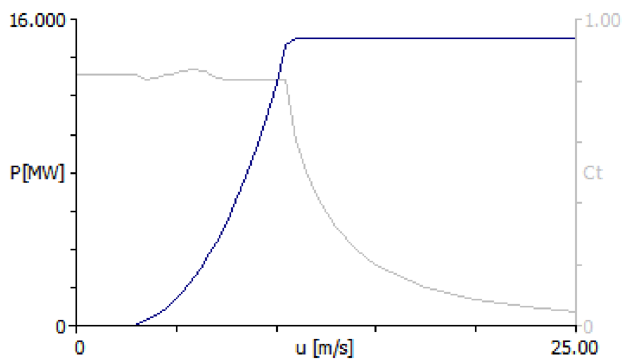

Figure 3.1 Power and thrust curve for the IEA 15 MW reference wind turbine used in this research

Our mesoscale wake simulations are performed using the WRF model with the Fitch and EWP wind parameterizations. The simulation domain covers all of the 16 US East coast lease areas. Over the 15 lease areas for the control simulation a) there are around 2000 wind turbines. We initially employed the Fitch parameterization and simulated 11 different representative 5 day periods and three different layouts:

a) control (uniform spacing of 1.85 km in the south-north and east-west directions, approx. installed capacity density of 4.3 $MWkm^{-2}$)
b) corridor (every 6^{th} north-south column from (a) removed)
c) half density (approx. installed capacity density of 2.1 $MWkm^{-2}$)

Results of our simulations with the Fitch parameterization with a projected annual power production of 116 TWh/yr and mean capacity factors of ~ 50% (Pryor et al. 2021). These can be achieved from the 15 U.S. northernmost east coast offshore wind energy lease areas by employing 15 MW wind turbines at the anticipated spacing of 1.85 km. Mean wake-induced power losses are 35.3%.

Once the EWP parameterization is included each simulation has five domains for (outer domain d01, nest domain d02, inner-most domain d03 run without wind farm parameterization for the freestream flow, d04 covering the same area as d03 but with the Fitch parameterization active, d05 covering d03 but with the EWP parameterization active).

In view of the large differences in results from Fitch and EWP wake parameterization (onshore) (Pryor et al. 2020), major effort has been placed on obtaining and successfully compiling an updated EWP parameterization. Each WRF release includes a number of patches to correct errors in prior versions and to introduce new parameterizations. The MYNN PBL scheme that is required for use with the Fitch wind farm parameterization was up-dated after the WRF v3.8.1 that we used for our simulations. But the new EWP formulation is available for v4.2.1 thus we performed a backward 'compatibility' check, where we completed simulations of WRF 4.2.1 with the Fitch wind farm parameterization active and compared those with WRF 3.8.1-Fitch. The results showed a very high degree of similarity (in terms of wake extent and intensity and PBLH) and thus allow us to move forward with WRFv4.2.1-EWP for parameterization sensitivity.

The resulting WRF output is then analyzed to characterize power production and wake intensity and spatial extent from each lease area. An article on the WRF wake simulations with the Fitch parameterization is published in the high prestige journal 'Joule' on 30 September 2021 (Pryor et al. 2021).

Our research has indicated wake generation and propagation from WRF exhibit a sensitivity to (i) the compiler used for WRF, the WRF version and the order of inner domain calculation, plus (ii) the wind farm parameterization (Pryor et al. 2018; Pryor et al. 2020). Additional sensitivity simulations were undertaken to quantify these effects. Results are reported in Pryor et al. Science of Making Torque from Wind 2022 (Pryor et al. 2022).

Full details of the WRF simulations comprising also the domains and namelist for the simulations were included in the technical report for this task. The main results are: (i) The velocity deficit of 5% or more can extend over very long distances downwind of each lease area. The velocity deficit for the block of 7 lease areas south of Massachusetts extends over downwind distances of over 90 km. (ii) The velocity deficit for the blocks of lease areas east of Delaware and Maryland are separated by 23 km but are impacted by the wake from each other. The overall electricity production is equivalent to about 3% of the US demand (not accounting for cable losses or O&M). Power losses due to wakes are about 35% of the average power which is larger than reported for European offshore wind arrays.

4 Task 3: Microscale Flow Conditions

We acquired and installed new versions of WAsP, FUGA and py-wake for the miscoscale modeling. The WAsP suite is the industry-standard PC software for wind resource assessment, siting and energy yield calculations for wind turbines and wind farms (www.wasp.dk) and includes a wake model that is referred to as PARK or NOJ, and FUGA – a linearized CFD solver.

The most recent version of WAsP(12) was installed and a test case for the NY Equinor lease area set-up. Unfortunately, WAsP12 is not compatible with FUGA so WAsP11 was also installed. A workspace was developed for the NY Equinor lease area. This involves developing input files such as an appropriate format roughness/elevation map, wind climate and wind farm layout (Figure 4.1, 89 turbines covering the NY Equinor lease area with turbines spaced at 1 nautical mile (1.85 km). Once this workspace is operational in WAsP11, and a wind climate generated, WAsP-PARK is able to calculate power output using the Weibull distributions in each sector and the power curve. Using WAsP-PARK, the estimated power from the control wind turbine layout is 6045 GWh/year with wake losses of 6.7%. The mean wind speed at 150 m is 9.13 ms^{-1} and the power density is 882 Wm^{-2} . It is also possible to export files including the turbine locations and the turbine power curve for import into the FUGA model.

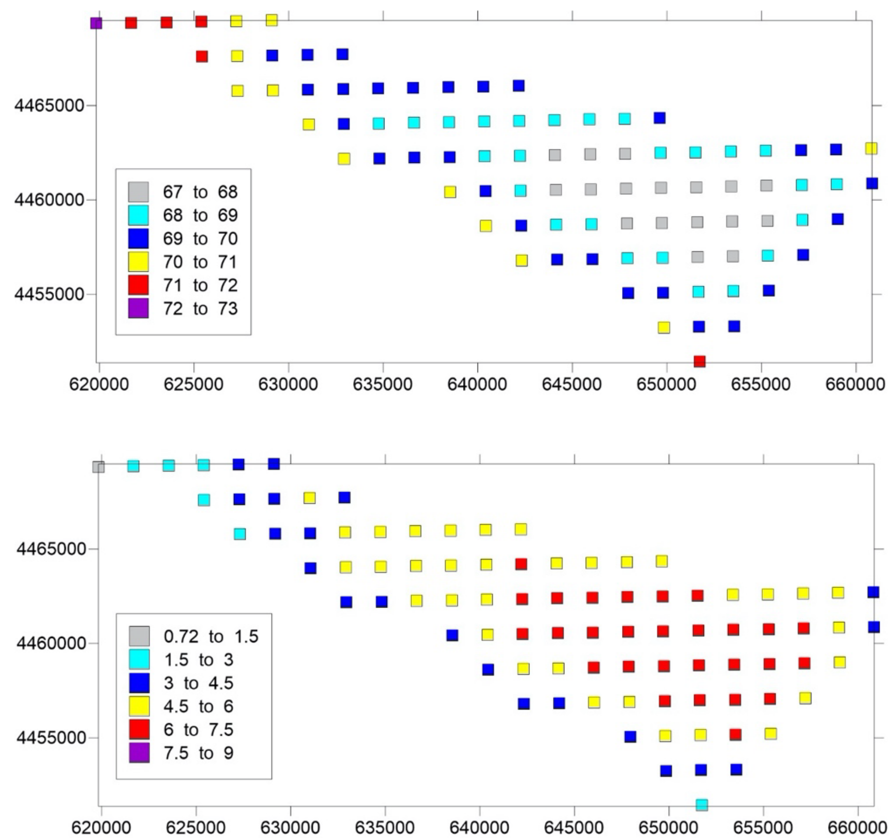

Figure 4.1. WAsP results for power production and wake losses in the NY lease area. The top figure is an estimated of power production (GWh) at each wind turbine assuming the 15 MW IEA turbine at each location and the lower figure is an estimate of wake losses in %.

Typically, WAsP and PARK or FUGA are designed to work with tens to a few hundred wind turbines representing a typical wind farm and rather short wind climates. FUGA is no longer supported as an independent model by DTU and the memory required to undertake the calculations for the US east coast lease areas exceeds that available on standard Windows-based personal computers. Thus, a transition to a new software package – py-wake and transition to running the microscale modeling on an NSF XSEDE instance was undertaken which involved obtaining the computing resources and installing the pywake platform.

Using the py-wake platform we have undertaken simulations for each of the 16 lease areas in 4 blocks: 1) the 7 lease areas south of Massachusetts (LA1-7), 2) the NY lease area (LA) 3) the lease areas off New Jersey and Maryland (LA9-13) and 4) the lease areas off Virginia/ North Carolina (LA14-16). We have run the microscale simulations for the same wind turbine layouts as described in Task 1 using py-wake modules that use the NOJ and FUGA wake parameterizations. We have also undertaken addition microscale simulations for the control layout but with the layout rotated around a central pivot by 30 degrees and 60 degrees, double density and 6MW per km^2 installed capacity density. Results are presented in (Barthelmie et al. 2022b). These provided not just different turbine layouts in terms of spacing and orientation but also a range of turbine densities similar to those that have been used in European offshore wind farms.

The main difference in approach compared to the WRF simulations are:

1) We are performing the simulations for the full wind climate using the entire 40-years of hourly ERA5 wind speeds and directions based on the wind speed and direction distribution at the center of the lease areas.
2) The platform is running on an NSF-XSEDE instance but there is insufficient memory to run for more than approximately 1000 turbines in a simulation which means the simulations are undertaken in four areas. Thus, the simulations do not include the full range of array-array impacts.

A detailed analysis of results for the NY lease area was published in (Barthelmie et al. 2022c). The results are now being compiled into a journal paper which has not yet been submitted. Preliminary analysis shows that AEP simulated using FUGA is generally lower than using NOJ/PARK.

5 Task 4: Feedback-Optimized Layouts in WRF

Based on the preliminary results in Task 3 that indicate that the annual energy production is much more sensitive to the turbine spacing/density than to the precise rotation of the rows, we have allocated the computing resources for this task to running additional simulations using both the Fitch and the EWP parameterizations for turbine spacing that is equivalent to about 6 MW per km^2. These results that indicate (within uncertainty) from the microscale modeling that there is a broadly linear relationship between turbine spacing/density and the annual energy production will then be evaluated using simulations with both WRF parametrizations. A major uncertainty that cannot yet be addressed in the microscale modeling is how critical the array-array impacts are to the overall results. There is sufficient analysis of the WRF-Fitch analysis to suggest array-array interactions are important but at this point we do not have additional resources to address this in the microscale modeling.

We completed the simulations with WRF and both the Fitch and EWP wind farm parameterizations for the optimal layout (6 MW per sq km) from the microscale modeling. We thus have simulations of ALL 11 flow cases with both wind farm parameterizations for:

i) control (uniform spacing of 1.85 km in the south-north and east-west directions, approx. installed capacity density of 4.3 MWkm^{-2}),
ii) corridor (every 6th north-south column from (i) removed),
iii) a higher density (approx. installed capacity density of 6 MWkm^{-2}) layout.

A preliminary precis of the mean CF frequency weighted over the 11 flow cases and for the 3 wind turbine layouts is given in Table 1. As shown, there are very large discrepancies between capacity factors (CF) computed from the two wind farm parameterizations with EWP generating persistently higher power generation estimates. The discrepancy is slightly larger for the higher density installed capacity layout. These were described in the technical report for this task and analyses for a new journal paper are ongoing. CF using Fitch are generally lower than those in the EWP simulations due to higher wake losses in Fitch.

Table 1. Frequency-weighted CF for the 11 flow scenarios computed from the sum of power generated in all 15 lease areas for the three wind farm layouts.

Name	Total # wind turbines	Approx ICD (MWkm^{-2})	Frequency-weighted mean CF (%)	
			Fitch	EWP
Control	1922	4.34	42.8	53.1
Corridor	1604	3.62	44.8	54.8
6MWsqkm	2598	6.00	38.7	49.6

6 Task 5. LCoE model

A new model was developed that accounts for the turbine size, distance to the coast, inter-array distances and power production with wake losses to evaluate the various layouts. The model contains a simplified version of the NREL Offshore Renewables Balance-of-System and Installation Tool (ORBIT)(Shields et al. 2021) and data from https://atb.nrel.gov/electricity/2021/offshore_wind. This suggests that LCOE is currently $80/MWh and could fall to below $60 /MWh by 2025.

$$\text{LCOE} = \frac{CAPEX * CRF + OPEX}{AEP}$$

Where

LCOE is the levelized cost of energy

CAPEX is the capital expenditure (Turbine+Balance of System)

CRF is the Cost Recovery Factor or fixed charge rate

OPEX are the operation and maintenance costs

CRF is assumed at some level either related to the depreciation or to the interest and can be calculated:

- Annualized cost = (CRF*capital cost)+O&M cost
- $CRF = \frac{i}{1-(1+i)^{-N}}$ i=discount or an interest rate

For the current version CRF is calculated on the basis of a 5% interest rate and a 30 year lifetime.

Hence $CRF = \frac{i}{1-(1+i)^{-N}} = \frac{0.05}{1-(1+0.05)^{-30}} = 0.065$

As an example, for the New York lease area that has 90 turbines at 1.85 km spacing (Figure 1) and estimated AEP of 6241.7 GWh/y from py-wake with NOJ wake farm parameterization and 6104.6 GWh/y from py-wake with FUGA wake farm parameterization (~2% lower). However, without observations it is not possible to identify which is performing better.

Example results from the py-wake simulations using NOJ and FUGA are shown in Table 6.1 for the different wind turbine layouts.

Table 6.1. Results from the LCoE model in $/MWh

Turbine layout	FUGA	NOJ
CNTR	78.7	77.0
CORR	78.0	76.7
HALF	77.7	77.0
DOUB	83.4	77.8
RO30	79.6	77.9
RO60	79.4	77.6
6MW	80.6	79.1

These results are consistent with the simulations with NOJ generating higher AEP than FUGA and are more sensitive to the turbine density than to particular turbine orientations for this lease area. Full details are given in the technical report for this task and a journal paper is being developed to include these results.

7 References

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