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Big wind power: Seven questions for turbulence research

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ABSTRACT
The accelerating growth of wind energy in recent years mandates improved understanding of wind turbine, wind farm and atmospheric turbulence interactions. Fluid turbulence plays a vital role in these interactions, motivating the present formulation of several pertinent questions for turbulence research. These questions touch upon the need for better analytical, synthetic, and reduced order models of turbulence, better model coupling methods and basic understanding of flow phenomena governing kinetic energy entrainment and limiting power densities. Responding to the formulated questions may lead to improvements in wind energy harvesting.

KEYWORDS
Turbulence, wind energy, boundary layers

1. Introduction

The remarkable growth of wind energy in recent years (wind energy generated 6.3 % of US electricity in 2017 [1]) calls for increased fundamental and applied research to better understand and engineer this renewable resource. Coupled with the electrification of our transportation system which is expected to further increase demand for renewable electricity and greatly enhance a distributed storage capacity, we are witnessing the beginnings of groundbreaking changes in our energy infrastructure. The "raw" wind energy resource is the kinetic energy available in the large-scale movements of air prevalent above the atmospheric boundary layer, forced by solar energy and buoyancy. Turbulence is the main mechanism by which the kinetic energy available in the geostrophic wind is transported down towards heights where it can be captured by clusters of wind turbines. Many aspects of the turbulence mechanisms involved in these atmosphere-wind farm interactions are not well understood or accurately predictable.

What follows is a list of several fundamental questions touching upon turbulence research with direct implications on further developments and improvements in methods of wind energy harvesting. The questions posed reflect the author's current views, are evolving, and should by no means be considered to be a complete list. Moreover, they are not listed in order of importance but in an order that helps readability. The questions are not new and considerable amount of research has already been performed touching on the various topics covered by the questions. Still, given the scale and scope of present and anticipated future wind energy developments, better answers to such questions are needed with some urgency.

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This article also is not meant to be a literature review, and so the references cited in the context of each of these questions are only broadly representative of the relevant literature and do not represent a complete list of all prior works touching on each of the questions. Several literature reviews have appeared in recent years. Particularly relevant to the questions at hand are reviews of the state-of-the art in the aerodynamics of wind farms [2–4], of various fluid dynamical and turbulence phenomena in wind farms [5], reviews of computational methods used in wind energy [4,6], and on uses of wake models for wind farm optimization (see e.g. [7]).

In the next section, seven questions are posed and elaborated upon by including some perspective on each of them.

2. Seven Questions for Turbulence Research

Question 1: Can analytical models represent the mean velocity and variance distributions in wind farms, at useful levels of accuracy and generality?

The distinguishing characteristic of analytical models is that they enable one to make predictions of the mean velocity at a particular location in a flow (e.g. at turbine rotor positions) without the need to solve, numerically, partial differential equations. Thus the prediction of mean velocity, and in some model versions also the turbulence second order moments or turbulence intensity, proceeds entirely by evaluating explicit formulae. This approach is much simpler than setting up a Computational Fluid Dynamics (CFD) project that would typically require deciding on a computational discretization method, include often complicated mesh-generation tasks, and decisions about turbulence modeling and data analysis. As reviewed in Ref. [5], analytical models of wind farms fall into two broad categories: static wake models (bottom up) and single column, boundary layer models (top-down). The best known of the former is the Jensen model [8], while the model by Frandsen [9] (see also Refs. [10,11]) represents a well-known example of the latter. A number of other models, and various combinations, have been proposed [12–14]. However, the development of such models has not been a research priority for some time. The majority of research in turbulence over the past decades has focused on models in the context of computational fluid dynamics (CFD), solving variants of the Navier-Stokes equations at various levels of averaging and representation. Accuracy has doubtlessly increased by significant amounts, both within the context of Reynolds Averaged Navier Stokes (RANS) models and with the advent of Large Eddy Simulations (LES). Using the latter, further flow phenomena such as unsteady and multiscale processes have become amenable to computer prediction. Moreover, Direct Numerical Simulations (DNS) have become impressively well resolved [15], also achieving ever higher Reynolds numbers [16]. While computer power has increased tremendously over the past decades, the cost of such simulations and the manpower required to set up a simulation for a specific flow condition has remained very high and is often prohibitive in practice. Arguably the gap between high-fidelity CFD and the needs from the field of applications, such as wind farm design, siting, and economic forecasting has been widening rather than narrowing.

Consider the following real-world situation: "*A small urban-scale wind farm with ten 30 m high Vertical Axis Wind Turbines (VAWTs) is located in a suburban region. After several years of operations, a developer builds a wide 12 story building 200 m upwind of the VAWT wind farm. After some years, the wind farm operator suspects that mean power production has been slightly reduced and that maintenance costs have increased, due to mean flow reduction and increase in turbulence level at the turbines,*

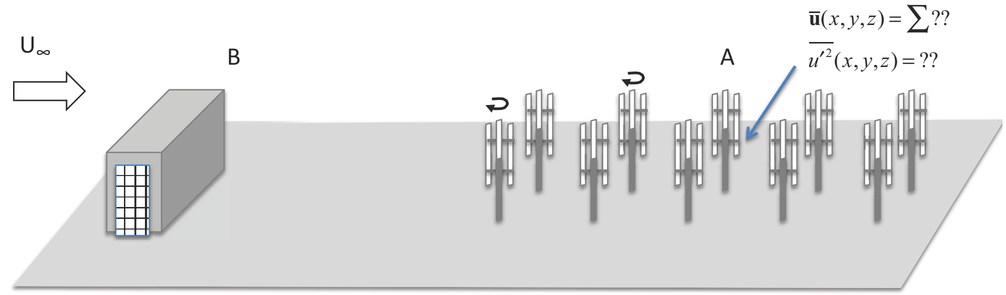

Figure 1. Sketch of complex flow in which the downstream effects of a building (B) constructed subsequent to the VAWT wind farm (A) must be evaluated efficiently without recourse to CFD.

respectively, caused by the wake of the new building. The wind farm operator sues the developer for a specified sum of money claiming loss of revenue caused by the developer's actions. The developer counters that the claim is without technical merit and that the effects on the flow are minimal and cannot possibly cause appreciable economic harm. As part of the legal proceedings, an expert witness/consultant must evaluate the claim and quantify economic losses, using sound physical and engineering judgement and established tools. The financial resources involved in the proceedings are such that a full 3D CFD (RANS) analysis of the geometry of the flow is beyond the means of either party, or the court system. The consultant is only allowed to spend, say, 5 hours on developing quantitative answers, and thus simplified flow modeling is required." Figure 1 is a sketch of the flow configuration.

The expert's pronouncements must be based on an 'established', proven approach and not some ad-hoc derivations and new assumptions that could be easily discredited in court. What are such an expert's options at this time, given the state-of-the-art knowledge in turbulence? Clearly, given time constraints and expenditure limitations, the approach must be based on analytical approaches to predict the flow without recourse to CFD. And yet, it must be sufficiently sophisticated to be able to distinguish between the case with and without the building, and must describe effects not only on the first upstream turbines in the farm closest to the building, but also in the entire farm. And, the approach must describe not only the mean flow but turbulence levels as well, with and without the building. Finally, the calculation methodology must be easily reproducible by others using, hopefully, well-accepted formulae and tabulated coefficients that can be found in, e.g., industry handbooks, government regulatory guidelines or norms.

Analytical modeling for such a configuration would typically begin by finding models for the mean velocity distribution of each constituent flow. In this case, (i) a wall attached parallelepiped for the building, (ii) flow behind a VAWT represented, perhaps, as an axial drag generating element of rectangular cross-section, and (iii) the surrounding atmospheric boundary layer. Models for the wake effects behind wall-attached parallelepiped can be found, for example, in a handbook [17] and references therein, and others are based on the notion of "sheltering models" as also used in the WAsP software [18]. The wind turbine wakes could be represented by the Jensen model [8] for which the wind turbine wake expands linearly. The question then is how these elements can be superposed in a complex 3D arrangement. The Jensen/Katic approach [8,19] assumes, implicitly, that these shear flows' wakes are somehow 'independent' and that their kinetic energy distributions can be added. Since turbulent velocity fluctuations tend to be proportional to the magnitude of the prevailing mean velocity deficit, the square of the combined resulting velocity deficit is assumed to equal the sum of each constituent flow's mean velocity deficit squared. Many valid objections to such severe simplifying assumptions can be made, but the approach has been quite popular in practice and is implemented in several industry-level codes. If complex terrain effects need to be accounted for, linearized models based on potential flow theory, as developed e.g. in [20], could be used. These too can be evaluated analytically in rather simple fashion and this has facilitated their implementation in industry codes (e.g. in WAsP[21]).

The expert witness would thus attempt to use superposition rules to combine the models of wakes from the building and the entirety of the turbines in the farm to predict the expected velocity reduction at each of the wind turbines. Based on turbine power curves such information could lead to predictions of power reduction due to the presence of the building. Nonetheless, the expert witness would be hard pressed to provide an authoritative statement of how uncertain the predicted power reduction really is, based on the collection of models and superposition principles employed.

Further careful studies are needed to enable more accurate comparisons between simplified models and RANS/LES/DNS, in order to both improve the structure of the analytical models or adjust free parameters with more predictive authority. At present this task is mostly performed by commercial providers of these tools with concomitant concerns about possible bias, insufficient transparency, and lack of reproducibility and uncertainty quantification.

In conclusion, the question posed in the title (Q1) does not yet have a satisfactory response. If the answer is 'yes', it will require additional sustained research activities to develop better models to predict mean flow and turbulence second order moment distributions, and better-grounded principles and methods for flow superposition. But it is also possible that the answer is simply 'no', that analytical models are unable to provide any reasonably accurate predictions of mean flow and turbulence quantities for a practically meaningful range of parameters. In that case, research and development must continue focussing on PDE-based approaches such as RANS or LES, but focussing on more user-friendly implementations so that CFD may truly become easily applicable to cases such as the example noted above (Fig. 1). Truly practical CFD deployment should not require turbulence specialists but be easily usable by broadly trained, practicing engineers. We are certainly nowhere near such a state so that for now the further development of better analytical models would seem as relevant as ever.

Question 2: Is there a systematic approach to formulate dynamic wake models and to represent the hierarchy of length and time scales in reduced order models for wind turbine wakes and turbulence?

The question treated in the first section (Q1) considered quasi-stationary conditions, and the ability of models to predict mean distributions of velocity or kinetic energy. For a number of applications though, most notably control, representation of the dynamics, i.e. time-dependent flow responses to changes such as control actions or sudden changes in inflow conditions, becomes crucial. The level of model fidelity required for control applications depends on the details of the control methodology, in particular on how much of the physics must be included. At present, there exist a number of very different starting points to derive dynamic wake models and thus the results are difficult to compare to each other or to catalogue into a coherent and self-consistent theory.

The most common dynamic wake models are based on "transporting material particles that represent the wake velocity deficit" with a velocity advection that includes wake meandering (e.g. the dynamic wake meandering (DWM) model [22,23]). The approach considers advection of the velocity deficit by means of the mean flow, some large-scale structures representing meandering (see Fig. 2), and possibly random turbulence. Various ad-hoc methodologies are used to generate the time-dependence of the large-scale meander-inducing motions, such as filtering of synthetic turbulence instances (e.g. in [24] they filter a turbulence box from the Mann spectral model [25], see also Q5 below), although no common agreed-upon methodology has emerged to render the approach to obtain these motions systematic.

A related question that further complicates the formulation of reduced models for wake meandering is whether the meandering is caused mostly by large-scale incoming atmospheric turbulence or whether it is caused by the smaller (but more more strongly vortical) wake eddies generated by the shear behind the wind turbine. The former is known to lead to a linear increase of the wake diameter $D_w \sim x^1$ of the wake (such as in the Jensen model), while the latter leads to a $D_w \sim x^{1/3}$ increase as in a free wake [26]. The prevalent view these days is that the former dominates the large scale meandering but it is also clear that the latter must have some effect and how to combine the two in formulating reduced models is far from obvious.

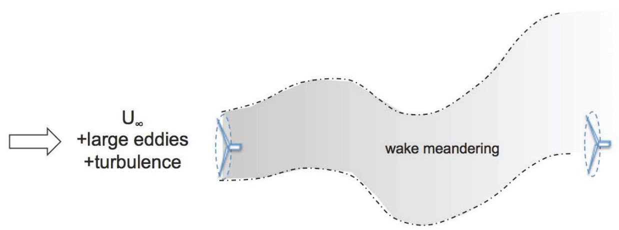

Figure 2. Sketch of meandering wake being transported downstream and impinging on a downstream turbine.

It is possible to derive a simplified PDE describing the streamwise and temporal evolution of the velocity deficit [27] via integration of the unsteady RANS equations across planes normal to the wake. The resulting reduced wake model describes both the streamwise and spanwise momentum deficits, the latter being relevant for turbines in yaw. The approach could be extended to capture explicitly large-scale unsteady meandering as in the DWM approach. So far the method has not been extended to predict turbulence quantities such as "unsteady" transport of turbulent kinetic energy in a meandering wake.

Some approaches are instead based purely on data, such as Proper Orthogonal Decomposition (POD [28]). Most of the existing work on POD focuses on analyzing wind turbine wake data (from simulations or field data, see e.g. [29–31]) and to present and describe characteristics of the spatial modes that result from the POD analysis. The second step, namely to write simplified ordinary differential equations (ODEs) for the time-dependencies of the modes' coefficients, however, is most often not done and only a limited number of works on POD have actually led to working dynamical system models that can be used for predictions (see e.g. Ref. [32] for such an applications, or [33] for an application in the context of stochastic modeling). This limitation of POD research is not limited to wind turbine wakes but applies quite in general for turbulent shear flows, for which POD modes have provided valuable information about the spatial structure of the most energetic motions of turbulent flows, but have produced less in terms of predictive models of the dynamics.

The next level of data-based approaches is the more recent Dynamic Mode Decomposition approach (DMD, see [34]) in which representation of time-periodic variation of modal coefficients arises as an inherent part of the analysis method. Hence, DMD provides information about the dynamics of the flow as part of the analysis methodology. For some initial applications to wind turbine wake dynamics, see [35,36]. Improved wake models with more systematic approaches to derive them from the dynamical equations and/or from data are needed for wind farm optimization and control applications (such as for [37,38]), or for new control applications such as using wind farms for secondary frequency regulation [39,40].

Question 3: What is the fate of mean flow kinetic energy in large wind farms, where is it dissipated, and how is it entrained from above?

The primary source of the kinetic energy that arrives just upstream to each wind turbine so that it can be transformed into electricity is, ultimately, the wind in the free atmosphere, the geostrophic wind above the atmospheric boundary layer (ABL). Denoting the geostrophic wind velocity as U_G, the kinetic energy density (per unit mass of air) is $\frac{1}{2}U_G^2$. It must be transferred to the turbine locations. An initially instructive framework to approach this question is to use the top-down model already mentioned in $Q1$ above. The approach views the flow structure above the wind turbine array as a classical turbulent boundary layer in which the turbulence establishes a mechanism for vertical flux of momentum and mean-flow kinetic energy, including a constant momentum flux (shear stress) region. It is instructive to examine the fate of mean kinetic energy in the classical logarithmic layer of a boundary layer flow without wind turbines, using the usual assumption that production equals dissipation. We then obtain that the rate of dissipation per unit mass as function of height above the ground (z) is given by $\epsilon(z) = -\overline{u'w'}\partial\bar{u}/\partial z = u_*^2(u_*/\kappa z)$. Here u_* is the friction velocity, κ is the von Karman constant, and u and w are the streamwise and vertical velocities, respectively. An over-bar denotes time/ensemble averaging and $-\overline{u'w'} = u_*^2$ has been assumed. The total dissipation per planform surface area below height z (and above a lower height taken as the roughness length z_0) is thus given by $\int_{z_0}^{z} \epsilon(z')dz' = (u_*^3/\kappa)\ln(z/z_0)$. In a fully developed equilibrium boundary layer flow this is also equal to the flux of mean kinetic energy at height z, defined as $\Phi(z) = -\overline{u'w'}\,\bar{u} = (u_*^3/\kappa)\ln(z/z_0)$. Clearly then, in a fully developed equilibrium boundary layer flow the flux of mean kinetic energy towards the surface at height z is ultimately dissipated entirely into heat in the region below z, because there is no work done on the stationary bottom surface and there is nowhere else for the energy to go (in neutrally stratified flow). The situation is depicted in Fig. 3(a).

Now, for a very large wind farm, and again assuming fully developed conditions, when considering the temporally (over-bar) and horizontal spatially (brackets) averaged velocity distribution, a logarithmic profile is established above the turbine region, as shown in extensive sets of numerical simulations [41]. The flow exhibits a momentum flux on the order of $u_{*,hi}^2$, where $u_{*,hi}$ is the friction velocity characterizing the flow that exists above the wind turbine array. The magnitude of $u_{*,hi}$ can be related to the geostrophic velocity existing above the ABL and parameters characterizing the wind farm [12,41,42], such as the turbine's hub-height z_h, turbine diameter D, its thrust coefficient, and average aerial turbine surface $(sD)^2$, where s is the turbine spacing in units of turbine diameter. There is another logarithmic region below the turbine region, with a characteristic friction velocity $u_{*,lo}$. The differences in momentum fluxes,

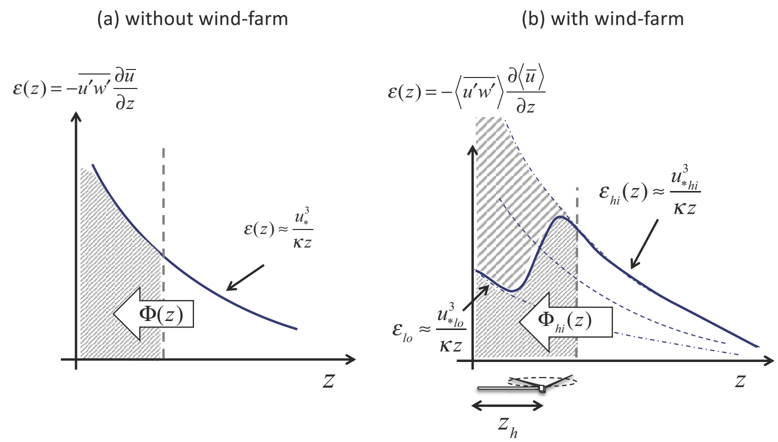

Figure 3. Vertical distribution of dissipation of mean kinetic energy in an equilibrium turbulent boundary layer without turbines (a), and in the presence of a large wind farm (b). The area under the curve up to some height z represents the total rate of energy dissipation per planform area, and also equals the vertical flux of mean kinetic energy due to turbulent shear stress.

$u_{*,hi}^2 - u_{*,lo}^2$, equals the momentum extraction of the turbines. As shown in [41,42], typically $u_{*,hi} > u_*$ and $u_{*,lo} < u_*$. At the turbine rotor's tip height $z = z_h + D/2$, the corresponding flux of mean kinetic energy is given by $\Phi_{hi}(z) = (u_{*,hi}^3/\kappa)\log(z/z_{0,hi})$ and equals the sum of the dashed areas below the upper dot-dashed line shown in Fig. 3(b). Conversely, the dissipation is the area under the blue curve (fine dashed region), representing the dissipation in the presence of the wind farm. In this rough schematic, the coarse dashed region above the blue line represents the power available to be extracted by the turbines. It is the result of the decreased dissipation below the wind turbines because of the reduced friction velocity there ($u_{*,lo}$), and the increased flux above the turbines due to the increased friction velocity there ($u_{*,hi}$). While the top-down horizontally averaged model provides some indications of the fate of kinetic energy, the exact partitioning of kinetic energy into flux and dissipation (production of TKE) remains uncertain. LES on very high domains coupling large wind farms with the atmospheric structure above [43] have highlighted the possible importance of internal gravity waves as an additional mechanism affecting wind farm energetics.

More detailed description of the fate of kinetic energy available in the mean flow is provided by so-called kinetic energy transport tubes. As derived in Ref. [44] a bundle of tangent lines to the vector field given by $\mathbf{B} = -\overline{\mathbf{u}' \otimes \mathbf{u}'} \cdot \bar{\mathbf{u}}$ that originates at the rotor disk perimeter generates a "tube" that can be used to visualize directly "where the mean kinetic energy arriving to each turbine" comes from. An experimental variant of the approach using PIV data was used in Ref. [45] to quantify effects of Reynolds stresses on a classic streamtube passing by the wind turbine. Using artificial means of flow forcing at the turbine locations it was shown in numerical simulations [46] that the energy flux to the turbines could be altered by timing the forces with large-scale features of the flow.

It is safe to say that given the importance of the problem, we have still insufficiently detailed understanding of fate of kinetic energy across the ABL into wind turbine arrays. Improved understanding of the fate of mean-flow kinetic energy in large wind farms will also be useful to provide responses to the next question posed below.

Question 4: Is there a theoretically derivable maximum power density for large wind farms?

Estimates of upper limits for energy extraction under idealized conditions have played a useful role in planning, extrapolations and order-of-magnitude estimates. Notably, the Betz limit for an individual wind turbine [47–49] provides a first-principles based and easy to apply upper limit of the fraction of the wind's kinetic energy flux that can be extracted at a rotor. It is based on ideal flow streamtube analysis, neglecting viscous and turbulence losses, and establishes the upper limit of power that can be extracted by a device that causes flow induction (reduction of velocity) as it goes through an actuator disk. The linear streamwise momentum equation is combined with the Bernoulli equation along streamlines from far upstream to just in front of the rotor, and again from behind the rotor to far downstream. The result shows that the difference in kinetic energy fluxes entering and leaving the streamtube, and thus the maximum possible power extraction at the turbine, is given by $P = 2a(1-a)^2 \rho U_\infty^3 A_r$, where a is the induction factor, i.e. assuming that the rotor velocity is $U_\infty(1-a)$, ρ is air density, U_∞ the far-field incoming wind velocity at hub-height, and $A_r = (\pi/4)D^2$ is the rotor area with D, as before, the rotor diameter. The expression is maximized for $a = 1/3$, yielding the Betz limit, which when expressed as maximum possible power coefficient is $C_p = 16/27 \approx 0.59$.

The question whether similar limits may be arrived at for the power density of large wind farms has attracted much attention. The reference area against which the density is defined is typically the horizontal ground surface. Estimates may then be compared to, for example, the power density of solar energy. Wind farms have values ranging on the order of 1-11 MW/km^2, with an average of about 3 MW/km^2 [50] in 2009 (note that this is the same as 3 W/m2 in units more familiar to solar energy which has much higher densities but of course must cover the entire surface with devises). How far these values are from theoretically possible limits for wind power is uncertain at present, and the question has turned out to be much more challenging than establishing limits for a single turbine. The reason is that the dominant mechanism governing power extraction for large wind farms is turbulence.

First, imagine a highly efficient turbulent wake recovery, characterize by a very large wake expansion coefficient k_w, where k_w is the wake recovery parameter in the Jensen [8] model, for which the wake radius $R_w(x)$ grows linearly with distance to the turbine according to $R_w(x) = D/2 + k_w x$. In this case ($k_w \to \infty$) the maximum power density is given by the Betz limit for an individual turbine. Assuming that turbines are placed at a minimal reasonable distance from each other, at a distance $S = sD$ with $s \sim 3$ (distance in units of rotor diameter D), yields a power density of about $0.59(\rho/2)U_0^3(\pi/4)s^{-2} \approx 30$ MW/km^2, when using $U_0 = 10$ m/s, $\rho = 1.2$, and $s = 3$; about an order of magnitude larger than prevailing systems today.

Conversely, in the absence of turbulence and mixing, analyses based on ideal flow would predict that successive streamtubes would slow the air down to asymptotically small hub height velocities, so that the power density of a very large wind farm would tend to zero, asymptotically. Consider a square wind turbine array with $n \times n$ turbines, with turbines placed at a distance equal to sD, where s is on the order of unity (e.g. consider again close spacings of $s \sim 3$), in an aligned configuration. Assuming that the outflow of upstream turbines provides the inflow to downstream ones (see Fig. 4) and assuming no turbulent mixing (no wake recovery), one obtains a total power of $P_{\rm tot} = n \sum_{j=1}^{n} (C_p)^j (1/2)\rho U_0^3 A_r = n(1/2)\rho U_0^3 (A_r)(\pi/4)D^2 C_p(1-C_p^n)/(1-C_p)$ and a power density equal to $n^{-1}s^{-2}(\pi/8)\rho U_0^3 C_p(1-C_p^n)/(1-C_p)$. For $C_p = 0.59$ the

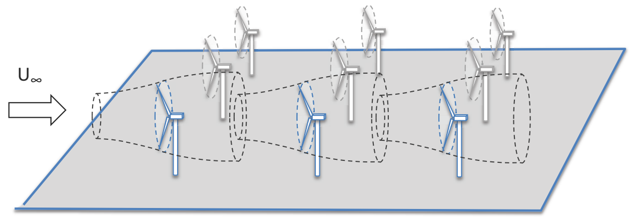

Figure 4. Sketch of aligned wind farm with $n \times n$ turbines ($n = 3$ shown), with individual turbine's ideal flow streamtubes feeding into downstream turbines without turbulent mixing and recovery.

geometric series tends to zero rather fast and the density decays as n^{-1}. Already for $n = 10$ one would obtain a density equal to only 25% of the case with maximum turbulent mixing. For very large asymptotic wind farms (e.g. $n = 100$, we obtain 0.7 MW/km^2). Hence, in order to arrive at power densities for asymptotically large wind farms that do not tend to zero requires inclusion of turbulence and mixing. Turbulence is not a mere correction to an ideal flow prediction, but represents the dominant mechanism providing the true 'rate limiting' factor leading to non-zero asymptotic power density.

Further insights may be obtained from the top-down approach already mentioned in $Q3$ above. As shown in [41] and reviewed in $Q2$ above, the flux of kinetic energy is given by $\Phi_{hi}(z) = (u_{*,hi}^3/\kappa)\log(z/z_{0,hi})$. The wind farm effective roughness length $z_{0,hi}$ may be computed from wind farm design parameters according to Eq. (10) in [42] (see also Eq. (39) [41]), where $c_{\rm ft} = \pi C_T/4s^2$ and $C_T \approx 0.8$ is the thrust coefficient, $\beta \approx 0.75$ represents effects of additional mixing in wakes [41], and $z_{0,lo}$ is the roughness length of the underlying ground surface upon which the wind farm is built. For a wind farm with $z_h = 100$m, $D = 100$m, turbine spacing of $s \sim 7$ and above grassy terrain with $z_{0,lo} \sim 5$mm, we obtain $z_{0,hi} \sim 1.6$ m. The ratio $u_{*,hi}/u_*$ can be estimated as $\log(H/z_{0,lo})/\log(H/z_{0,hi}) \sim 2$ (if we use $H \sim 1$ km as height of the ABL and above-mentioned parameters). Hence a typical value to be expected for the increased above-wind farm friction velocity is $u_{*,hi} \sim 1$ m/s (since $u_* \sim 0.5$m/s is common). Then the flux evaluated at the turbine tip, $\Phi_{hi}(z_h + D/2) = (u_{*,hi}^3/\kappa)\log((z_h + D/2)/z_{0,hi}) \sim 5$ (m/s)^3. Multiplication by air density yields an aerial power density of ~ 6 kg/s^3 ($= 6$ MW/km^2). Parts of this flux must be dissipated and only a fraction thereof can be extracted at the turbines. Only if the turbulence levels and transport efficiency above the wind farm could be increased to, say $u_{*,hi} \sim 1.7$ m/s, the analysis would yield a power density close to the 30 MW/km^2 mentioned above. Hence, transporting turbulence would have to be increased quite a bit above typical values to support the sorts of idealized power densities hypothesized under idealized maximal turbulent transport conditions.

A recent paper [51] approaches the problem using an even more simplified, but manageable, two-layer box model of the atmospheric surface layer in the presence of a large wind farm. The flow inside the wind farm is assumed to be plug-flow (constant velocity U_f inside the farm) with a step towards the above-wind farm constant velocity layer (velocity U_b) that extends up to the height of a growing internal boundary layer, above which the velocity is constant equal to U_0. The vertical exchanges among the layers are modeled using mixing coefficients, inspired by thin shear layer (e.g. mixing layer) dynamics that relate vertical transport velocities with horizontal velocity differences across the layer interfaces. The approach introduces two coefficients, an entrainment coefficient E and a momentum exchange coefficient, C_M. The main result (their Eq. 34) is that the power density is, to a large degree, proportional to the exchange coefficients. In ideal flow these coefficients are zero, and their model indeed then predicts a power density of zero. This again shows that turbulent mixing is the dominant effect and not a correction to an ideal flow estimate of an upper limit. Conversely, the most efficient turbulent mixing imaginable would yield vertical entrainment velocities even exceeding the prevailing horizontal velocity, i.e. $E = C_M >> 1$. Under these arguably unphysical conditions, the maximum efficiency predicted by the two-layer model of [51] (equation 34 with $c_{fp} = c'_{ft}$) would imply that $U_f = U_0$, i.e. complete velocity recovery inside the wind farm layer, and thus a situation similar to the idealized case with $k_w \to \infty$, leading again to a power density or around 30 MW/km^2 (for $U_0 = 10$ m/s and $s = 3$). A range of more realistic intermediate values for E and C_M are developed in Ref. [51], using data and empirical knowledge.

Clearly then, we are in a situation where going from ideal flow to unrealistically high turbulence mixing efficiencies yields power density estimates ranging from very small values all the way up to values that exceed currently prevailing values by an order of magnitude. Thus more research to respond to the important question whether an upper limit can be derived appears warranted.

Question 5: Can synthetic turbulence models represent the spatio-temporal structure of atmospheric and wind farm turbulence, together with its non-Gaussianity and including external effects?

Synthetic turbulence provides the ability to mimic unsteady turbulence without having to perform expensive time-dependent CFD simulations. Such models have stimulated interesting research in fundamental turbulence [52,53], perhaps under the premise that "if you can build it, you understand it". Synthetic turbulence has also been used to generate inflow conditions for simulations such as DNS or LES [54]. In the context of wind energy, synthetic turbulence has played an important role especially for predictions of structural loading [55]. Many approaches focus on generating simple time series of hub-height velocity [56–58] without attempting generate full 3D fields. Early versions of spectral methods to generate 3D fields applied to wind energy can be found in Veers [59]. The best know methods are based on the Mann spectral model [25] in which Rapid Distortion Theory-derived factors to account for mean shear effects on the wave-number spectrum, and correlations among modes to generate shear stress, can be included. Typically a spatial field in a box that is very long in the streamwise direction is generated and the field is swept past the rotor using Taylor's frozen flow hypothesis. The resulting temporal periodicity is mitigated by using a very long box [25]. Other applications can be found, e.g. in [60]. To introduce temporal fluctuations without having to use Taylor's frozen flow hypothesis, so-called kinematic simulations based on sparse subsets of Fourier spatio-temporal modes (traveling waves) [61] have been explored.

Spectral models for the full spatio-temporal (wave-number frequency) spectrum of turbulence can be derived from Kraichnan's random sweeping hypothesis [64,65] (for a physical-space implementation based on correlation functions, see Ref. [66]). These models have not yet been employed to generate spatio-temporal synthetic instantiations, and it is unclear how expensive generating such synthetic 4D spatio-temporal fields would be in practice.

The classic synthetic turbulence models typically assume Gaussian statistics for the turbulent velocity fluctuations. However, there are indications that turbulence relevant

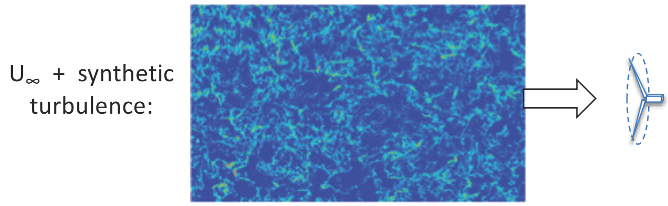

Figure 5. Sketch of synthetic turbulence (in this case generated using a Lagrangian map method to reproduce both spectral and non-Gaussian turbulence statistics [62,63]) being transported by the mean flow at hub height through a wind turbine rotor.

to wind power production displays non-Gaussian statistics [67–70] and this insight has motivated some extensions of the time-series synthetic modeling in which non-Gaussianity and non-homogeneities are included by skewing the probability density distribution functions [71] or using a Langevin equation-based model and stochastic differential equations [72,73]. How much non-Gaussianity of turbulence affects turbine loading and power variability is, however, not yet a settled question. The filtering inherent from rotor averaging has been shown to decrease the effects of non-Gaussian statistics appreciably [74].

In order to help settle such questions, it is important to be able to generate 3D synthetic vector fields that are non-Gaussian. However, the non-Gaussian models typically are restricted to representations of time-series representing the wind at a single (e.g. hub-height) location, but these cannot represent variations across the rotor. Extension of such approaches to generate 3D vector fields is very challenging and only a few attempts have been reported. One example uses multi-scale Lagrangian maps [62,63] which can generate non-Gaussian 3D velocity fields in which the increments and gradients display turbulence-like non-Gaussian statistics [62,63]. Figure 5 shows the vorticity field generated by the Lagrangian map approach [62] clearly displaying highly intermittent features not present in Gaussian fields. However, these approaches cannot as of yet reproduce temporal fluctuations and are limited to generating static 3D fields. Also, they have not yet been tested in the context of wind energy.

Effects of shear and strain, as well as thermal stratification on the non-Gaussian fields are additional topics that are not yet explored actively in the context of synthetic turbulence generation. But given the usefulness of synthetic turbulence to wind energy engineering, further research on the question of synthetic turbulence appears worthwhile.

Question 6: How can information about regional meso-scale phenomena be included as inflow/outer boundary conditions in wind-farm level simulations (super-grid modeling for LES)?

Many of the large eddy simulation studies of flow in wind farms have been performed under steady state forcing conditions, in which distributed body forces represent the pressure gradients either directly imposed [41,75–77] or by relating it to the (fixed) geostrophic wind above the ABL [78–80]. This may be representative of realistic conditions over relatively short time periods (perhaps for 10 to 30 minutes, at most) but typically in the atmosphere, large scale outer conditions are subjected to temporal variability, fronts, time-dependent radiative forcing, etc. Thus, in addition to the inherent variability of turbulence including time-scales up to about 10-20 minutes, larger scale (meso-scale) variability from the regional atmospheric motions, typically with time scales 10 minutes and longer (up to hours), will "modulate" the smaller-scale turbulence. Hence, for LES of wind farms, there exists a "supergrid modeling" challenge meaning that the inflow, outer, and/or forcing terms in the LES equations must be made time-dependent and somehow prescribed/modeled. A natural approach is to obtain the relevant information from larger-scale simulations. A popular code to simulate atmospheric flow at those scales is the Weather Research and Forecasting (WRF) model [81]. The coupling of LES to large-scale models has been examined already in a number of papers, e.g. to enable varying wind directions in concurrent precursor simulations [82], to couple with WRF [83,84].

The coupling among codes, e.g. WRF at the large scales (regional scale down to kilometers), and LES at the smaller scales (kilometers down to meters), remains a challenging problem. It is not just a numerical problem but one intimately linked to turbulence physics, since the response of ABL turbulence to temporally varying modulations involves inherently nonlinear and nonlocal flow responses that are difficult to model. One of the largest challenges in such couplings is to populate small-scale motions. The information provided by a regional simulation may contain motions down to, e.g. kilometers in the horizontal direction. But at the inflow of the LES domain, scales down to meters must be prescribed. Typically, waiting for the turbulence dynamics to generate these smaller scales via the nonlinear cascade mechanism takes time or lengthy downstream development lengths. A similar challenge occurs in LES in which the flow goes from a coarse mesh to a finer mesh downstream [85]. One approach is to "enrich" these scales with synthetic turbulence (see Q5), see e.g. [86]. Data assimilation tools such as Kalman filtering and ideas from control represent active areas of research. At the heart of the problem lies the basic physics of the response of wall-bounded turbulence to unsteady large-scale forcing.

The goal of capturing different physics when coupling the various simulation levels has led to a plethora of different more or less ad-hoc practical approaches, well adapted to each situation, but lacking a unified systematic procedure to transfer and enrich relevant information from large to small-scale computational domains. Better understanding of non-equilibrium (non quasi-steady) boundary layer turbulence should lead to more systematic ways of deriving improved "supergrid-models" for LES of wind farms.

Question 7: How can effects of wind turbines and wind farms best be represented (windfarm subgrid-scale modeling) in geophysical models?

Representation of individual wind turbines in fine-scale models such as LES has advanced considerably, with actuator disk model (ADM) [41,87,88] and actuator line modeling (ALM) [89,90] being constantly improved. These require grid resolutions of between meters (ALM) [91] to tens of meters (ADM). But when simulating the effects of wind turbines and wind farms in the context of large-scale geophysical models, such as in regional-scale or global climate models grid resolutions of kilometers to 100s of Km must be used. Such geophysical CFD model runs are needed to quantify the expected effects of very large wind farms [92–94] on weather and climate, or to quantify mutual effects among neighboring wind farms [95], which is becoming a burning issue for the growing number of planned off-shore wind farms, e.g. in the North Sea in Europe (it will soon also become an issue on the US East Coast). Clearly at these resolutions, ALM and ADM models are not appropriate.

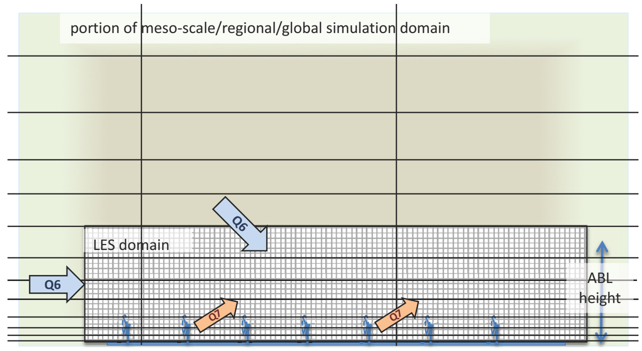

Figure 6. Sketch of coupling between LES and large-scale geophysical models. The top-down problem how to incorporate information from regional meso-scale phenomena as inflow/outer boundary conditions for wind farm level LES motivates question 6 (Q6) while the reverse, how to model wind turbines and wind farms in the context of meso-scale/regional and global scale geophysical models motivates Q7.

In early applications of geophysical CFD, the effects of continent-wide implementations of wind power were studied [92,93] by prescribing an enhanced roughness scale $z_{0,hi}$ to mimic the effects of large wind farms on the surface stress. These early studies in fact motivated improved roughness models that were obtained from detailed LES studies [41]. There, an expressions for $z_{0,hi}$ was derived describing the equilibrium logarithmic law expected on flat terrain with very large wind farms that would occur above the wind farm (see also discussion in Q4). Application of this model assumes that the wind turbines are located below or near the vertical resolution of the large-scale model since the roughness only affects the drag force at the bottom surface. As wind turbines have gotten taller, and vertical grid resolutions have gotten finer, these assumptions are not relevant any longer. Even in large-scale models the vertical resolution in the ABL can be tens of meters near the surface and thus several grid points fall below and on the wind turbine height. In these cases the effects of wind turbines are typically represented by body forces acting at the relevant grid points (vertical layers), where the mean flow momentum should be reduced while turbulence should be increased, especially turbulence at scales comparable or smaller than the rotor diameter. Most approaches, including the model in Ref. [96], apply a drag force to extract momentum from the flow. The concomitant mechanical power extracted goes into generator power (here the power coefficient is used), while the difference is used as a source of turbulent kinetic energy.

It bears mentioning that the length and time-scales at which this kinetic energy is added to, e.g. the turbulent kinetic energy (TKE) field in a turbulence prognostic equation, are very different – smaller – from the scales that dominate the underlying ABL turbulence. The remainder of the model parameters in the usual transport equations for TKE and dissipation (or frequency) have not been calibrated for such injections of kinetic energy at scales below the local integral scales. Hence, the representation of turbulence caused by wind turbines and wind farms is an additional open question. And, approaches in which LES and large-scale geophysical models are two-way coupled require addressing both questions, Q6 and Q7.

3. Closing

Each of the issues and questions raised here touch upon rather fundamental properties of turbulence. Many other areas of turbulence overlap with the needs of wind energy. Clearly, CFD has played a very important role in the design of modern wind turbine blades, enabling them to grow in span from a few tens of meters just two decades ago to the present stage of gigantic blades of sizes that dwarf large commercial airliners. The availability of CFD and appropriate models of turbulence (mostly RANS models) have played a key role in these developments and further improvements are likely to benefit wind turbine designers. This is especially true as new system designs may be required to deal with entirely new types of platforms (floating wind turbines, vertical axis, multiple rotor turbines, etc.).

Each of the posed questions highlights the challenges of translating whatever fundamental knowledge we might have on fluid dynamics and turbulence to a relatively new technological challenge. The wind energy challenge is quite unique in the sense that geophysical turbulent flows interact with machinery whose scales are unparalleled in prior applications of turbulence research. It is known that Eiffel, while designing the tower that bears his name, used the assumption of a constant mean velocity distribution in the atmosphere and that using a more realistic turbulent mean boundary layer profile would have in fact yielded a modified shape [97]. Now imagine the challenges of designing a "dynamic" Eiffel Tower containing moving parts that speed along five times faster than the wind velocity. The challenges involved are uniquely interesting.

Finally, it is hoped that working towards satisfactory answers to the seven questions posed here will assist, in some measure, in the transition to a more sustainable energy infrastructure.

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