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# Multidisciplinary design optimization of large wind turbines—Technical, economic, and design challenges

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ABSTRACT

Wind energy has experienced a continuous cost reduction in the last decades. A popular cost reduction technique is to increase the rated power of the wind turbine by making it larger. However, it is not clear whether further upscaling of the existing wind turbines beyond the 5–7 MW range is technically feasible and economically attractive. To address this question, this study uses 5, 10, and 20 MW wind turbines that are developed using multidisciplinary design optimization as upscaling data points. These wind turbines are upwind, 3-bladed, pitch-regulated, variable-speed machines with a tubular tower. Based on the design data and properties of these wind turbines, scaling trends such as loading, mass, and cost are developed. These trends are used to study the technical and economical aspects of upscaling and its impact on the design and cost. The results of this research show the technical feasibility of the existing wind turbines up to 20 MW, but the design of such an upscaled machine is cost prohibitive. Mass increase of the rotor is identified as a main design challenge to overcome. The results of this research support the development of alternative lightweight materials and design concepts such as a two-bladed downwind design for upscaling to remain a cost effective solution for future wind turbines.



## 1. Introduction

Over the last decades, the cost of wind generated electricity has experienced a continuous reduction thanks to research and development [1–3]. This cost reduction has enabled wind energy to become more viable, and today wind energy is one of the most affordable forms of renewable energy [4–7]. Upscaling has been performed as the basis to enable this cost reduction [8,9]. The development of larger wind turbines is supported by several factors, such as higher energy capture per area land use, and cost reduction per rated mega Watt (MW) capacity with fewer larger machines for the same installed capacity. Therefore, turbine size is often considered as a merit index for technology progress and development [10–13].

Despite significant technological improvements, the average cost of wind generated electricity is higher than that from traditional energy resources such as coal and natural gas [14,15], and it is subject to a larger variability [16–18]. It is not clear whether further upscaling beyond the existing 5–7 MW range is both technically feasible and economically attractive. Typically, analytic scaling laws, and extrapolation of existing wind turbine data are used to develop different scaling trends. These scaling trends are needed to investigate the impact of size on the technical design and the associated cost [19–21].

However, analytic scaling laws are not capable of providing accurate realizations of large scale wind turbines. This is related to the simple formulation of analytic scalings, which makes them suitable for the conceptual design phase. As the size increases beyond the few MW range, the pronounced interaction between disciplines such as aerodynamics, structures, and controls, as well as the complex system dynamics of more flexible components, presents design challenges [22–25]. Therefore, it is questionable whether analytic scaling can model the complex scaling behavior of large wind turbines to accurately quantify the impact of size.

Extrapolation of the existing wind turbine data also introduces large uncertainties in the design, and it is of limited use for this research. Additionally, distributed model properties can not be extracted from existing data trends to take into account the wide range of design solutions from every different manufacturer present in the trends.

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To address these problems, this research uses 5, 10, and 20 MW wind turbines that are developed using multidisciplinary design optimization (MDO) [26] with a similar design concept and design assumptions for all sizes. This enables the incorporation of all important disciplines and components for making reliable scaling trends that are needed to accurately quantify the technical and economical aspects of upscaling.

Compared to classical upscaling methods, the same design assumptions reduce the scattering of the data points used for scaling trends. It may also help to identify which aspects of the chosen concept have strong or weak scaling behavior. Therefore, using the design data of the developed 5, 10, and 20 MW turbines, loading, mass, and cost trends are constructed and used to predict what exactly happens to the design and its associated costs as the size increases. This enables a more accurate prediction of the economic viability of upscaling, and the identification of the design challenges that need to be overcome to achieve that viability.

The remainder of this paper is organized as follows. First, a brief overview of the two classical upscaling methods is presented. Then, the development of the 5, 10, and 20 MW wind turbines is explained. Next, the construction of the scaling trends using the developed wind turbines as scaling data points is discussed and trends for loads, mass, and cost are presented. Next, the design challenges of larger wind turbines using the developed scaling trends are identified and discussed. Finally, conclusions on the economic viability of existing wind turbine upscaling are discussed.

## 2. Classical upscaling methods

To examine the effect of size on the design, two different methods are frequently used. First, the analytic relation between a number of important parameters that govern the design can be formulated as a function of rotor diameter (or radius) by assuming that all geometrical parameters vary linearly with size [27,28]. This approach is called the analytic scaling law (also known as the similarity or linear scaling rule). Appendix A gives a detailed overview of the method.

Analytic scaling enables the realization of scaling trends based on wind turbines that are not size optimized, and that may not meet all design constraints. Therefore, the usage of this method is limited to the conceptual design phase [29]. This makes the method less suited for studying detailed technical and economical characteristics, in which the optimized end results are important.

Second, parameters of interest can be statistically correlated to rotor diameter using the existing wind turbines' data. In this approach, real data are viewed collectively, and scaling trends are developed by correlating these data [30]. As an example, Fig. 1 shows the correlation of the rated power output of 27 wind turbines to rotor diameter in the range of 15–130 m.

In this figure, the curve fit to the data points shows almost a square relation with size, and to study wind turbines that are larger than existing ones, the curve can be extrapolated. However, extrapolation beyond the data range introduces uncertainty in the results, which is considered to be the main drawback of this technique. Furthermore, the data points used to develop the scaling trends are obtained with wind turbines of different concepts and design assumptions, and this introduces scattering in the data points.

To overcome the drawbacks of these two methods, the present paper develops a novel method where for several given scales of interest, optimized wind turbines are developed. Based on these optimized designs, the relation between different parameters and rotor diameter can be extracted and used to develop more accurate trends [31,32]. This method is explained in the next section.

## 3. Development of large scale wind turbines

The design of a wind turbine operating in a wind farm is a complex decision making process [33]. To facilitate the understanding of the work presented in this research, a brief summary of the MDO approach that serves as the basis for the study is presented.

An earlier study showed that the economies of scale are negligible in the rated power range of 0.75–3 MW [34]. To study the challenges and trends of wind turbines beyond the existing 5–7 MW range, technical and economical data of large scale wind turbines are needed. Therefore, the realization of 5, 10, and 20 MW wind turbines is performed using MDO to obtain the required technical and economical data. This section explains how these wind turbines are designed.

### 3.1. Aeroservoelastic simulation

MDO requires the numerical computation of the objective function and design constraints, using simulations that represent the underlying physics. Among the various simulations that have been developed for the wind energy research community, a series

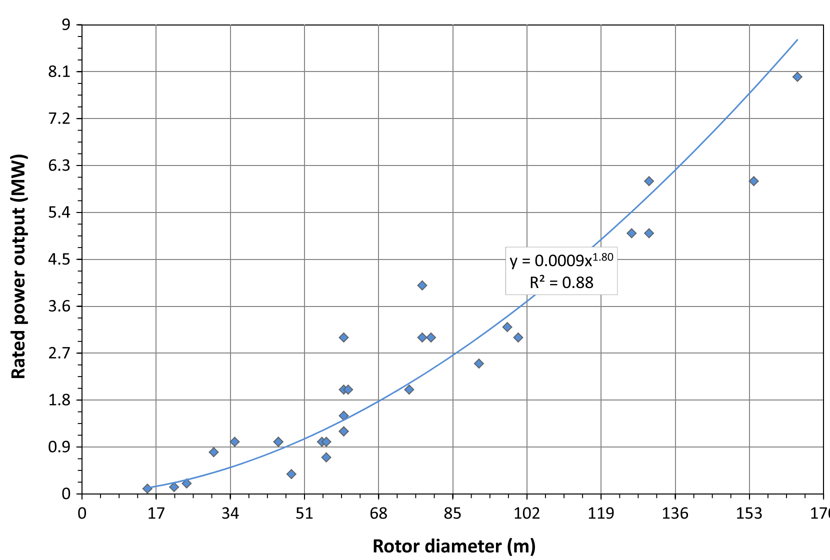


**Fig. 1.** Rated power output of the wind turbine as a function of rotor diameter. These data are collected by the authors from public product brochures and company web sites. Professional database services also exist to buy these data collectively. (http://www.thewindpower.net/turbines_databases_en.php, last accessed May 22, 2016).