Technical challenges and trends in upscaling wind turbines

A review

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Abstract

The upscaling of wind turbines has been increasing in recent years and will continue to play a significant role in the future, as it allows for the reduction of electricity generation costs. Various challenges arise when it comes to upscaling. This article summarizes the technical challenges associated with upscaling wind turbines and presenting their problem-solving approaches and research trends based on other reviews. It was found that the most frequently cited challenges are related to individual components, such as rotor blades, drive train, generator, tower, and noise impact.

For rotor blades, the challenges are increased flexibility, more aeroelastic vibrations, increased wear, interferences with radar and transportation difficulties. Proposed solutions include the use of carbon-fiber blades, prebending, novel paints, and for transportation, segmented rotor blades and on-site manufacturing. In the gearbox, torque increases, leading to higher weight and susceptibility to errors. As a result, the trend is moving towards gearless systems with permanent magnet synchronous generators. Transportation is the major issue with towers, which can be resolved with on-site manufacturing. In terms of noise emission, reducing aerodynamic noise plays the most significant role.

Keywords: upscaling wind turbines, large wind turbines, trends and challenges wind turbines, wind turbine enlargement

1 Introduction

The goal of European climate and energy policy by 2030 is an increased proportion of renewable energy to 45%. To achieve this goal, among others the expansion of wind power in Europe is continuously progressing. In addition to more wind parks, the capacity of individual turbines is increasing which can be achieved by upscaling the turbines. It is still an ongoing trend for both onshore and offshore wind turbines because a higher-power wind turbine system leads to a lower levelized cost of energy (LCOE) [1]. Current developments range from 6 to 8 MW for onshore wind turbines [2]. Offshore wind turbines aim for capacities of 10 to 15 MW [2]. The largest onshore turbines reach heights of 200 m with a rotor diameter of 150 m, while the largest offshore turbines reach heights of 250 m with a diameter of 200 m [3]. The enlargement of wind turbines presents a range of challenges. This paper summarizes the challenges, problem-solving approaches and trends associated with the upscaling of wind turbines.

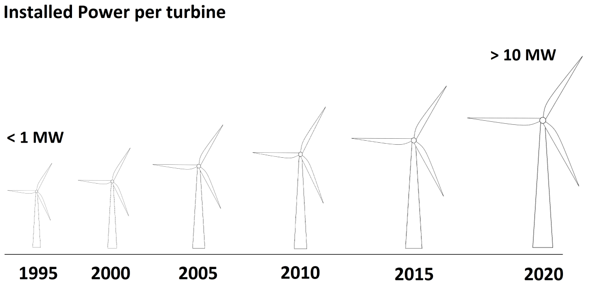

Fig. 1: Size evolution of wind turbines [Source: Author]

2 Methods

This paper is written as a systematic review, as the challenges associated with upscaling are multifaceted and manifest in multiple domains. The research for the cited articles was conducted using Google Scholar with the assistance of ChatGPT. Specifically, ChatGPT generated search terms that were then put into Google Scholar. Literature maps were created using Researchrabbit, but they proved unhelpful, as they included articles unrelated to the topic and many sources were outdated. Initially, more general articles on wind power were read to identify articles related to upscaling and extract relevant articles. Subsequently, information on the challenges, solving approaches and trends associated with upscaling gathered from the relevant articles were compiled.

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3 Challenges and Trends

3.1 Rotor blades

When enlarging the rotor, a challenge arises in that the flexibility of the rotor blades increases. This results in a reduction in the distance between rotor blades and the tower under heavy loads. Methods to increase this distance include pre-bending the blades, which leads to difficulties in manufacturing and transportation as the blade size increases. Another option is the use of carbon fiber instead of commonly used glass fiber, which has a higher specific stiffness, but carbon fiber is more expensive than glass fiber [3].

Additionally, there is an increased occurrence of harmonic and aeroelastic vibrations with blade enlargement. One approach to address this is improved damping, which can be passive (structural and aerodynamic) or active through the turbine controller [3].

Another problem is the wear (fouling) caused by insect impacts and icing. Increasing erosion due to abrasive particles is also a concern. These problems increase especially in regions with higher wind speeds, and lead to poorer aerodynamic performance. Novel paints with nano-composites can provide a solution [4].

Moreover there are concerns regarding the interference with radar. For this, the employment of anti-reflection or stealth rotor blades has been explored, but requires further research [4, 5].

Fig. 2: Segmented rotor blade of an Enercon E115 with mechanical joints [6]

A further challenge related to enlarged rotor blades is their transportation. Transportation can occur by road, rail, water, or air. On the road, there are limits regarding width, height, and weight. On rail, trains must travel at slower speeds. Shipping requires the use of expensive fixtures to prevent twisting of the ship. In the air, helicopters are considered risky, so research is being conducted on blimp-like air lifting devices [7]. There are suggestions to improve transportation methods, such as rotatable rotor blades on truck to pass bridges [8], or floating sealed rotor blades via waterways [9]. The production in small on-site factories with prepared material kits from the main factory is also suggested [10].

Furthermore, there is the possibility of segmented rotor blades. This leads to smaller lengths, heights, widths, and weights and therefore easier transportation. To attach the segmented blades, there are options for adhesive joints or mechanical joints [7]. Fig. 2 shows a segmented blade with a mechanical joint.

3.2 Gearbox

The drive trains can be distinguished into systems with and without gearboxes. With the increase in rotor diameter and consequently its weight, higher torques occur in the drive train. This increases the susceptibility to errors in the bearings and, if present, in the gearbox, thereby raising the requirements. The most powerful gearboxes for wind turbines can support up to 15 MW, with torque densities of 200 Nm/kg and gear ratios of up to 200 [2].

The trend for larger wind turbines is increasingly moving towards systems without gearboxes due to size, efficiency and availability [11]. There are several advantages of direct-drive systems. While the error rate is highest in blades/pitch, electric, and control systems, errors in the gearbox, bearings, and hydraulic system have the most significant impact on downtime, especially in hard-to-reach offshore environments [4, 11]. The global efficiency increases due to reduced friction losses. Furthermore less oil needs to be changed. The reduction in moving parts enhances reliability, thereby reducing maintenance costs. Additionally, the elimination of the gearbox leads to a decrease in noise emissions and vibrations [11]. Advantages of indirect-drive systems are reliability, simplicity and low cost, but the advantages of direct-drive systems outweigh the disadvantages for large systems [11].

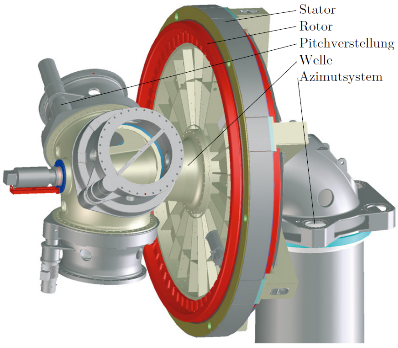

Fig. 3: Direct-drive turbine [6]

3.3 Generator

For larger wind turbines without gearboxes (low-speed direct-drive systems), electrically excited synchronous generators (EESG) and permanent magnet synchronous generators (PMSG) have gained popularity among manufacturers [11]. The trend is moving towards PMSG because EESG involves higher maintenance requirements for brushes and more heat losses due to current in the excitation windings, leading to increased complexity in the cooling system. In contrast, PMSG eliminates the excitation current and the need for brush maintenance. The electrical properties, such as copper losses, are improved, and the overall weight is reduced. In PMSG, the energy yield and efficiency increase overall [11]. A disadvantage of PMSG is that they require expensive rare-earth elements like neodymium, praseodymium, and dysprosium. To reduce the demand for rare-earth elements, new technologies are under development, including high-temperature superconducting generators, which could become commercially viable in the next decade [3]. These promise higher efficiency and lower weight compared to conventional generators [11]. The power converters in systems exceeding 10 MW are duplicated to prevent excessive current loading per converter [2].

3.4 Tower

The most commonly used types of towers are steel towers and hybrid towers made of both steel and concrete. With increasing tower height, either the tower base must become wider or the wall thickness must be increased while keeping the diameter constant due to the statics. It is cost-effective to keep the wall thickness constant to minimize material costs. However, since prefabricated tower segments made of steel or concrete are limited in diameter for transportation reasons, reinforcing the wall thickness remains the option for prefabricated tower segments [12, 13]. In addition to prefabricated steel or concrete tower segments, there is the opportunity of large diameter steel towers, which are additionally segmented lengthways to reduce diameter during transportation with an on-site assembly after transportation [12].

On-site manufacturing to avoid transportation is another option. For this purpose, the tower must be at least partially made of concrete to be cast on-site [4]. There is also a proposal to cast the entire tower on-site (Full-Concrete Field-Cast Towers). Advantages of this technology include a reduction in primary material costs and independence from steel prices. A disadvantage is the higher labor costs on-site. Another mentioned alternative is lattice towers, which facilitate transportation, but the labor costs are also high due to the relatively challenging construction process [13].

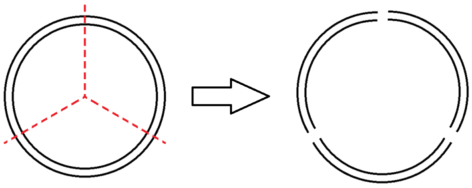

Fig. 4: Lengthways segmented tower segment (front view) [Source: Author]

3.5 Noise emissions

Noise emissions from wind turbines require an increased distance from settlements and/or residential houses. With larger turbines, the noise emissions are amplified. The noise emitted by a wind turbine can be categorized into mechanical and aerodynamic noise. Mechanical noise is generated by moving components such as the gearbox, electrical generator, and bearings. Mechanical noise can be reduced through design measures and acoustic insulation. Aerodynamic noise results from the airflow over and around the turbine blades. It increases with the blade tip speed. This is why the aerodynamical noises are dominant in larger systems, while the mechanical noises dominate in smaller ones [4, 11]. Individuals may experience headaches and other health issues due to aerodynamical noises [14]. They can be mitigated through blade design improvements such as trailing edge serrations [15, 16]. Additionally, reduction is possible through lower angles of attack, higher stall angles, and automatic blade pitching [4]. It is also feasible to place obstacles in the propagation path to alleviate aerodynamic noises [14].

Fig. 5: Trailing edge serrations for mitigating noise emissions [6]

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Tab. 1: Summarized Challenges and their problem-solving approaches and trends [Source: Author]

Component	**Challenges**	**Problem-solving approaches & Trends**
Rotor blades	Flexibility	Pre-bending Carbonfiber blades
	Vibrations	Active and passive damping
	Erosion & Fouling	Novel paints
	Radar interference	Stealth blades Anti-reflection blades
	Transportation	Segmented blades On-site manufacturing Concepts like floating sealed blades or blimp-like air lifting devices
Gearbox	Higher requirements	More powerful gears Trend: direct-drive (gearless) systems
Generator	Less maintenance, more reliability & heat losses	Permanent Magnet Synchronous Generators (PMSG)
	PMSG: reducing rare-earth elements & weight	Superconducting generators
	High current in Power Converter	Duplicated Power Converters
Tower	Transportation	Pre-fabricated: Thicker walls due to width-limit or lengthways segmented segments On-site manufacturing: Partial concrete or Full-Concrete Field-Cast Towers Lattice towers
Noise emissions	Mechanical noises	Direct-drive systems Acoustical insulation
	Aerodynamical noises	Blade design improvements Lower angles of attack Higher stall angles Automatic blade pitching Obstacles in propagation path

4 Summary

In this review, the technical challenges and trends in upscaling wind turbines which are mentioned in other reviews have been compiled. Onshore turbines are currently being upscaled to 6-8 MW, and offshore turbines to 10-15 MW, as this can lead to a reduction in the cost of electricity generation. The main focus areas in this article are rotor blades, gearbox, generator, tower and noise emissions. Tab. 1 lists the challenges and their problem-solving approaches and trends for each of these components.

In the case of rotor blades, one issue is an increase in flexibility, which can be addressed by employing pre-bending or rotor blades made of carbon fiber with a higher specific stiffness than glass fiber. Increased vibrations can be reduced through active or passive damping. Additionally, fouling due to insect impacts, icing and erosion is a concern. Countermeasures may include novel paints. For interference with radar, anti-reflection and stealth blades are under research. Another important aspect is the transportation of rotor blades, which becomes more challenging with upscaling. In addition to segmented rotor blades, which are assembled during installation, there are proposals like floating sealed blades or blimp-like air lifting devices. On-site manufacturing, eliminating the need for transportation, is also suggested.

With upscaling, higher demands arise for the gearbox. As the gearbox is one of the components which is responsible for the longest downtime, the trend is clearly moving towards direct-drive systems without a gearbox. For the generator, there is a shift towards permanent magnet synchronous generators, as heat losses and maintenance can be minimized by eliminating brushes and exciting current. However, the use of expensive rare-earth elements is necessary in this case. Superconducting generators are under research and could become market-ready in the next decade. Regarding the power converter, a dual design is necessary due to high current.

For the tower, the most crucial aspect is transportation. As the facilities become larger, either the diameter or the wall thickness must increase for prefabricated tower segments. Due to road restrictions, the options here are to reinforce the wall thickness or to segment the segments additionally lengthways. On-site manufacturing can also provide a solution. For this purpose, the towers must be at least partially made of concrete. There is also the proposal of the Full-Concrete Field Cast Towers, which consists entirely of concrete. Another option are lattice towers.

Concerning noise emissions, either the distances to homes and settlements must be increased, or the noises must be reduced, as excessive noise levels can lead to health issues. In wind turbines, there are mechanical noises caused by moving parts, and more importantly for larger turbines, aerodynamic noises caused by the flow of air over and past the blades. Aerodynamic noises can be reduced through constructive blade design, lower angles of attack, higher stall angles, and automatic blade pitching. Placing obstacles in the propagation path is also an option.

5 Conclusion and Outlook

This review deals with the challenges and trends in upscaling wind turbines. The relevance of this topic is high because manufacturers are increasingly moving towards upscaling wind turbines due to levelized costs of energy. The most frequently mentioned challenges and trends were summarized from current literature. It can be said that upscaling extends to all areas of a wind turbine from a technical point of view. In some cases, there are already solutions for the mentioned challenges, which then have to be dimensioned according to size, such as reducing noise, while in other cases new technologies such as superconducting generators or stealth blades are being developed or tested. There are also problems that only arise with an increase in size, such as transportation, where one solution is on-site manufacturing, for example. This paper can be used to gain an initial overview of the technical problems associated with upscaling wind turbines. It should be noted that the challenges and trends illustrated here do not reflect the full spectrum, and that there are certainly other technical challenges as well as challenges relating to the environment, the legal situation and the economic aspects of upscaling wind turbines. This could be points for future work in order to obtain a more interdisciplinary overview of the topic.

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