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Wind Turbine Generators— They Just Keep Getting Bigger

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ABSTRACT

The wind turbine industry is evolving. One notable trend is to design, develop, and install ever-larger wind turbine generators. Is bigger really better? When using machines of larger capacities their efficiencies increase. Fewer are required to generate the electricity needed. This article discusses the shift in the wind power industry to producing larger capacity machines for use in the development of both land-based and offshore wind farms. This article further considers the reasons why manufacturers are racing to build larger wind turbine generators, discusses development limitations, and identifies the electrical power capacities of the largest ones that have been installed. While there are no theoretical limits, the size of wind turbine generators is limited by technical, economic, and developmental challenges. The basic mechanics of wind turbines are detailed. This article also considers the importance of making on-site operational performance assessments after prototypes have been placed into operation. The author concludes that there are opportunities for efficiency improvements and growth in the wind power industry that will drive future innovation and create the ability to produce machines with larger capacities.

INTRODUCTION

Though economic constraints hindering the development of wind farms must be overcome, wind power is a renewable energy resource which offers many important benefits. Wind power provides mechanical capabilities and generates clean electricity. Unlike other forms of electrical generation, it coexists with agricultural and other land uses. Wind power is becoming more economically competitive when compared to fossil fuel-fired means of electrical generation. It provides needed revenues, creates local employment, and increases the property tax base in rural areas. Perhaps more importantly, in some regions of the world locally available wind resources offer the lowest cost of producing electricity. The expansion of electrical generation using wind power is viewed by some countries as a strategic solution to help them meet their environmental and sustainability objectives. This is because harvesting wind power does not produce air pollution nor emit greenhouse gas (GHG) emissions.

Wind power requires optimum site selection and is an intermittent renewable energy resource. Overcoming the problem of variable electrical generation when base load power is often required remains a problem for the industry. This issue can be resolved by interconnecting to a host electric grid, using energy storage to smooth the power produced, or by developing microgrids.

Despite the inherent issues with using wind power for electrical generation, the industry is rapidly increasing generation capabilities and capacity. It was only about 20 years ago when the standard wind turbine generators (WTGs) used for commercial windfarms were rated at 1.5 to 2.0 MW. Today's super-sized horizontal axis wind turbines (HAWTs) are taller than some of the skyscrapers found in nearby cities. Bigger is not necessarily better; building larger turbines entails resolving numerous, logistical, engineering, and manufacturing challenges. While land-based wind farms have different requirements depending on the site, offshore wind power developments often deploy the newest, tallest, and most efficient turbines [1].

INCREASING ELECTICAL PRODUTION FROM WTGs

The world's growing use of wind and solar power for electrical generation has been particularly impressive since 2020 (see Figure 1). This is especially true in European and Asian countries due to recent wind power capacity additions. Several European countries have achieved relatively high levels of wind energy penetration in their electricity grids [2]. Denmark supplies 48% of its grid electricity using wind power, Ireland (33%), Portugal (27%), Spain (23%), the UK (21%), and Germany (20%) [2]. Denmark has substantial investments in offshore windfarms. The trains in the Netherlands operate on electricity which is totally supplied by harnessing wind, some purchased from neighboring countries. The South American country of Uruguay obtains 43% of its electricity from wind power.

In the U.S., renewable energy—biomass, geothermal, hydropower, solar, and wind—provide nearly 30% of total electrical generating capacity. More electricity is now produced from wind power than any other form of renewable generation. This is due to increases in U.S. fleet capacities and recent declines in electrical production from hydropower caused by drought conditions in the western regions of the country. Another reason is economic—U.S. capacity-weighted, utility-scale installation costs for wind power declined by 2022 to $1,451/kW while solar PV costs $1,588/kW, or 9.4% more. The U.S. relies primarily on land-based wind farms which are less costly to develop than those located offshore; the country has only a couple of small offshore installations in operation. For example, the Block Island Wind Farm, located 3.8 mi (6.1 km) offshore from the state of Rhode Island in the Atlantic Ocean, has five turbines with a total capacity of 30 MW. In 2022, wind turbines were the source of about 10.2% (499,846 GWh) of total U.S. utility-scale electricity generation—a substantial increase compared to 2021. The country has just over 150 GW of installed wind energy capacity with about 74,700 turbines across 45 states. The states of Texas, Iowa, Oklahoma, and Kansas (in that order) are the leaders in the use of wind resources for the generation of electricity. Some turbines from the early 1990s are still in operation.

Regardless of regional declines in global capacity additions, the world's new land-based wind installations rebounded 65% to 107 GW in 2023. This increase came mostly from expanded wind power development in China, and to a lesser extent India. While China has seen success in offshore wind farm development, elsewhere in the world the industry is experiencing increasing costs, abandoned leases, project delays, and limited supply chain investment that hinders development. Some countries are belatedly discovering that offshore windfarms require that specific policies, supply chains, and infrastructure, that must be in place to support their development. Despite these struggles, the world's wind-based electrical generation is expected to surpass hydropower by 2030 (see Figure 1) [3].

There are reasons for making wind turbines bigger. One is to quickly add renewable capacity to national electric grids or support remote microgrids [4]. Larger capacity wind machines reduce the geographic footprint needed for windfarm development. When using WTGs of larger capacities, fewer machines are required to generate the electricity needed. Their greater height and expansive swept areas provide the ability to harvest more consistent winds that are unobstructed by variable landscape conditions or nearby structures. For example, a single 15 MW HAWT when properly sited replaces a least ten older 1.5 MW machines. As a result, a developing industry trend is to reduce the total number of installed machines and use larger, more efficient, and higher capacity WTGs that increase total electrical production.

MECHANICS THAT LIMIT THE CAPACITIES OF WTGs

Today's commercial wind turbine generators are classified as either vertical or horizontal axis machines. Vertical axis wind turbines (VAWT) are omni-directional machines so the problem of orienting the machines into the wind is resolved by their configuration. Despite their robust designs using blades fixed in position, they can extract a maximum of only 15% of the wind's energy—a key limitation to their broader use. The two main types are the Savonius (drag-type) and the Darrieus (lift-type) vertical axis wind turbines. The largest installed prototypes are rated at about 1.5 MW. The modern, lift-type, three-blade, horizontal axis wind turbines (HAWTs) with longer airfoils and larger swept areas are simply more efficient than vertical axis machines. HAWTs are designed to automatically orient themselves upwind or toward the oncoming winds to optimize their capability of generating electricity. The pitch of their blades is adjusted to help regulate the speed of rotor rotation.

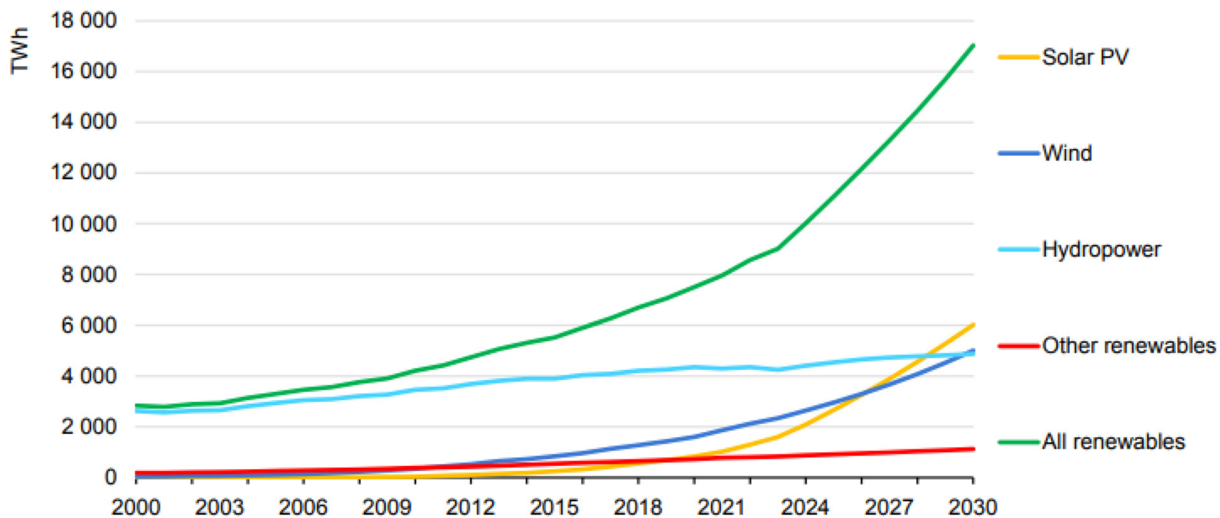

Figure 1. Global electricity generation by renewable energy technologies (2000-2030) [3].

Gauging the Efficiency of HAWTs

For horizontal axis wind turbines, increasing the diameter of the swept area of the rotating blades increases the power extracted from the wind. For HAWTs, Betz's Law (a.k.a., Betz's limit) indicates the extractable power from the wind, independent of the design of the turbine in open air flow. It states that the theoretical maximum extractable power is a function of the swept area of the blades, the wind velocity, air density, and the power coefficient (a measure of efficiency) of the specific machine being studied. Betz's Law establishes an upper limit—no HAWT can capture more than 16/27 or 59.3% of the wind's kinetic energy [5].

While lower-rated WTGs are somewhat less efficient, the larger utility-scale horizontal axis wind turbines achieve a maximum theoretical efficiency of 75% to 80% of the Betz limit. Actual operating efficiencies are less as they are constrained by the height of the tower, the mechanical configuration of the equipment (see Figure 2), efficiency losses, and blade designs. Rarely do WTGs operate at rated capacity. A HAWT when well-matched for a given site will operate 60% to 80% of the time and provide full rated power only about 10% of the time. On an average day, at typical machine will generate about 30% to 35% of what it would generate if it operating continuously at full power.

Most HAWTs are direct drive, variable speed, and blade pitch-regulated. The long, and narrow design of the airfoils (typically with three and sometimes two rotor blades) function like an airplane wing. The rotating speeds can be lowered or increased by changing the pitch of the blade and its orientation to the wind. Because of the aerodynamic design and length of the blade, the rotation speed at the tip of the airfoil during normal operation is a multiple of the wind speed. WTGs designs are configured either with or without gearboxes (see Figure 2). Digital sensing, control, and wireless communication systems enable remote data accumulation, system observation, management, and diagnostics. Once installed, the larger WTGs have an on-board digital computer control system that accumulates data and optimizes the output based on recorded wind speeds and ambient weather conditions.

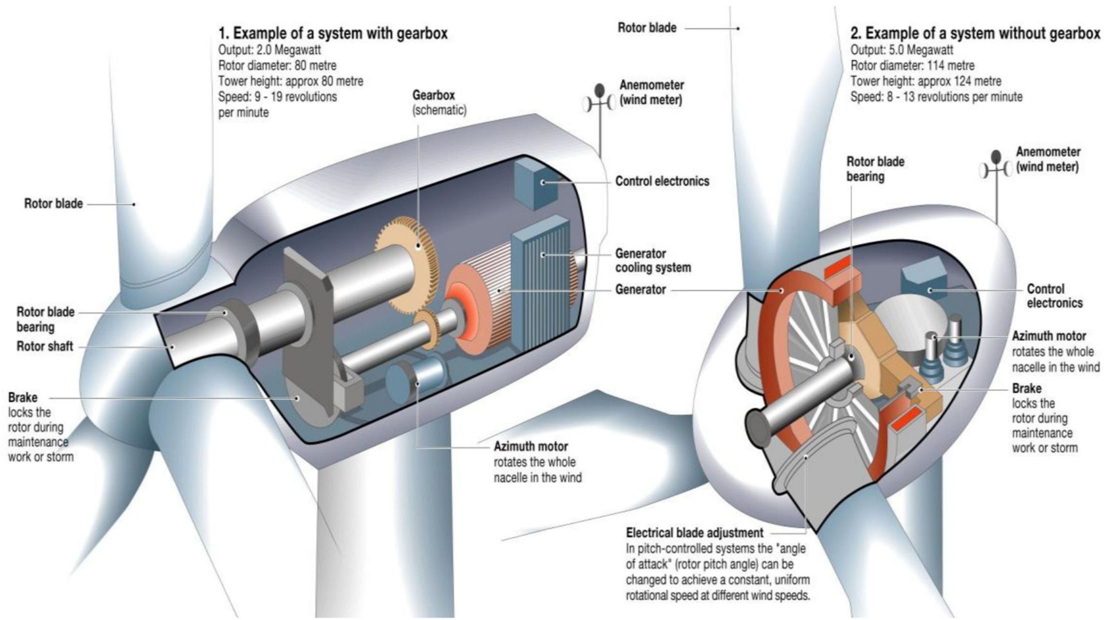

Figure 2. Typical wind turbine designs (source: Agenur für Erneuerbare Energien).

Limits to the Size of WTGs

While there is no theoretical physical limit to the height of wind turbine generators, there are engineering and cost constraints that must be overcome as the machines get larger. While inadequate maintenance and premature gearbox failures are recurrent issues, blade damage is the most common problem that causes failures. As blade length increases, so do the demands for greater stiffness and strength to prevent issues like stall, vibration, and blade breakage [6]. Blade fatigue is manageable but of greater concern is the erosion caused when blades collide with raindrops, sea spray, sleet or hail [7]. When operating, the rotational speed of the blades multiplies the damage from repeated impacts. Blades damage is often visible because cracks and pits will appear on the leading edges of the blades. If unrepaired, structural damage to the blades will occur. With modern HAWT designs, the blade tip speed is usually limited to about 90 meters per second (just under 200 mph) to help avoid blade erosion [7].

As turbines get bigger and blades get longer, their rotors must be designed to rotate at slower speeds. Designed to rotate 10-20 times per minute, there are consequences when slowing the rotor speed. To produce the same amount of power, the blades must deflect the wind to a greater extent; this greatly increases the forces on the other turbine components [7]. As the wind turbine blades increase in length, they also tend to become more flexible. Because the blades are upwind of the tower, during extreme wind conditions it becomes increasingly difficult to ensure that the blades do not strike the turbine tower while rotating [7]. Braking systems are designed to slow or stop hub rotation when such conditions occur. Finally, the longer the blades, the more difficult they are to manufacture, transport, install and maintain. On land, component transport can be limited by the design of existing roadways and overpasses. For off-shore wind farm developments, this requires bigger port facilities, larger and specially designed ships, and taller cranes that can operate reliably in variable ocean conditions [7]. Accommodating the various engineering design and component transportation challenges for off-shore installation increases the production and delivery costs of WTGs.

The taller the wind turbines, the more difficult they are to maintain. The larger the WTGs, the more complex the control systems and mechanical components. Safe access and emergency egress are primary concerns. For land-based machines, turbine cowboys can access the towers at the base and ascend the ladders to the nacelle. This can be challenging when carrying tools or other equipment. Offshore wind farms can be more difficult to access under variable weather and sea conditions. Maintenance personnel must be ferried to the tower base by boat. Some nacelles are designed to be accessed by helicopter. This may be difficult under certain conditions—large WTGs are strategically located in places with consistent and higher velocity wind patterns.

Capacities of Utility-scale WTGs

Once rare but no longer unusual in its capacity, the world's largest horizontal axis WTG was once the SeaTitan rated at 10 MW, designed by AMSC an American energy technologies company; it uses a direct-drive turbine with 190 m rotor diameter and hub height of 125 m [8]. The Sway Turbine ST10 offshore wind turbine, designed and developed by the Norwegian technology company Sway, is also rated at 10 MW. It is equipped with a rotor diameter of 164 m, has a 2-rpm nominal speed, and blades 67 m in length [8]. The turbine features a direct drive, permanent magnet, ring-style generator with ironless stator core [8]. The turbine was developed between 2005 and 2012 with an investment of €20 million ($27.4 million) and is suitable for both fixed and floating foundations [8].

Afterwards, WTGs of larger capacities began moving to assembly line production. The world's expanding manufacturing infrastructure has enabled the construction of ever-larger HAWTs. These broader manufacturing capabilities are being driven by the lower costs of installing WTGs on land and in-country requirements for domestic content in their production. Components for WTGs are being manufactured worldwide, but mainly in China, the European Union (EU), India, and North America (see Figure 3). Most are for onshore developments. While manufacturing in China and the EU includes producing offshore WTGs, the U.S. and India have focused mostly on the production of machines to be placed in onshore windfarms.

On a world-scale production basis component manufacturing is often mismatched—especially for those used by onshore wind farms (see Figure 3). In 2023, global onshore wind turbine manufacturing capacity increased by 6 GW for towers, 22 GW for blades and 23 GW for nacelles [3]. Capacity at the least developed stage of the supply chain (towers) reached 134 GW. As of September 2024, manufacturing projects under development comprised about 10 GW of towers, 20 GW of blades, and 55 GW of nacelles [3]. Offshore wind global manufacturing capacity in 2023 expanded by 6 GW for blades and 9 GW for nacelles. Almost all of the new manufacturing plants coming online are in China.

Many of the largest HAWTs are atypical or only have a few units in production. Individual components are custom designed and manufactured for the specific prototype. The Swedish company Vestas completed its V236-15.0 MW production prototype which started producing electricity in January of 2023; mounted at a height of 280 m, it has a blade length of 116 m and a rotor diameter of 236 m [2]. The company at present has no plans to build anything with greater capacity. In October 2024, a 15-MW onshore WTG (the SI-2701150) developed by SANY Renewable Energy was installed in Tongyu, Jilin Province, China. It has a design life of 25 to 30 years [9]. With a rotor diameter of 270 m and a blade length of 131 m, it has a maximum swept area of 57,256 m^2 (616,159 ft^2) [6]. With its swept area boosting wind capture ability, optimized aerodynamic blade design (using a larger thickness and blunt trailing edge), and control technologies to enhance efficiency, a single unit can generate electricity to power 160,000 households annually* [6]. The drivetrain includes a dual tapered roller bearing integrated main shaft support system that ensures high load-bearing capacity and stability making it more resilient in variable operating conditions [6]. The Siemens SG 14-222 DD turbine model has a 14 MW capacity, reaching up to 15 MW using what the company calls its power boost function. The model installed in Østerild, Denmark, features a 222 m diameter rotor and 108 m blades [10].

WTGs just keep getting bigger and have higher capacities. The Chinese company MingYang Smart Energy (MySE) recently installed its first MySE 16-260 with a rotor diameter of 260 meters (853 feet) and its swept area of 53,902 m^2 (580,196 ft^2); it is among the most powerful

*The total number of households a WTG can supply varies based on location. Such estimates require context. In China the average electricity use of a household is 756 kWh/year. A U.S. household consumes an average of about 10,800 kWh/year.

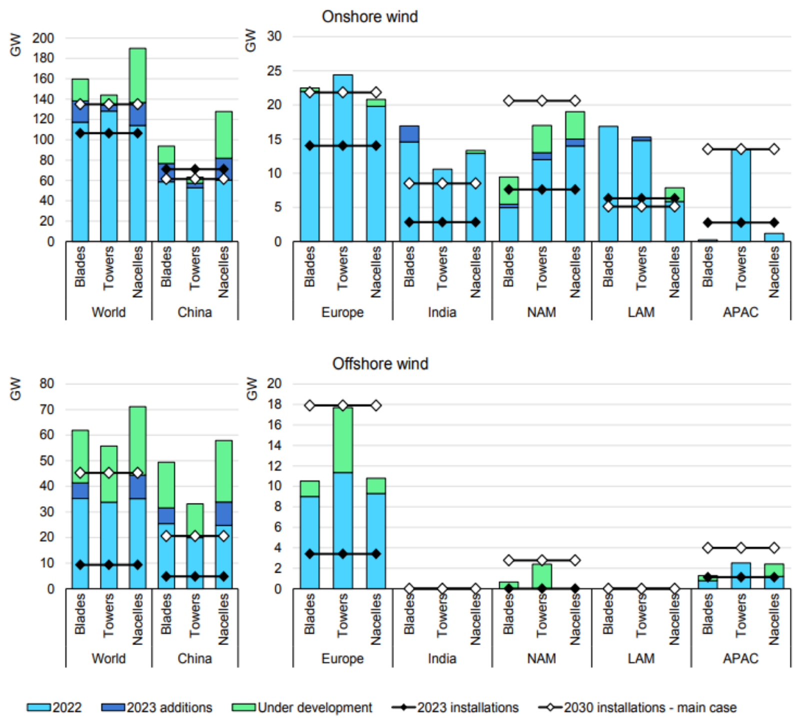

Figure 3. Wind equipment nameplate manufacturing capacity by region, component, and WTG installation, 2022-2030 (NAM, North America; LAM, Latin America, APAC, Asia-Pacific excluding China and India) [3].

wind turbines so far, offering 16 MW of power which is enough to supply approximately 36,000 homes [11]. It was installed on a wind farm off the coast of the Fujian Province in China. The company has a 16 MW production machine (MySE 16.0-242) with a blade length of 118 m and a rotor diameter of 242 m [2]. Each unit can power 20,000 homes over a 25-year service life [2]. MySE lays claim to the largest WTG installed to date—the MySE18.X-20 offshore prototype in Hainan, China—which has a power output up to 20 MW [12]. It is designed to be more lightweight, modular, and reliable. With its massive wind rotor diameter of 260-292 m (853-958 ft), it has a maximum wind sweeping area of 66,966 m^2 (720,816 ft^2)—more than 12 NFL football fields [12]. When sited in locations with average wind speeds of 8.5m/s, it generates 80 million kWh annually. Its reliability and survivability in high winds remain to be proved. Installed in August 2024, it survived typhoon Yagi in September without damage, but pieces of wind turbine's blades broke off the following December and fell while the rotor continued to spin. The company has announced plans for a larger offshore turbine, capable of delivering 22 MW of power.

THE VALUE OF MAKING PERFORMANCE OBSERVATIONS

The output of wind turbine generators is enhanced when they are properly sited. While both land-based and offshore locations are available, offshore locations benefit from more consistent wind flows that are not disrupted by geographic features and nearby buildings.

Actual performance observations are important to estimate the efficiency and power generated by the WTGs at diffident wind speeds. This is particularly true for prototypes installed at a specific site. Assessments of wind turbine operation are data-driven and require on-site operation of the machines after installation and commissioning. The 14 MW Siemens SG 14-222 DD in Denmark first generated electricity in December 2021 and produced 359 MWh within a 24-hour period; the turbine maker said this was the most power a single wind turbine has ever produced over this duration [10]. The previous record was held by the GE Haliade-X offshore wind turbine prototype installed at the Port of Rotterdam which generated 312 MWh of electricity in November

2020 [10]. Better assessments can be made when multiple prototype WTGs are in closer proximity and operate in similar environmental conditions.

It will be interesting to see what happens when these larger, utility-scale, wind turbine prototypes are manufactured at production scale and installed in commercial offshore wind farms. The ability to make direct performance observations of multiple similar machines is likely to improve during the next few years. This will enable engineers and scientific researchers to study recorded data and compare the efficiency and capabilities of these large WTGs when operating under real-world and highly variable conditions.

Numerous opportunities for operational assessments will soon to be available. GE Wind Energy's Haliade-X (14 MW) prototype is planned for commercial deployment by the Vinyard Wind and Ocean Wind project in the U.S. and on Doffer Bank in the UK. Siemens Gamesa will supply 72 units of its flagship 14 MW SG 14-236 DD wind turbines to the 1 GW Danish Thor offshore wind farm based at Thorsminde, Denmark near the Nissum Fjord [13]. The SG 14-222 DDs feature a rotor diameter of 222 m and swept area of 39,000 m^2 (419,792 ft^2). This design has been configured for sustainable deconstruction. After reaching end-of-life, the decommissioning process enables the separation and recycling of the blade materials. These units are also planned to spin in wind farms being developed at Moray West off the coast of Scotland (882 MW), the Hai Long projects offshore Taiwan, and the Dominion Energy Coastal Virginia Offshore Wind Project (2,640 MW) in U.S. waters [10]. Because of the larger number of similar WTGs being installed and the numerous site locations, operating data will be valuable to optimize engineering decisions regarding operational adjustments, siting and design improvements.

CONCLUSION

There is a strong industry commitment to delivering larger WTGs in greater numbers. As a result, the costs for wind power are expected to further decline in the future. Like automobiles, the price for wind machines declines precipitously after assembly line production of a particular model occurs. The production of components for WTGs is happening worldwide. After 2,000 to 3,000 units of a model are manufactured, costs can decline by as much 20% to 30%. At some point in the manufacturing process, most engineering flaws have been resolved and the output of each specific model is optimized.

As production and operation costs for WTGs decline and the costs for grid-supplied electricity increase, the economic feasibility of wind power improves. Many naysayers who once shunned wind power now believe a closer look is justified. Onshore wind power development is already competitive with conventional fossil fuel-fired generation in some regions of the world. Offshore windfarms make use of no-cost real estate unavailable to fossil plants and their supportive infrastructure—they simply cannot be constructed in offshore locations. The global weighted-average lifecycle cost of energy for offshore wind power dropped from being more than twice as expensive as the least costly fossil fuel alternative in 2010 to just 17% more expensive by 2022 [14]. During that period, the average lifecycle cost of electricity produced by wind power fell from $0.197/kWh to $0.081/kWh [14].

We will see wind farms in the future being developed with multiple WTGs rated at over 10 MW. While much of this expansion is occurring in China, the annual global supply chain potential has reached almost 35 GW for towers, over 400 GW for blades and almost 45 GW for nacelles; all are significantly greater than the 9 GW of installations in 2023 [3]. China's share in the global offshore supply chain reached 60% in 2023; with the commissioning of projects under development, it is expected to expand further by 2030 [3]. China's manufacturers are pushing the limits on scale and striving not to being outdone by their domestic competitors. Dondfang Electric Corporation, a Chinese state-owned manufacturer of power generators, has unveiled a typhoon-resistant 26 MW offshore WTG that has rolled off the production line; its height equals that of a 63-story residential building [15]. After it is installed, it will be the world's largest in both size and capacity given its swept area of 53,000 m^2 [15].

Whether bigger wind generators are better is a question whose answer requires observation, study and assessments. As these larger wind energy conversion systems are completed and become operational, we will gain the ability to study the economic viability and environmental impacts of these installations more fully [16]. While technical and engineering challenges remain, getting the large capacity wind machines into assembly line production and installed in offshore wind farms is the probable next step [16]. No doubt some of the larger installations will be hindered and delayed by permitting, financing, interconnection requirements, and site development constraints. Ultimately, many will prevail and become operational.

There is enormous worldwide potential to generate electricity using wind turbines whether located on land or offshore. The larger the capacity of the machines, the fewer that are needed. Tomorrow's wind farms will gradually use fewer and fewer WTGs. Needing fewer turbines on land-based wind farms allows power plant developers more flexibility in siting—creating opportunities to avoid culturally and environmentally sensitive areas [17]. Increasing wind power capacities and developing offshore wind farms are trends that will shape the future of wind power developments [18]. Because of the consistently strong winds at sea, turbines can produce energy more reliably and efficiently than onshore wind turbines [12]. Typhoon-proof turbines will become the standard; already some HAWTs are capable of withstanding winds up to 220 kph (137 mph). We will also see hybrid renewable energy systems that use wind power, greater grid integration, and creative applications of energy storage.

As larger WTGs come into production and their costs decline, wind power will have an increasingly important role in meeting the world's hunger for renewable energy [18]. When wind resources are available and WTGs are properly sited, they can generate large amounts of electricity near densely populated coastal regions [19]. Due primarily to accessibility and logistics, onshore wind farm developments predominate. Economic challenges remain, especially for offshore wind power development. While costs for land-based wind farms are declining, offshore wind farms have a global average development cost of $230 per MWh produced—their costs have increased somewhat in the past couple of years to more than triple the average of $75/MWh for onshore facilities [19].

Wind power is a mature technology which provides pollution-free electrical generation [20]. As a result, it has a key role in meeting regional sustainable development goals. Wind turbines are a crucial component for the generation of clean energy at a time when the world is transitioning away from fossil fuels [21]. From a policy perspective, wind power will form a considerable part of government strategies to incentivize local electrification. Wind power offers a technically viable renewable energy alternative in an era dedicated to decarbonization. No greenhouse gas emissions are emitted in the process of producing electricity. Emissions are limited to those in the manufacture of components and their delivery, site preparation, and assembly—which in sum are much less than the carbon footprints of developing new fossil fuel-fired plants. To alleviate environmental concerns about decommissioning, future WTG components will be designed to be reused (foundations and towers) or recycled (blades, metals, and electronic parts).

Harnessing wind energy provides opportunities for continued innovation which will drive future development. Surprising technological innovations in wind power generation are just over the horizon—where the wind farms can be found. In some remote areas of the world that lack grid interconnections, wind power will offer the first source of electrification by producing electricity for local microgrids. With such large capacities for power production, we may decide that our newest and biggest blade runners are big enough—at least now.

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