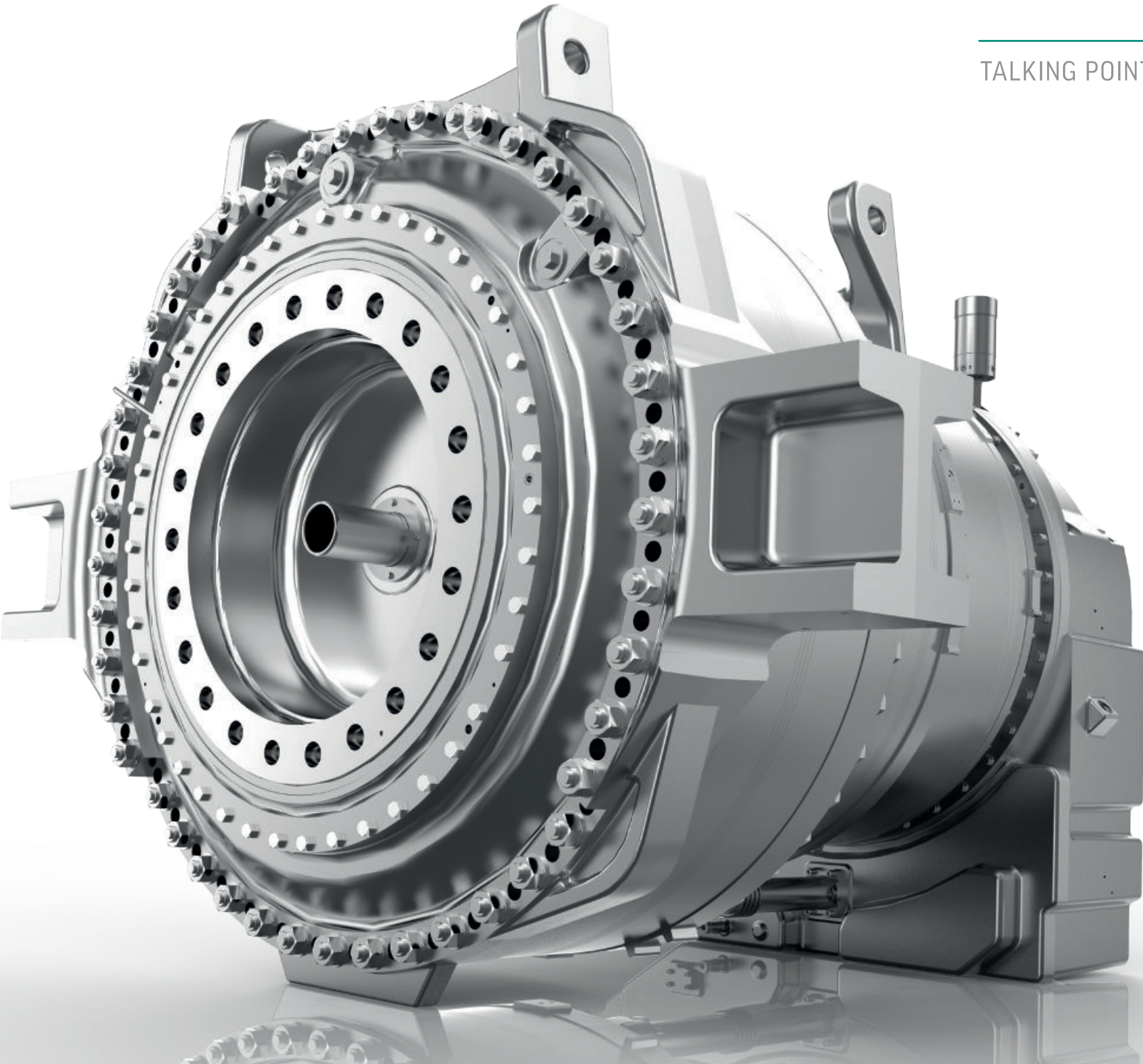
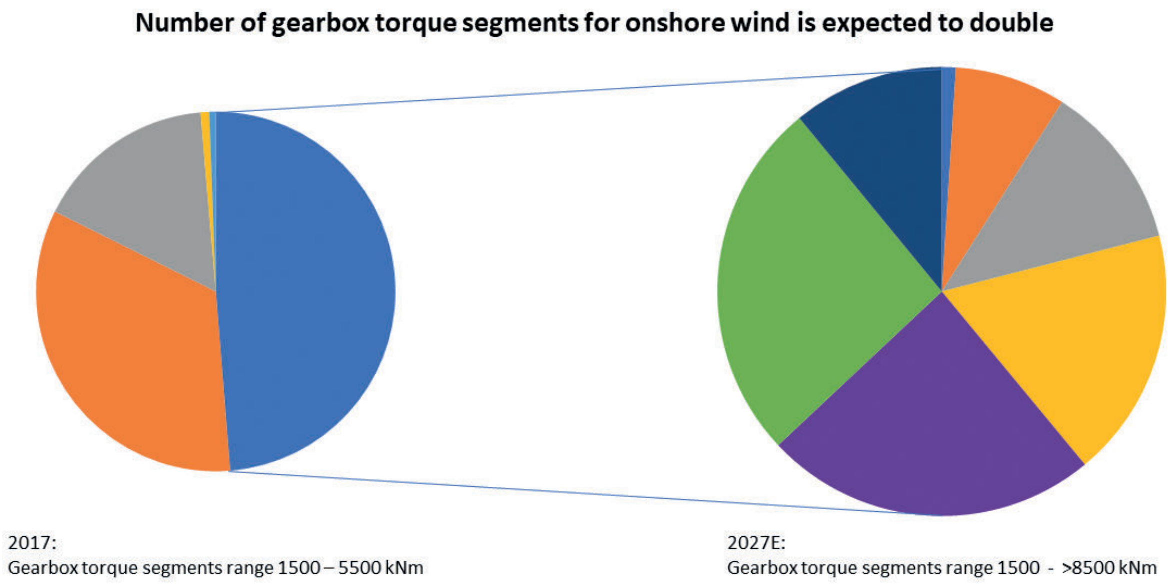


The wind market revolutionized

SHIFTing the limits

With an increasing number of countries adopting a considerable share of wind into their energy mix, the wind market is maturing. Typical signs of this are the fact that incentives, like subsidies and flexible feed-in tariffs, are being reduced or are completely cut. Instead, target levels for investments in renewable energy capacity have been set. The wind market revolutionized itself with the introduction of an auction-based market mechanism, resulting in record lows in the Levelized Cost of Energy (LCOE), which could not have been imagined in the pioneering years of this industry.



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Wind turbines get segmented into an increasing number of torque segments. By 2027 the number of gearbox torque segments for onshore wind is expected to double. Therefore, ZF shifted its designs to a modular gearbox architecture that anticipates the growing number of torque segments

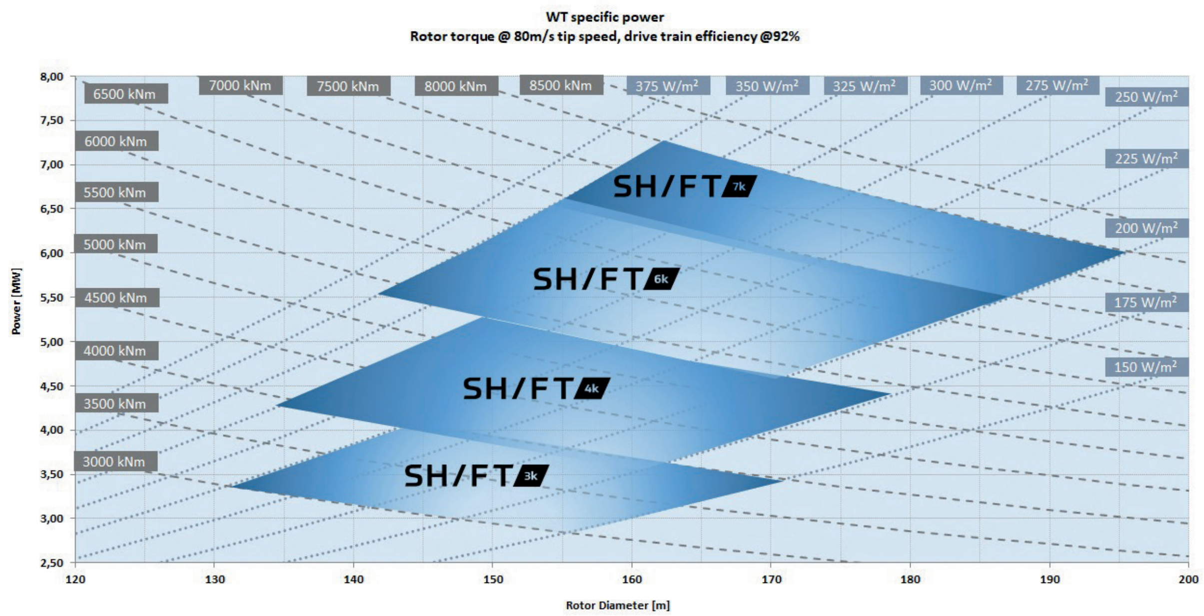
In order to bring the LCOE down, the major players in the wind industry find themselves in a race where the winner is the turbine with the maximum annual power output for the given site conditions at the sharpest possible investment costs. Competitiveness is defined in terms of flexibility and speed of introducing new turbine variants with ever-growing rotor diameters.

'Go modular'

ZF Wind Power anticipated the market trend and, since 2016, it's been positioning itself as the pioneer of the 'modular platform approach'. In order to compete in different onshore market segments, with different requirements, OEMs continue to introduce turbine designs with optimized LCOE by reducing costs and boosting annual energy production. As a result, wind turbines for the onshore wind market get segmented into an increasing number of torque segments.

Therefore, ZF shifted its designs to a modular gearbox architecture that anticipates the growing number of torque segments: SHIFT. The modular platform structure provides greater flexibility in new turbine development and allows further optimization potential over the turbine's lifetime. The entire modular SHIFT platform is extended across different torque ranges, from SHIFT 3k; 3000-4000 kNm, over to SHIFT 4k and SHIFT 6k, even up to SHIFT 7k; 7000-8000 kNm. Each SHIFT 'xk' platform of gearboxes is designed for a predefined market segment in terms of prevailing wind speeds and thus needed power ranges and capacity factors.

The platform designs are also driven by logistical constraints and the interchangeability of components within each SHIFT 'xk' platform is taken into consideration. This drives the torque



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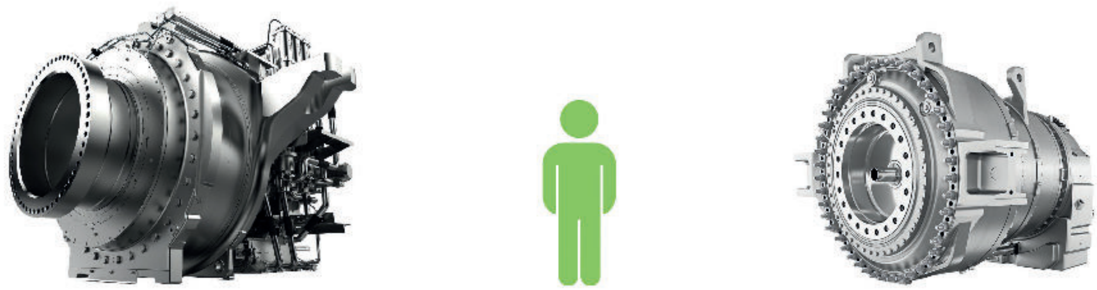
The evolution of the wind market, pushes the boundaries of innovation: the SHIFT 7k torque density surpasses the 200 Nm/kg barrier

Impact of Torque Density Increase

Launch 2010	ORKA	Improvements*	Launch 2020	SHIFT 7k
Ring gear diameter [mm]	2540	Size: -15%	Ring gear diameter [mm]	2150
Tmech [kNm]	**5425**	**Torque: +47%**	**Tmech [kNm]**	**~8000**
Mass [kg]	**61500**	**Mass: -35%**	**Mass [kg]**	**~ 40000**
Torque Density [Nm/kg]	88	Torque density: +127%	Torque Density [Nm/kg]	~200



New innovations enable ZF to keep outside dimensions identical with growing torque levels. The real innovation lies in the size similarity to fit in the nacelle while doubling torque requirements

positioning per platform as well as the lower and upper ratio limit. Keeping the gear unit interfaces and outer dimensions identical across the torque range of a SHIFT 'xk' platform eliminates the need for major drive train/nacelle redesigns over the lifetime of the wind turbine platform. Upon receiving new customer specifications, ZF offers the platform member that most economically meets the application requirements.

In addition, using standardized building blocks inside the gearbox leverages the platform supply chain and operational synergies. The building blocks offer platform flexibility for future turbine power upgrades. As the SHIFT platform portfolio covers a torque range of 3000 kNm up to 8000 kNm for onshore and specific offshore applications, it offers customers a choice in turbine designs and roadmaps dedicated to specific wind-market segments.

The ZF platform approach has several advantages for customers. Extensive validation of a new gearbox platform is done only once. This massively reduces time-to-market for a specific customer application, as time for design work as well as validation are reduced to a minimum. Variants of a platform only go through a limited validation trajectory based on specific changes in the design.

Furthermore, the modular platforms offer benefits in terms of logistics, supply chain, and operations. The standardized building blocks within one platform are identical for different customer applications, which are the typical long lead-time items in the supply chain. This enables ZF to react faster to changes in order intake, as typically, multiple customers within the same platform are competing for the same type of wind sites.

Moreover, it helps to minimize sudden underutilization in ZF's production plants and boosts efficiency and output per plant. Machine utilization is optimized for larger batch sizes, thus avoiding time lost when switching machine tools and programs. The SHIFT philosophy is well suited for global manufacturing in different plants. A new modular gearbox platform is typically launched in one manufacturing location, and then extended to a second or third location if the market requires. This makes SHIFT a truly global platform, with quality levels independent of its manufacturing location, and a supply chain optimized for local markets and best cost.

SHIFT 7k: new torque density level hits the market

The trend towards more powerful wind turbines with increasing rotor sizes is simultaneously paired with challenging target cost levels as well as limitations on nacelle transport in terms of dimensions and weight. These physical design limitations in combination with cost target requirements prompted ZF to rethink the gearbox designs. New technologies on different levels enabled ZF to keep outside dimensions identical e.g. ring gear diameters, with growing torque levels. Concretely, the ring gear diameter of ZF's SHIFT 7k platform for the latest 6.xMW turbines is not larger than that for state-of-the-art 4.xMW turbines. The real innovation lies in the size similarity to fit in the nacelle while doubling torque requirements.

The evolution towards higher torque ranges, currently up to 8000 kNm, challenges the supply chain to handle these requirements at competitive costs, pushing the boundaries of innovation. Seven years ago, 100 Nm/kg torque density of a wind gearbox was the norm. It's only been two years since ZF's SHIFT 6k raised the bar towards 175 Nm/kg. Today, the SHIFT 7k torque density surpasses the 200 Nm/kg barrier for a high speed gearbox configuration. ZF received the Wind Power Monthly gold medal in the category 'drivetrain of the year 2020' for this major achievement.

SHIFT 7k leads the high power, high output onshore market segments as well as dedicated offshore markets in the wind industry. The 7k four-stage version has three multiple-planet planetary stages – with 7, 6 and 4 planets respectively – and journal bearings. Four-stage gearboxes have more components than their three-stage equivalents, but most parts are smaller in size. To meet global transportation standards, ZF engineers took a maximum nacelle width of 4.2 m into consideration. This resulted in a maximum outer diameter, i.e. the ring gear diameter of the first stage, of 2.1 m, which is kept the same over the SHIFT 4k, SHIFT 6k and the SHIFT 7k platform modules.

'The key to the next level in torque density lies in further shifting currently accepted limits.'

Leveraging torque density

Reaching a torque density level of 200 Nm/kg* is a gradual approach that requires a combination of technological elements: most obviously, the number of gear stages and the number of planet gears in the planetary stages, as well as the right choice of bearings. Depending on the torque level, the cost of the optimum number of planets in a planetary stage can vary. However, it's safe to say that more than 5 planets will typically be used for high-torque machines in at least the first stage of the gearbox in the future. Depending on the required outer diameter of the gearbox, roller bearing solutions can still lead to competitive torque density levels. But journal bearings make it possible to build gearboxes with smaller outer diameters and thus reach higher torque density levels.

Optimal load distribution across the different planets becomes an issue as the number of planets in the gear stages increases. Typically, loads are unevenly distributed to a certain extent. However, ZF manages to arrive at a close-to-optimal load balance between the planets. This is achieved by a smart combination of advanced simulation models and use of production data. The simulation models take all flexibilities and deformations of the system into account, while the data models take the spread on tolerances in the chain of components i.e. gears, shafts, and bearings, into account.

By combining the simulation models with a statistical data approach, ZF engineers succeeded in predicting the best achievable load distribution factor in a multi-planet gear stage. In order to reach this target value repetitively, a 'smart assembly' process was established. This process takes measured data from the components into account and selects the optimum combination for assembly, a typical example of how an Industry 4.0 approach leads to increased ratings for a gearbox.

Further steps in torque density require pushing boundaries even further without jeopardizing reliability. When it comes to gear materials, ZF detected and leveraged the potential in well-known materials, by moving from synthetic material properties to grade-specific material properties. For this, ZF analyzed and tested, in gear component test rigs, how different material properties influence fatigue strength of the gear material. ZF now uses strict material specifications for steel suppliers. In combination with establishing in-depth quality control processes on incoming steel, ZF was able to get this 'ZF material specification' certified, thus allowing the use of higher fatigue strengths in gear rating calculations.

Another typical boundary in gearbox design is fatigue strength for castings. Standard calculations typically limit the strength assessment approach. However, new influence factors on fatigue strength of cast iron, such as the effect of local plasticization on durability, have been developed in the last decade. ZF engineers have incorporated these new insights into existing calculation approaches.

What's next: mechanics go digital

The torque density curve does not end at 200 Nm/kg. ZF sees potential in further leveraging the value of data. This starts in the factory and at suppliers, and the loop is closed by the use of detailed field data. The key to the next level in torque density lies in further shifting currently accepted limits. SHIFT 7k sets an example of how consistently tracked manufacturing and quality data can help to shift limits in design without jeopardizing reliability. Therefore, ZF will continue to invest in a combination of system analysis, data analysis, and consequent implementation in smart production processes.

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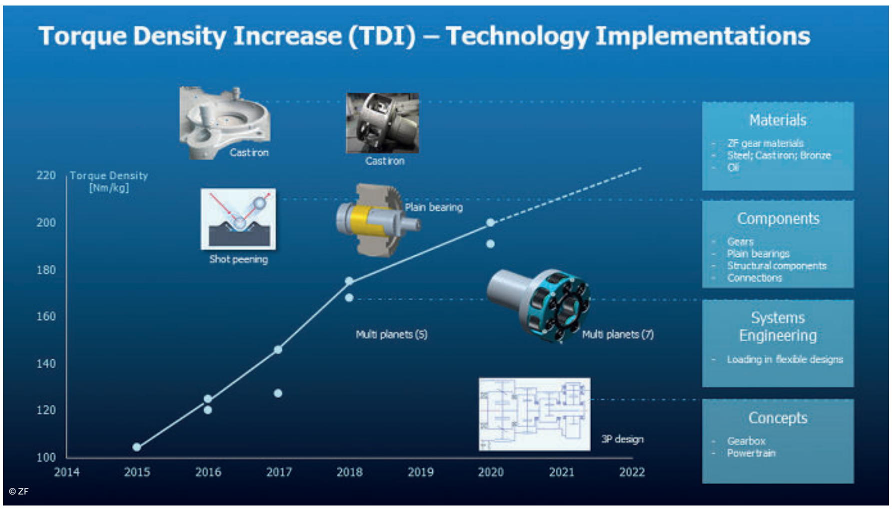
* for high speed gearbox configuration



Technological innovations, like journal bearings make it possible to build gearboxes with smaller outer diameters and thus reach higher torque density

ZF Wind Power

ZF Wind Power is a global technology-driven manufacturing leader and pioneer in the global wind turbine gearbox industry.

The company is leading the high-performance onshore segments with products up to 8000 kNm and is the first to exceed 200 Nm/kg torque density in compact designs.

ZF delivered the world's first offshore 9.5 MW wind turbine gearbox and has the largest global installed capacity of +8 MW offshore wind turbine gearboxes.

Since the company entered the wind industry in 1979, ZF Wind Power has delivered more than 75,000 gearboxes, powering as much as 150 GW wind turbines, covering approximately 25 percent of the total installed capacity of gear-driven wind turbines worldwide.