Report 2023

Germany

On-Shore Wind Turbines. *Source: Tim Siegert, batcam.de – stock.adobe.com*

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Germany's Federal Government decided in 2023 that renewable energies are of overriding public interest. Many measures have been taken to reach climate neutrality by 2045 [1] and an energy system based on renewables needs wind energy.

In 2023, wind energy provided the biggest contribution to electricity supply within renewable energy in Germany, with a 27% share of electricity demand [8]. Wind-generated electricity amounted to more than 142 TWh from all installed land-based and offshore wind turbines, an increase of 14% compared to the previous year [8]. Wind energy deployment increased by about 3.3 GW of newly installed capacity whereof 329 MW stem from offshore wind turbines [9] [10].

With regard to RD&D funding, application-oriented projects supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) contributed to a reliable, cost efficient and environmentally compatible use of wind energy in Germany taking all lifetime phases of wind turbines into account as well as grid

Table 1. Key National Statistics 2023: Germany.

Total (net) installed wind power capacity	69.474 GW
Total offshore capacity	8.458 GW
New wind power capacity installed	3.362 GW
Decommissioned capacity (in 2023)	0.423 GW
Total electrical energy output from wind	142.103 TWh
Wind-generated electricity as percent of national electricity demand	27%
Average national capacity factor	23.9%
Target	80% renewable energies by 2030
National wind energy R&D budget	69.999 million USD

integration, also in combination with other renewable energy sources. Thus, research results help accelerate the energy transition by removing barriers, enabling repowering and exploiting additional sites [2].

In 2023, land-based wind energy in Germany was the most important power source: 22.9% of the provided gross electricity generation stemmed from onshore wind turbines, totalling 61 GW of capacity installed.
One can also see a dynamic development with regard to offshore wind energy: in 2023, 4.6% of the provided gross electricity generation stemmed from offshore wind turbines, totalling 8.5 GW of installed offshore wind capacity. At the same time, an additional capacity of 8.8 GW of offshore wind turbines were successfully awarded, which brings more capacity into development than the amount that is already installed [1] [7] [38] [39] [43]. Figure 1 also compares the current state of offshore wind farms in the North and Baltic Seas that are completely integrated and those that have been awarded in tenders and have a grid connection claim [12]. Thereby, for the first time wind turbines provided more electricity in Germany than all lignite (17%) and coal-fired power plants (8.6"%) together [13]. Further, it is worth noting that Germany stopped nuclear energy for commercial power generation in April 2023 [2].

Electricity provided by wind energy plays the largest role in avoiding CO2 emissions, offsetting 108 million tons of CO2-equivalents [8].

Highlight(s)

- Wind energy reached 27%, while all renewable electricity reached a record of 51.8% of German gross electricity consumption– the latter was an increase of more than 5% compared to year 2022 and a historic high for Germany.
- Targets for offshore wind were increased, now aiming for 30 GW by 2030, **50 GW by 2035** and 70 GW by 2045.
- The Land-based Wind Energy Strategy aims to remove barriers to reach land-based capacity targets with 115 GW by 2030 and 160 GW by 2035.
- A record of 8.8 GW in new offshore projects were awarded in 2023 to be installed in the future.

Market Development

Targets and Policy

Targets for offshore wind were adjusted to reach 30 GW by 2030, 50 GW by 2035 and 70 GW by 2045. This is supported by an amendment of the Offshore Wind Energy Act (WindSeeG) taking yearly tender amounts of 4 GW into account from 2027, as well as by a dedicated land use at sea (updating the area development plan) and a nature-compatible offshore deployment (connecting power lines must not warm up sediments above 3 Kelvin in the Exclusive Economic Zone and 2 Kelvin in Territorial Sea), and by strengthening authorities like The Federal Maritime and Hydrographic Agency (BSH).

With regard to onshore wind energy, the Land-based Wind Energy Strategy supports the targets to reach 160 GW by 2035 [4] [36].

The so called "Solar Package I" is also addressing wind energy deployment targets by facilitating permitting procedures until June 2025 and by fostering innovative energy generation technologies like airborne wind energy systems by enabling renumeration in tenders (limited to 50 MW) [5].

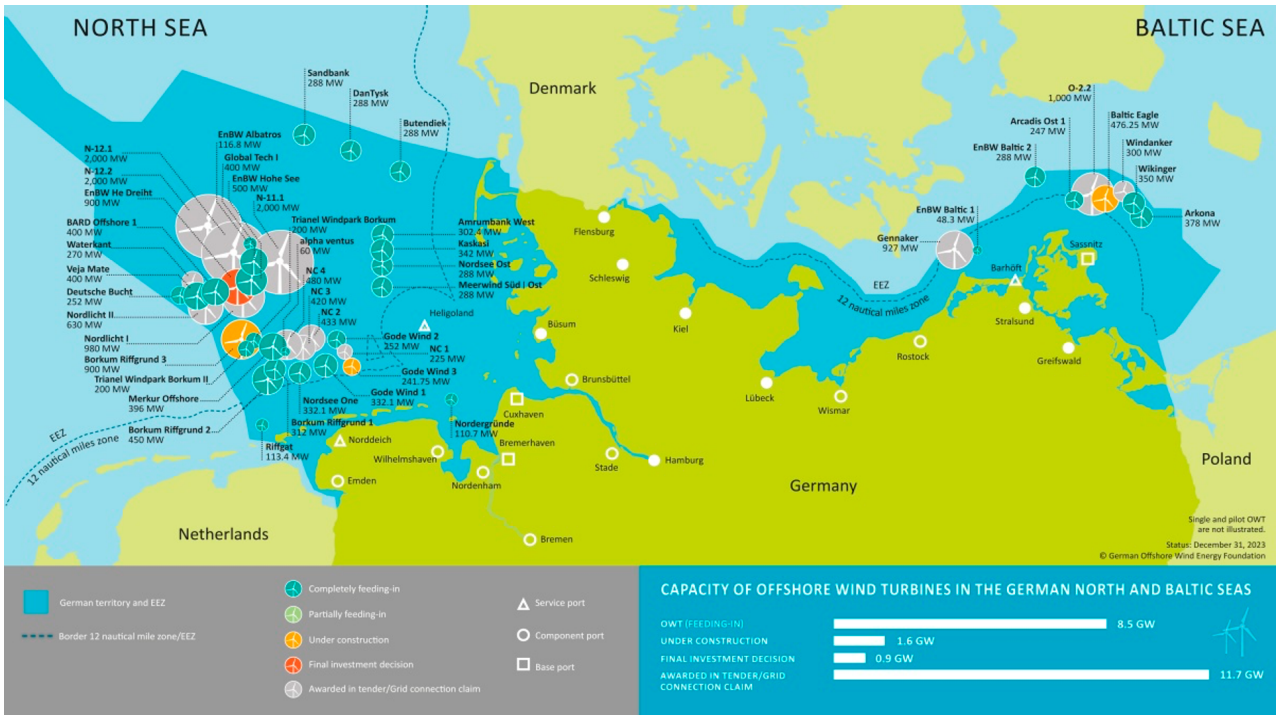

Figure 1: Capacity of Offshore Wind Turbines in the German North and Baltic Seas. *Source: German Offshore Wind Energy Foundation*.

Furthermore, the amendment of the Federal Emission Protection Act (BImSchG) and the change of the Federal Nature Conservation Act (BNatSchG) guarantee an acceleration of added wind energy capacity [6].

Progress and Operational Details

In 2023, wind energy continued as the largest contributor to renewable electricity generation. Wind energy constituted 27% of gross electricity consumption, while renewable energies collectively contributed 51.8%. The amount of new added capacity amounted to 2.75 GW in 2023, which is an increase compared to the previous year where 1.95 GW was installed. The additional capacity in 2022 increased partly due to the 342 MW from newly installed offshore wind turbines.

In 2023, 142.1 TWh of electricity was generated by onshore and offshore wind energy plants - this corresponds to a significant increase of 14% compared to the previous year (124.8 TWh). Wind energy therefore covered over 27% of Germany's gross electricity consumption and was the most important energy source in the German electricity mix in 2023. For the first time, wind turbines generated more electricity than lignite and hard coal-fired power plants combined. However, the significant growth in wind power is also due to previous years with relatively little wind. Higher average wind speeds were observed in 2023 than in the two previous years. In a direct comparison with 2022, the current growth in electricity from onshore wind energy is particularly striking: at 118.2 TWh, 19% more electricity was generated than in 2022 (99.7 TWh).

Compared to previous years, significantly more new onshore wind turbines were connected to the grid in 2023. At 3,028 MW, annual net additions rose by 44% (2022: 2,102 MW). However, the increase was still well below the previous record set in 2017 (4,891 MW). At the end of 2023, onshore wind turbines with a total capacity of 61.0 GW were installed in Germany. The turbine fleet thus grew by around 5% compared to the previous year.

Only a few new offshore wind turbines were commissioned in 2023. Overall, the installed capacity increased by 258 MW to 8.5 GW. Thus, the total electricity generation capacity at sea grew by 3%. To achieve the expansion targets of 115 GW (onshore) and 30 GW (offshore) by 2030, set out in the EEG 2023, a significant acceleration in the pace of expansion is required in each case [8].

With a capacity of 4,788 kW, the average onshore wind turbine installed in Germany in 2023 is 10% more powerful than the average turbine installed in the previous year. However, the average overall height of 206 m is virtually unchanged from the previous year. On average, slightly smaller hub heights (Ø 136 m) and slightly larger rotor diameters (Ø 141 m) were installed than in the previous year [9].

Offshore, the most powerful wind turbines in Germany to date have a nominal capacity of 9.5 MW. For the entire portfolio of all turbines in operation at the end of 2023, the average turbine capacity was around

5.4 MW. Many of the turbines in operation have undergone subsequent capacity increases during the operating period; these are not structural changes to the turbines, but software upgrades. The installation of 9.5 MW and 11 MW turbines is planned for 2024. In 2025, a 15 MW turbine is to be commissioned in Germany for the first time. Current plans for future projects up to 2025 also envisage significant increases in rotor diameter and hub height, compared to existing turbines in 2023. Depending on the project, rotor diameters of between 174 m and 236 m and hub heights of between 107 m and 145 m are planned [10].

On average, the existing offshore projects have a water depth of around 30 m and are located around 75 km from the coast. Future projects are planned in areas that are increasingly further from the coast. In terms of foundation type, the monopile foundation has established itself as the most used type in Germany. All foundations installed in the course of 2023 were monopiles and future projects have already announced the installation of monopile foundations [10].

Matters Affecting Growth and Work to Remove Barriers

In contrast to onshore wind, electricity generation from offshore installations declined: at 23.9 TWh, electricity generation fell by 5% (2022: 25.1 TWh). One of the reasons for this was a significant increase in grid-related curtailments of offshore wind farms [8].

According to the Offshore Wind Energy Act (WindSeeG) the offshore auction system differs between pre-assessment-areas and those areas that have not yet gone through state-run pre-assessment, both have yearly auction rounds.

Pre-assessed areas undergo a weighted scoring system with five qualitative criteria: bid amount with cash payment, contribution to decarbonisation by offshore wind deployment, amount of the power purchase agreement for produced energy on the area, according to the chosen foundation technology the associated noise exposure and seabed sealing, the extent of securing skilled personnel. For pre-assessment areas the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (Bundesnetzagentur) is in charge to assess areas in the German Exclusive Economic Zone (supported by The Federal Maritime and Hydrographic Agency, BSH) as well as in the territorial sea (supported by regional authorities).

Not pre-assessed areas are combined with further awarding criteria in case of zero bids (0.0 EUR/MWh), a second bid component with dynamic bid rounds (increasing bid levels per MW). For not pre-assessment areas the bidding winner has to carry out assessments of the site on his own before applying for a permit. Part of the permitting procedure are several consultation rounds with stakeholders. A plan may only be approved if there is no threat to the marine environment, no threat to shipping or national/allied defence, and meets other public law requirements (such as Marine Spatial Planning).

In 2023, an amount of 7 GW for four not pre-assessed areas for wind turbines operating from 2030 on ward was awarded. Furthermore, for wind turbines operating from 2028 on four pre-assessed areas an amount of 1.8 GW was awarded [38] [39] [42].

Four onshore wind tenders were held in 2023. All four rounds were under-subscribed, so that the total tender volume of 9,829 MW was offset by awards of only 6,377 MW. Originally, a tender volume of 12,840 MW was planned, but this was reduced in advance by the BNetzA due to an expected lack of competition. Although the desired volumes have not yet been awarded, the volume awarded in 2023 represents a doubling compared to the previous year.

The average award value across all 2023 auctions is 7.33 ct/kWh, just below the maximum value. At the end of 2023, the BNetzA announced that the maximum value of 7.35 ct/kWh would also apply for 2024. This value has been in place since the increase at the end of 2022 due to significant cost increases [9] [37].

Some installations with older permits are currently not participating in a tender, for reasons such as long implementation times (e.g. due to supply chain problems or re-approval procedures) or other justified eligibility (pilot or community wind turbines). Approximately 10% of the permits issued in 2021 and 2022 have not yet been awarded [9].

According to some market actors, logistics could prove to be the bottleneck in the energy transition. Faster approval processes, more rapid road and bridge repairs and the opening of more ports for major components are all important prerequisites for accelerating the expansion of wind energy and to avoid experienced extra-long and time-consuming detours. Companies try to ease the situation with flexible planning processes, early provision of planning data and a thorough assessment of alternatives such as inland waterways [35].

With the Land-based Wind Energy Strategy, which was published in May 2023, solving measures in different Action Fields help to accelerate the installation of wind turbines (WT), increase WT reliability, reduce the cost of energy, improve acceptance among the public, educate skilled personnel, facilitate transportation, and continue supporting research. For example, the Action Field "land securement" established a so called 2% -area target which is underlined by the Wind Energy Area Requirement Act (WindBG) with binding area targets in the Federal States: Up to 1.8% of the German land area by 2027 and up to 2.2"% by 2033 shall be available for land-based wind energy (exact values vary between 0.5% and 2.2% for the different

Federal States due to their individual landscape) [36].

RD&D Activities

National RD&D Priorities and Budget

- Germany continues to pursue a very broad R&D programme (7th Energy Research Programme of the Federal Government, subsided by the mission-oriented 8th Energy Research Programme of the Federal Ministry for Economic Affairs and Climate Action (BMWK) which started in June 2024) rather than focusing on a specific subject. Two of the main goals are to generate renewable energy efficiently and sustainably and to guarantee a robust grid for a reliable power supply. To this end, several options are taken into account: Increasing turbine reliability, extending turbine lifetime, enabling higher wind turbine performance by using bigger rotors or increased hub heights, optimising turbine operation, development of new methods for condition monitoring, identifying new onshore sites for wind turbines, and including combined approaches using multiple renewable energy sources with power storage technologies. As well as building new wind turbines, the decommissioning of end-of-life wind turbines needs to be examined, e.g. in terms of recyclability and circularity, as well as social acceptance.

- The Federal Ministry for Economic Affairs and Climate Action (BMWK) has provided EUR 74.97 million (USD 80.44 million) as funding for 471 active and ongoing application-oriented research projects in the field of wind energy in 2023, see Figure 2. Additionally, BMWK started 105 new research projects with a new funding amount of EUR 65.237 million (USD 69.999 million), maintaining the amount of subsidies from the previous years.

National Research Initiatives and Results

- The research project **GruenWinT** (03EE3085A-C) aims to significantly shorten the waiting time until a wind turbine can be founded on freshly recultivated lands of opencast mines. The large thickness of the recultivated lands and their material inhomogeneity are main challenges in that respect. Based on a field test and numerical simulations a concept is developed which allows to reliably judge the suitability of a place for an early foundation of a wind turbine. Furthermore, it is numerically investigated if foundation concepts developed for offshore conditions, particularly the vibratory installation of single large-diameter monopiles

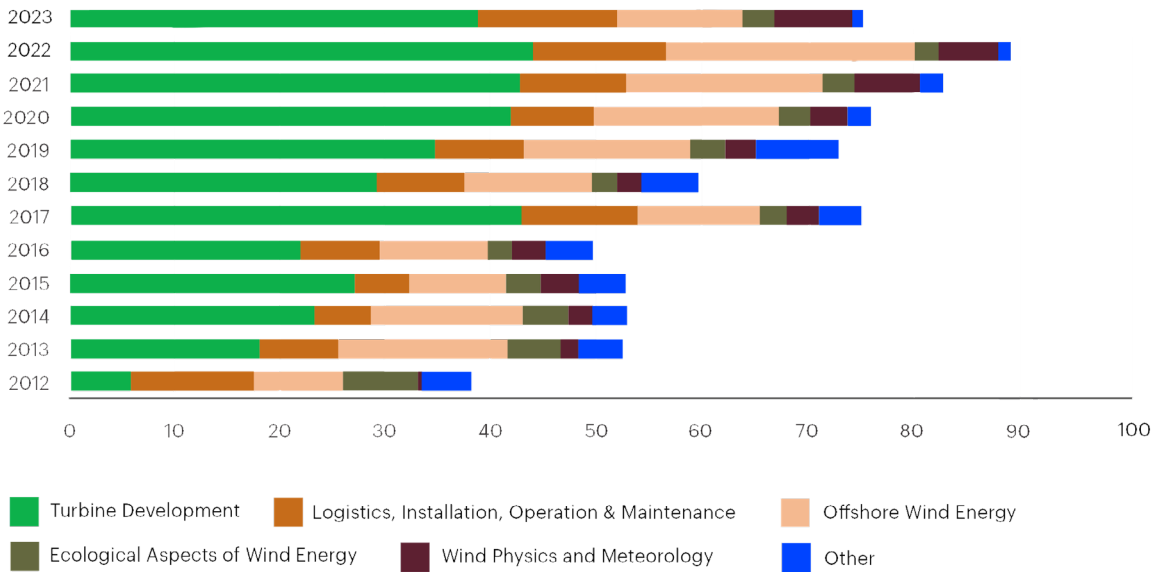

Figure 2: Development of yearly funds flow in Germany, Federal Ministry for Economic Affairs and Climate Action (BMWK) [2].

can be applied to allow an early foundation of wind turbines in the freshly dumped ground. In these studies, it is of particular importance to consider changes of the state of the loose or soft soil due to pile installation [16].

- In **ReSort** (03EE3075A-F) the central issues of microwave pyrolysis, wet and dry chemical coating processing of recycled fibers and testing of fiber reinforced plastics that are manufactured based on the recovered fibers in order to recycle wind turbine rotor blades after their dismounting are analysed [18], whereas in **ReusaBlade** (03EE3095A-C) the recycling cycle of rotor blade components with detachable matrix systems through fiber and component separation is investigated. The performance of the reused materials is later on assessed on the basis of mechanical and manufacturing tests [19].

- **SupraGenSys2** (03EE3093A-G) builds on the results of the SupraGenSys project (03EE3010A-E) for the design and optimization of a fully superconducting and directly driven generator for wind turbines with a rated output of 10 MW. The aim of the project is the development and construction of a 250 kW demonstration generator in the laboratory based on the optimized 10 MW full HTS generator. With the help of this machine, the results developed in SupraGenSys are validated and the developed calculation routines are checked [20].

- In **AR4Wind** (03EE3046A-D) the overall acceptance of wind turbines shall be increased by a realistic experience of planned projects. Therefore, the development and use of mobile augmented reality (mAR) technologies in public participation processes is proposed as a solution. In order to achieve a high level of acceptance, the project envisages an agile and user-centred approach on a workable mAR visualisation system to be used in public participation processes with intensive integration of real demonstration scenarios by the use of mobile phones and tablets [21].

- The **WindRamp II** (03EE3101A-D) project uses as Basis the results from the WindRamp (03EE3027A-E) project, in which an observer-based minute-scale forecast has been investigated. WindRamp II will further develop this towards the goals of 1) extension of observer-based forecasts to heterogeneous wind farm clusters with very large turbines, 2) the development of new methods for increased forecast accuracy, 3) extended forecast horizon and more reliable system integration with less balancing energy requirements through improved power forecasts and 4) system integration methods and ramp warnings. A novel long-range scanning lidar technology deployed in this project offers promising opportunities for the extension of forecast horizon and quality. The aim is to show that it is possible to reduce the curtailment of offshore wind energy due to grid congestions and the need for energy to compensate for forecast errors [22].

Test Facilities and Demonstration Projects

- In the research project **ENGEL** (03EE2063A-C), a 30 MW test facility specialised in grid integration tests of offshore turbines, will be set up as an extension building at the DyNaLab site of Fraunhofer IWES. On the basis of tests on two wind turbines with its partners, new procedures for model validation will be transferred to the state-of-the-art and operation in realistically simulated offshore grids will be tested. The operation of offshore grids with 100% converters is characterised by a lack of energy storage and low impedance. Inherent in this is strong coupling of all grid connected equipment and power generation units, leading to strong interactions amongst wind turbines or between wind turbines and HVDC converter stations. Through the results of this project, the acceleration of project implementation will be increased to reach the German targets on expanding the offshore wind energy in the German North Sea by 2030 [15].

- In the second phase of the project **Zukunftskonzept** (0325939A), the procedures for segmented, sectional and component testing are now being implemented and put to the test. A key element is the construction of a new test rig for segmented blade testing in order to meet the demands of future generations of rotor blades (up to 120 metres). This initiative will be accompanied by the expansion of measurement procedures and documentation of rotor blade testing in order to establish a valuable database of testing history that can be used beyond the initial scope of the test [17].

- The reporting year has been particularly successful in inaugurating world class wind energy R&D infrastructures and test facilities.

In summer 2023, the upgraded wave and current flume **GWK+** in Hanover (3 m wave heights, 20 m3/s ≈ 0.8 m/s flow) [26], the **115 m+ rotor blade test rig** in Bremerhaven (160 MNm static and 70 MNm fatigue root bending moments) [24] and the research wind farm **WiValdi** in Krummendeich in the North of Germany with two multi-MW turbines (4.2 MW each) and one modular turbine under construction (500 kW) with an IECplus measurement mast, met mast array and field instrumentation [25], have been put in operation. As well as the inauguration of the

Photo 1: WiValdi Wind Energy Research Park. *Source:* DLR (CC BY-NC-ND 3.0).

Photo 2: Southern German Wind Energy Test Site WINSENT at the Swabian Alb. *Source: Maayen Wigger, ZSW.*

Southern German test site **WINSENT** (Wind Science and Engineering Test Site in Complex Terrain) with two identical research turbines (750 kW each) with four met masts and field measurement systems including nature conservation research, took place in September 2023 [40] [41].

While WiValdi by Research Alliance Wind Energy with DLR WX (German Aerospace Center, Wind Energy Experiments) as its operator is located in flat terrain, WINSENT by WindForS (Wind Energy Research Cluster), operated by ZSW (Center for Solar Energy and Hydrogen Research Baden-Württemberg), is located in complex terrain of the Swabian Alp.

Collaborative Research

- The Federal Ministry for Economic Affairs and Climate Action (BMWK) is the German Contracting Party in the IEA Wind TCP. In 2023, German research institutions and industry representatives were involved in 20 of 22 active Research Tasks (11, 25, 28, 39, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56 and 57). Task 52 "LIDAR" is led by a German Operating Agent from Fraunhofer Institute for Wind Energy Systems (IWES). Most of Germany's Task participants also execute nationally funded projects in their related topics, benefitting the mutual worldwide information exchange within their IEA Wind TCP Tasks and to some extent between different TCPs.

- Furthermore, Germany is a Federal partner in the Clean Energy Transition Partnership (CET Partnership). Since the first joint call was launched in 2022, wind energy related topics are included amongst a variety of renewable technologies and system solutions within the Transition Initiative (TRI) 2, "Enhanced zero emission power technologies". Yearly calls are foreseen until 2028. Germany is involved in the current joint call 2023 and plans its participation in the announced joint call 2024 [11]. One of the first CETP-projects is **NextGen** (03EE3103), with Swedish and Danish partners where a direct-drive generator for a 10 MW wind turbine is developed, evaluated and validated by testing a multi-MW prototype in a relevant environment to raise the technology readiness level (TRL) from 3 to 5 [14].

Impact of Wind Energy

Environmental Impact

- In 2023, the generation of around 142 TWh of wind energy led to a reduction of almost 108 million tons of CO2-equivalent greenhouse gas emissions [8].

- In the research project **VISSKA** (03EE3043A-E), an innovative installation method of vibratory pile driving as a low-noise and sustainable alternative to impact hammering regarding duration and underwater noise emission, has been developed. The measurements are conducted during the installation of the offshore wind farm "KASKASI II" in the German North Sea [23].

Economic Benefits and Industry Development

In total, investments in construction of wind power plants increased significantly: onshore EUR 5.96 billion (EUR 3.83 billion in 2022), offshore EUR 1.38 billion (EUR 1.25 billion in 2022). Economic stimuli from the operation of wind power plants were again at a constant level: onshore EUR 2.28 billion (EUR 2.3 billion in 2022), offshore EUR 0.75 billion (EUR 0.65 billion in 2022) [1a].

The market value of onshore wind energy fell sharply after the record levels seen in 2022. The downward trend continued throughout 2023, with a volume-weighted annual average of 7.62 ct/kWh. In December 2023, the price fell below 5 ct/kWh for the first time since spring 2021. [9]

The monthly market value of electricity from offshore wind energy fluctuated during 2023 between a maximum of 11.05 ct/kWh (February 2023) and a minimum of 5.56 ct/kWh (December 2023). The volume-weighted average monthly market value for offshore wind in 2023 is 8.19 ct/kWh, which is significantly lower than the 2022 average of 18.35 ct/kWh [10].

The development within the main two German wind turbine manufacturers proceeds as follows:

The 40-year-old German wind turbine manufacturer **Enercon** reached 60 GW of installed capacity worldwide in September 2023. With their E-nacelle, the electrical systems are now fully integrated into the nacelle. There is no need for a separate complete electrical module in the tower base, resulting in cost and time savings in production, transport and logistics, as well as installation and commissioning. The box-shaped component is completed and tested at the factory and shipped to the installation site ready to plug and play. At full capacity, the factory will produce up to 800 E-nacelles per year. [35] A next-generation E-nacelle has already been introduced that provides a significant simplification of the production process. [33]

Next to performance increases and higher wind classes for their turbine portfolio, the turbine manufacturer Enercon announced a typhoon version based on the more powerful E-138 EP3 E3 with 4.5 MW. The new strong-wind version comes with reinforcement of certain components and will be certified according to the specifications provided by the Japanese Ministry for the Economy, Trade and Industry (METI), targeting installation sites in Asia Pacific market regions that are rated as typhoon zones. [32]

Furthermore, Enercon develops a

permanent magnet generator with a two-part design to increase the rated output of the top model to 7.0 MW in the standard configuration. Unlike previous Enercon generator models, the new model has the stator on the inside and the rotor on the outside. In addition, the permanent magnets allow the rotor rim to be kept relatively narrow and the new design reduces the required magnet mass by more than 40"% [34].

The **Nordex Group** increased its order intake for 2023 by 16"% to a total of 7.4 gigawatts (GW) with 1,270 wind turbines (previous year: 6.3 GW with 1,235 wind turbines) and installed a total of 1,429 wind turbines in 24 countries (2022: 1,129 in 19 countries) with a total rated output of just under 7.3 GW (2022: 5.2 GW). Group sales increased by 14% to EUR 6.5 billion (2022: EUR 5.7 billion) [28] [29].

In February 2023, Nordex started the series production of the nacelles for the 6 MW class at the lead assembly plant in Rostock. Almost 50% of Nordex's nacelles worldwide are manufactured at the German site. In the long term, annual production of these large turbines alone is expected to total around 1 GW [27].

In Finland, the Nordex Group has installed the first N163/5.X turbines with a specially developed concrete-steel hybrid tower, with a hub height of 168 metres. The first installation of a 179-metre hybrid tower based on the same technology is planned for 2024 in Germany [31].

The Nordex Group has entered into two joint ventures. The joint venture with Acciona - Nordex H2 S.L. - will develop green hydrogen projects in areas with extensive onshore wind resources. These are in regions that are not connected to conventional electricity grids and where green hydrogen can be produced at competitive costs. With a target renewable energy development pipeline of 50 GW, the joint venture aims to develop projects that will produce 0.5 Mt of green hydrogen per year over the next ten years. The first projects should be ready for construction by 2027. The second initiative, "Nordex Electrolyzers", aims to develop, manufacture and market electrolysers based on proprietary technology. Both the Nordex Group and Sodena, a public company of the Government of Navarra, intend to invest EUR 15 million in this initiative over the next five years to advance the development of a commercial prototype and its first industrial deployment [30].

Next Term

Wind energy continues to be central to the German Energy Transition as the backbone of electricity generation (together with PV) for a resilient and reliable electricity supply [4]. Federal and State Governments are working on removing barriers specifically for onshore wind and strengthening offshore deployment.

Furthermore, with the launch of the 8th Energy Research Programme in the Federal Ministry for Economic Affairs and Climate Action (BMWK) supports wind energy RD&D through a mission-oriented approach that will help optimise the energy system to reach climate neutrality by 2045. This 8th Energy Research Programme is built on applied research for the electricity transition, the heat transition, a progression of the hydrogen economy, and a transfer process for participation and practice orientation [3].

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