Estimating offshore wind farm insta installation performance with satellite data

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Abstract.

– Offshore wind maturing, installations are a massive challenge

– Little public data on offshore wind farm installation performance available

– Offshore Wind Farm Installation massively influenced by weather limits

– Combining Automatic Identification System (AIS), ERA5 and public wind farm data allows to assess performance of offshore wind farm installation as a function of metocean data, location, wind turbine type and installation vessel

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1 Introduction

With 5,795 offshore wind turbines operational in Europe alone in August of 2022 (windeurope.org, 2022), offshore wind has become a major source of electricity in several countries, and more than 20 years of installing offshore wind farms has led to a significant amount of learning in the industry. While a great deal of scientific literature is available on wind turbine design and operations, the body of literature dealing with offshore wind farm installations is comparatively small, even though installing wind turbines offshore imposes a complex and thus scientifically challenging problem.

Wind turbines are today among the largest artifacts produced in series, easily surpassing even the larges of planes in their dimensions. Hence, installing them in an inherently windy location on the open ocean is by no means an easy undertaking: metocean conditions must be within narrow limits to allow save operations as wind and waves will inevitably induce motions of components during installations. Jiang (2021) provides an in-depth technical review of the current state-of-the-art of offshore wind farm installations and the associated challenges and potentials. In addition to the challenging environment, specialized equipment, vessels, and crews are required which due to the high level of specialization may not be available at all times or only at adverse cost. Last, the continuously increasing size of turbines, as well as increasing water depths, and new locations where little experience with regards to soil and metocean conditions is available, add to the risks associated with installations. All these factors may add to unforeseen cost which in turn put unnecessary strain on already difficult operations. In a brief review of lessons learned from the installation of one of the first offshore wind farms in Europe, Middelgrunden, Sørensen et al. (2001) already reports the adverse effects of changes in policy or logistics on the successful erection of a wind farm. It required a few more years and a considerable uptake in wind turbine rated power and size, until the first studies systematically investigating offshore wind farm installations were published. Gintautas et al. (2016) and Gintautas and Sorensen (2017) noted that, indeed, not the sea state or the wind speed is the limiting factor of any offshore wind operation, but the response of components and vessels to the latter. Thus, the authors proposed a novel decision making support tool that incorporated not only improved weather forecasts, but also the physical response of any components and vessels involved. Li et al. (2016) derived allowable sea states during monopile installation by conducting fully-coupled simulations of a heavy lift vessel and a monopile. Acero et al. (2017) extended this onto the installation of transition pieces. In 2018 Lacal-Arántegui et al. (2018) published a comprehensive study on the evidence behind cost reductions in offshore wind farm installations by comparing various key performance indicators; their data set included 87 wind farms installed between 2000 and 2017. Turbine rated power in that period increased by a factor of 4. They observed, that the overall installation duration per turbine stayed constant and the installation duration per monopile only tapered slightly. However, if the installation duration per Megawatt was calculate, a strong reduction in installation duration was observed. Paterson et al. (2018) investigated how installation vessels performed between the United Kingdoms round one and two using a probabilistic modeling approach. Tranberg et al. (2019) used vessel tracks recorded by the international *Automatic Identification System* (AIS) of offshore wind farm installation vessels to extract turbine installation duration for 16 wind farms using a clustering approach. They showed, that median and average installation duration differ significantly, indicating a highly skewed distribution of installation duration within a wind farm. As an outlook, they also showed installation duration as a function of average wind speed: turbines with a longer installation duration tended to experience higher wind speeds. A series of publications from Verma et al. (see e.g.: Verma et al. (2017, 2019b, a, c, 2020)) explored the impact of weather onto single blade installation using fully coupled simulations of a wind turbine under installation conditions. In a measurement campaign conducted during the installation of the offshore wind farm *Trianel Windpark Borkum II*, the structural response of 32 wind turbines during installation was recorded and consequentially correlated with the metocean conditions experienced by the turbines. While the structural response of the turbines was stochastic in nature, a clear correlation between maximum tower to displacement, wind speed and significant wave height was observed. The data allowed derivation of structural installation limits, as opposed wind speed and wave height limits (Sander et al., 2020a; Sander, 2020a, b). During the installation *Trianel Windpark Borkum II*, a tuned mass damper was used to reduce structural response of turbines during installation, effectively increasing the maximum allowable wind speed and significant wave height. The measurements confirmed the effectiveness of the damper (Sander et al., 2020b). The concept was picked up by Oelker et al. (2021), who modeled the impact of the tuned mass damper as increased wind and wave limits, showing a significant cost saving potential. Further, the measurements also showed, that most of the structural response, limiting the installation was caused by the turbine and not by the blade (Stroer et al., 2022).

With the present body of literature dealing with the link between structural response of components and metocean conditions, several questions remain: how long does the installation of turbines take on average? How are installation duration and turbine size, prevailing metocean conditions, vessel size, location and foundation type correlated? These data are necessary if the push towards a response based limits is to be successful.

– Li et al. (2021)

– Li et al. (2021)

– Tjaberings et al. (2022)

– Wu et al. (2022)

– Yang et al. (2022)

In this study, we investigate how metocean conditions correlate with offshore wind farm installation times. We compile a statistical overview of offshore wind farm installations: from satellite data, we extract correlations between turbine size, wind farm locations, installation vessels and installation duration with metocean conditions during the installation process. Finally, we extract the observed metocean limits for turbine sizes, manufacturers, vessels, and locations.

2 Material and Methods

2.1 Vessel tracks

2.1.1 Data acquisition and pre-processing

To reliably extract installation times for as many offshore wind farms as possible, we acquired hourly *Automatic Identification System* (AIS) vessel data from a data broker. The AIS data includes 9 offshore wind installation vessels over a period of 11 years (see Table 1).

Each AIS vessel record includes latitude, longitude, speed, heading, course and a timestamp for a given vessel.

2.1.2 Clustering vessel tracks to extract wind farms

To extract installation times per turbine per offshore wind farm, we preselected vessel records where the speed of the vessel was 0 and further removed records where the vessel was close to shore or in port. The vessel records were then automatically clustered using the DBSCAN algorithm as implemented in the scikit-learn python package.

2.1.3 Clustering wind farms to extract single turbines

To yield vessel records corresponding to single turbine installations, each wind farm cluster was clustered again with the DBSCAN algorithm, yielding vessel records corresponding to individual turbines. Only turbine locations where at least two

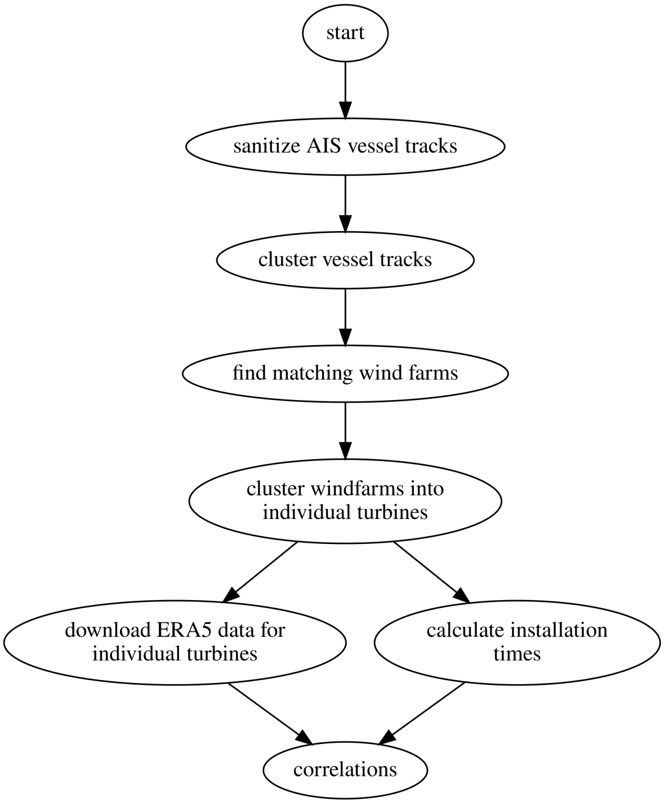

Figure 1. analysis flowchart

Table 1. AIS vessel data used in this study.

MMSI	Name	Data time range
218389000	Thor	2010 - 2021
218657000	Vole au Vent	2013 - 2021
219019002	Sea Challenger	2013 - 2021
229044000	Brave Tern	2012 - 2021
229080000	Bold Tern	2013 - 2021
235090598	Blue Tern	2015 - 2021
245179000	Aeolus	2010 - 2021
245924000	MPI Adventure	2010 - 2021
246777000	MPI Resolution	2010 - 2021

vessel records were available were kept for further analysis. Installation times per turbine were then calculated by assuming, that the first available AIS vessel record corresponds to the beginning of turbine installation activities and the last AIS record marks the end of installation activities.

2.2 Wind farms

These clusters were then cross-referenced with the locations of offshore wind farms to select vessel records within a given radius of a known wind farm.

2.3 Metocean data

Based on the time stamps of the AIS records per turbine, ERA5 metocean data was requested for the wind farm location. ERA5 data includes wind speed and wind direction at several altitudes, wave direction, wave period and significant wave height. For each wind farm, metadata such as wind turbine model, rated power and foundation type were collected, and all data was combined into a SQLite database. The database will be made available to the public once analysis has been completed.

3 Results and Discussion

Table 2. Overview of detected wind farms and number of extracted wind turbines per wind farm

Wind Farm Name	Number of Turbines	Rated Turbine Power	Wind Farm Capacity	Number of Extracted Wind Turbines
Luchterduinen	43	3.00	129.00	4
Westermost Rough	35	6.00	210.00	32
Arkona	60	6.42	385.00	49
East Anglia One	102	7.00	714.00	11
Dudgeon	67	6.00	402.00	61
Gode Wind I & II	97	6.00	582.00	61
Hornsea	174	7.00	1218.00	100
Borssele I/II	94	8.00	752.00	55
Humber Gateway	73	3.00	219.00	83
Northwind	72	3.00	216.00	52
Deutsche Bucht	31	8.40	260.40	14
Veja Mate	67	6.00	402.00	19
Galloper	56	6.30	352.80	11
Global Tech I	80	5.00	400.00	22
Butendiek	80	3.60	288.00	76
Moray East	100	9.50	950.00	68
Borkum Riffgrund 2	56	8.00	448.00	48
Borkum Riffgat	30	3.77	113.25	20
Merkur	66	6.00	396.00	59
Trianel Borkum 2	32	6.33	202.56	9
Gemini	150	4.00	600.00	29
Albatros	16	7.00	112.00	11
Nobelwind	50	3.30	165.00	41
Kriegers Flak	72	8.00	576.00	72
Wikinger	70	5.00	350.00	64
Yunlin	80	8.00	640.00	11
Horns Rev 3	49	8.30	406.70	46
Sandbank	72	4.00	288.00	73
Teesside	27	2.30	62.10	25
Rampion	116	3.45	400.20	41
BARD Offshore I	80	5.00	400.00	15
Northwester 2	23	9.50	218.50	41
EnBW Baltic II (MP)	39	3.60	140.40	42

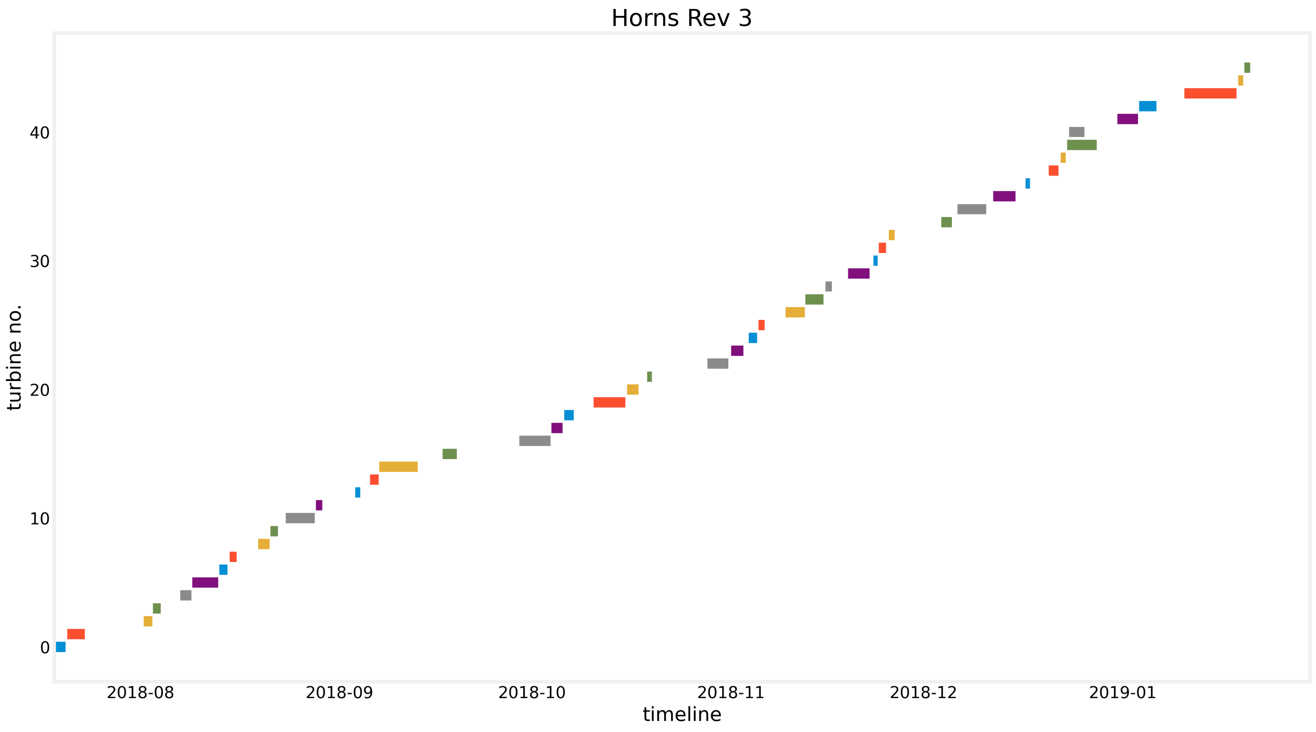

Figure 2. duration distribution

4 Conclusions

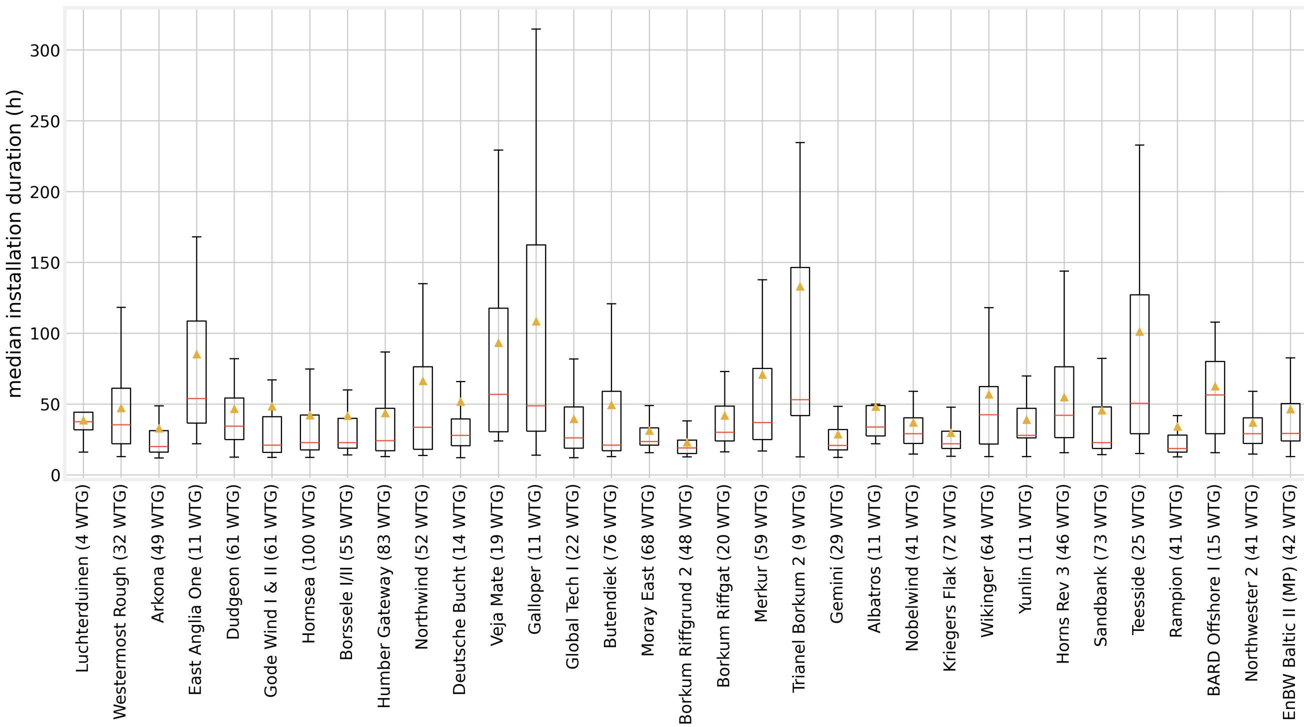

Figure 3. Overview of installation data

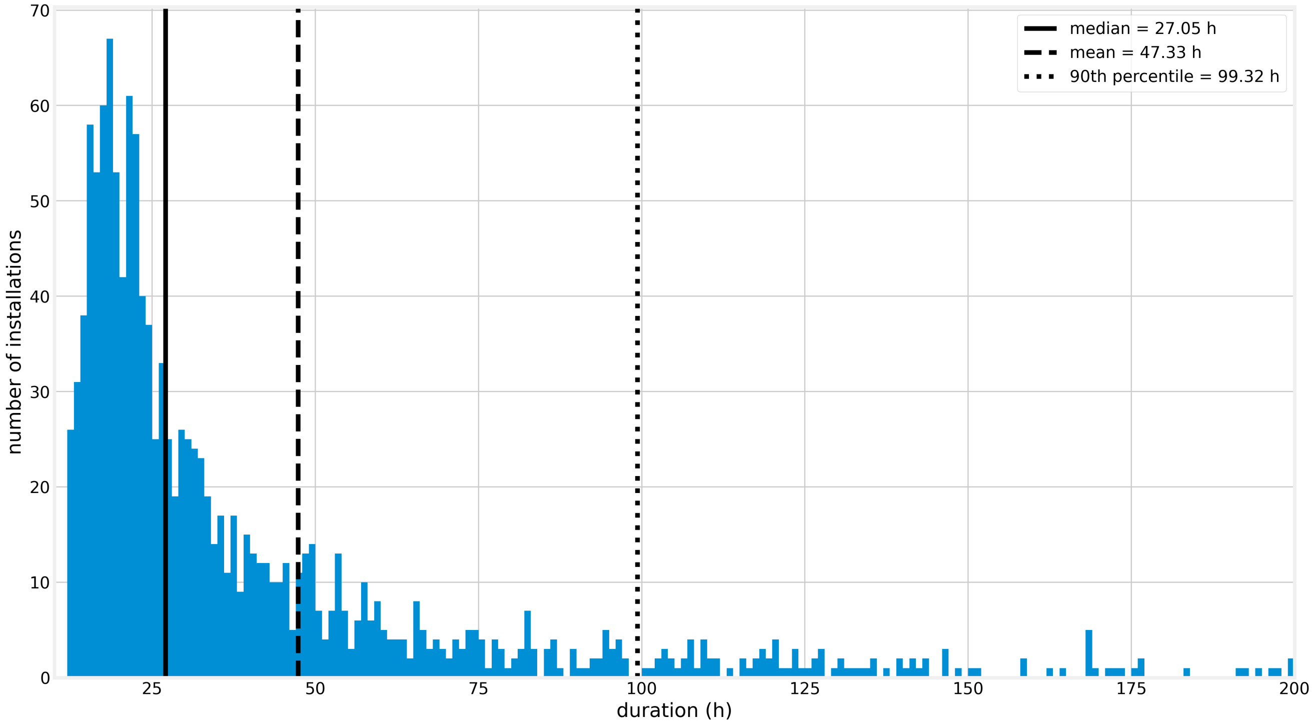

Figure 4. duration distribution

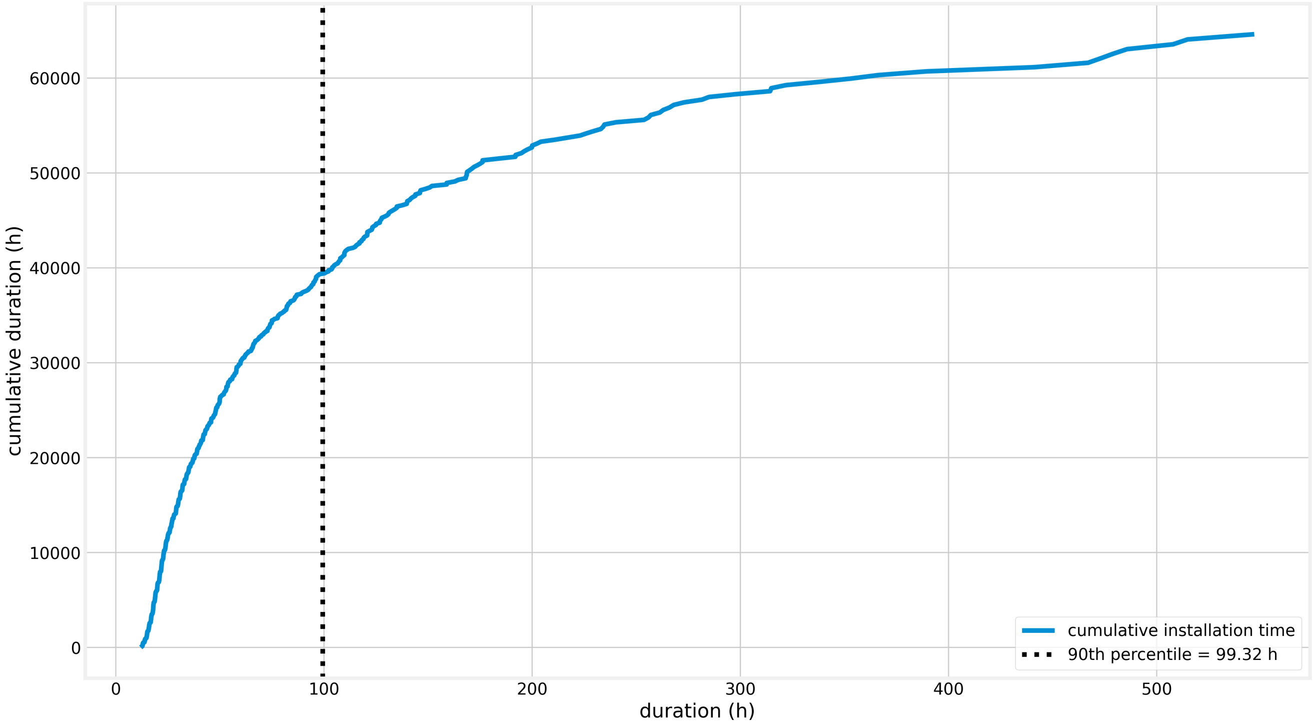

Figure 5. duration distribution

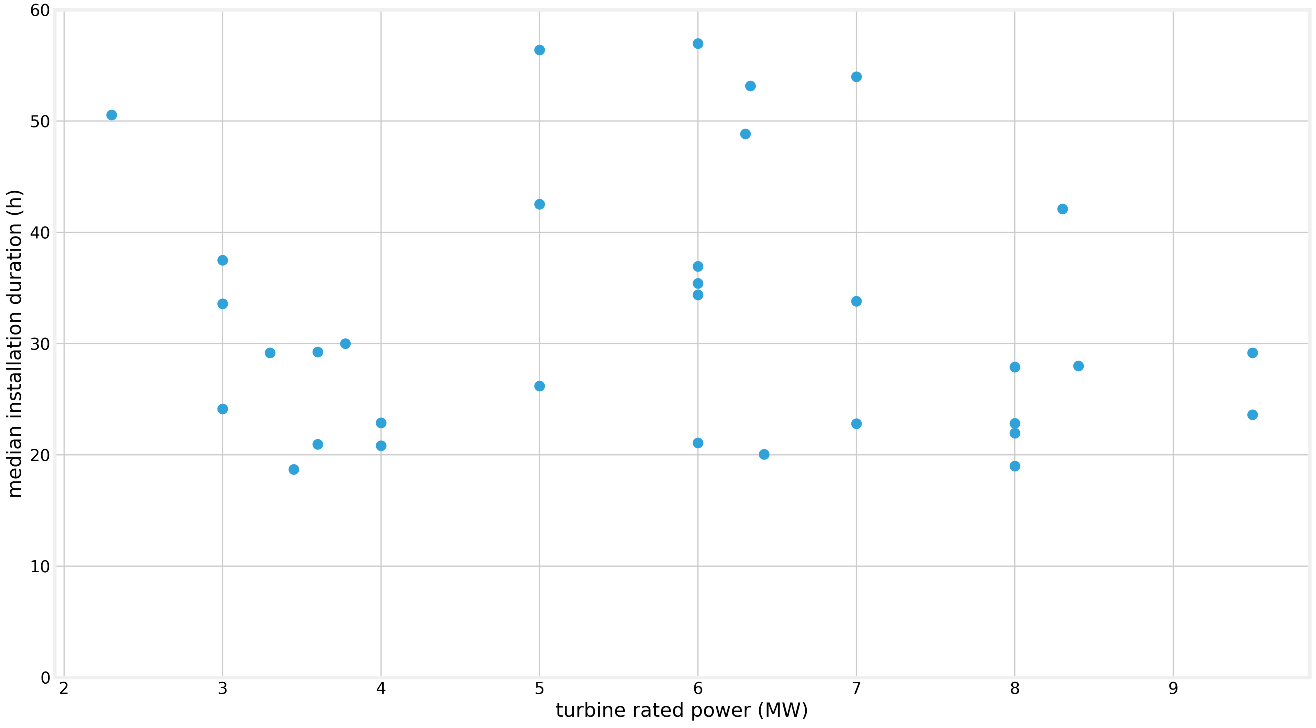

Figure 6. duration distribution

5 Conclusions

Code and data availability. All code related to the present publication is available on github under creative-commons licence: https://github.com/k323r/2022_WES_offshore-wind-installation

Sample availability. TEXT

Appendix A: Appendix

A1 Wind Farm Gantt Charts

Author contributions. TEXT

Competing interests. TEXT

Disclaimer. TEXT

Acknowledgements. TEXT

References

Acero, W., Gao, Z., and Moan, T.: Methodology for assessment of the allowable sea states during installation of an offshore Wind turbine transition piece structure onto a monopile foundation, Journal of Offshore Mechanics and Arctic Engineering, 139, https://doi.org/10.1115/1.4037174, tex.ids= aceroMethodologyAssessmentAllowable2017a, 2017.

Gintautas, T. and Sorensen, J. D.: Improved Methodology of Weather Window Prediction for Offshore Operations Based on Probabilities of Operation Failure, Journal of Marine Science and Engineering, 5, 20, https://doi.org/10.3390/jmse5020020, wOS:000423689700006, 2017.

Gintautas, T., Sorensen, J. D., and Vatne, S. R.: Towards a risk-based decision support for offshore wind turbine installation and operation & maintenance, in: 13th Deep Sea Offshore Wind R&d Conference, Eera Deepwind'2016, edited by Tande, J. O. G., Kvamsdal, T., and Muskulus, M., vol. 94, pp. 207–217, Elsevier Science Bv, Amsterdam, wOS:000387586600021, 2016.

Jiang, Z.: Installation of offshore wind turbines: A technical review, Renewable and Sustainable Energy Reviews, 139, 110 576, https://doi.org/10.1016/j.rser.2020.110576, 2021.

Lacal-Arántegui, R., Yusta, J. M., and Domínguez-Navarro, J. A.: Offshore wind installation: Analysing the evidence behind improvements in installation time, Renewable and Sustainable Energy Reviews, 92, 133–145, https://doi.org/10.1016/j.rser.2018.04.044, tex.ids= lacal-aranteguiOffshoreWindInstallation2018a, lacalaranteguiOffshoreWindInstallation2018, 2018.

Li, L., Guachamin Acero, W., Gao, Z., and Moan, T.: Assessment of Allowable Sea States During Installation of Offshore Wind Turbine Monopiles With Shallow Penetration in the Seabed, Journal of Offshore Mechanics and Arctic Engineering, 138, 041 902, https://doi.org/10.1115/1.4033562, tex.ids= liAssessmentAllowableSea2016a, 2016.

Li, L., Haver, S., and Berlin, N.: Assessment of operational limits: Effects of uncertainties in sea state description, Marine Structures, 77, 102 975, https://doi.org/10.1016/j.marstruc.2021.102975, 2021.

Oelker, S., Sander, A., Kreutz, M., Ait-Alla, A., and Freitag, M.: Evaluation of the Impact of Weather-Related Limitations on the Installation of Offshore Wind Turbine Towers, Energies, 14, 3778, https://doi.org/10.3390/en14133778, 2021.

Paterson, J., D'Amico, F., Thies, P., Kurt, R., and Harrison, G.: Offshore wind installation vessels – A comparative assessment for UK offshore rounds 1 and 2, Ocean Engineering, 148, 637–649, https://doi.org/10.1016/j.oceaneng.2017.08.008, 2018.

Sander, A.: Oscillations of Offshore Wind Turbines undergoing Installation I: Raw Measurements, https://doi.org/10.5281/zenodo.4498779, type: dataset, 2020a.

Sander, A.: TWBII Final Report, Tech. rep., University of Bremen, Bremen, 2020b.

Sander, A., Haselsteiner, A. F., Barat, K., Janssen, M., Oelker, S., Ohlendorf, J.-H., and Thoben, K.-D.: Relative Motion During Single Blade Installation: Measurements From the North Sea, American Society of Mechanical Engineers Digital Collection, https://doi.org/10.1115/OMAE2020-18935, 2020a.

Sander, A., Meinhardt, C., and Thoben, K.-D.: MONITORING OF OFFSHORE WIND TURBINES UNDER WAVE AND WIND LOADING DURING INSTALLATION, pp. 2189–2205, Athens, Greece, https://doi.org/10.47964/1120.9178.19731, 2020b.

Stroer, L., Haselsteiner, A., Sander, A., and Thoben, K.-D.: A STATISTICAL MODEL OF MOTION MAXIMA OF OFFSHORE WIND TURBINE COMPONENTS DURING INSTALLATION, 2022.

Sørensen, H. C., ApS, S., Hansen, J., Vølund, P., and Denmark, H.: EXPERIENCE FROM THE ESTABLISHMENT OF MIDDELGRUNDEN 40 MW OFFSHORE WIND FARM, p. 4, 2001.

Tjaberings, J., Fazi, S., and Ursavas, E.: Evaluating operational strategies for the installation of offshore wind turbine substructures, Renewable and Sustainable Energy Reviews, 170, 112 951, https://doi.org/10.1016/j.rser.2022.112951, 2022.

Tranberg, B., Kratmann, K., and Stege, J.: Determining offshore wind installation times using machine learning and open data, 2019.

Verma, A. S., Vedvik, N. P., and Gao, Z.: Numerical assessment of wind turbine blade damage due to contact/impact with tower during installation, IOP Conference Series: Materials Science and Engineering, 276, 012 025, https://doi.org/10.1088/1757-899X/276/1/012025, publisher: IOP Publishing, 2017.

Verma, A. S., Jiang, Z., Ren, Z., Gao, Z., and Vedvik, N. P.: Response-Based Assessment of Operational Limits for Mating Blades on Monopile-Type Offshore Wind Turbines, Energies, 12, 1867, https://doi.org/10.3390/en12101867, wOS:000471016700046, 2019a.

Verma, A. S., Jiang, Z., Vedvik, N. P., Gao, Z., and Ren, Z.: Impact assessment of a wind turbine blade root during an offshore mating process, Engineering Structures, 180, 205–222, https://doi.org/10.1016/j.engstruct.2018.11.012, tex.ids= vermaImpactAssessmentWind2019a, 2019b.

Verma, A. S., Vedvik, N. P., and Gao, Z.: A comprehensive numerical investigation of the impact behaviour of an offshore wind turbine blade due to impact loads during installation, Ocean Engineering, 172, 127–145, https://doi.org/10.1016/j.oceaneng.2018.11.021, 2019c.

Verma, A. S., Jiang, Z., Ren, Z., Gao, Z., and Vedvik, N. P.: Effects of Wind-Wave Misalignment on a Wind Turbine Blade Mating Process: Impact Velocities, Blade Root Damages and Structural SafetyAssessment, Journal of Marine Science and Application, https://doi.org/10.1007/s11804-020-00141-7, tex.ids= vermaEffectsWindWaveMisalignment2020, 2020.

windeurope.org: Offshore Wind Energy 2022 Mid-Year Statistics, Tech. rep., https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaDdDRG9JYTJWNVNTSWhNM3B1T1c4NE5HZGxjbVJ4T0c5eFpEWnJhSGs1YzJJNGR6U 2022%20Offshore%20wind%20mid-year.pdf?content_type=application%2Fpdf&disposition=inline%3B+filename%3D%222022+Offshore+wind+mid-year.pdf%22%3B+filename%2A%3DUTF-8%27%272022%2520Offshore%2520wind%2520mid-year.pdf, 2022.

Wu, M., Gao, Z., and Zhao, Y.: Assessment of allowable sea states for offshore wind turbine blade installation using time-domain numerical models and considering weather forecast uncertainty, Ocean Engineering, 260, 111 801, https://doi.org/10.1016/j.oceaneng.2022.111801, 2022.

Yang, Z., Lin, Y., and Dong, S.: Weather window and efficiency assessment of offshore wind power construction in China adjacent seas using the calibrated SWAN model, Ocean Engineering, 259, 111 933, https://doi.org/10.1016/j.oceaneng.2022.111933, 2022.