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

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. More than 20 years of installing offshore wind farms has led to a significant amount of learning in both industry and academia. While a great deal of scientific literature is available on wind turbine design and to operations, the body of literature dealing with offshore wind farm installations is comparatively small, even though installing wind turbines at an offshore location imposes physically complex and thus scientifically interesting problem.

Wind turbines are today among the largest human made artifacts produced in series, easily surpassing even the larges of plane in their dimensions. Hence, installing them in an inherently windy location on the open ocean is by no means an easy undertaking: wind and sea state conditions, generally abbreviated as metocean conditions, must be within narrow limits to allow save operations as wind and waves will inevitably induce motions of components during installations. For more technical details on the installation of offshore wind turbines, see Jiang (2021), who provides an in-depth technical review of the current state-of-the-art of offshore wind farm installations and the associated challenges. In addition to the challenging environment, specialized equipment, vessels, and crews are required which due to being scarce resources may not be available at all times or only at high cost. Lastly, the continuously increasing size of turbines, increasing water depths, and new locations where little experience with regards to soil, metocean conditions and local regulations is available, add to the risks associated with offshore wind installations. All these factors may add to unforeseen cost which in turn put unnecessary strain on already difficult projects.

A fist indication of the difficulties one may encounter when installing offshore wind turbines is given by Sørensen et al. (2001), who summarize the installation of the Middelgrunden offshore wind farm, one of the first wind farms installed in Europe. The authors already report on the adverse effects of changes in policy or logistics on the successful erection of the 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 metocean conditions directly limit offshore wind operations, but the response of components and vessels to the prevailing conditions, emphasizing the importance of reliable weather forecasts. The authors proposed a novel decision making support tool that incorporates not only improved weather forecasts, but also the physical response of any components and vessels involved. Acero et al. (2017) extended this to the installation of transition pieces.

A series of publications from Verma et al. (see e.g.: Verma et al. (2017, 2019a, c, b, 2020)) explored the impact of weather onto single blade installation using fully coupled simulations of a wind turbine under installation conditions, completing the simulation based approach to estimating allowable metocean conditions.

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. The authors showed the significant waiting times caused by metocean limitations on the complete vessel spread.

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 presented installation duration as a function of average wind speed during the installation period: Turbines with a longer installation duration tended to experience higher wind speeds.

Tjaberings et al. (2022) evaluated different installation strategies for offshore wind turbine foundations using a discrete event simulation approach.

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 during the installation, 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.

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.

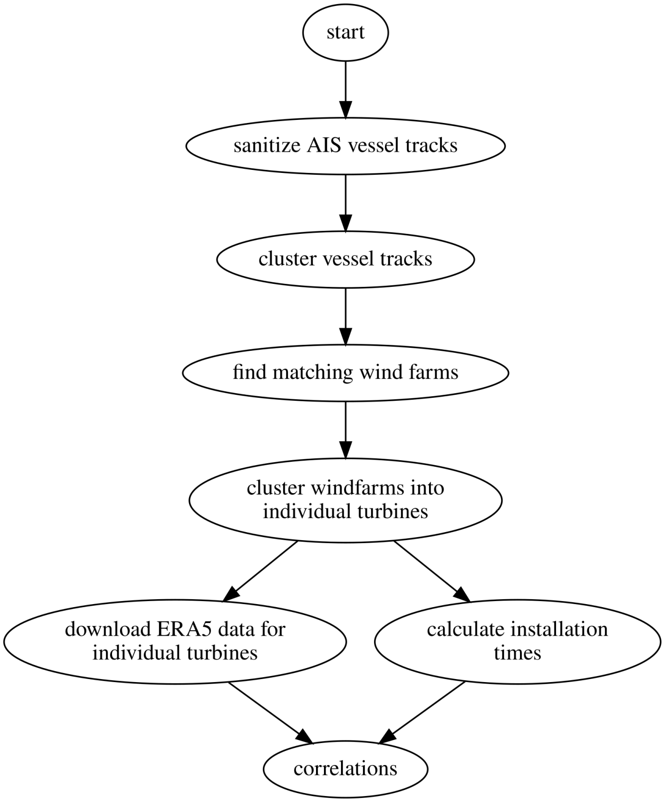

Figure 1. analysis flowchart

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

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

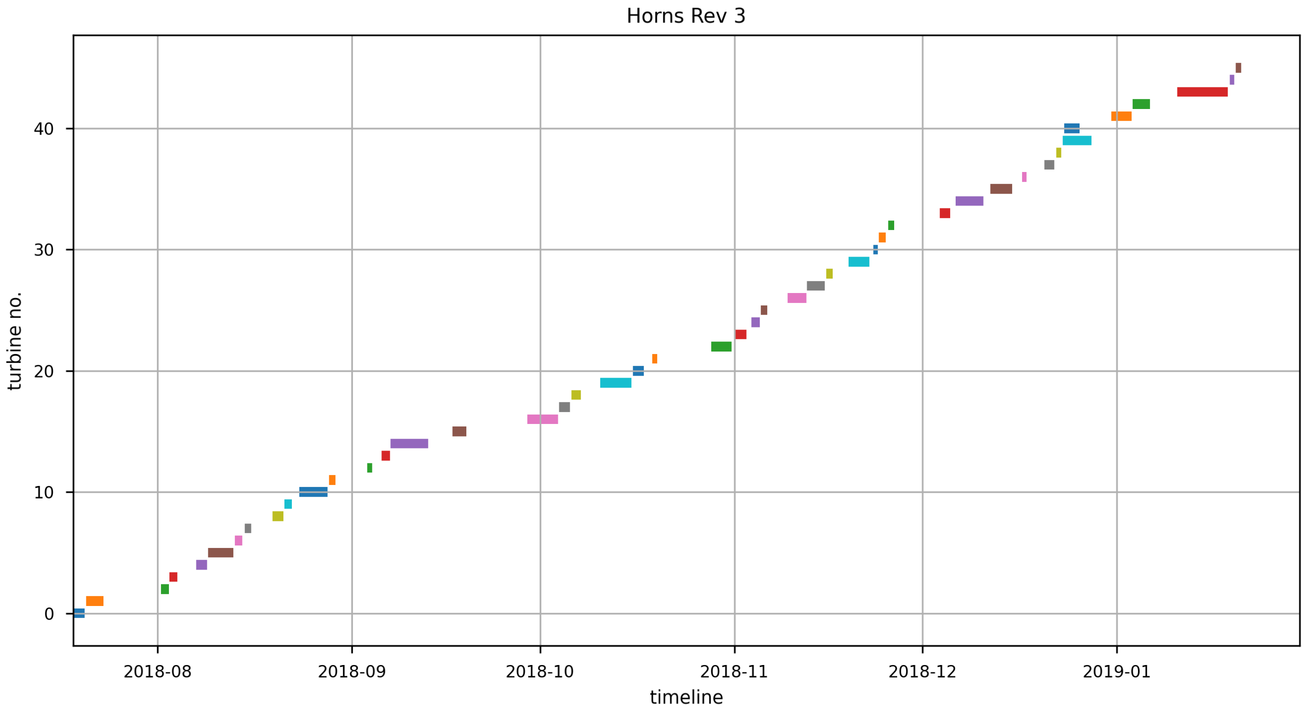

Figure 2. duration distribution

4 Conclusions

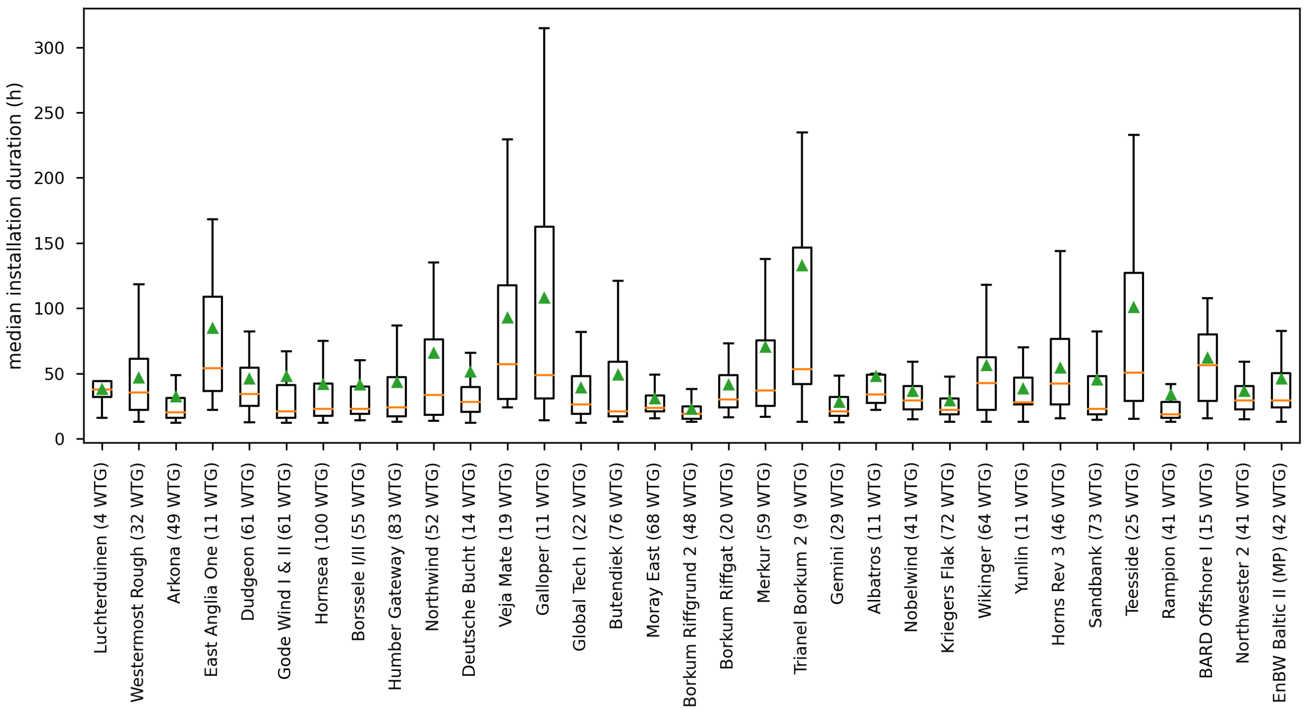

Figure 3. Overview of installation data

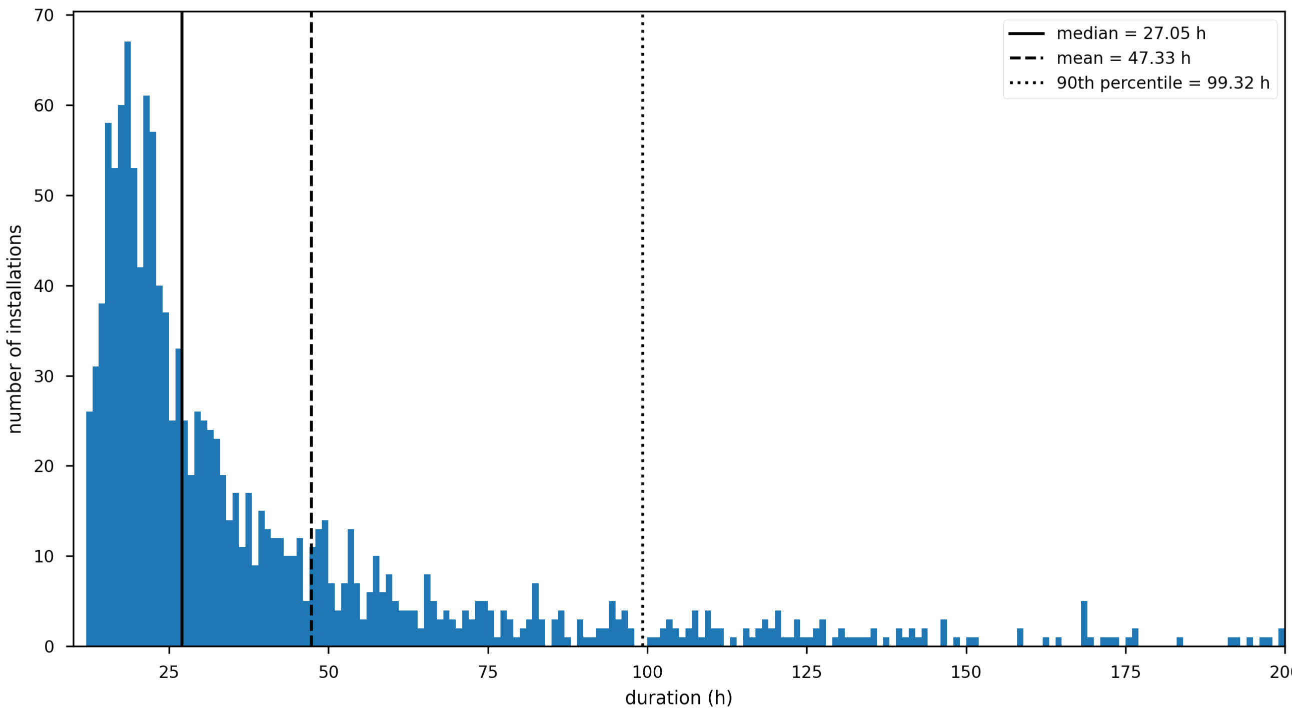

Figure 4. duration distribution

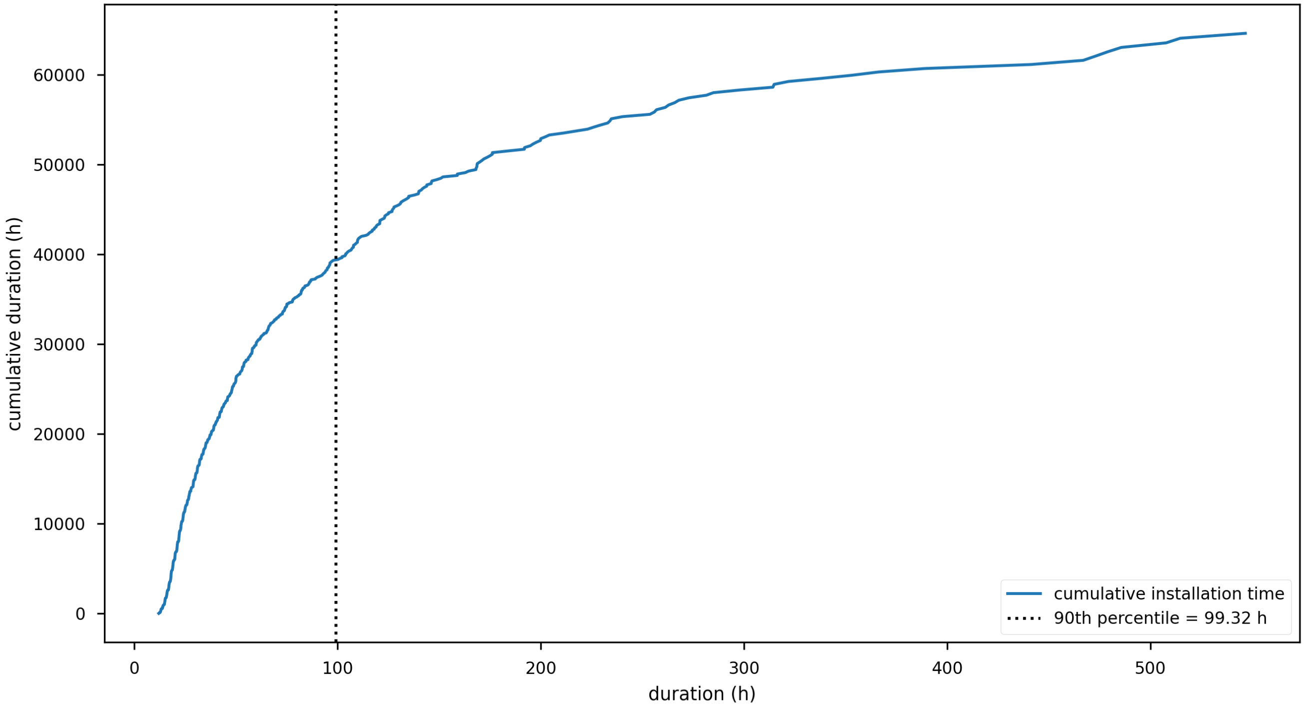

Figure 5. duration distribution

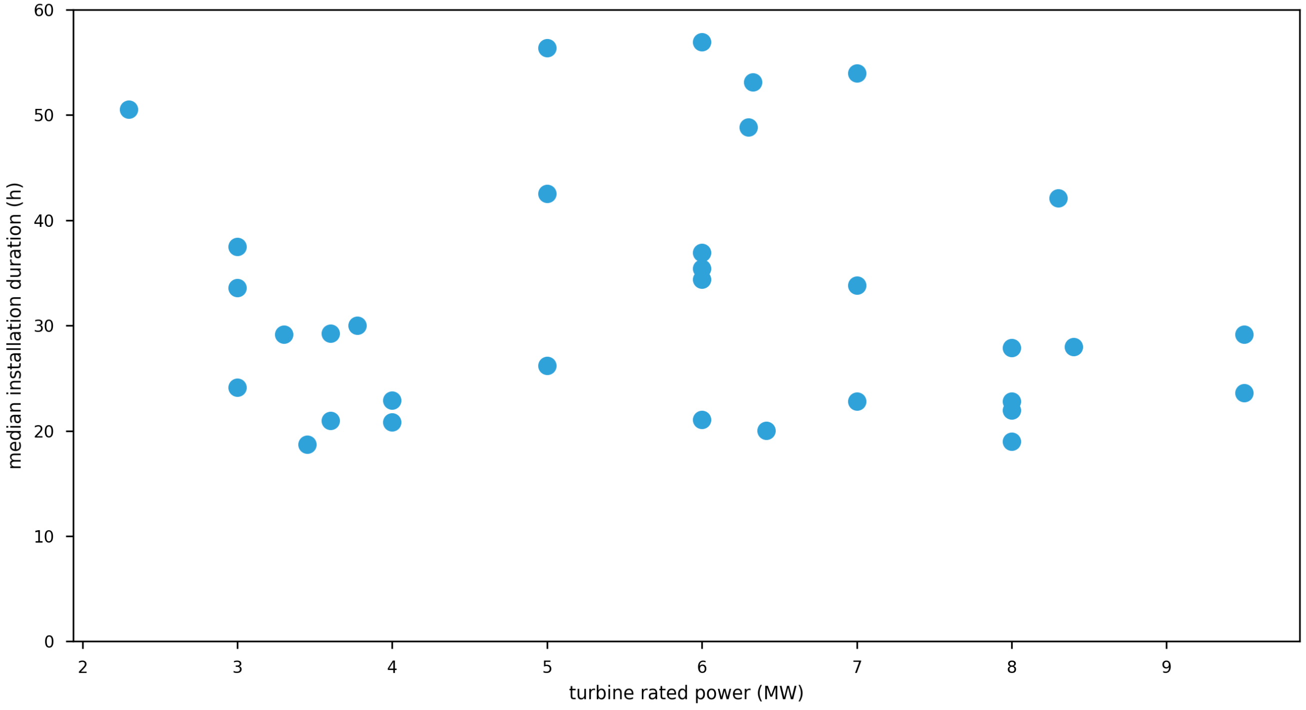

Figure 6. duration distribution

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

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