Validated onshore and offshore wind time series for European countries (1979-2017). Methods description

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June 13, 2019

This document provides details on the generation and validation of time series representing the hourly capacity factors for onshore and offshore wind at a national scale for every country in Europe (EU-28 except the islands Malta and Cyprus plus Norway and Switzerland).

This time series were generated in the framework of RE-INVEST project. A similar dataset comprising solar photovoltaic time series at national scale can be accessed through the zenodo repository 10.5281/zenodo.1321809 and details can be found in [1]. The Global Renewable Energy Atlas (REatlas) from Aarhus University [2] has been used to generate the wind time series. For every country, onshore wind time series are produced. For some of the countries offshore wind time series are also generated. In both cases, the time series include data for the period 1979-2017. However, for every year, the installed capacity layout is kept fixed and corresponds to turbines running in 2015. By doing so the time series for different years represent the weather influenced on the wind generation and are not impacted by differences in installed capacities.

The REatlas uses as input reanalysis data, that is, the output of global atmospheric simulations, together with simplified models of renewable technologies, *i.e.*, power curves for wind turbines and efficiency curves, inclination, and orientation for solar panels. The Climate Forecast System Reanalysis (CFSR) from the National Center for Environmental Prediction (NCEP) [3] is used as input for the model. It comprises a 39 years-long global high-resolution dataset (hourly time resolution and approximately 40 x 40 km^2 space resolution). The characteristics of wind power plants in Europe are retrieved from a comprehensive database [4] that includes, among others, the location, installed capacity and commissioning data of almost every wind power plant in Europe.

The procedure to obtain the time series for every country and technology (onshore or offshore) for a certain year can be described as follows. First, the turbines in the database are classified into several 250 kW-wide categories according to their capacity. For every category, a representative turbine and hub height is selected (see Table 1 in reference [2]). Every power plant within a category X is associated to the point n in the 40 x 40 km^2 CFSR grid that is closer to its actual position. This allows to obtained a capacity layout map $\{C_{X,n}\}_{y,s}$ for the year y and the country s. For future years, either the planned power plants or a heuristic distribution can be used to obtain capacity layouts. For the time series accompanied by this text, the capacity layout corresponding to year 2015 is used to model all the years.

Second, the CFSR data provides instantaneous wind velocity at 10 m above ground/sea level. A logarithm curve is used to estimate the wind speed ν at hub height H from the speed at 10 m height. The surface roughness z_0 is calculated as the average for the 40 x 40 km^2 area around the corresponding CFSR point n.

$$\nu(H) = \nu(10m)\frac{ln(H/z_0)}{ln(10m/z_0)} \quad (1)$$

For every wind turbine category, the corresponding representative turbine power curve is used to transform the wind velocity grid data into a grid of energy generation time series $W_{X,n}(t)$.

Third, all categories and all the grid points within a country are aggregated together to obtain a time series representative for the onshore/offshore generation in that country.

$$W_{y,s}(t) = \sum_{X,n} C_{X,n} W_{X,n}(t) \quad (2)$$

where $C_{X,n} \in \{C_{X,n}\}_{y,s}$

In [2] a simple heuristic smoothing function is applied to the single turbine power curves before they are used in the wind conversion. This is proposed in order to account for the effects of variations in the wind speed within each grid cell and each time step, as well as to include the possible unavailability of some turbines due to planned or unplanned maintenance. We follow the same approach here. A modified power curve is used where P_{mod} is calculated for all wind speeds ν_0 as:

$$P_{mod}(\nu_0) = \eta \int_0^\infty P_0(\nu) Ker(\nu_0, \nu - \Delta\nu) d\nu \quad (3)$$

The smoothing function Ker is defined as the Gaussian with standard deviation σ_0 and mean value $\nu_0 + \Delta\nu$.

$$Ker(\nu_0, \nu - \Delta\nu) = \frac{1}{\sqrt{2\pi\sigma_0^2}} e^{\frac{(\nu_0+\Delta\nu-\nu)^2}{2\sigma_0^2}} \quad (4)$$

η represents the average wind turbine fleet availability. η lower than one is expected as some turbines may not be operating due to maintenance or repair works or just because they have been ordered to stop by the Transmission System Operator (TSO). The three parameters (η, $\Delta\nu$, and σ_0) are assumed to be identical for every category within a country. They are determined, for every country, by minimizing the Kullback-Leibler divergence D_{KL} between the modelled time series CF_M (t, η, $\Delta\nu$, σ_0) for 2015 and the historical reference CF_R(t).

$$D_{KL} = \sum_i CF_{R,i} \ln\left(\frac{CF_{R,i}}{CF_{M,i}}\right) \quad (5)$$

where the sum in D_{KL} expands over the intervals i of the the probability distributions.

The historical reference time series are calculated by dividing historical wind (onshore or offshore) electricity generation by the cumulative installed capacity. The electricity generation time series are obtained from ENTSO-e or national TSOs trough the convenient compilation carried out by the Open Power System Data initiative [5]. For Ireland, historical generation data was provided by the Irish Wind Energy Association (IWEA). The cumulative installed capacity is obtained on a monthly basis from the wind power database [4]. For those countries whose historical data is not available, time series from the Renewables Ninja dataset [6] are used as a reference (see Table 1). Renewables Ninja time series also use reanalysis data but the bias correction in their case is based on the historical annually-averaged capacity factors [7]. This allows the generation of time series for countries in which hourly-resolved historical data is not available.

In order to compute the histograms of historical and modelled time series to evaluate D_{KL}, a number of binning categories or intervals n_{bins} must be selected. Once n_{bins} has been chosen, the range of every interval is determined based on the reference time series. Then, the modelled time series histogram is generated using the same intervals as those in the reference time series histogram. If, for any of the parameters combination (η, $\Delta\nu$, σ_0), the modelled time series histogram shows a probability equals to zero for any of the intervals, that combination is discarded. As a consequence, the value selected for n_{bins} has a direct impact on the results as shown in Figure 1. Since historical time series usually include values with capacity factor equal to zero, choosing a large

Table 1: Source used as reference time series for every country.

Onshore	
country	source
AUT	Historical, OPSD
BEL	Historical, OPSD
BGR	Historical, OPSD
CHE	Historical, OPSD
CZE	Historical, OPSD
DEU	Historical, OPSD
DNK	Historical, OPSD
ESP	Historical, OPSD
EST	Historical, OPSD
FIN	Historical, OPSD
FRA	Historical, OPSD
GBR	Historical, OPSD
HRV	Renewables Ninja
GRC	Historical, OPSD
HUN	Renewables Ninja
IRL	Historical, IWEA
ITA	Renewables Ninja
LVA	Historical, OPSD
LTU	Renewables Ninja
LUX	Renewables Ninja
NLD	Historical, OPSD
NOR	Historical, OPSD
POL	Renewables Ninja
PRT	Historical, OPSD
ROU	Historical, OPSD
SVK	Renewables Ninja
SVN	Renewables Ninja
SWE	Renewables Ninja
Offshore	
country	source
BEL	Historical, OPSD
DNK	Historical, OPSD
DEU	Renewables Ninja
FIN	Renewables Ninja
FRA	Renewables Ninja
GBR	Historical, OPSD
IRL	Renewables Ninja
NLD	Renewables Ninja
NOR	Renewables Ninja
SWE	Renewables Ninja

value for n_{bins} forces the modelled time series to reproduce the reference time series at very low CF. This is achieved at the expenses of large disagreement at intermediate CF values. A large value for n_{bins} also provides a better match with reference for the maximum CF value. However this condition is less strict due to the fact that the probability of occurrence of maximum CF is very low, that is, the weighting factor on the evaluation of D_{KL} is low, see Eq. (5). Conversely, selecting fewer and wider intervals (lower n_{bins}) produces a better global match but larger differences at the extremes. Since the wind time series will later be used as input for energy system models, it is important that they adequately reproduce reality for hours whose capacity factor is close to zero. Hence, $n_{bins} = 20$ was selected. This corresponds to intervals whose width is around 0.05.

Tables 2 and 3 reproduce the optimum combination (η, $\Delta\nu$, and σ_0) for every country across Europe. Figures 2, and 3 show the duration curves for onshore and offshore wind in Denmark. In addition, duration curves calculated using the time series from the Renewables Ninja dataset [6, 7] and EMHIRES dataset [8] are also shown. Equivalent plots for other European countries are shown in Appendix A.

Different metrics can be defined to evaluate how good is the match between a modelled time series and the reference. Tables 4 and 5 show the annually-averaged capacity factors and the the Root Mean Square Error (RMSE).

The annually-averaged hourly capacity factor $\overline{CF_h}$ is defined as

$$\overline{CF_h} = \frac{\sum_h CF_h}{n_h} \tag{6}$$

where n_h is the number of hours in a year.

Root-Mean-Square Error (RMSE) is calculated using hourly values for the modelled $CF_{M,h}$ and reference time series $CF_{R,h}$.

$$RMSE = \sqrt{\frac{\sum_h (CF_{M,h} - CF_{R,h})^2}{n_h}} \tag{7}$$

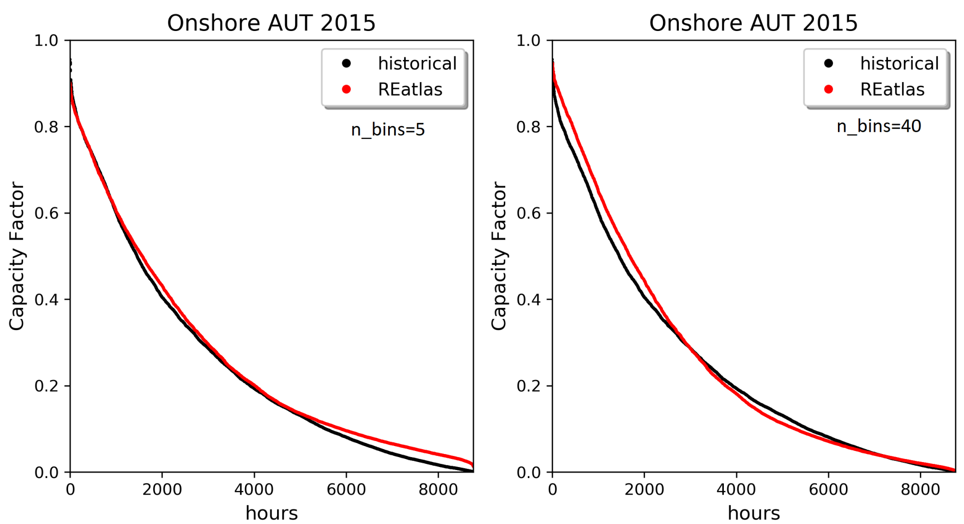

Figure 1: Duration curve comparison for different number of binning categories n_{bins}. Optimum parameters combinatin (η, σ_0, and $\Delta\nu$) for the modelled REatlas time series have been selected based by minimizing D_{KL}, Eq. (5), with n_{bins} equal to 5 (left plot) and 40 (right plot).

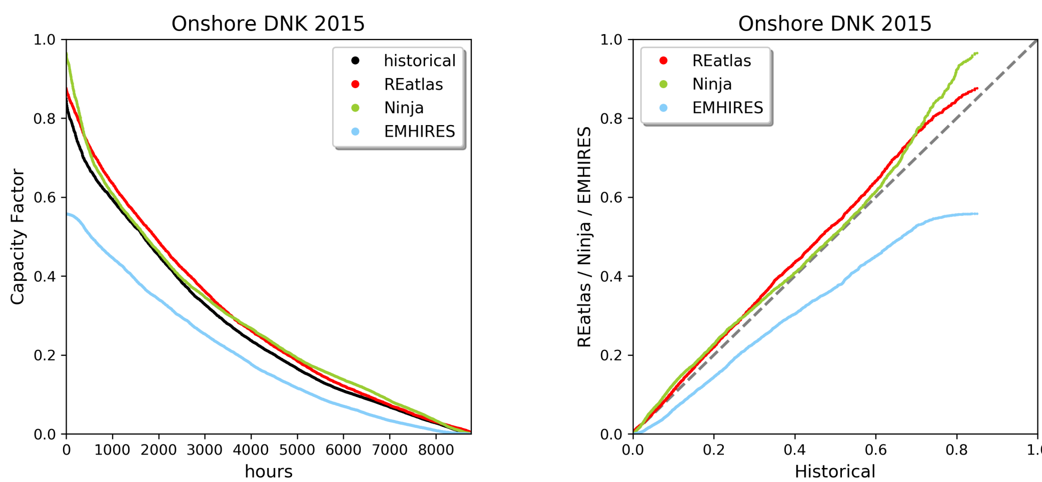

Figure 2: Duration curve for Denmark onshore wind in 2015 according to different sources.

Finally, Figures 4 and 5 plot the annually-averaged capacity factors for all the years included in the dataset. As previously mentioned, capacity layouts are fixed and corresponds to year 2015. This allows investigating the impact of weather variability on the wind generation time series.

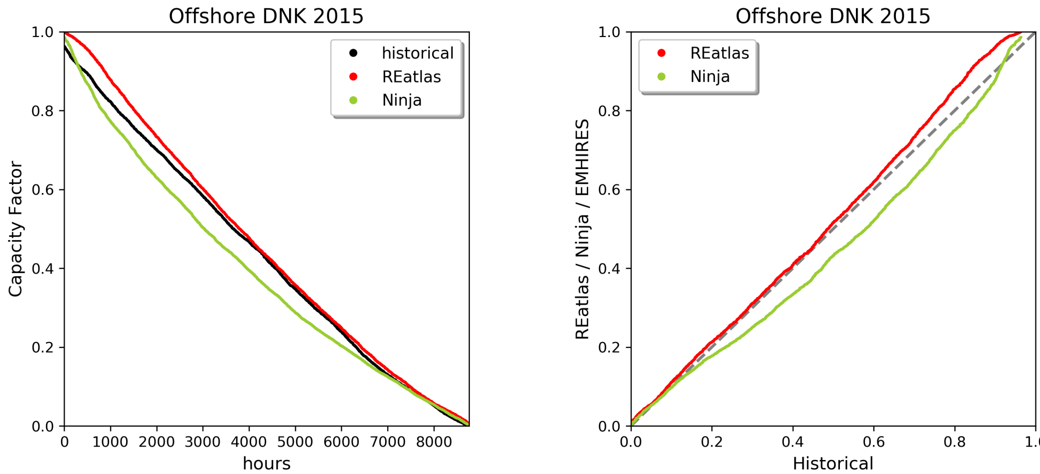

Figure 3: Duration curve for Denmark offshore wind in 2015 according to different sources.

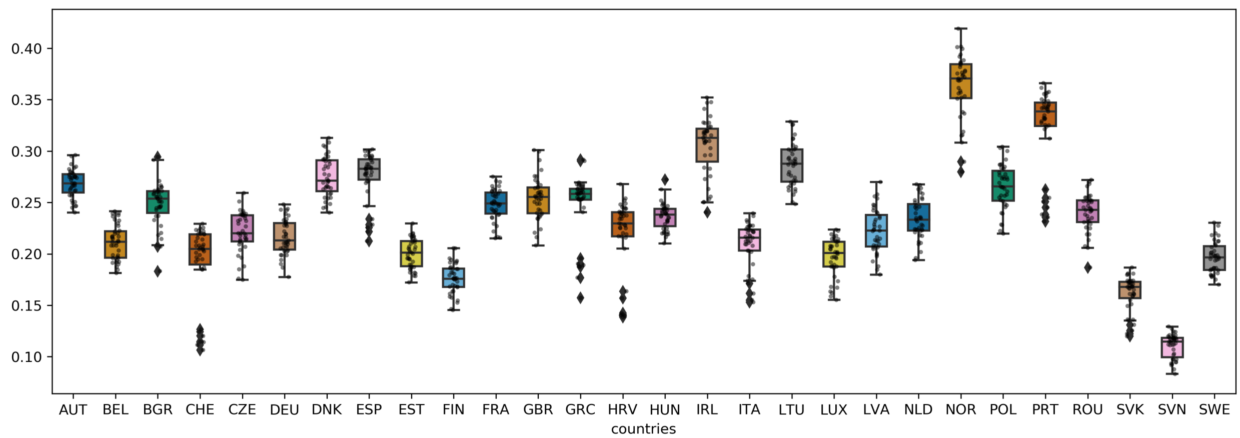

Figure 4: Onshore wind time series. Annually-averaged capacity factors for the years and countries included in the dataset

References

[1] M. Victoria, G. B. Andresen, Using validated reanalysis data to investigate the impact of the PV system configurations at high penetration levels in european countries, Progress in Photovoltaics: Research and Applications 0 (0). doi:10.1002/pip.3126.
URL https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.3126

[2] G. B. Andresen, A. A. Søndergaard, M. Greiner, Validation of Danish wind time series from a new global renewable energy atlas for energy system analysis, Energy 93 (Part 1) (2015) 1074–1088. doi:10.1016/j.energy.2015.09.071.
URL http://www.sciencedirect.com/science/article/pii/S0360544215012815

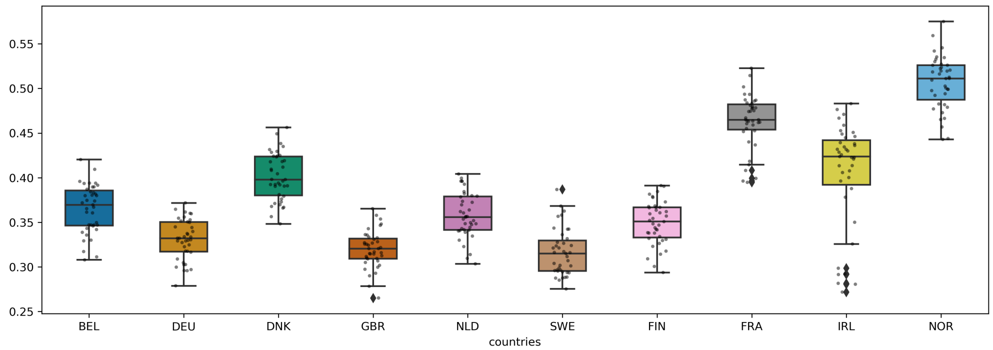

Figure 5: Offshore wind time series. Annually-averaged capacity factors for the years and countries included in the dataset

Table 2: Parameters used to create the REatlas onshore time series by minimized the KL divergence with historical data.

country	$\Delta\nu$ (m/s)	σ_0	η
AUT	-1.00	1.75	0.94
BEL	0.50	2.50	0.76
BGR	-1.50	0.50	0.96
HRV	0.50	1.75	0.85
CZE	-2.00	0.50	0.70
DNK	1.00	2.00	0.84
EST	1.50	3.50	0.78
FIN	1.00	2.50	1.00
FRA	-0.50	2.25	0.78
DEU	-0.50	1.75	0.78
GRC	-1.50	0.50	1.00
HUN	-1.50	1.50	0.92
IRL	0.00	2.00	0.96
ITA	-1.50	1.50	0.94
LVA	1.50	2.00	0.80
LTU	1.50	3.00	1.00
LUX	-1.00	2.00	0.94
NLD	1.00	2.50	0.86
NOR	0.50	3.25	0.92
POL	0.00	2.00	1.00
PRT	-2.50	0.50	0.94
ROU	-1.50	0.50	1.00
SVK	-1.50	1.50	0.84
SVN	2.00	3.25	0.98
ESP	-2.50	0.50	0.82
SWE	0.00	1.00	1.00
CHE	-1.40	0.60	0.74
GBR	1.00	2.75	0.72

Table 3: Parameters used to create the REatlas offshore time series by minimized the KL divergence with historical data.

country	$\Delta\nu$ (m/s)	σ_0	η
BEL	1.50	1.50	0.92
DEU	3.50	2.50	1.00
DNK	1.00	1.75	0.96
FIN	-0.60	2.2	0.94
FRA	-2.00	1.68	0.96
GBR	1.00	1.25	0.76
NLD	0.00	2.00	0.85
IRL	1.60	2.55	0.96
NOR	-1.20	2.2	0.98
SWE	-1.00	0.50	0.96

[3] S. Saha, S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y.-T. Hou, H. Chuang, M. Iredell, M. Ek, J. Meng, R. Yang, M. P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, E. Becker, NCEP climate forecast system version 2 (CFSv2) selected hourly time-series products (2011).
URL https://doi.org/10.5065/D6N877VB

[4] Wind energy database.
URL https://www.thewindpower.net/

[5] Data Platform Open Power System Data.
URL https://data.open-power-system-data.org/

Table 4: Onshore wind annual capacity factor $\overline{CF_h}$ and RMSE for reference and modelled time series: REatlas (REa), Renewables Ninja (Nin), and EMHIRES (EMH), for the year 2015.

	$\overline{CF_h}$				$RMSE$		
country	ref	REa	Nin	EM	REa	Nin	EM
AUT	0.248	0.230	0.261	0.275	0.116	0.097	0.149
BEL	0.207	0.201	0.258	0.232	0.074	0.156	0.149
BGR	0.253	0.238	0.234	0.170	0.132	0.119	0.174
CZE	0.198	0.208	0.225	0.242	0.166	0.163	0.226
DNK	0.269	0.275	0.292	0.197	0.052	0.059	0.104
EST	0.236	0.240	0.266	0.258	0.079	0.144	0.135
FIN	0.276	0.271	0.352	0.221	0.103	0.135	0.111
FRA	0.221	0.223	0.252	0.240	0.053	0.051	0.064
DEU	0.207	0.212	0.206	0.223	0.052	0.041	0.071
GRC	0.209	0.184	0.268	0.211	0.099	0.126	0.119
LVA	0.228	0.242	0.270	0.172	0.093	0.094	0.107
NLD	0.242	0.230	0.260	0.267	0.069	0.208	0.220
NOR	0.324	0.334	0.294	0.244	0.090	0.084	0.109
PRT	0.257	0.239	0.256	0.223	0.159	0.100	0.102
ROU	0.252	0.213	0.236	0.198	0.142	0.253	0.268
ESP	0.235	0.233	0.251	0.259	0.075	0.061	0.112
CHE	0.114	0.266	0.178	0.182	0.439	0.433	0.450
GBR	0.247	0.238	0.319	0.300	0.084	0.132	0.121

Table 5: Offshore wind annual capacity factor $\overline{CF_h}$ and RMSE for reference and modelled time series: REatlas (REa), Renewables Ninja (Nin), and EMHIRES (EMH), for the year 2015.

	$\overline{CF_h}$				$RMSE$		
country	ref	REa	Nin	EM	REa	Nin	EM
BEL	0.412	0.427	0.337	0.232	0.132	0.269	0.308
DEU	0.380	0.375	0.363	0.223	0.212	0.210	0.309
DNK	0.434	0.450	0.394	0.197	0.129	0.138	0.291
GBR	0.327	0.326	0.406	0.300	0.099	0.136	0.144

[6] Renewables.ninja.
URL https://www.renewables.ninja/

[7] I. Staffell, S. Pfenninger, Using bias-corrected reanalysis to simulate current and future wind power output, Energy 114 (Supplement C) (2016) 1224–1239. doi:10.1016/j.energy.2016.08.068.
URL http://www.sciencedirect.com/science/article/pii/S0360544216311811

[8] EMHIRES dataset . Part I, Wind power generation., Tech. rep., Joint Research Center (Nov. 2016).
URL https://publications.europa.eu/en/publication-detail/-/publication/85b2dc7f-aa61-11e6-aab7-01aa75ed71a1/language-en

A Duration curves comparison for 2015

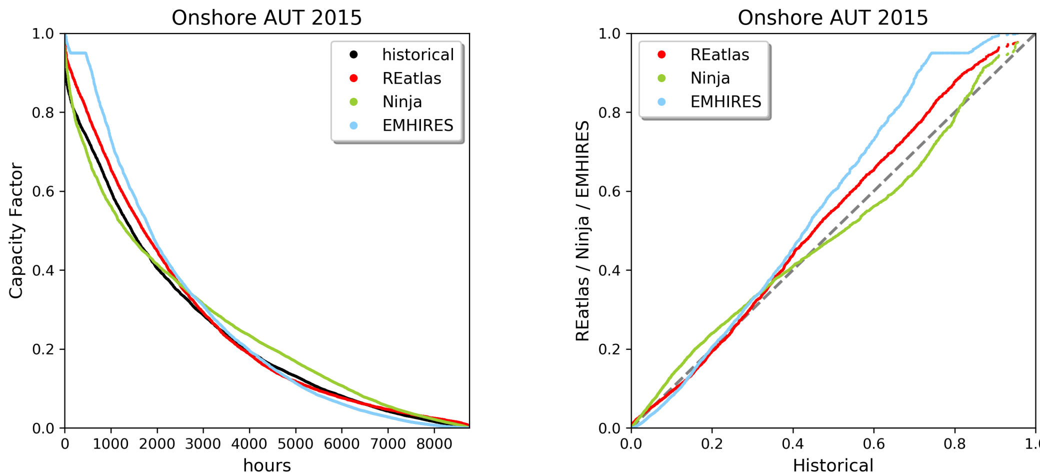

Figure 6: Duration curve for Austria onshore wind in 2015 according to different sources.

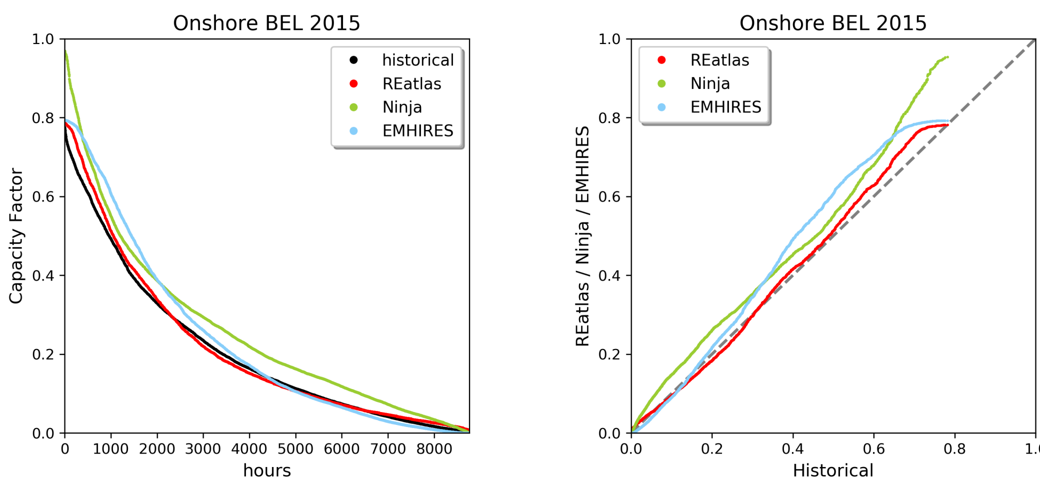

Figure 7: Duration curve for Belgium onshore wind in 2015 according to different sources.

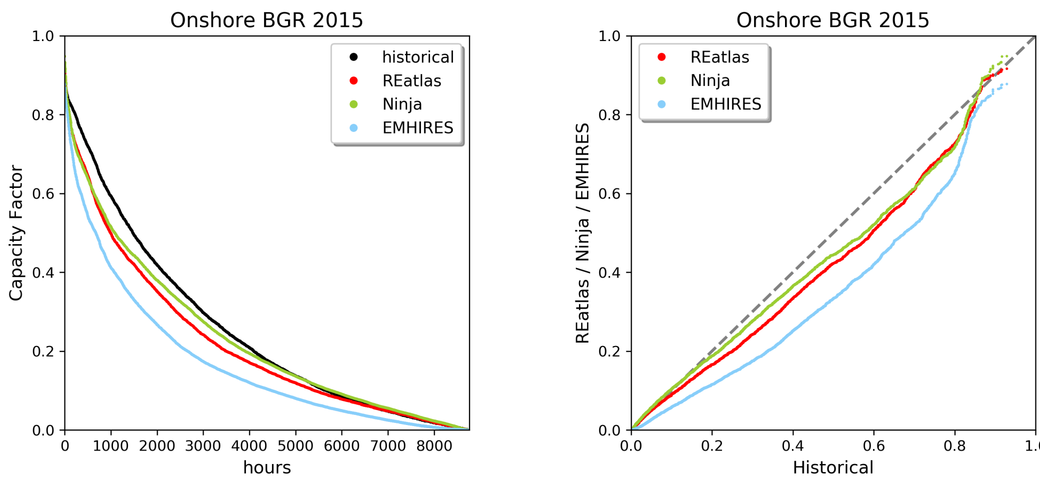

Figure 8: Duration curve for Bulgaria onshore wind in 2015 according to different sources.

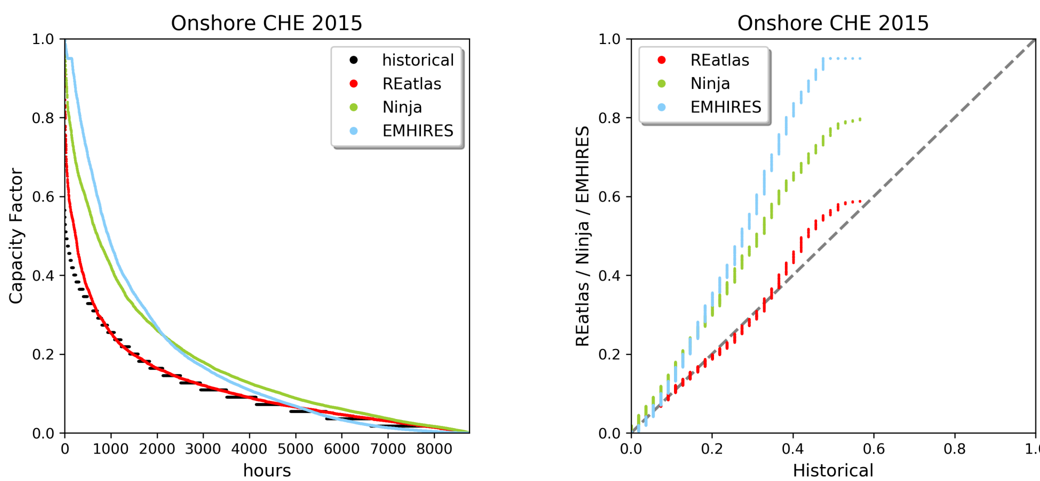

Figure 9: Duration curve for Switzerland onshore wind in 2015 according to different sources.

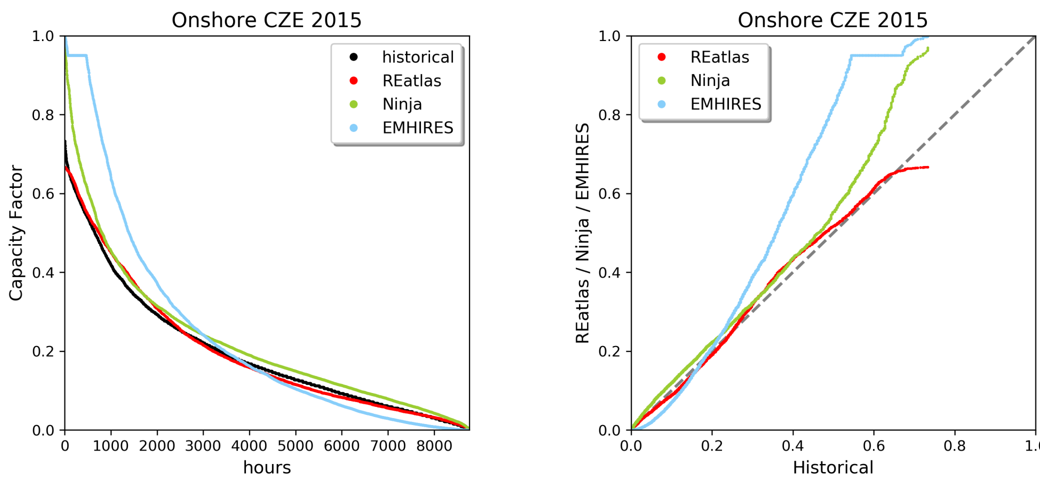

Figure 10: Duration curve for Czech Republic onshore wind in 2015 according to different sources.

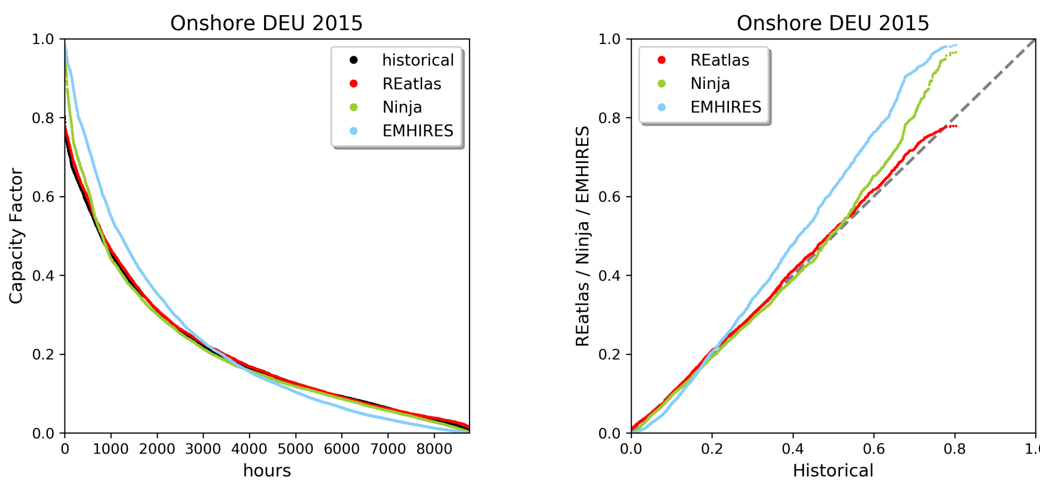

Figure 11: Duration curve for Germany onshore wind in 2015 according to different sources.

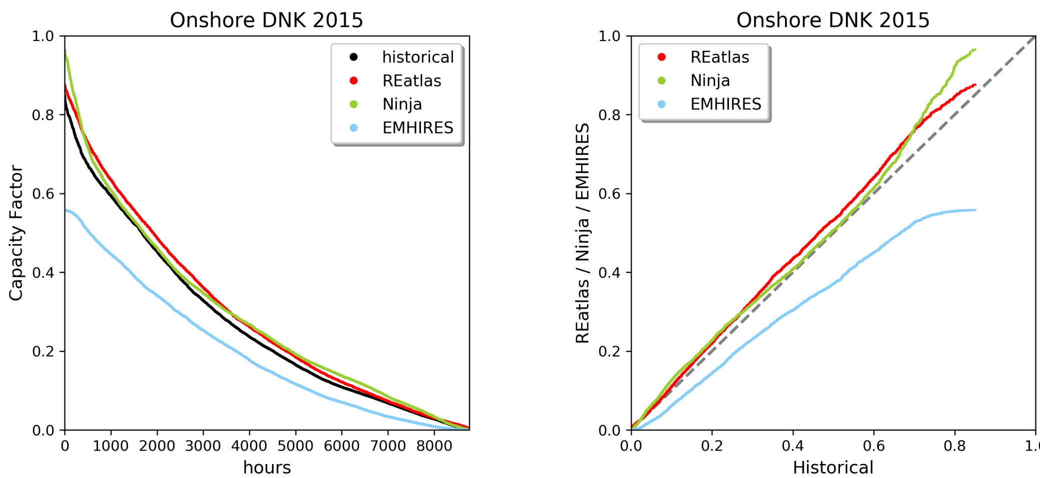

Figure 12: Duration curve for Denmark onshore wind in 2015 according to different sources.

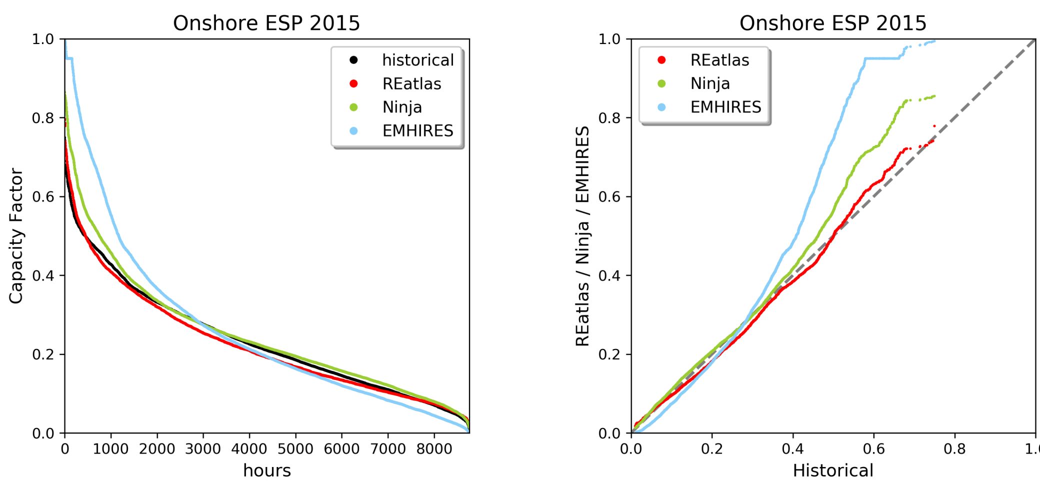

Figure 13: Duration curve for Spain onshore wind in 2015 according to different sources.

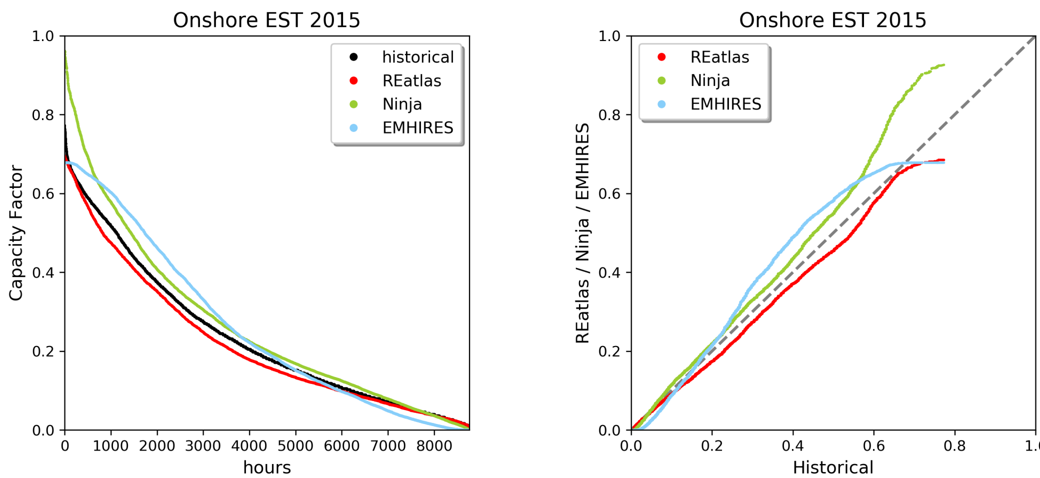

Figure 14: Duration curve for Estonia onshore wind in 2015 according to different sources.

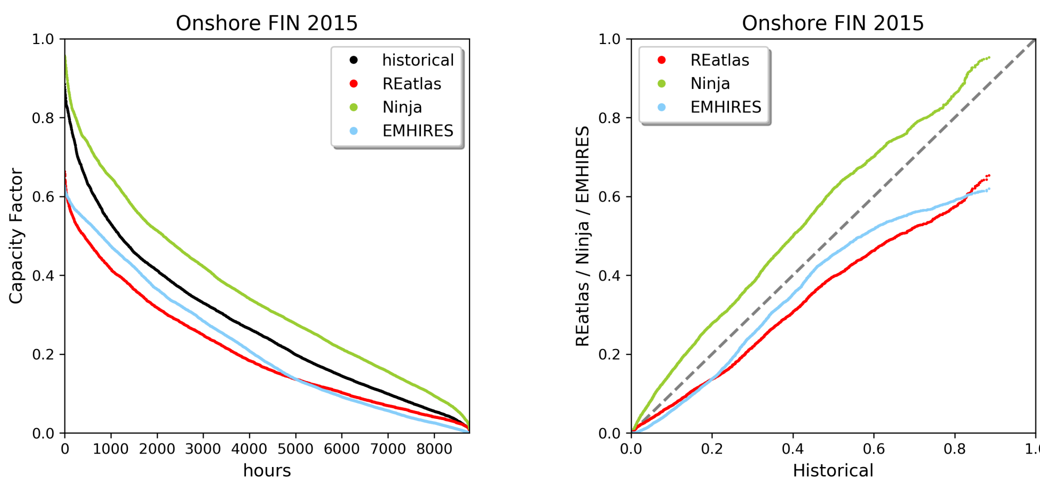

Figure 15: Duration curve for Finland onshore wind in 2015 according to different sources.

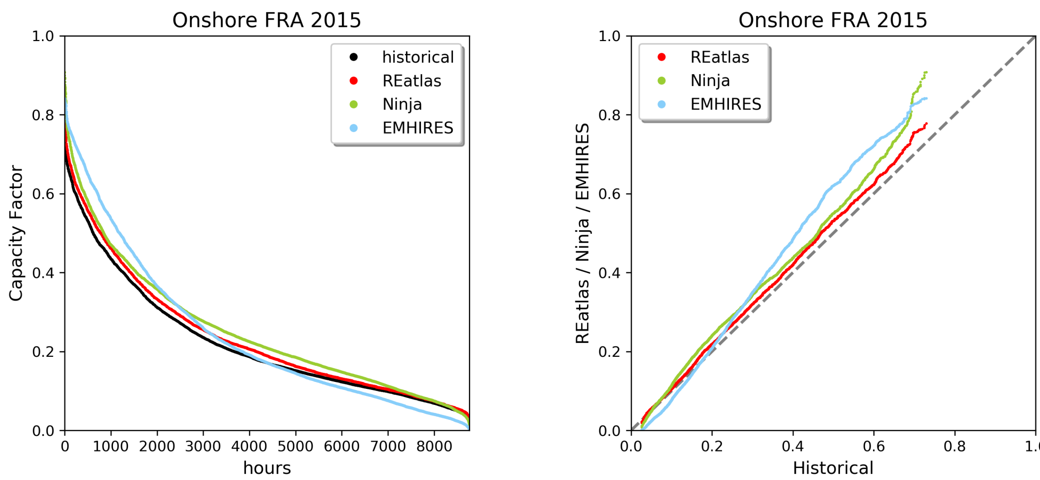

Figure 16: Duration curve for France onshore wind in 2015 according to different sources.

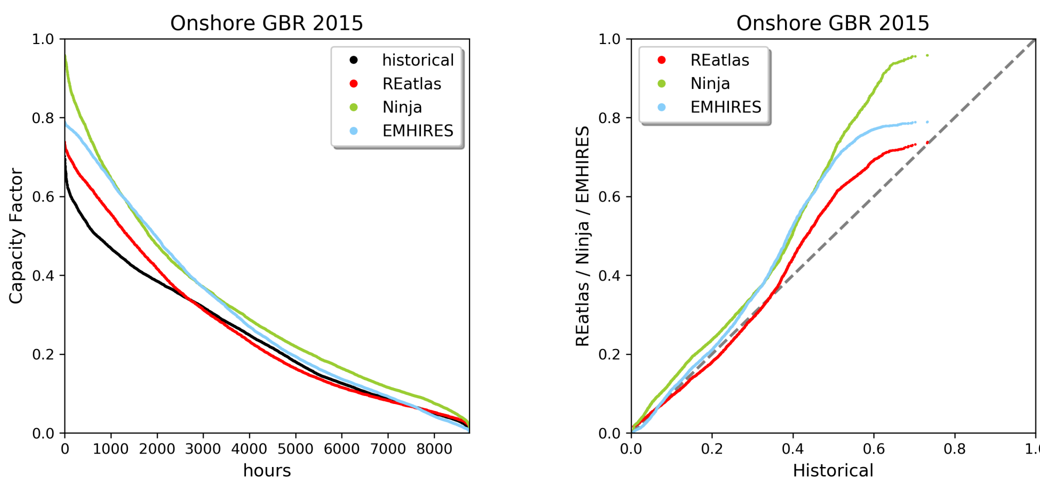

Figure 17: Duration curve for United Kingdom onshore wind in 2015 according to different sources.

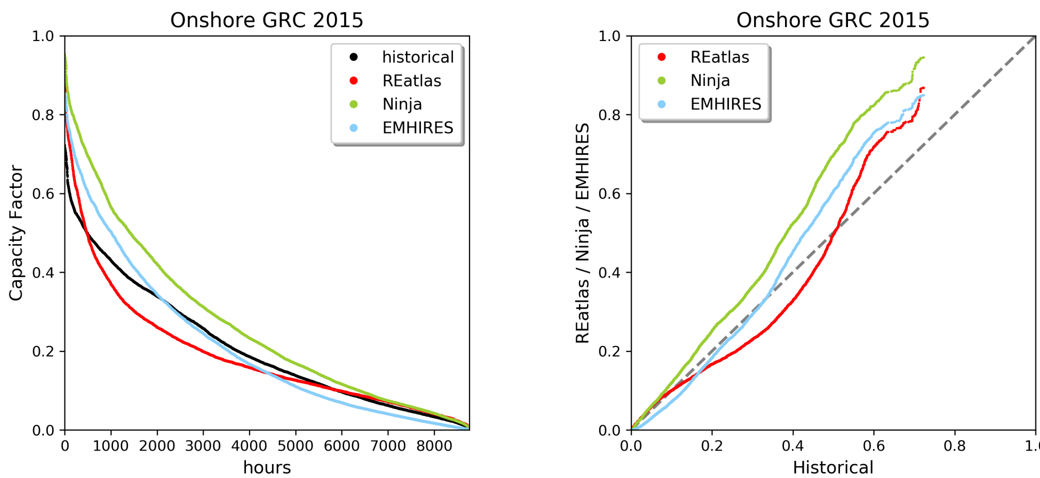

Figure 18: Duration curve for Greece onshore wind in 2015 according to different sources.

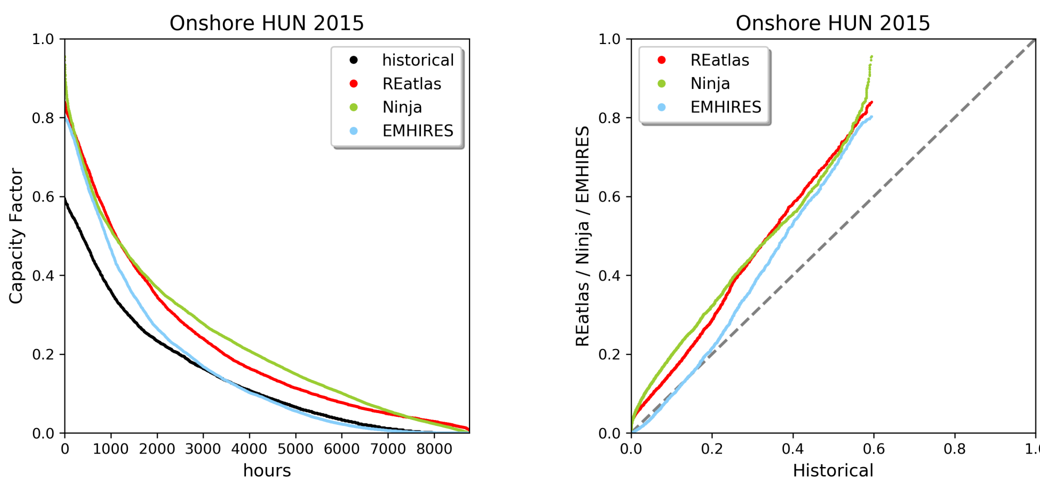

Figure 19: Duration curve for Hungary onshore wind in 2015 according to different sources.

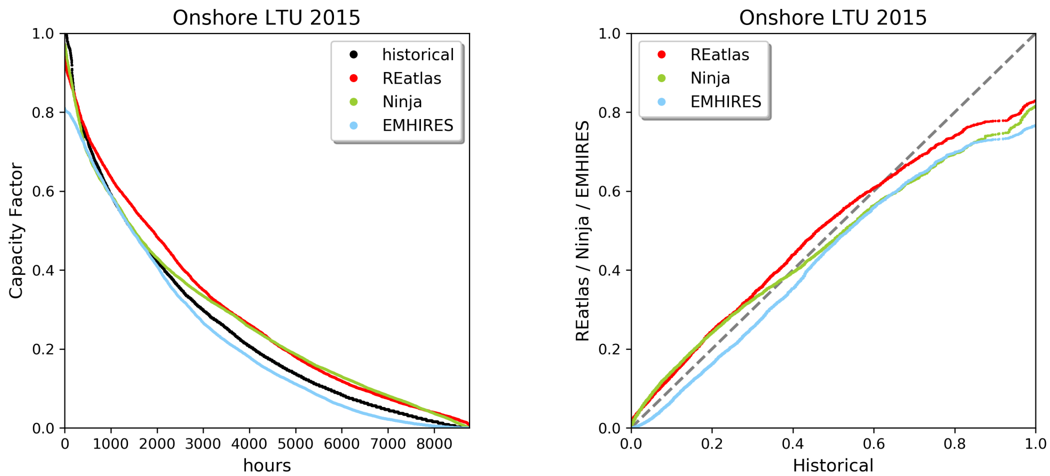

Figure 20: Duration curve for Lithuania onshore wind in 2015 according to different sources.

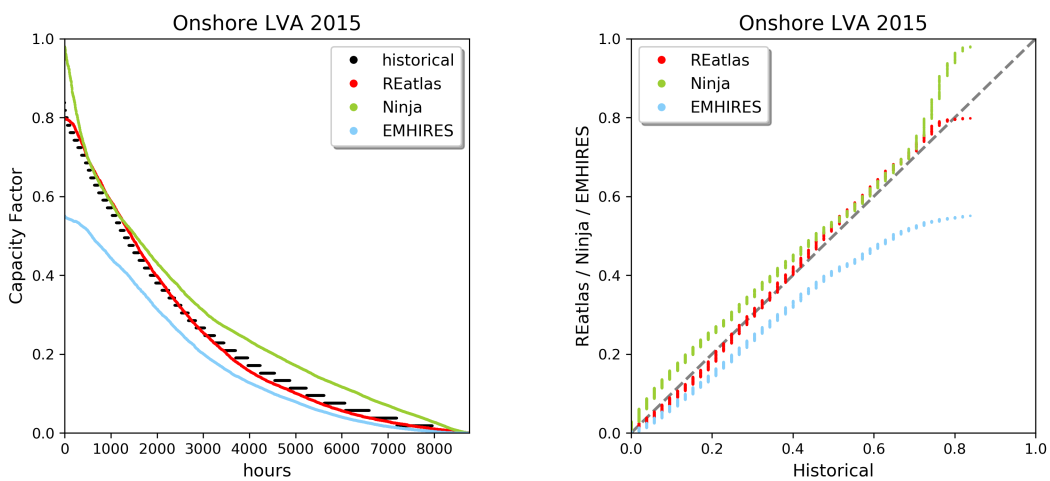

Figure 21: Duration curve for Latvia onshore wind in 2015 according to different sources.

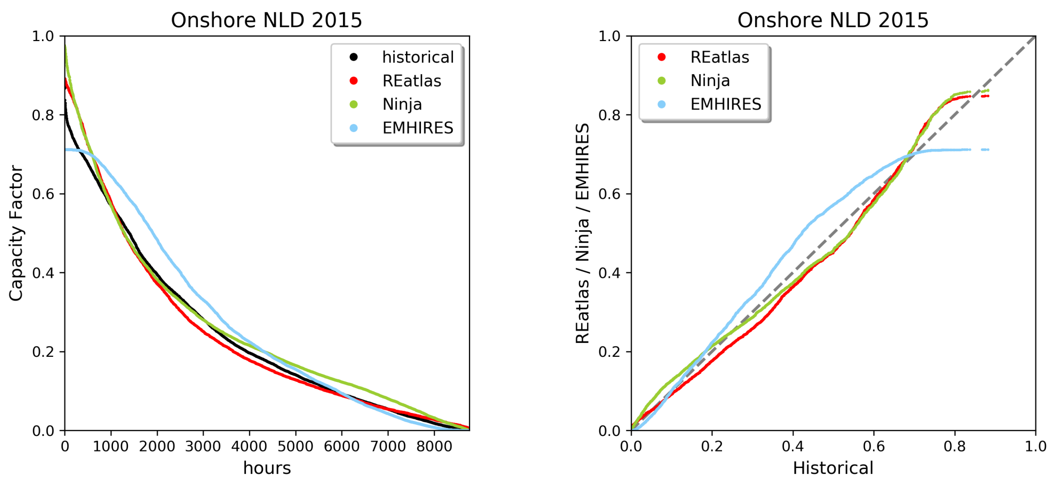

Figure 22: Duration curve for Netherlands onshore wind in 2015 according to different sources.

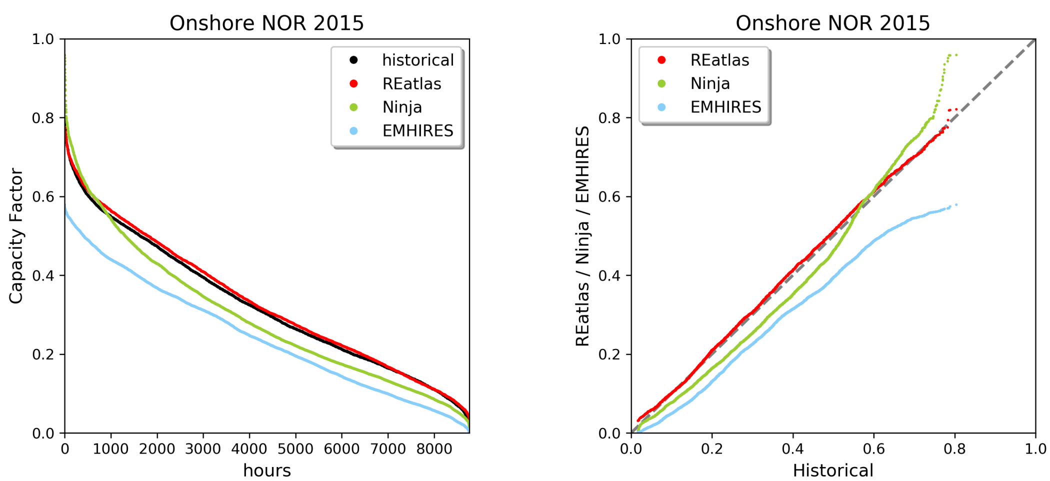

Figure 23: Duration curve for Norway onshore wind in 2015 according to different sources.

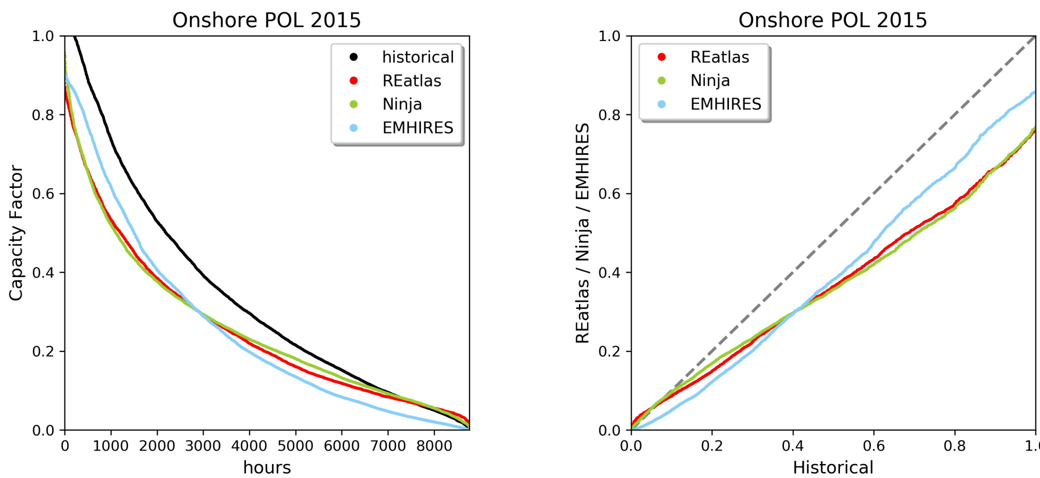

Figure 24: Duration curve for Poland onshore wind in 2015 according to different sources.

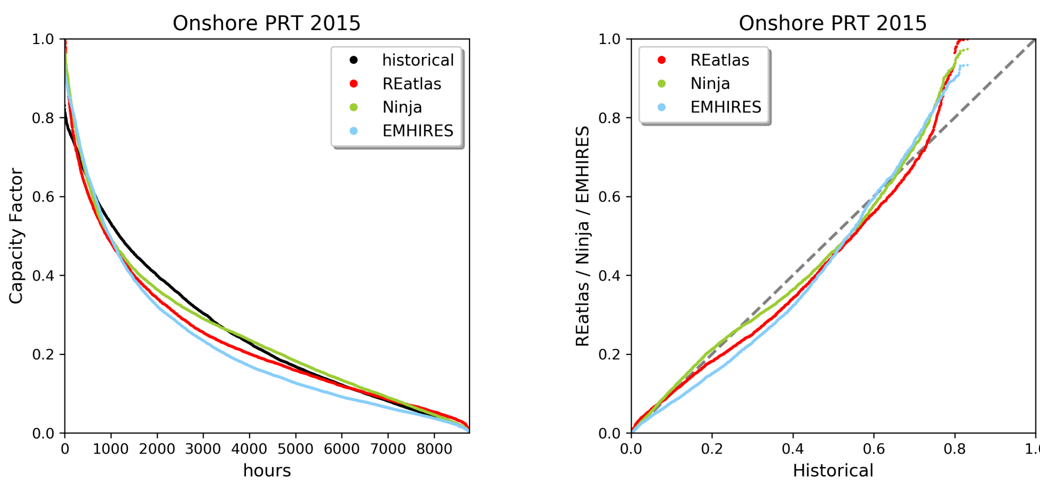

Figure 25: Duration curve for Portugal onshore wind in 2015 according to different sources.

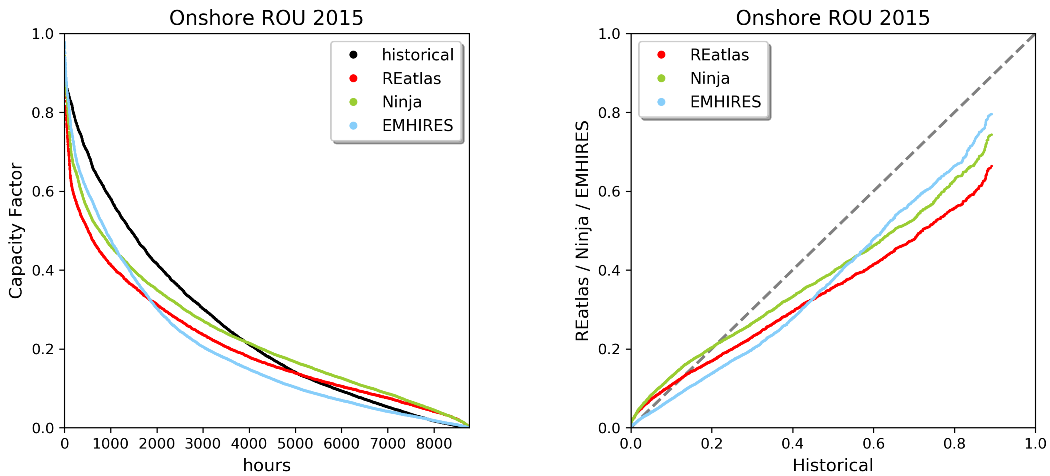

Figure 26: Duration curve for Romania onshore wind in 2015 according to different sources.

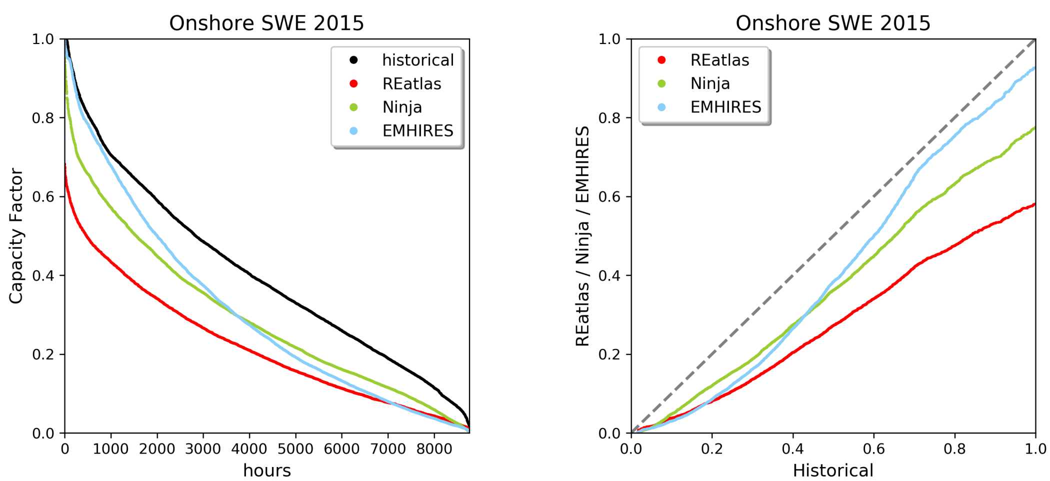

Figure 27: Duration curve for Sweden onshore wind in 2015 according to different sources.

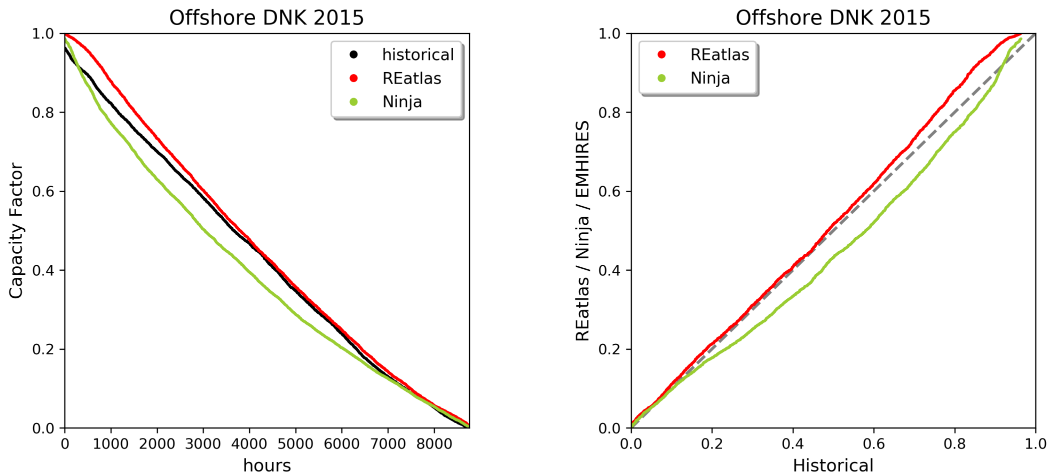

Figure 28: Duration curve for Denmark offshore wind in 2015 according to different sources.

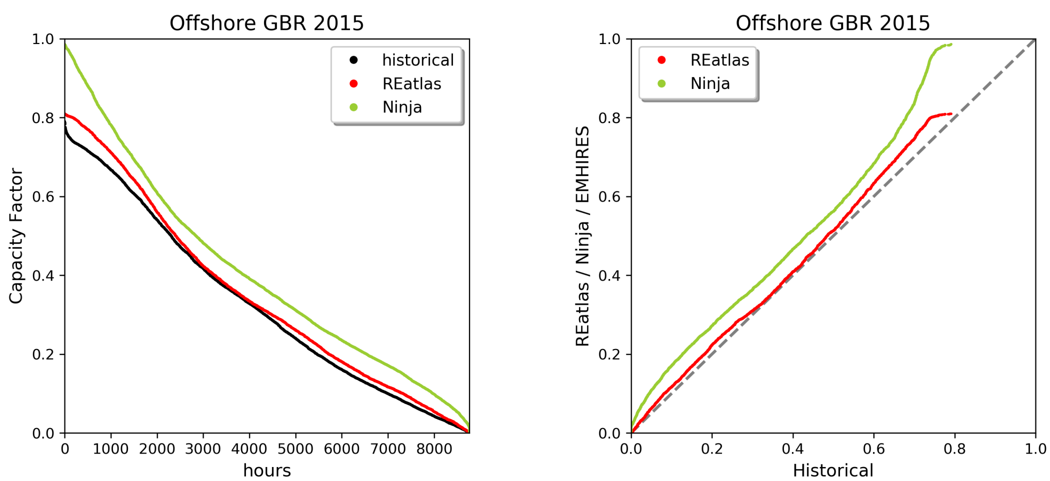

Figure 29: Duration curve for United Kingdom offshore wind in 2015 according to different sources.

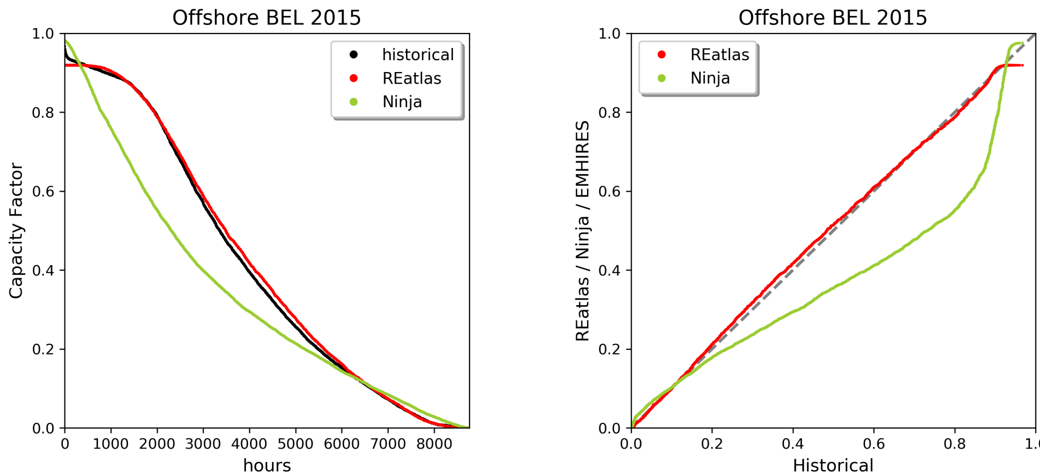

Figure 30: Duration curve for Belgium offshore wind in 2015 according to different sources.

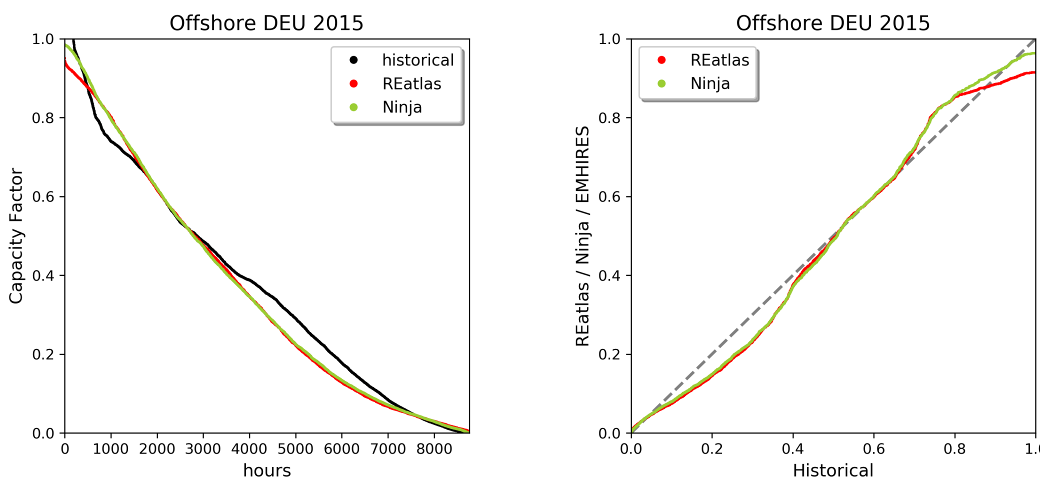

Figure 31: Duration curve for Germany offshore wind in 2015 according to different sources.