Wind Power Generation Variations and Aggregations

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***Abstract*—Climate and weather-propelled wind power is characterized by significant spatial and temporal variability. It has been substantiated that the variability of wind power, in addition to contributing hugely to the instability of power grids, can also send the balancing costs of electricity markets soaring. Existing studies on the same establish that curtailment of such variability can be achieved through the geographic aggregation of various widespread production sites; however, there exists a dearth of comprehensive evaluation concerning different levels/scales of such aggregation, especially from a global perspective. This paper primarily offers a fundamental understanding of the relationship between the wind power variations and aggregations from a systematic viewpoint based on extensive wind power data, thereby enabling the benefits of these aggregations to be quantified from a state scale ranging up to a global scale. Firstly, a meticulous analysis of the wind power variations is undertaken at 6 different levels by converting the 7-year hourly meteorological re-analysis data with a high spatial resolution of 0.25° × 0.25° (approximate 28 km × 28 km) into a wind power series globally. Subsequently, the proposed assessment framework employs a coefficient of variation of wind power as well as a standard deviation of wind power ramping rate to quantify the variations of wind power and wind power ramping rate to exhibit the characteristics and benefits yielded by the wind power aggregation at 6 different levels. A system planning example is adopted to illustrate the correlation between the coefficient of variation reduction of wind power and investment reduction, thereby emphasizing the benefits pertaining to significant investment reduction via aggregation. Furthermore, a wind power duration curve is used to exemplify the availability of wind power aggregated at different levels. Finally, the results provide insights into devising a universal approach towards the deployment of wind power, principally along the lines of Net-Zero.**

***Index Terms*—Energy quality, meteorological re-analysis data, wind power aggregation, wind power ramping rate, wind power variation, wind power variability.**

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I. Introduction

AGAINST the backdrop of rapid cost reduction of wind generation and minimizing of carbon emissions, the last decade bears witness to the accelerated global deployment of wind power with the total installed capacity increasing from 181 GW in 2010 to 622 GW in 2019 [1].

Nonetheless, the wind speed possesses an inherent variability that is associated with the mesoscale circulations of the wind along with the localized factors, including topographic features such as elevation, aspect, slope, surface roughness, and thermal contrast near water bodies. Thus, wind power is highly variable, both temporally and spatially [2], [3]. It has been observed that increased penetration of such volatile power proves highly challenging for the stability and reliability of a power grid, which in turn would result in curbing of the large-scale wind power implementation [4]–[6]. Moreover, the mounting penetration of this volatile power is bound to skyrocket the electricity market balancing costs, as witnessed in the UK where the variations of similar renewable energy resulted in a sharp surge of the market balancing costs amounting to 39% overall in the spring and summer of 2020 [7]. A suitable solution to this could be the aggregation of wind power. Existing studies ascertain that the variability of wind power can be moderated by means of the geographic aggregation of widespread production sites, where complementary/smoothing effects are present since the wind speeds experienced around the geographically diverse areas do not corelate 100% over time [8]–[31].

The geographical smoothing effects of wind power utilizing frequency-dependent analysis was first presented along with a review of relevant previous studies using the time-domain analysis [9]. In recent years, the complementary/smoothing effects were characterized with respect to standard deviation [10]–[16], coefficient of variation [17]–[19], hourly variation/ramp rate [20]–[22], [24], power deviation to a scheduled value [25], power fluctuation spectrum [26], [27], duration curve [24], [26], [28], in addition to some newly proposed metrics [29], [30], [32]. Most recently, an 'Energy Quality' system was established to determine and characterize the variations of renewable power generation [7]. Majority of the existing studies were conducted based on two categories of data, i.e., the converted wind power from meteorological re-analysis data (e.g., ERA5 [21], [29], MERRA [14]–[17], [28], HIRLAM [18], NARR [19], GEOS-5 [20], COSMO-REA6 [31]) and the historical generation data [22]–[26]. Additionally, the aggregation of wind power together with the complementarity analysis was conducted within a different geographical scale, e.g., Nova Scotia [23], single region of US [9], [28], Eastern US [12], Midwestern US [19], Nordic region [18], the US [24], [26], Spain [25], China [15]–[17], [20], Iberian Peninsula [13], western Europe [29], and Europe [10], [14], [21], [31], [32].

It was revealed that correlations of wind power tend to reduce with the separation distance in an exponential manner among the European countries [10], [14], US regions [24], and China [15], while the correlations appear even lesser at an hourly timescale and much higher at longer time scales (e.g., monthly). Furthermore, the geographic allocation can substantially decrease the system-wide low-output instances as well as the short-term jumps at the output for a fully integrated Europe [21], with the lower occurrence of these events also being validated in [23], [29], [31]. The duration curve of wind power became smoother upon the interconnection of four independent system operators (ISO) of North America [24], [26], and it also turned smoother when the wind farms were aggregated for seven individual ISOs of the US [28]. A novel quantitative index illustrating the wind power smoothing effect based on set pair analysis theory was proposed in [30]. Moreover, to enhance the smoothing effects, the aspect of optimal geographical allocation of wind power capacity was exploited maximally as well [16], [18], [20], [21], [25]. An optimization model with an objective function of minimum wind deviation has been proposed [24], indicating that the aggregation can appreciably reduce deviation from the scheduled values as compared to the individual wind farms. Similarly, a multi-objective optimization model (maximum generation and firm capacity, minimum hourly variation) has been proposed for the allocation of the wind power capacity among some 7 regions of China [20].

The prevailing studies regarding the complementary effects of wind power aggregation tend to be limited in scale, level, and global scope, hence this paper seeks to surpass the current analyses by taking into account the variations of wind power with the global 7-year hourly high spatial resolution data and by subsequent application of the 3 metrics to characterize the variations of wind power, and thus quantify the benefits of different levels of aggregation. The main contributions can be summarized as:

1) Six levels/scales of aggregation: A 6-level hierarchy of the geographical gradation for wind power aggregation is proposed, ranging from state (or equivalent province/ country), sub-region, region, continent, inter-continent, and all the way up to the global level.
2) High resolution global wind power series data generated using 7-year historic hourly meteorological re-analysis data: Global hourly meteorological re-analysis data from the years 2011 $\sim$ 2017 with a high spatial resolution of $0.25^\circ \times 0.25^\circ$ is employed to generate the wind power series for states (or equivalent elements) worldwide. In particular, 50% of the grid cells, with the highest 7-year average capacity factor, are selected, sorted, and grouped with an interval of 10%, and the weighted sum of the wind power series of the above five groups is treated as the equivalent wind power series of a certain state. The wind power of an area positioned at a higher level in the gradation is aggregated from the power series of its sub-areas, taking the resource potential to be the weight.
3) Variability assessment metrics to quantify the variations of wind power at different levels: Variability assessment measures, such as coefficient of variation (CV) and standard deviation (STD), are adopted to measure the fluctuation recorded in the wind power series as well as the wind power ramping rate series, respectively. Moreover, a duration curve is used to quantify the availability of wind power and hence, evaluate the characteristics and benefits of such availability owing to the different levels/scales of aggregation.

Section II below illustrates the way in which the wind power series is generated and then aggregated within the outline of the proposed geographical hierarchy, exhibiting the metrics for the variability assessment of the wind power. Section III presents the results using the assessment metrics and delivers an analysis of the aggregation results. Finally, conclusions are drawn, and recommendations are offered in Section IV. Table AI $\sim$ Table AXI and Fig. A1 $\sim$ Fig. A6 are shown in the Appendix.

II. Materials and Methods

A. Hierarchy of Geographical Scale

The hierarchy must be designed from the perspective of practical power grid interconnection. By and large, small scale regional power grids are formed at the earlier stages for adjacent areas, then they shift up in the structure towards building larger complex interconnected systems at different scales. In this paper, 6 aggregation levels are proposed to investigate the complementary effects of wind power, namely Country/Province/State, Sub-region, Region, Continent, Inter-continent, and Global. The geographical scale of the elements present within each level is demonstrated in detail in Table AI $\sim$ Table AIII in the Appendix.

1) Country/Province/State (Level 1)

It is deemed the lowest level within the hierarchy and the name may vary in different parts of the world, e.g., Country in the European Union (EU), Province in China and Canada, and State in the United States (US).

2) Sub-region (Level 2)

Several Countries/Provinces/States are aggregated into a Sub-region and it is observed that the division for onshore and offshore generation may be disparate. For example, the United Kingdom belongs to the British Isles and North Sea sub-regions for onshore and offshore generation, respectively.

3) Region (Level 3)

It is considered the sub-area of a Continent. Onshore and offshore wind power series are merged into a single sequence of power series from this level upwards. Specifically, for levels below Region, the onshore and offshore power series are aggregated correspondingly; for levels higher than Region (including), the aggregated power series of both onshore and offshore sites are used to represent the wind power generation at the said levels.

4) Continent (Level 4)

Typically, one Continent is made up of several Regions. Here, it refers to six continents, namely Europe, Asia, Africa, North America, South America, and Oceania. The wind power series are aggregated at each continental level/scale accordingly.

5) Inter-continent (Level 5)

It consists of possible aggregations between two or more of the above-mentioned 6 continents.

6) Global (Level 6)

It entails all the major countries worldwide on these six continents except Antarctica, which is positioned at the highest level within the hierarchy for aggregation and possesses the largest geographical scale.

The hierarchy can be illustrated by the three regions, i.e. European Union (EU), Eastern Asia, and Eastern US, which form the particular focus of this study, as shown in Table I. It should be clarified that except for Russia, Canada, China, and the US, Country or equivalent remains as the minimum scale considered under most circumstances.

TABLE I
CAPACITY AND COST OF SYSTEM PLANNING

Level	EU	Eastern Asia	Eastern US
1	Germany	Jiangsu	New Jersey
2	Europe_CW	CN_East	US_Mid_Atlantic
3	Europe_EU_plus	Asia_E	US_East
4	Europe	Asia	North_America
5	Europe-Africa	Europe-Asia	North-South_America
6	Global	Global	Global

Note: 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global.

B. Hourly Wind Power Series from 2011 to 2017

In this study, the historical meteorological re-analysis data of up to seven years, retaining spatial resolution (longitude $\times$ latitude) of $0.25^\circ \times 0.25^\circ$ (approximate 28 km $\times$ 28 km) and temporal resolution of one hour, is converted into wind power series based on a method analogous to the one proposed in [33] and has been widely applied in [34]–[37]. It is assumed that the offshore wind generation sites are restricted to those with a maximum sea depth of 50 m [34], [38].

There are a total of 224,750 grid cells for onshore sites and 19,958 grid cells for offshore sites. The meteorological data takes up a storage space of around 5 Terabytes (TB). Due to the large amounts of data involved, it is of note that the 7-year hourly weather data took us more than one month to download and further 70 hours were devoted to convert the downloaded weather data into the hourly wind power series.

All the data sets for results and analysis are coded through Python on an IntelCore-i5-8300H/2.3 GHz personal laptop with 8 G RAM.

1) Weather Datasets

A dataset called 'ERA5' is adopted for this study, which is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [39]. The water depth of the marine area is derived from the General Bathymetric Chart of the Oceans (GEBCO) [40] and National Centers for Environmental Information (NCEI) [41]. The geographical shape files of administrative boundaries are retrieved from the Natural Earth Dataset [42] for country shapes, and the Database of Global Administrative Areas (GADM) [43] is used to allocate the different layers of boundaries within each country.

2) Converting Model

The Enercon E-101 model of a wind turbine with rated capacity of 3050 kW and 150 m hub height is employed to generate the onshore power series, whose power curves can be acquired from the wind turbine repository on an open platform [44], while the NREL Reference Turbine with 5 MW at 90 m is utilized to generate the offshore power series. The original power curve is further enhanced to account for the smoothing effects of wind speed within each cell by Gaussian kernel [33]. The wind speed at the height of 100 m provided in the dataset is extrapolated to that of 150 m, using a logarithmic method with roughness [33].

3) Conversion and Aggregation at Country/Province/State Level

An equivalent 1-MW wind turbine is placed at the center of each raster cell to represent the wind generation of the cell. Subsequently, the 7-year wind power series is converted for each cell using the weather data, and the corresponding average capacity factor (CF) is calculated as well. Based on this CF, 50% of the grid cells within a 'Country/Province/State' that possess the highest average CF are selected, sorted, and aggregated into 5 groups with an interval of 10%. The wind generation sites are scattered on 50% of the overall geographical area within a Country/Province/State.

The top $0 \sim 10\%$ and $10\% \sim 20\%$ of the raster cells with the highest CF within a Country/Province/State are weighted by 0.3, $20\% \sim 30\%$ of the cells are weighted by 0.2, and lastly, $30\% \sim 40\%$ and $40\% \sim 50\%$ of the cells are weighted by 0.1 [45]. Therefore, the final wind power series expressed as CF at the lowest level of Country/Province/State is generated as:

$$cf_t = \sum_{i=1}^{5} w_i \left(\frac{p_{i,t}}{c_i} \right) \quad t \in [1, T_{\max}] \tag{1}$$

where $p_{i,t}$ denotes the aggregated power of group i at hour t, c_i is the corresponding aggregated capacity within a country/province/state, w_i is the weight, and cf_t represents the equivalent CF series of onshore or offshore generation. $T_{\max} = 61320$, denotes the total number of hours for 7 years.

4) Potential Capacity at Level Country/Province/State

Within a Country/Province/State, it is assumed that only 4% of the land area is operable for onshore wind farms due to societal constraints, while up to 10% of the marine area can be covered by offshore wind farms [46]. The installation densities for both the onshore and offshore wind turbines are assumed to be 10 MW/km^2 [37].

$$\text{Cap} = (\alpha S)\rho \tag{2}$$

where S, α, and ρ denote the total land or marine area of a country/province/state, the ratio of available area for installing wind generation, and installation density, Cap respectively. represents the potential capacity of the onshore or offshore wind generation in that country/province/state.

Noticeably, with the same potential capacities, the graphical scale of the onshore sites is approximately 2.5 times the scale of the offshore sites attributable to the value of α.

5) Aggregating at Higher Levels

The wind power series expressed as CF and the installing potential for any level higher than Country/Province/State is aggregated from the wind power series at its corresponding lower level. The capacity (Cap^n) of a certain area is calculated as the sum of the capacities of all the sub-areas ($\mathrm{Cap}_{\mathrm{j}}^{n-1}$) within this area; the equivalent CF series (cf_{t}^{n}) of a certain area is calculated as the weighted sum of the wind power series of all its sub-areas ($cf_{j,t}^{n-1}$), where the ratio between potential capacities of the sub-area and the area is regarded as the weight.

$$\begin{cases} \mathrm{Cap}^n = \sum_j \mathrm{Cap}_j^{n-1} \\ cf_t^n = \sum_j cf_{j,t}^{n-1} \frac{\mathrm{Cap}_j^{n-1}}{\mathrm{Cap}^n} \quad t \in [1, T_{\max}] \end{cases} \tag{3}$$

C. Variability Metrics

In this paper, we aim to investigate the aggregation benefits of the production sites from state level all the way up to global level. Three metrics are applied to quantify the benefits from the perspectives of power variability and power availability. The advantage and suitability are discussed as follows.

1) CV of 7-year Wind Power Series

$$\begin{cases} p_t = cf_t \mathrm{Cap} \quad t \in [1, T_{\max}] \\ \sigma = \sqrt{\frac{1}{T_{\max}} \sum_{i=1}^{T_{\max}} (p_t - \mu)^2} \\ \varphi = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{1}{T_{\max}} \sum_{i=1}^{T_{\max}} (p_t - \mu)^2}}{\mu} \times 100\% \end{cases} \tag{4}$$

where φ, σ, and μ denote the CV, STD, and mean of the 7-year wind power series, respectively, of a certain area at a particular level. The statistical index, STD, is essentially utilized to measure the dispersion of a dataset relative to its mean and is suitable to quantify the overall variations of the 7-year wind power series in this paper. Nonetheless, its value is regulated by the overall sample magnitudes within the dataset. The average power, reflecting the overall power magnitude, can vary enormously among the different aggregation levels; therefore, the CV, also known as the relative STD, is employed to compare the disparity of wind power at different levels, which is calculated as shown in (4).

2) STD of 7-year Series of Wind Power Ramping Rate

The ramping rate expresses how quickly the generation output changes over time. It is a common metric used in power system operations, as well as indicates the requirements of system ramping reserve due to the wind power fluctuations. To address the challenge of comparisons at different levels when the mean (μ^{Δ}) 7-year ramping rates are close to zero, the STD metric is employed rather than using CV. The power ramping rate series is standardized by dividing its STD by the mean of the original wind power series instead of the mean of the ramping rate series.

$$\begin{cases} p_t^{\Delta} = p_t - p_{t-1} \quad t \in [2, T_{\max}] \\ \sigma^{\Delta} = \frac{\sqrt{\frac{1}{T_{\max}-1} \sum_{i=2}^{T_{\max}} (p_t^{\Delta} - \mu^{\Delta})^2}}{\mu} \times 100\% \end{cases} \tag{5}$$

where σ^{Δ} denotes the STD relative to μ, and μ^{Δ} represents the mean of the 7-year wind power ramp rate series. Positive value of p_t^{Δ} indicates the need for negative ramping reserve and vice versa.

3) Duration Curve

The duration curve, defined as the wind power time series sorted in descending order, forms another effective approach for expressing the complementary/smoothing effect of aggregated power output in terms of availability. To compare the duration curves for wind power aggregated at different levels, each wind power duration curve of the 7-year wind power series of a certain area is therefore standardized/unified in accordance to its 7-year average, as follows:

$$p_t' = \frac{p_t}{\mu} \quad t \in \ [1, T_{\max}] \tag{6}$$

III. Results and Discussions

A. Wind Power Series and Capacity Factors

The global average capacity factors for wind generation from 2011 to 2017 are as shown in Fig. 1, based on 224,750 onshore grid cells and 19,958 offshore grid cells. As shown in Fig. 1, it is noted that the zones close to the Poles have higher CFs up to 0.5, while those near the Equator possess lower CFs. Central USA, Central Asia, and Northern Africa also maintain higher CFs. Furthermore, CFs of the offshore sites are usually higher than that of the onshore sites, e.g., North Sea in Europe, northern coastline of Russia, eastern coastlines of both China and the USA, etc.

A segment of the wind power series at Country, Sub-region, and Region levels is illustrated in Fig. 2 for onshore and offshore wind generation, respectively, where region 'Europe_EU_plus' is taken as an example. The wind power series is normalized by being divided by its average.

The fluctuations at Region level (black line in Fig. 2(b)) for onshore power series are substantially reduced as compared to those at Sub-Region level (black line in Fig. 2(c)). Similar phenomenon can be observed for offshore power series (black lines in Fig. 2(e) and Fig. 2(f)). Additionally, due to smaller geography scale, stronger correlation characteristics of the wind speeds exist in countries within the same Sub-Region (e.g., 'Europe_CW'), and hence, their wind power profiles reflect analogous fluctuation trends. As a result, the fluctuation is alleviated only to a smaller extent when the power series of those countries are aggregated. For example, during the week around 27th November 2017 in Fig. 2(b), the onshore generation outputs of Netherlands, Germany, and France are seen soaring first and then decline alike, but the fluctuation of aggregated power series of 'Europe_CW' can still be subsided slightly. This process is more evident for the offshore generation series, as shown in Fig. 2 (e).

Furthermore, at the Sub-Region level, 'North Sea' offshore generation exhibits stronger stability, whose CV and peak-to-peak (PTP) values are 0.50 and 1.71, respectively, as compared to 'Europe_CW' onshore power series with CV of 0.57 and PTP of around 2.67. This can be attributed to the North Sea retaining high wind speeds all year round and the output of wind turbines being maintained at their rated value for wind

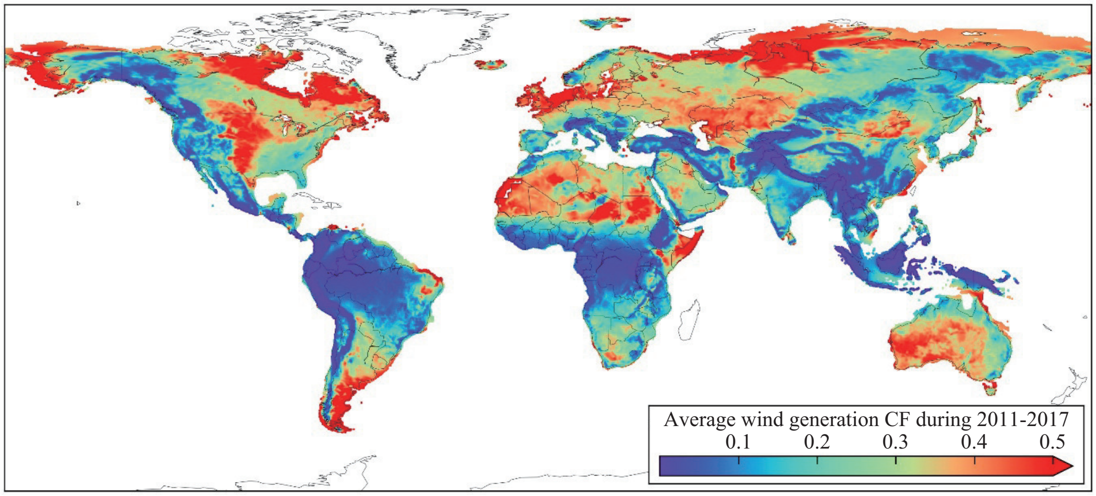


Fig. 1. Global capacity factors of wind generation (offshore sea depth $\leq$ 50 m).

speeds higher than the rated input, which indirectly curtails the fluctuation. The peak value of the normalized power series in North Sea appears lower because its average wind power tends to be higher than that of the onshore wind generation. It should be noted that the seas within areas elsewhere, e.g., 'Bohai and Yellow Sea' (Fig. A1) and 'US_Atlantic' (Fig. A2), can barely manage to produce power series as stable as the 'North Sea' due to its unique advantage of high wind speeds all year round.

B. CV of Power Series at 6 Different Aggregation Levels

The varying trends of CV of onshore wind power series from Country level to Global levefor regions of 'Europe_EU_plus', 'Asia_E', and 'US_East' are illustrated, respectively, in Fig. 3. Those of offshore series are shown in Fig. A3. It should be noted that the onshore and offshore sites are aggregated at Region level and above; in other words, the wind power series for Region level and above account for both onshore and offshore wind generation. Specifically, Country, Sub-region in the x-axis tick label in Fig. 3 represent the onshore generation only, while all those labels on the right of 'Region [both]' in the x-axis tick label in Fig. 3 indicate the aggregated onshore and offshore generation.

The varying trends of CV from state/country/province level to the global level for all the regions worldwide are further shown in Fig. 4, where onshore and offshore generation are marked by 'Δ' and 'x', respectively. Noticeably, except for the three regions of particular focus, there are only four levels for other regions without the consideration of Sub-region level. The CVs used for plotting the figures, as well as potential capacities, CFs, and peak-to-peak (PTP) values of onshore and offshore wind power series from 2011 to 2017 at each aggregation level are summarized in Table AIV $\sim$ Table AIX. The CV of wind power and STD of wind power ramping rate for all the countries, provinces, and states worldwide are summarized in Tables AX and AXI.

As shown in Fig. 3, regional aggregation typically yields better results in reducing CV than sub-regional aggregation for onshore generation. The reasons are that countries (provinces/states) within a sub-region generally share comparable wind dynamics, and a region usually comprises of several sub-regions; as a result, the complementary effect of wind generation within a sub-region is not as apparent as that within a region. However, for offshore generation, the aggregation at region and sub-region level performs comparably well as shown in Fig. A3, because an offshore Region consists of fewer Sub-regions than an onshore region, leading to limited smoothing effects.

As shown in Fig. 4 (data in Table AVI $\sim$ Table AVIII), at regional level, aggregation of onshore generation typically possesses a CV lower than that of the offshore generation (except 'South_America_E'). This is primarily because the geographical spread of onshore sites tends to be much wider than that of offshore sites. It should be noted that even though the capacity of offshore generation for 'Asia_RU' is higher than its onshore capacity (5458 GW VS 5239 GW), the geographical spread of onshore sites is wider, since the available area for installing onshore sites accounts for just about 4% of regional land area, while 10% of regional marine area is available for offshore sites.

Moreover, the CV drops slightly from the perspective of onshore generation (solid lines) when both onshore and offshore wind power series are aggregated, because regional average power of onshore generation appears to be much larger than that of the offshore generation for most regions, and there also exist certain complementary effects between the two types of generation. This occurs even for regions that maintain comparable average power from onshore and offshore sites ('Europe_EU_plus', 'N_America_High', and 'Asia_RU'). The average onshore power outputs of 'Asia_SE' is almost half (63%) of that of the offshore power, as a result, the CV of aggregated series tends to mount towards that of the offshore series.

As shown in both Figs. 3 and 4, when the wind generation is aggregated at higher levels, the CV will continuously decline. Specifically, the CV drops significantly at the level of Continent as compared to the lowest level of Country/State/Province, and then decreases further (but slightly)

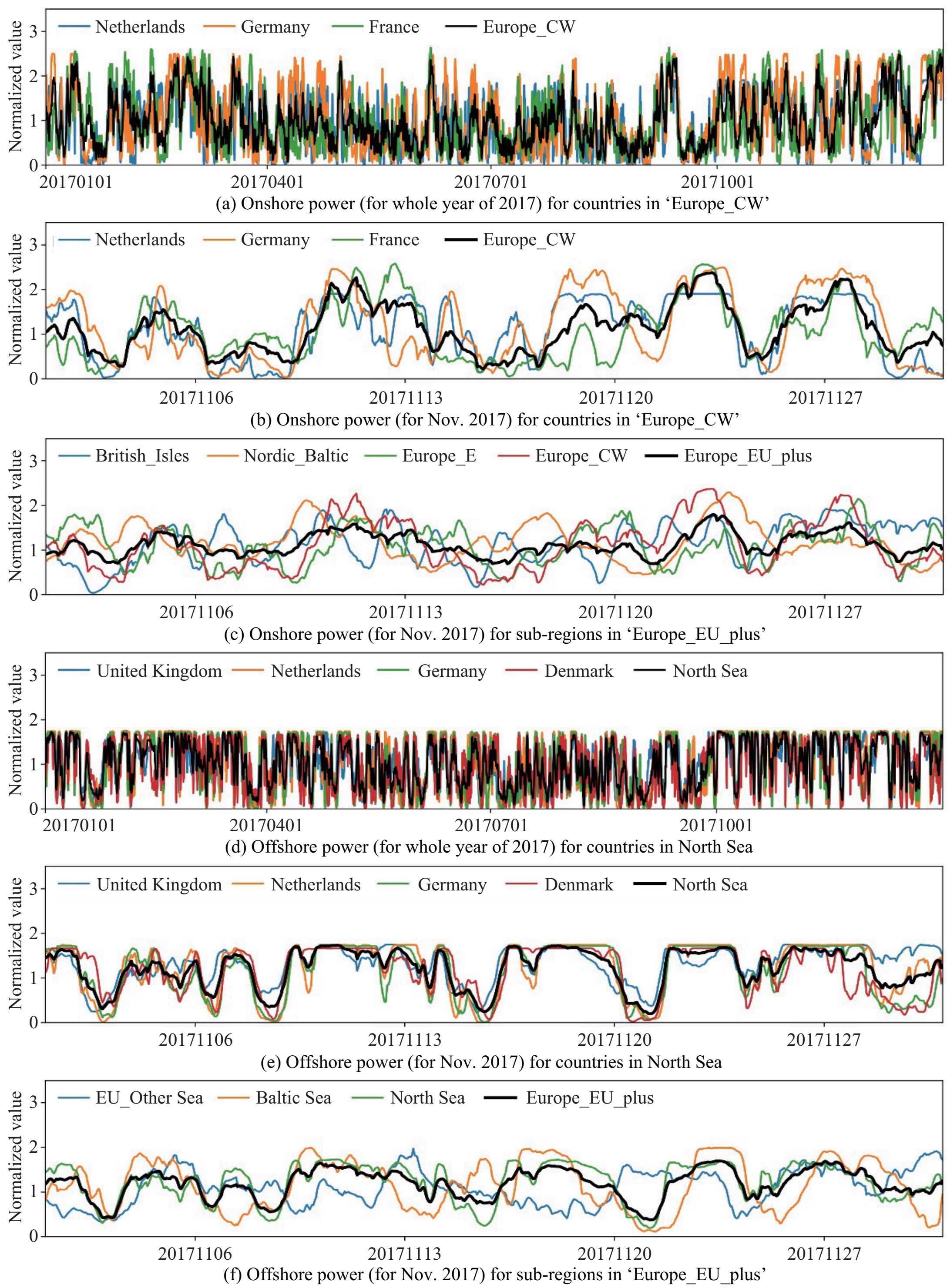
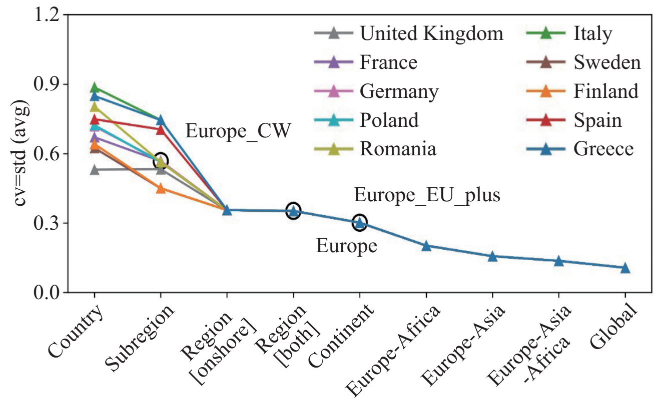
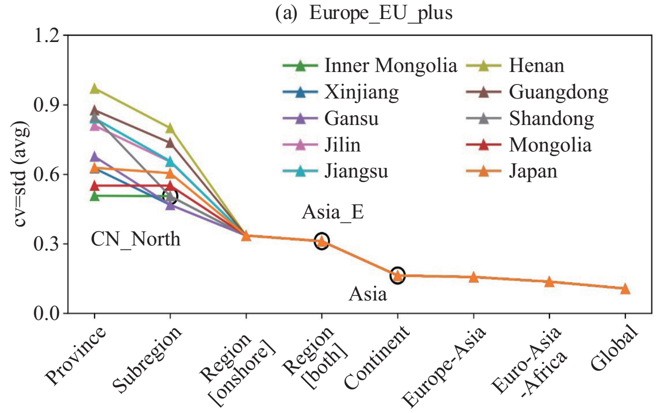


Fig. 2. Wind power series of selected countries/sub-regions within region.

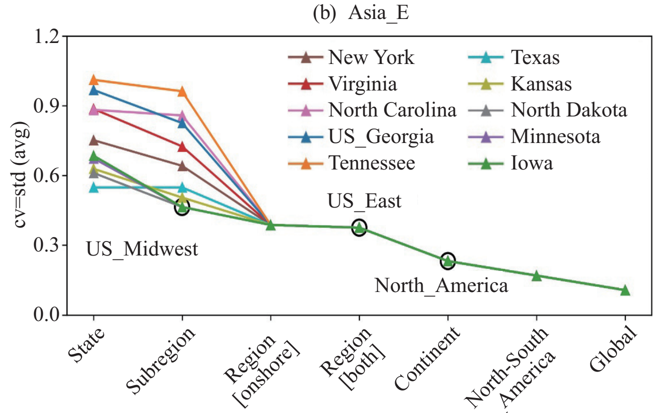
when intercontinental and global aggregation are considered, especially for continent Asia whose onshore and offshore capacities are the largest among all the continents (Table A-VIII). For example, the CV of Japan in Fig. 3 (b) drops from 63% to 16% at level Asia and drops slightly further to 11% at level Global (47% VS 5%); the CV of New York in Fig. 3(c) drops from 75% to 23% at level North America and reaches to 11% at level 'Global' (52% VS 12%). As a result of the relatively low potential capacities of wind generation for continent Europe (Table AVIII), its CV is higher than most of the other continents. Although the CV at continent level has already dropped significantly as compared to that of country level (e.g., Germany onshore, by 42%), Europe can further decrease its overall fluctuation to a great extent by aggregating its wind power with adjacent continents (by 14% under Europe-Asia).



(a) Europe_EU_plus



(b) Asia_E



(c) US_East

Fig. 3. CV of 7-year onshore power series for three typical regions at different aggregation levels.

In this paper, wind power for Region and above accounts for both onshore and offshore generation, as mentioned previously. Therefore, varying trend of CV of onshore wind power from Country to Global starts from CV of onshore power for ‘Country’ and considers the aggregated onshore and offshore power for Region and upward levels. When aggregated from country to continental level, the median of CV reduction (CV of Continent minus that of Country/Province/State) of onshore wind power for Europe, Asia, North_America, South_America, and Africa are found to be 47%, 66%, 56%, 49%, and 33%, respectively, which are tabulated in Tables AX and AXI. As shown in Table AVIII, the intercontinental aggregation facilitates a further reduction (CV of Inter-continent minus that of Continent) of 14% for Europe under Europe-Asia (10% under Europe-Africa), 3% for Asia under Europe-Asia-Africa, 6% for North America under North-South America, 7% for South America under North-South America, and 5% for Africa under Europe-Africa (12% under Europe-Asia-Africa). Global aggregation (all 6 continents together) can further introduce a reduction, particularly, 5% for Europe-Asia, 10% for Europe-Africa, 3% for Europe-Asia-Africa, and 6% for North-South America.

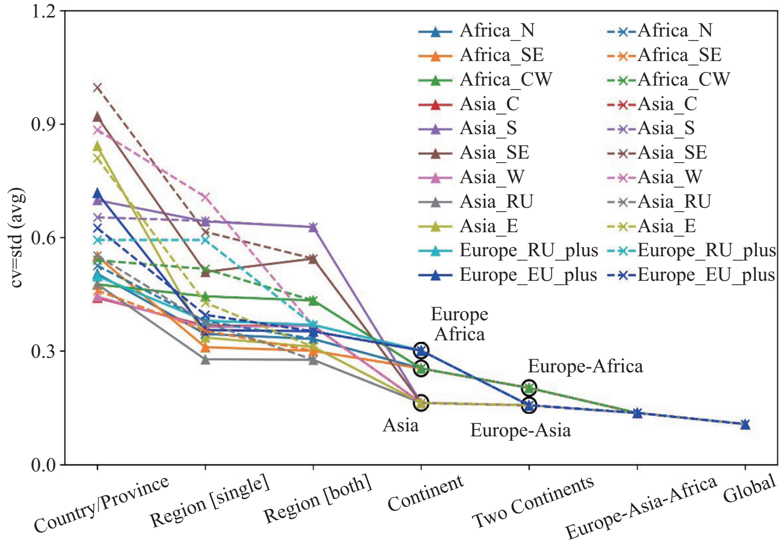
By and large, the fluctuations decline constantly with the increment in aggregation scale for both onshore and offshore power series. The fluctuation is seen alleviated significantly at level Continent, while the level Global, which consists of all the aggregations between two or more of these 6 continents, can generate further reductions, but not as prominent as the reductions from country to continental level.

C. STD of Power Ramping Rate at Different Aggregation Levels

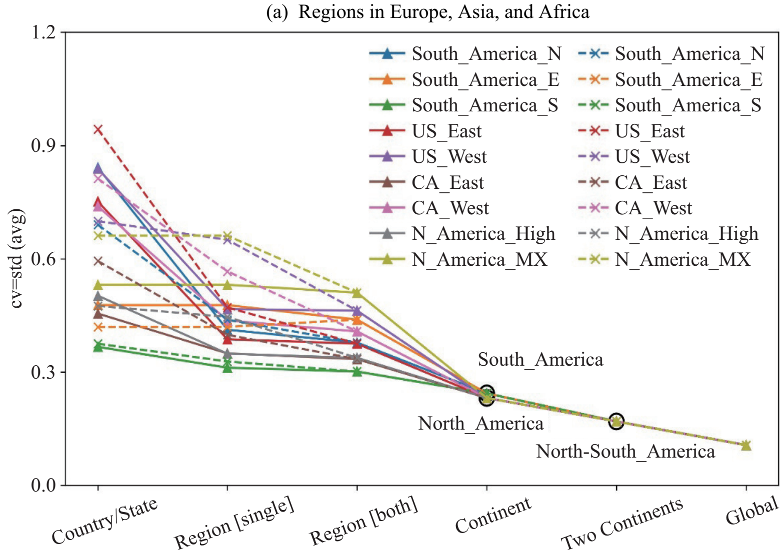
The ramping rate series of onshore generation from the lowest Country level to the highest ‘Global’ level for region ‘Europe_EU_plus’, ‘Asia_E’, and ‘US_East’ are shown in Fig 5, where the box spans the first quartile to the third quartile of the ramping rates during the 7 years. The whiskers give the ranges of 5 $\sim$ 95 percentile across the power ramping rate sets, and the short line and the triangle in the box represent the median and mean, respectively.

When the wind power is aggregated onto a larger scale, the ranges of ramping rates within each set get narrower from both the perspectives of ‘25 $\sim$ 75 percentile’ and ‘5 $\sim$ 95 percentile’. In addition, the aggregation of wind power involves limited enhancements for lowering the dispersion of overall ramping rates for each set when it is conducted at levels higher than the Continent.

The varying trends of STD for wind power ramping rates from lowest country/state/province level to global level are shown in Fig. A4 $\sim$ Fig. A5. As shown in Figs. A4 and A5, the STD of ramping rates becomes much smaller at the continent level in comparison to that of the country/province/state level, analogous to the varying trends of CV of the wind power series. Further aggregation of wind power into intercontinental and global level barely trims down the STD for Europe, Asia, and North America, while the STD for Africa and South America continue to decrease. It is therefore evident that Africa should aggregate its wind power with its adjacent continent, i.e., either Europe or Asia; and South America should aggregate its wind power with North America. Beyond these aggregations, the global aggregation of wind power exhibits only limited STD reduction. Also, it is noted that although the wind power series of continent Europe fluctuates more (higher CV) than most of the other continents, its ramping rates are relatively stable with STD (2.25% in Table AIX) being the second lowest, behind Asia (1.89%). The results also reflect that Europe should aggregate its wind power with Asia rather than Africa, which has the second highest STD of ramping rates (5.82%, second to 6.08% in Oceania) among all the continents, and hence, generates an increased STD for Europe-Africa aggregation, as shown in Fig. A4 (a).



(a) Regions in Europe, Asia, and Africa



(b) Regions in North_America and South_America

Fig. 4. CV of 7-year onshore power series for all regions at different aggregation levels.

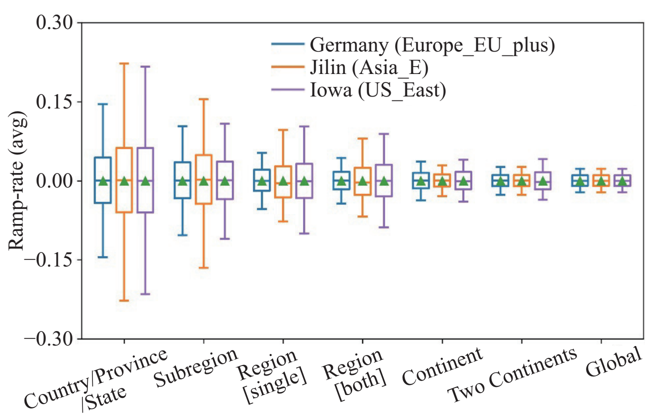


Fig. 5. Normalized 7-year onshore power ramping rates.

When aggregated from country to continental level, the median of STD reduction (STD of Continent minus Country/Province/State) of onshore wind power ramping rate series for Europe, Asia, North America, South America, and Africa are 8%, 13%, 11%, 10%, and 7%, respectively, tabulated in Tables AX and AXI. Global aggregation (all the 6 continents) tends to introduce a further reduction, but less significant and smaller than 1% for Europe and Asia, 1% for North America, 2% for South America, and 4% for Africa (Table AIX).

D. Duration Curves at Different Aggregation Levels

The duration curves of 7-year wind power aggregated at different levels are shown in Fig. 6 for Europe and Asia, where the solid line and dashed line represent the onshore and offshore power, respectively.

The duration curves for North America, South America, and Africa are shown in Fig. A6. It is noted that aggregated wind power for Region level (and above) accounts for both onshore and offshore generation, therefore the bold line in Fig. 6 refers to the aggregated power, if not specified.

The duration curves of the wind power under various scenarios of intercontinental aggregation along with global aggregation are shown in Fig. 7.

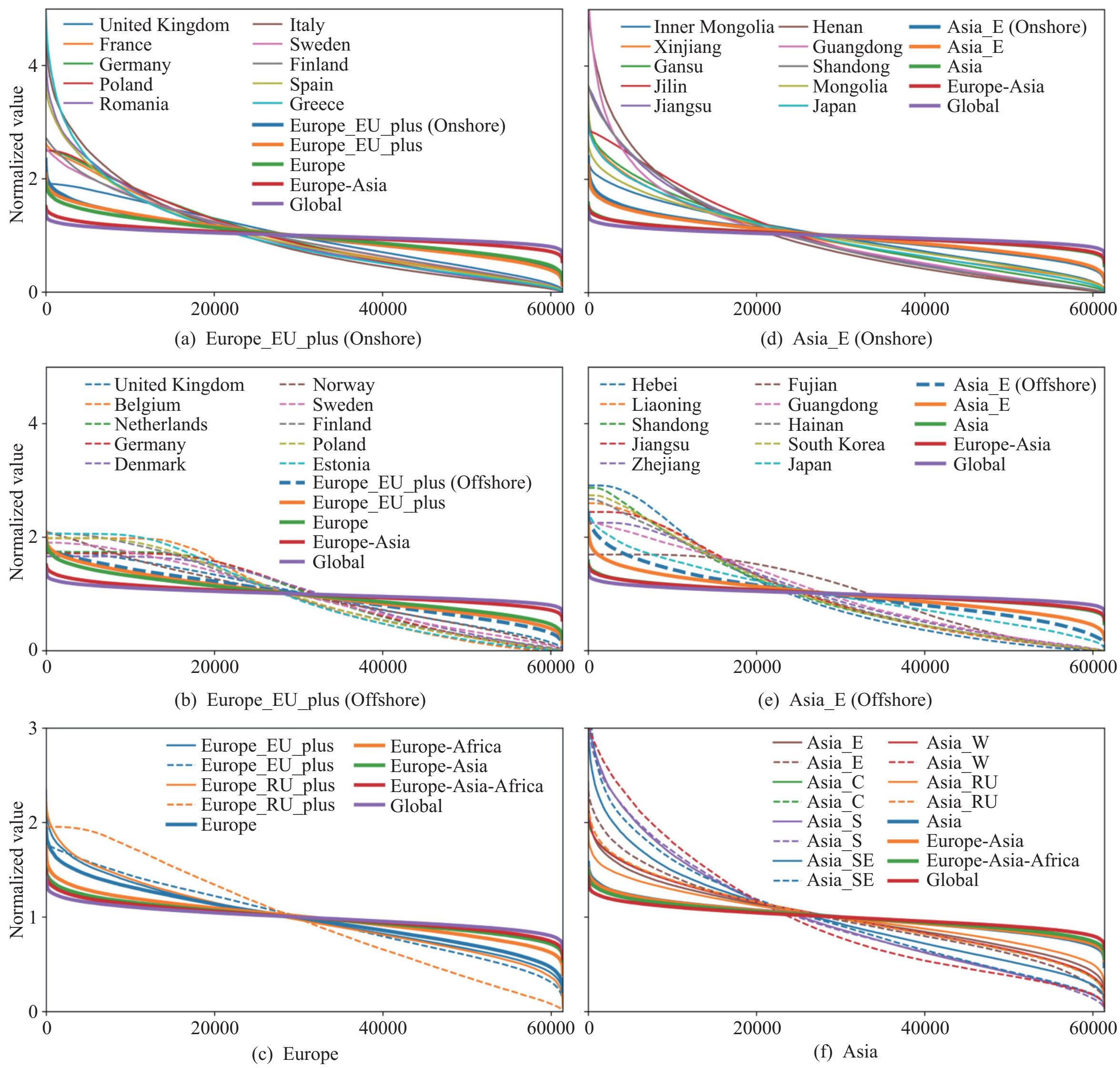


Fig. 6. Duration curve of 7-year wind power aggregated at different levels (Europe and Asia).

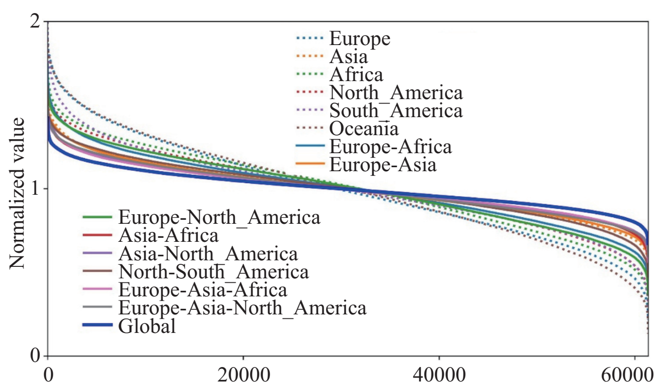


Fig. 7. Duration curve of aggregated at intercontinental, global levels.

From Figs. 6, 7, and A6, it can be observed that as the wind power aggregation moves upward from country/province/state level to higher levels, the duration curves of wind power become increasingly flat, which signifies that the availability of the aggregated wind power becomes more stable.

Furthermore, as shown in Figs. 6(c), 6(f), and A6, the duration curve of onshore wind power is flatter than the offshore power when the wind power series of each country is aggregated into regional level, which is consistent with the results in the previous Section B. However, at country level, the offshore wind power can appear more stable as compared to the onshore wind power (e.g., Sweden, Germany, Guangdong, and Jiangsu), particularly for extremely high values since the outputs of wind turbines are restricted to the rated values for high wind speeds at offshore sites.

E. Wind Power Aggregation Benefits in System Planning

To evaluate the benefits of wind power aggregation in system planning, the infrastructure capacity and investment cost can be calculated using power series at country level and sub-region level, respectively (‘Nordic_Baltic’ is exemplified in this study).

An optimization planning model coupled with full year dispatch (8760 h) seeking to minimize annual cost is used to determine the capacity of onshore wind power and storage system (Li-ion batteries), which are considered to be the two instrumentally contributing technologies to maintain grid power balance. Annual wind power curtailment is restricted to 5%. The load series of the countries are from TYNDP released by ENTSO-E in 2018 (scenario '2040_GCA'). The planning results are as shown in Table II.

TABLE II
CAPACITY AND COST OF SYSTEM PLANNING

Level	Elements	Capacity (GW)		Cost (billion USD)	
		Wind	Storage	Annual	LCOE [a]
Country	Denmark	17	787	12	221
	Estonia	7	117	2	199
	Finland	73	1,359	25	247
	Latvia	6	132	2	240
	Lithuania	11	175	3	222
	Sweden	83	980	21	148
	Norway	89	1,049	23	155
	Iceland	11	468	7	333
	Sum (T_1)[b]	297	5,068	97	191
Sub-Region	Nordic_Baltic (T_2)	225	1,788	46	92
Decrease	$\frac{T_1-T_2}{T_1}$	24%	65%	52%	52%

Note: [a] The LCOE is abbreviated for levelized cost of electricity (USD/MWh) and calculated as dividing the annual cost by the annual electricity consumption of a certain area.
[b] In both Table II and Table III, T_1 indicates the case without aggregation and T_2 indicates the case with aggregation.

It is shown in Table II that adopting aggregated power series reduces the overall capacity of wind power and storage system in 'Nordic_Baltic' countries by 24% and 65%, respectively, and subsequently can yield a reduction of 52% for annual cost and LCOE (the Levelized Cost of Electricity), which is highly correlated with the CV reduction from country level of 64% (median) to sub-region level of 45%. It is worth mentioning that the above reductions may be influenced by the demand complementarity.

To illustrate the impact of demand complementarity, four cases in Table III, which take the load pattern of Denmark, Finland, Sweden, and Norway, respectively, as the normalized load patterns of all the countries, are analyzed. From Table III, it can be concluded that the annual cost decrease is analogous to that in Table II, by approximately 50% $\sim$ 54%. Hence, we can infer from Table II that the investment cost is primarily affected by the CV of the aggregated wind generation.

TABLE III
CAPACITY AND COST OF SYSTEM PLANNING WITH COMPARISON OF THE IMPACT OF DEMAND COMPLEMENTARITY

Load Profile	Item	Capacity (GW)		Cost (billion USD)	
		Wind	Storage	Annual	LCOE
Denmark	T_1	309	5,085	98	194
	T_2	233	1,963	50	98
	$\frac{T_1-T_2}{T_1}$	25%	61%	50%	50%
Finland	T_1	310	5,082	98	194
	T_2	229	1,815	47	93
	$\frac{T_1-T_2}{T_1}$	26%	64%	52%	52%
Sweden	T_1	302	5,004	96	190
	T_2	220	1,689	45	88
	$\frac{T_1-T_2}{T_1}$	27%	66%	54%	54%
Norway	T_1	303	5,130	98	194
	T_2	232	1,924	49	97
	$\frac{T_1-T_2}{T_1}$	23%	62%	50%	50%

IV. CONCLUSIONS AND RECOMMENDATIONS

As a well-known fact, wind power inherently exhibits significant spatial and temporal variability and the aggregation of wind power from geographically wide-spread sites reduces such variability. In this paper, we investigate how such aggregation can be developed on a global scale. The analysis draws on a vast data set assembled from globally available sources and utilizes six levels from a low state/province/country level to a high global level to develop a suitable strategy for variability reductions. The 7-year (2011 $\sim$ 2017) hourly meteorological re-analysis data with a spatial resolution of 0.25° $\times$ 0.25° was converted into wind power series globally, resulting in a total of 224,750 grid cells for onshore sites and 19,958 grid cells for offshore sites, accounting for close to 5 Tb of data. Wind power from 50% of the grid cells with highest average capacity factor within each state/province/country worldwide were aggregated to represent the area wind power. A six- level aggregation hierarchical structure is proposed from which it can be concluded that:

1) As has been assumed for some time but not hitherto analyzed on a global scale, the wind power variability is constantly reduced with the increasing geographical aggregation scale for both onshore and offshore sites in terms of two metrics, namely, CV of 7-year wind power series and STD of 7-year wind power ramping rate series.
2) The variability of wind power is significantly reduced at the continental level as compared to that of the state level, especially in terms of CV of wind power series. For example, the CV of Japan drops from 63% to 16% at level Asia and drops slightly further to 11% at level Global (47% VS 5%); the CV of New York drops from 75% to 23% at level North America and reaches 11% at level Global (52% VS 12%). However, although the intercontinental and global aggregation can produce a further reduction, the reduction becomes less significant.
3) When the wind power is aggregated onto a larger scale, the ranges of ramping rates within each set get narrower from both the perspectives of '25 $\sim$ 75 percentile' and '5 $\sim$ 95 percentile'. Additionally, the aggregation of wind power offers limited improvements in lowering the dispersion of overall ramping rates at levels higher than the Continent level.
4) Duration curves, indicating the availability of wind power, become increasingly flat as the geographical scale of aggregation increases.
5) The reductions in variability illustrated in the analysis directly reflect the economic advantages through active power reserve and back-up capacity reductions as well as balancing cost reductions for the energy markets, together with stability enhancements of power grids. Particularly, potent benefits ensue for the North Sea Wind Power Hubs [47] as well as European wide electricity network interconnection. The results fetch additional benefits for the existing proposals for North Sea Wind Power Hubs and should lead to an appreciable reduction in the UK's electricity market balancing costs, which recorded a massive overall increase of 39% in the spring and summer of

2020 [45].

6) Sub-regional (e.g., 'Nordic_Baltic') aggregated power series decreases the overall capacity of wind power and storage system by 24% and 65%, respectively, and yields a reduction of 52% for annual cost and LCOE, which is highly correlated with the CV reduction from country level of 64% (median) to sub-region level of 45%.

7) This work has yielded comprehensive results from the analysis of the characteristics and benefits of wind power aggregation at different levels/scale, which are in favor of the wind power aggregation. The global nature of this analysis can now be utilized to devise a universal approach for the deployment of wind power, especially along the lines of Net-Zero.

APPENDIX

TABLE AI
GEOGRAPHICAL SCALE OF SUB-REGIONS IN US, EAST ASIA, AND EUROPE

Sub-region	Elements
US_NENY	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, New York
US_Mid_Atlantic	Delaware, Maryland, New Jersey, Ohio, Pennsylvania, West Virginia, Virginia
US_Carolinas	North Carolina, South Carolina
US_South	Alabama, US_Georgia, Florida
US_Tennessee	Tennessee, Kentucky
US_Midwest	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, North Dakota, South Dakota, Wisconsin, Arkansas, Louisiana, Mississippi
US_Central	Kansas, Nebraska, Oklahoma
US_Texas	Texas
US_Southwest	Arizona, New Mexico
US_Northwest	Colorado, Idaho, Montana, Nevada, Oregon, Utah, Washington, Wyoming
US_California	California
CN_North	Beijing, Hebei, Inner Mongolia, Shandong, Shanxi, Tianjin
CN_Northwest	Gansu, Ningxia, Qinghai, Shaanxi, Xinjiang
CN_Northeast	Heilongjiang, Jilin, Liaoning
CN_East	Anhui, Fujian, Jiangsu, Shanghai, Zhejiang
CN_Central	Chongqing, Henan, Hubei, Hunan, Jiangxi, Sichuan
CN_South	Guangdong, Guangxi, Guizhou, Hainan, Yunnan
CN_Tibet	Tibet
Japan_Korea	North Korea, South Korea, Japan
Asia_Mongolia	Mongolia
Iberia	Spain, Portugal
British_Isles	United Kingdom, Ireland
Europe_CW	Germany, Netherlands, Belgium, Luxembourg, Austria, Switzerland, France
Nordic_Baltic	Denmark, Norway, Sweden, Finland, Estonia, Latvia, Lithuania, Iceland
Europe_E	Poland, Czechia, Slovakia, Hungary, Romania, Bulgaria
Europe_S	Italy, Slovenia, Croatia, Bosnia and Herz., Serbia, Greece, Albania, Macedonia, Kosovo, Montenegro
Five Lakes	New York, Ohio, Michigan, Wisconsin
US_Atlantic	US_Georgia, North Carolina, South Carolina, New Jersey, Virginia, Maine, Massachusetts, New York
Mexico Gulf	Texas, Louisiana, Florida
Bohai&Yellow Sea	Hebei, Liaoning, Shandong, Jiangsu
East&South China Sea	Zhejiang, Fujian, Guangdong, Hainan
Japan_Korea Sea	Japan, South Korea, North Korea
North_Sea	United Kingdom, Belgium, Netherlands, Germany, Denmark, Norway
Baltic_Sea	Sweden, Finland, Estonia, Latvia, Lithuania, Poland
EU_Other_Sea	Bulgaria, Croatia, Greece, Ireland, Italy, Portugal, Romania, Spain, France, Iceland

Note: 1) An element at the lowest level (country, province, or state) are marked by quotation marks, whose meteorological re-analysis data is downloading based on its shapefile provided by Natural Earth Dataset or GADM. 2) This study takes no position on any sovereign status and boundary delimitation. 3) Shapefiles for elements in Russia in Table A-II are manually generated according to the division of federal districts along with nearly 85 subject shapefiles of Russia, see Table A-III. 4) Geographical scale of inter-continent scenarios is not shown here, which can be identified directly according to its name.

TABLE AII
GEOGRAPHICAL SCALE OF REGIONS AND CONTINENTS

Region/Continent	Elements
US_East	*Onshore:* US_NENY, US_Mid_Atlantic, US_Carolinas, US_South, US_Tennessee, US_Midwest, US_Central, US_Texas *Offshore:* Five Lakes, US_Atlantic, Mexico Gulf
US_West	US_Southwest, US_Northwest, US_California
CA_East	Ontario, Quebec, New Brunswick, Prince Edward Island, Nova Scotia, Newfoundland and Labrador
CA_West	Manitoba, Saskatchewan, Alberta, British Columbia
N_America_H	USA_Alaska, CA_Yukon, CA_Northwest, CA_Nunavut
N_America_MX	Mexico
Asia_E	*Onshore:* CN_Northwest, CN_North, CN_Northeast, CN_East, CN_Central, CN_South, CN_Tibet, Asia_Mongolia, Japan_Korea *Offshore:* Bohai&Yellow Sea, East&South China Sea, Japan_Korea Sea
Asia_C	Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, Turkmenistan, Afghanistan
Asia_S	India, Pakistan, Bangladesh, Bhutan, Nepal, Sri Lanka
Asia_SE	Cambodia, Thailand, Laos, Myanmar, Vietnam, Philippines, Malaysia, Indonesia (merge with Timor-Leste, Brunei, and Papua New Guinea)
Asia_W	Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, Turkey, Palestine

TABLE AII
GEOGRAPHICAL SCALE OF REGIONS AND CONTINENTS (CONTINUED)

Region/Continent	Elements
Asia_RU	RU_Ural_N, RU_Ural_S, RU_Siberian_W, RU_Siberian_E, RU_Siberian_N, RU_FarEastern_NW, RU_FarEastern_L, RU_FarEastern_U
Europe_EU_plus	*Onshore:* Iberia, British_Isles, Europe_CW, Nordic_Baltic, Europe_E, Europe_S *Offshore:* North_Sea, Baltic_Sea, EU_Other_Sea
Europe_RU_Plus	RU_Central, RU_Volga, RU_Northwestern_E, RU_Northwestern_W, RU_Southern_Caucasian, Ukraine, Belarus, Georgia
Africa_N	Egypt, Libya, Algeria, Morocco, Tunisia
Africa_SE	Dem. Rep. Congo, Angola, Zimbabwe, Botswana, Namibia, Zambia, Mozambique (merge with Malawi), South Africa (merge with eSwatini, Lesotho), Tanzania (merge with Burundi, Rwanda), Somalia, Sudan, S. Sudan, Ethiopia (merge with Djibouti, Eritrea), Kenya (merge with Uganda)
Africa_CW	Chad, Cameroon, Congo (merge with Gabon, Eq.Guinea), Central African Rep., Mali, Mauritania, Niger, Nigeria, Guinea (merge with Senegal, Gambia, Guinea-Bissau, Sierra Leone, Liberia), Ghana (merge with Togo, Benin, Burkina Faso, Cote dlovire)
South_America_N	Guatemala, Honduras, Panama, Colombia, Venezuela, Guyana, Guyane, Suriname, Ecuador, Peru, Bolivia
South_America_E	Brazil
South_America_S	Chile, Argentina, Uruguay, Paraguay
Europe	Iberia, British_Isles, Europe_CW, Nordic_Baltic, Europe_E, Europe_S, Europe_RU_Plus
Asia	Asia_E, Asia_C, Asia_S, Asia_SE, Asia_W, Asia_RU
Africa	Africa_N, Africa_SE, Africa_CW
North_America	US_East, US_West, CA_West, CA_East, N_America_H, N_America_MX
South_America	South_America_N, South_America_E, South_America_S
Oceania	Australia
Global	Europe, Asia, Africa, North_America, South_America, Oceania

TABLE AIII
ELEMENTS IN RUSSIA

Elements in Russia	Federal subjects
RU_Siberian_W	Altay, Gorno-Altay, Kemerovo, Novosibirsk, Omsk, Tomsk, Khakass,
RU_Siberian_E	Irkutsk, Tuva, Buryat
RU_Siberian_N	Krasnoyarsk
RU_FarEastern_NW	Sakha
RU_FarEastern_L,	Amur, Yevrey, Zabaykal'ye, Primor'ye, Sakhalin, Khabarovsk
RU_FarEastern_U	Kamchatka, Maga, Buryatdan, Chukot
RU_Central	Belgorod, Bryansk, Vladimir, Voronezh, Ivanovo, Kaluga, Kostroma, Kursk, Lipetsk, Moscow City, Moskva, Orel, Ryazan, Smolensk, Tambov, Tver, Tula, Yaroslav
RU_Volga	Bashkortostan, Kirov, Mariy-El, Mordovia, Nizhegorod, Orenburg, Penza, Perm, Samara, Saratov, Tatarstan, Udmurt, Ul'yanovsk, Chuvash
RU_Northwestern_E	Arkhangel'sk, Vologda, Komi, Nenets
RU_Northwestern_W	Karelia, Leningrad, Murmansk, Novgorod, Pskov
RU_Southern_Caucasian	Adygey, Astrakhan, Kalmyk, Krasnodar, Rostov, Volgograd, Dagestan, Ingush, Kabardin-Balkar, Karachay-Cherkess, North Ossetia, Stavropol, Chechnya,
RU_Ural_N	Yamal-Nenets
RU_Ural_S	Kurgan, Sverdlovsk, Tyumen, Khanty-Mansiy, Chelyabinsk,

TABLE AIV
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE SERIES (ONSHORE) FROM LEVEL 1 TO LEVEL 3

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg'	STD (%)	ptp'/avg
1	United Kingdom	97	51	53.06	1.90	52.32	0	5.23	0.71
1	France	219	83	67.04	2.64	37.70	0	8.36	1.16
1	Germany	140	56	71.77	2.49	40.08	0	9.08	1.47
1	Poland	122	49	72.24	2.50	40.04	0	9.67	1.33
1	Romania	92	21	80.29	4.20	23.14	0	12.32	1.89
1	Italy	118	23	88.60	4.90	19.55	0	9.16	1.38
1	Sweden	163	64	62.40	2.54	39.23	0	7.07	0.96
1	Finland	122	45	64.11	2.72	36.78	0	6.80	1.09
1	Spain	200	53	74.84	3.69	26.63	0	9.17	1.21
1	Greece	52	10	84.89	5.10	18.49	0	10.68	2.38
1	Inner Mongolia	458	193	50.73	2.34	42.02	0	7.71	1.09
1	Xinjiang	653	162	62.56	3.51	24.84	0	8.39	1.15
1	Gansu	170	50	67.64	3.30	29.28	0	11.47	1.54
1	Jilin	76	27	80.99	2.87	34.88	0	14.03	2.62
1	Jiangsu	43	12	84.14	3.60	27.79	0	14.89	2.38
1	Henan	66	13	97.06	4.93	20.28	0	19.64	3.76
1	Guangdong	72	13	87.67	5.50	18.01	0	15.84	2.85
1	Shandong	63	17	84.75	3.65	27.36	0	14.91	2.79
1	Mongolia	621	229	55.07	2.67	36.79	0	8.40	1.14
1	Japan	146	47	62.78	3.04	32.18	0	8.34	1.35
1	New York	49	19	75.18	2.64	37.92	0	12.29	1.89
1	Virginia	41	11	88.63	3.56	28.07	0	17.36	2.89
1	North Carolina	50	15	88.23	3.38	29.62	0	17.17	2.79

TABLE AIV
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE SERIES (ONSHORE) FROM LEVEL 1 TO LEVEL 3 (CONTNUED)

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg'	STD (%)	ptp'/avg
1	Georgia	60	14	96.77	4.36	22.96	0	19.92	4.50
1	Tennessee	43	11	101.12	4.01	24.94	0	20.82	3.94
1	Texas	271	130	54.86	2.07	48.08	0	10.25	1.67
1	Kansas	85	41	62.87	2.05	48.76	0	13.23	2.19
1	North Dakota	71	36	61.08	2.01	49.69	0	11.04	1.60
1	Minnesota	82	37	67.35	2.21	45.32	0	11.63	1.83
1	Iowa	58	27	68.52	2.12	47.10	0	13.15	3.03
2	British_Isles	124	64	53.21	1.93	51.36	0	4.89	0.62
2	Europe_CW	434	160	56.73	2.67	36.78	0	6.44	0.92
2	Europe_E	344	103	56.31	3.22	29.93	0	7.36	1.02
2	Europe_S	286	50	74.44	5.18	17.39	0	7.62	1.13
2	Nordic_Baltic	555	222	44.98	2.36	40.05	0	3.72	0.48
2	Iberia	236	66	70.43	3.55	27.71	0	8.72	1.06
2	CN_North	671	243	50.53	2.51	36.21	0	7.43	1.07
2	CN_Northwest	1205	301	46.81	2.89	25.01	0	7.13	0.82
2	CN_Northeast	317	103	65.41	3.06	32.56	0	9.93	1.75
2	CN_East	194	41	65.65	4.37	21.08	0	10.63	1.64
2	CN_Central	520	64	79.93	5.61	12.25	0	11.57	2.08
2	CN_South	405	63	73.53	5.38	15.49	0	12.84	2.25
2	CN_Tibet	481	137	93.06	3.52	28.40	0	21.85	2.80
2	Japan-Korea	233	67	60.47	3.38	28.62	0	7.92	1.17
2	Mongolia	621	229	55.07	2.67	36.79	0	8.40	1.14
2	US_NENY	114	42	64.15	2.72	36.68	0	9.54	1.34
2	US_Mid-Atlantic	174	56	72.51	3.07	32.40	0	11.59	1.90
2	US_Carolinas	82	24	85.81	3.46	28.87	0	15.96	2.55
2	US_South	168	38	82.54	4.42	22.47	0	14.28	2.62
2	US_Tennessee	84	21	96.21	3.96	25.24	0	17.75	3.19
2	US_Midwest	718	288	46.44	2.43	40.10	0	6.70	0.87
2	US_Texas	271	130	54.86	2.07	48.08	0	10.25	1.67
2	US_Central	235	118	50.50	1.98	50.11	0	9.44	1.39
3	Europe_EU_plus	1980	664	35.53	2.22	33.54	0	3.30	0.39
3	Asia_E	4646	1246	33.55	2.21	26.83	0	5.26	0.65
3	US_East	1845	717	38.71	2.21	38.84	0	6.01	0.64

Note: 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global.

TABLE AV
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE SERIES (OFFSHORE) FROM LEVEL 1 TO LEVEL 3

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg'	STD (%)	ptp'/avg
1	United Kingdom	218	125	50.36	1.73	57.27	0	5.53	1.26
1	Belgium	6	2	74.82	1.98	40.40	0	14.04	3.96
1	Netherlands	116	67	63.30	1.74	57.53	0	9.19	2.79
1	Germany	91	53	62.51	1.71	58.37	0	9.08	2.18
1	Denmark	135	82	58.25	1.66	60.21	0	8.31	2.09
1	Norway	27	13	54.92	2.08	48.11	0	7.03	1.73
1	Sweden	123	65	59.25	1.90	52.55	0	7.04	1.51
1	Finland	91	44	68.27	2.06	48.46	0	9.14	2.08
1	Poland	32	16	69.42	1.99	50.35	0	9.62	2.40
1	Estonia	36	18	74.65	2.06	48.57	0	10.75	2.17
1	Hebei	36	12	93.31	2.91	34.36	0	19.34	3.35
1	Liaoning	67	26	82.95	2.60	38.50	0	15.08	2.53
1	Shandong	99	34	84.55	2.87	34.86	0	11.98	2.72
1	Jiangsu	157	64	81.00	2.44	40.92	0	11.17	2.34
1	Zhejiang	47	21	73.59	2.25	44.39	0	9.42	1.91
1	Fujian	48	29	61.26	1.69	59.10	0	6.03	1.16
1	Guangdong	98	43	70.56	2.27	44.03	0	8.16	1.82
1	Hainan	23	9	80.65	2.67	37.42	0	11.07	2.07
1	South Korea	58	21	83.02	2.74	36.54	0	11.94	2.13
1	Japan	93	37	53.49	2.48	39.83	0	7.50	1.34
1	Wisconsin	17	7	78.16	2.64	37.92	0	12.41	2.07
1	Michigan	75	31	70.76	2.39	41.78	0	9.78	1.40
1	Ohio	34	14	86.25	2.38	41.99	0	16.16	2.48
1	New Jersey	40	18	78.44	2.18	45.91	0	15.09	3.15
1	Virginia	44	20	78.19	2.20	45.41	0	14.14	3.88
1	North Carolina	42	19	78.05	2.21	45.27	0	13.62	2.91
1	Georgia	25	9	94.84	2.88	34.72	0	18.37	4.66
1	Texas	50	20	79.06	2.55	39.26	0	14.16	2.99
1	Louisiana	75	24	98.57	3.14	31.87	0	17.17	4.31
1	Florida	172	46	90.38	3.74	26.75	0	11.98	2.33

TABLE AV
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE SERIES (OFFSHORE) FROM LEVEL 1 TO LEVEL 3 (CONTINUED)

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg’	STD (%)	ptp’/avg
2	North Sea	593	342	49.57	1.71	57.58	0	5.07	1.38
2	Baltic Sea	313	158	55.86	1.98	50.38	0	5.65	0.92
2	EU_Other Sea	261	98	40.48	2.28	37.66	0	4.36	0.67
2	Bohai&Yellow Sea	359	137	61.59	2.62	38.14	0	8.11	1.30
2	East&South CN Sea	217	102	54.01	2.13	46.77	0	5.31	0.89
2	Japan_Korea Sea	178	67	52.93	2.60	37.89	0	6.88	1.16
2	Five Lakes	136	56	65.63	2.44	40.91	0	8.30	1.25
2	US_Atlantic	239	105	58.22	2.27	43.82	0	8.22	1.43
2	Mexico Gulf	297	90	70.17	3.31	30.16	0	9.50	1.64
3	Europe_EU_plus	1167	598	39.57	1.77	51.20	0	3.40	0.72
3	Asia_E	754	306	42.79	2.38	40.56	0	5.05	0.72
3	US_East	663	247	47.13	2.60	37.22	0	5.91	0.86

Note: 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global.

TABLE AVI
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (ONSHORE) (SUPPLEMENTARY TO TABLE A-IV)

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg’	STD (%)	ptp’/avg
1	Colombia	444	35	84.18	7.80	7.83	0	16.69	3.89
1	Brazil	3343	678	47.74	3.19	20.27	0	7.62	0.77
1	Argentina	1095	546	36.70	1.90	49.92	0	5.25	0.54
1	New York	49	19	75.18	2.64	37.92	0	12.29	1.89
1	California	161	26	83.90	5.57	16.14	0	13.25	1.88
1	Quebec	546	291	45.52	1.85	53.37	0	4.47	0.60
1	British Columbia	370	68	73.90	4.83	18.45	0	9.65	1.46
1	USA_Alaska	591	223	50.25	2.52	37.76	0	4.04	0.53
1	Mexico	778	176	53.14	3.56	22.57	0	9.52	1.09
1	Egypt	398	157	50.44	2.47	39.42	0	9.94	0.89
1	South Africa	504	177	55.01	2.75	35.06	0	10.53	1.16
1	Mauritania	412	201	47.62	2.04	48.63	0	9.53	1.11
1	Kazakhstan	1080	477	44.08	2.20	44.22	0	5.72	0.64
1	India	1189	265	69.86	3.67	22.29	0	10.56	1.57
1	Thailand	204	31	91.96	5.96	15.26	0	15.05	2.87
1	Saudi Arabia	860	297	44.38	2.57	34.56	0	10.42	1.03
1	RU_FarEastern_NW	1233	415	47.69	2.64	33.63	0	4.30	0.57
1	Jiangsu	43	12	84.14	3.60	27.79	0	14.89	2.38
1	RU_Northwestern_E	460	217	49.80	2.09	47.19	0	4.58	0.56
1	Germany	140	56	71.77	2.49	40.08	0	9.08	1.47
3	South_America_N	2219	278	41.23	2.86	12.53	0	7.03	0.90
3	South_America_E	3343	678	47.74	3.19	20.27	0	7.62	0.77
3	South_America_S	1621	766	31.18	1.83	47.22	0	4.34	0.48
3	US_East	1845	717	38.71	2.21	38.84	0	6.01	0.64
3	US_West	1216	350	46.69	2.80	28.79	0	6.88	0.83
3	CA_East	1115	549	34.96	1.91	49.23	0	3.39	0.40
3	CA_West	1085	357	43.67	2.65	32.95	0	5.69	0.66
3	N_America_High	2029	851	34.89	1.95	41.95	0	3.01	0.39
3	N_America_MX	778	176	53.14	3.56	22.57	0	9.52	1.09
3	Africa_N	2295	961	34.51	2.04	41.85	0	6.78	0.48
3	Africa_SE	5655	1577	31.02	1.91	27.89	0	6.73	0.56
3	Africa_CW	3617	1150	44.46	2.32	31.80	0	8.38	0.59
3	Asia_C	1831	709	36.67	2.12	38.72	0	5.36	0.51
3	Asia_S	1647	360	64.25	3.36	21.84	0	9.28	1.31
3	Asia_SE	1917	205	50.89	3.32	10.67	0	7.30	1.23
3	Asia_W	2492	731	36.33	2.25	29.34	0	6.85	0.56
3	Asia_RU	5239	1883	27.79	1.77	35.94	0	2.10	0.30
3	Asia_E	4646	1246	33.55	2.21	26.83	0	5.26	0.65
3	Europe_RU_plus	1965	788	38.02	2.21	40.10	0	3.78	0.43
3	Europe_EU_plus	1980	664	35.53	2.22	33.54	0	3.30	0.39

Note: 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global.

TABLE AVII
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (OFFSHORE) (SUPPLEMENTARY TO TABLE A-V)

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg’	STD (%)	ptp’/avg
1	Colombia	20	6	69.03	3.07	28.20	0	9.12	1.21
1	Brazil	418	177	41.98	2.20	42.28	0	5.02	0.67
1	Argentina	249	140	37.53	1.73	56.50	0	6.31	0.89

TABLE AVII
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (OFFSHORE) (SUPPLEMENTARY TO TABLE A-V) (CONTINUED)

Level	Name	Cap (GW)	Original Power Series				Ramping Rate Series		
			avg	CV (%)	ptp/avg	CF (%)	avg'	STD (%)	ptp'/avg
1	New York	9	3	94.36	2.82	35.43	0	19.18	3.79
1	California	8	3	69.97	2.61	38.29	0	13.64	2.64
1	Quebec	134	67	59.43	1.98	50.39	0	8.22	1.53
1	British Columbia	29	12	81.26	2.34	42.77	0	13.25	3.18
1	USA_Alaska	1457	790	47.53	1.82	54.24	0	3.92	0.72
1	Mexico	234	82	66.13	2.82	35.23	0	12.24	2.23
1	Egypt	54	15	52.60	3.16	28.01	0	7.66	1.00
1	South Africa	19	8	46.01	2.38	41.32	0	8.87	1.21
1	Mauritania	30	18	53.99	1.66	60.41	0	10.40	1.38
1	Kazakhstan	0	0	0.00	0.00	0.00	0	0.00	0.00
1	India	219	68	65.33	3.14	31.26	0	7.81	1.30
1	Thailand	148	25	99.70	5.87	16.76	0	14.29	3.01
1	Saudi Arabia	187	54	88.46	3.43	29.16	0	10.06	2.11
1	RU_FarEastern_NW	3378	1357	55.24	2.48	40.18	0	4.26	0.69
1	Jiangsu	157	64	81.00	2.44	40.92	0	11.17	2.34
1	RU_Northwestern_E	372	190	59.34	1.95	51.19	0	6.18	0.84
1	Germany	91	53	62.51	1.71	58.37	0	9.08	2.18
3	South_America_N	369	128	43.86	2.38	34.60	0	6.09	0.78
3	South_America_E	418	177	41.98	2.20	42.28	0	5.02	0.67
3	South_America_S	300	177	32.82	1.64	59.01	0	5.22	0.75
3	US_East	663	247	47.13	2.60	37.22	0	5.91	0.86
3	US_West	22	7	65.03	3.00	30.25	0	12.17	2.27
3	CA_East	395	209	39.87	1.85	52.98	0	5.06	0.81
3	CA_West	104	50	56.68	2.07	48.22	0	8.28	1.70
3	N_America_High	1610	849	44.62	1.86	52.77	0	3.70	0.68
3	N_America_MX	234	82	66.13	2.82	35.23	0	12.24	2.23
3	Africa_N	177	68	37.87	2.20	38.11	0	5.94	1.11
3	Africa_SE	198	62	35.34	2.23	31.27	0	5.84	0.69
3	Africa_CW	234	49	51.68	3.28	20.88	0	9.49	1.52
3	Asia_C	0	0	0.00	0.00	0.00	0	0.00	0.00
3	Asia_S	278	86	64.39	3.18	30.73	0	7.16	1.12
3	Asia_SE	1600	326	61.49	4.07	20.37	0	5.17	0.99
3	Asia_W	308	96	70.73	3.14	31.01	0	7.81	1.76
3	Asia_RU	5458	2339	37.59	2.10	42.86	0	2.90	0.45
3	Asia_E	754	306	42.79	2.38	40.56	0	5.05	0.72
3	Europe_RU_plus	372	190	59.34	1.95	51.19	0	6.18	0.84
3	Europe_EU_plus	1167	598	39.57	1.77	51.20	0	3.40	0.72

Note: 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global.

TABLE AVIII
CV OF WIND POWER SERIES (AGGREGATED ONSHORE AND OFFSHORE) FROM LEVEL 3 TO LEVEL 6

Level	Name	Cap (GW)		avg		CV (%)			ptp/avg			CF (%)		
		on-	off-	on-	off-	on-	off-	both	on-	off-	both	on-	off-	both
3	Europe_EU_plus	1980	1167	664	598	35.53	39.57	35.21	2.22	1.77	1.96	33.54	51.20	40.09
3	Europe_RU_plus	1965	372	788	190	38.02	59.34	36.90	2.21	1.95	2.15	40.10	51.19	41.86
3	Asia_E	4646	754	1246	306	33.55	42.79	31.11	2.21	2.38	2.05	26.83	40.56	28.75
3	Asia_C	1831	0	709	0	36.67	0.00	36.67	2.12	0.00	2.12	38.72	0.00	38.72
3	Asia_S	1647	278	360	86	64.25	64.39	62.76	3.36	3.18	3.27	21.84	30.73	23.13
3	Asia_SE	1917	1600	205	326	50.89	61.49	54.41	3.32	4.07	3.45	10.67	20.37	15.09
3	Asia_W	2492	308	731	96	36.33	70.73	36.67	2.25	3.14	2.21	29.34	31.01	29.52
3	Asia_RU	5239	5458	1883	2339	27.79	37.59	27.69	1.77	2.10	1.76	35.94	42.86	39.47
3	US_East	1845	663	717	247	38.71	47.13	37.55	2.21	2.60	2.17	38.84	37.22	38.41
3	US_West	1216	22	350	7	46.69	65.03	46.28	2.80	3.00	2.78	28.79	30.25	28.82
3	CA_East	1115	395	549	209	34.96	39.87	33.45	1.91	1.85	1.84	49.23	52.98	50.21
3	CA_West	1085	104	357	50	43.67	56.68	40.77	2.65	2.07	2.54	32.95	48.22	34.28
3	N_America_High	2029	1610	851	849	34.89	44.62	33.78	1.95	1.86	1.76	41.95	52.77	46.74
3	N_America_MX	778	234	176	82	53.14	66.13	51.04	3.56	2.82	3.28	22.57	35.23	25.50
3	South_America_N	2219	369	278	128	41.23	43.86	37.82	2.86	2.38	2.47	12.53	34.60	15.67
3	South_America_E	3343	418	678	177	47.74	41.98	43.90	3.19	2.20	2.84	20.27	42.28	22.72
3	South_America_S	1621	300	766	177	31.18	32.82	30.16	1.83	1.64	1.77	47.22	59.01	49.07
3	Africa_N	2295	177	961	68	34.51	37.87	33.18	2.04	2.20	2.00	41.85	38.11	41.58
3	Africa_SE	5655	198	1577	62	31.02	35.34	30.04	1.91	2.23	1.86	27.89	31.27	28.00
3	Africa_CW	3617	234	1150	49	44.46	51.68	43.36	2.32	3.28	2.26	31.80	20.88	31.13
4	Europe	3945	1539	–	–	–	–	30.13	–	–	1.72	–	–	40.84
4	Asia	17772	8398	–	–	–	–	16.29	–	–	1.10	–	–	31.66
4	North_America	8067	3028	–	–	–	–	23.17	–	–	1.47	–	–	40.06
4	South_America	7183	1087	–	–	–	–	24.38	–	–	1.78	–	–	26.64
4	Africa	11567	610	–	–	–	–	25.39	–	–	1.50	–	–	31.75
4	Oceania	3077	1187	–	–	–	–	31.55	–	–	1.76	–	–	43.30

TABLE AVIII
CV OF WIND POWER SERIES (AGGREGATED ONSHORE AND OFFSHORE) FROM LEVEL 3 TO LEVEL 6 (CONTINUED)

Level	Name	Cap (GW)		avg		CV (%)			ptp/avg			CF (%)		
		on-	off-	on-	off-	on-	off-	both	on-	off-	both	on-	off-	both
5	Europe-Asia	21717	9937	–	–	–	–	15.65	–	–	0.98	–	–	33.25
5	Europe-Africa	15513	2149	–	–	–	–	20.23	–	–	1.35	–	–	34.57
5	Europe-Asia-Africa	33285	10547	–	–	–	–	13.64	–	–	0.92	–	–	32.84
5	North-South_America	15251	4116	–	–	–	–	16.94	–	–	1.13	–	–	34.33
6	Global	51612	15849	–	–	–	–	10.68	–	–	0.75	–	–	33.92

TABLE AIX
STD OF WIND POWER RAMPING RATE SERIES (AGGREGATED ONSHORE AND OFFSHORE) FROM LEVEL 3 TO LEVEL 6

Level	Name	STD (%)			ptp'/avg		
		on-	off-	both	on-	off-	both
3	Europe_EU_plus	3.30	3.40	2.71	0.39	0.72	0.38
3	Europe_RU_plus	3.78	6.18	3.42	0.43	0.84	0.36
3	Asia_E	5.26	5.05	4.50	0.65	0.72	0.52
3	Asia_C	5.36	0.00	5.36	0.51	0.00	0.51
3	Asia_S	9.28	7.16	8.29	1.31	1.12	1.16
3	Asia_SE	7.30	5.17	5.27	1.23	0.99	0.88
3	Asia_W	6.85	7.81	6.30	0.56	1.76	0.56
3	Asia_RU	2.10	2.90	1.96	0.30	0.45	0.31
3	US_East	6.01	5.91	5.33	0.64	0.86	0.54
3	US_West	6.88	12.17	6.80	0.83	2.27	0.81
3	CA_East	3.39	5.06	3.08	0.40	0.81	0.37
3	CA_West	5.69	8.28	5.21	0.66	1.70	0.56
3	N_America_High	3.01	3.70	2.49	0.39	0.68	0.34
3	N_America_MX	9.52	12.24	8.84	1.09	2.23	1.02
3	South_America_N	7.03	6.09	5.84	0.90	0.78	0.67
3	South_America_E	7.62	5.02	6.57	0.77	0.67	0.64
3	South_America_S	4.34	5.22	4.03	0.48	0.75	0.44
3	Africa_N	6.78	5.94	6.42	0.48	1.11	0.45
3	Africa_SE	6.73	5.84	6.49	0.56	0.69	0.55
3	Africa_CW	8.38	9.49	8.17	0.59	1.52	0.58
4	Europe	–	–	2.25	–	–	0.25
4	Asia	–	–	1.89	–	–	0.22
4	North_America	–	–	2.45	–	–	0.26
4	South_America	–	–	3.78	–	–	0.37
4	Africa	–	–	5.82	–	–	0.35
4	Oceania	–	–	6.08	–	–	0.54
5	Europe-Asia	–	–	1.67	–	–	0.17
5	Europe-Africa	–	–	3.90	–	–	0.25
5	Europe-Asia-Africa	–	–	1.92	–	–	0.15
5	North-South_America	–	–	2.37	–	–	0.22
6	Global	–	–	1.41	–	–	0.12

Note: 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global.

TABLE AX
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (ONSHORE) GLOBALLY AT LEVEL 1 (PART I)

Level	Name	Original Power Series		Ramping Rate Series		Name	Original Power Series		Ramping Rate Series	
		CV (%)	Reduction	STD (%)	Reduction'		CV (%)	Reduction	STD (%)	Reduction'
1	Spain	74.84	44.71	0.23	6.92	Anhui	93.01	76.73	0.01	16.58
1	Portugal	79.08	48.95	0.00	11.17	Fujian	79.89	63.60	0.00	10.37
1	United Kingdom	53.06	22.93	0.07	2.98	Jiangsu	84.14	67.85	−0.02	13.00
1	Ireland	68.47	38.34	0.04	6.75	Shanghai	78.71	62.42	0.00	13.20
1	Germany	71.77	41.65	0.00	6.82	Zhejiang	92.97	76.69	−0.02	13.74
1	Netherlands	66.33	36.20	0.00	8.00	Chongqing	165.33	149.04	−0.01	40.00
1	Belgium	79.18	49.06	0.02	10.81	Henan	97.06	80.78	0.00	17.75
1	Luxembourg	92.94	62.82	0.00	17.99	Hubei	117.74	101.45	−0.02	17.32
1	Austria	100.10	69.97	0.00	14.19	Hunan	118.21	101.92	−0.03	16.16
1	Switzerland	155.80	125.67	0.01	29.01	Jiangxi	109.82	93.54	−0.03	16.01
1	France	67.04	36.92	0.32	6.10	Sichuan	106.71	90.42	−0.05	17.69
1	Denmark	55.20	25.07	0.00	4.49	Guangdong	87.67	71.39	−0.03	13.94
1	Norway	51.45	21.32	−0.01	2.20	Guangxi	102.16	85.87	−0.02	14.38
1	Sweden	62.40	32.27	−0.07	4.82	Guizhou	110.68	94.39	−0.01	18.62
1	Finland	64.11	33.98	0.03	4.55	Hainan	81.39	65.10	−0.01	12.73
1	Estonia	73.87	43.75	−0.01	7.28	Yunnan	122.75	106.46	−0.01	25.08
1	Latvia	74.02	43.89	−0.01	7.90	Tibet	93.06	76.77	−0.17	19.96
1	Lithuania	77.21	47.08	−0.01	9.70	Mongolia	55.07	38.78	0.01	6.51
1	Iceland	64.87	34.74	0.01	4.64	North Korea	98.02	81.73	−0.01	13.34
1	Poland	72.24	42.12	−0.01	7.42	South Korea	96.36	80.08	−0.02	13.79
1	Czechia	88.14	58.01	0.01	12.12	Japan	62.78	46.49	−0.06	6.45

TABLE AX
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (ONSHORE) GLOBALLY AT LEVEL 1 (PART I) (CONTINUED)

Level	Name	Original Power Series		Ramping Rate Series		Name	Original Power Series		Ramping Rate Series	
		CV (%)	Reduction	STD (%)	Reduction'		CV (%)	Reduction	STD (%)	Reduction'
1	Slovakia	97.61	67.48	0.00	15.21	Kazakhstan	44.08	27.79	−0.38	3.83
1	Hungary	96.53	66.40	0.03	15.00	Uzbekistan	59.76	43.47	−0.19	7.47
1	Romania	80.29	50.17	−0.01	10.07	Tajikistan	108.41	92.12	0.00	23.76
1	Bulgaria	94.31	64.18	0.01	12.35	Kyrgyzstan	110.05	93.76	−0.01	26.36
1	Italy	88.60	58.47	0.03	6.91	Turkmenistan	63.63	47.34	−0.21	9.00
1	Slovenia	130.46	100.33	0.01	23.88	Afghanistan	63.38	47.10	−0.03	5.81
1	Croatia	101.56	71.43	0.02	14.55	India	69.86	53.57	0.00	8.67
1	Bosnia and Herz.	140.68	110.55	0.00	21.95	Pakistan	64.33	48.05	0.02	7.86
1	Serbia	105.91	75.78	0.01	16.55	Bangladesh	115.53	99.24	0.00	17.49
1	Greece	84.89	54.76	0.00	8.43	Bhutan	197.80	181.52	0.00	67.51
1	Albania	151.17	121.05	0.00	26.83	Nepal	136.49	120.20	0.00	31.22
1	Macedonia	178.02	147.90	0.00	40.81	Sri Lanka	81.98	65.69	0.00	7.30
1	Kosovo	156.66	126.53	0.00	38.46	Cambodia	102.63	86.34	0.02	16.36
1	Montenegro	180.89	150.76	0.00	34.73	Thailand	91.96	75.67	0.03	13.16
1	RU_Central	67.87	37.74	−0.19	6.01	Laos	108.12	91.83	0.01	15.88
1	RU_Volga	59.29	29.16	−0.18	4.62	Myanmar	92.68	76.39	0.01	12.62
1	RU_Northwestern_E	49.80	19.68	−0.18	2.33	Vietnam	72.52	56.24	0.03	8.82
1	RU_Northwestern_W	54.80	24.67	0.03	3.14	Philippines	100.45	84.17	0.03	9.48
1	RU_Southern_Caucasian	63.18	33.06	0.04	6.11	Malaysia	129.31	113.03	0.00	22.96
1	Ukraine	64.02	33.89	−0.06	5.81	Indonesia	69.30	53.01	−0.03	7.70
1	Belarus	76.86	46.73	−0.03	8.56	Iran	63.28	46.99	−0.03	7.37
1	Georgia	75.60	45.47	0.00	10.71	Iraq	64.82	48.54	0.07	8.55
1	Gansu	67.64	51.35	−0.03	9.58	Israel	118.09	101.80	0.01	25.96
1	Ningxia	93.97	77.68	−0.01	18.01	Jordan	77.94	61.66	−0.01	15.33
1	Qinghai	75.33	59.04	−0.05	14.95	Kuwait	77.82	61.53	0.00	15.72
1	Shaanxi	93.20	76.92	−0.01	16.15	Lebanon	163.96	147.67	0.00	25.89
1	Xinjiang	62.56	46.27	0.04	6.50	Oman	67.77	51.48	0.00	9.73
1	Beijing	145.95	129.66	0.00	38.85	Qatar	98.31	82.02	0.00	14.91
1	Hebei	73.32	57.03	−0.02	11.27	Saudi Arabia	44.38	28.09	0.39	8.53
1	Inner Mongolia	50.73	34.44	−0.01	5.82	Syria	79.57	63.28	−0.01	10.43
1	Shandong	84.75	68.46	−0.06	13.02	United Arab Emirates	85.16	68.87	0.00	16.77
1	Shanxi	115.23	98.94	0.00	19.80	Yemen	61.09	44.80	−0.03	12.82
1	Tianjin	103.06	86.78	0.00	26.28	Turkey	75.10	58.81	0.02	9.12
1	Heilongjiang	71.38	55.09	−0.10	9.21	Palestine	166.61	150.32	0.00	40.96
1	Jilin	80.99	64.71	−0.02	12.14	RU_Ural_N	48.93	32.65	0.00	2.74
1	Liaoning	77.49	61.20	−0.04	11.64	RU_Ural_S	58.04	41.76	0.10	4.83

Note: 1) 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global. 2) Reduction is calculated by the CV of Continent minus that of Country, e.g., the CV of Germany (onshore) is 71.77% and the CV of corresponding continent Europe is 30.13%, thus the difference is 41.65%. 3) Reduction' is calculated by the STD of Continent minus that of Country.

TABLE AXI
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (ONSHORE) GLOBALLY AT LEVEL 1 (PART II)

Level	Name	Original Power Series		Ramping Rate Series		Name	Original Power Series		Ramping Rate Series	
		CV (%)	Reduction	STD (%)	Reduction'		CV (%)	Reduction	STD (%)	Reduction'
1	RU_Siberian_W	67.56	51.27	0.05	6.03	British Columbia	73.90	50.73	−0.02	7.19
1	RU_Siberian_E	71.86	55.57	0.03	7.99	Ontario	47.59	24.42	−0.05	3.96
1	RU_Siberian_N	45.95	29.67	−0.30	1.52	Quebec	45.52	22.35	−0.13	2.01
1	RU_FarEastern_NW	47.69	31.40	−0.28	2.41	New Brunswick	70.80	47.63	0.02	8.74
1	RU_FarEastern_L	54.30	38.01	−0.34	3.66	Prince Edward Island	57.22	34.05	0.00	8.53
1	RU_FarEastern_U	59.95	43.66	−0.15	1.96	Nova Scotia	61.63	38.46	0.01	6.00
1	Connecticut	89.97	66.80	0.00	18.86	Newfoundland and Labrador	45.92	22.75	0.02	2.71
1	Maine	72.44	49.27	0.02	9.79	USA_Alaska	50.25	27.08	0.30	1.58
1	Massachusetts	76.52	53.35	0.00	13.51	CA_Yukon	81.53	58.36	−0.06	7.46
1	New Hampshire	90.90	67.73	0.01	16.85	CA_Northwest	52.04	28.87	0.28	3.12
1	Rhode Island	81.26	58.09	0.00	17.50	CA_Nunavut	47.61	24.44	−0.08	2.09
1	Vermont	95.77	72.60	0.00	16.78	Mexico	53.14	29.97	−0.41	7.06
1	New York	75.18	52.01	−0.04	9.83	Egypt	50.44	25.05	0.17	4.12
1	Delaware	91.67	68.50	0.00	20.07	Libya	45.66	20.26	−0.16	4.05
1	Maryland	87.10	63.94	0.00	14.90	Algeria	45.83	20.44	0.44	3.01
1	New Jersey	90.08	66.91	0.00	18.03	Morocco	41.28	15.88	0.06	1.78
1	Ohio	83.27	60.10	−0.06	13.06	Tunisia	70.67	45.28	0.03	6.72
1	Pennsylvania	83.87	60.70	−0.03	13.58	Dem. Rep. Congo	91.14	65.75	0.06	14.51
1	West Virginia	99.16	75.99	−0.02	18.47	Angola	82.76	57.37	0.10	15.33
1	Virginia	88.63	65.46	0.00	14.91	Zimbabwe	77.76	52.36	−0.04	10.52
1	North Carolina	88.23	65.06	0.03	14.72	Botswana	65.72	40.32	0.08	8.42
1	South Carolina	92.50	69.33	0.00	16.79	Namibia	56.22	30.83	0.33	7.88
1	Alabama	99.23	76.06	−0.03	18.10	Zambia	81.52	56.13	−0.06	11.45
1	US_Georgia	96.77	73.60	−0.05	17.46	Mozambique	58.64	33.25	−0.06	5.72
1	Florida	87.11	63.94	−0.03	11.30	South Africa	55.01	29.62	0.37	4.71
1	Tennessee	101.12	77.95	−0.04	18.36	Tanzania	71.80	46.41	−0.13	9.57

TABLE AXI
CV OF WIND POWER SERIES AND STD OF WIND POWER RAMPING RATE (ONSHORE) GLOBALLY AT LEVEL 1 (PART II) (CONTINUED)

Level	Name	Original Power Series		Ramping Rate Series		Name	Original Power Series		Ramping Rate Series	
		CV (%)	Reduction	STD (%)	Reduction’		CV (%)	Reduction	STD (%)	Reduction’
1	Kentucky	97.89	74.72	−0.04	16.53	Somalia	52.92	27.52	0.07	0.48
1	Illinois	79.54	56.37	−0.04	13.14	Sudan	48.01	22.62	0.09	3.75
1	Indiana	82.19	59.02	−0.04	14.30	S. Sudan	91.23	65.84	0.05	13.30
1	Iowa	68.52	45.35	−0.06	10.69	Ethiopia	58.24	32.85	0.00	2.84
1	Michigan	65.02	41.85	0.00	6.81	Kenya	51.63	26.24	−0.08	3.83
1	Minnesota	67.35	44.18	−0.04	9.17	Chad	49.52	24.12	0.03	2.13
1	Missouri	78.80	55.63	−0.07	13.11	Cameroon	82.85	57.46	0.03	14.57
1	North Dakota	61.08	37.91	−0.08	8.59	Congo	78.86	53.46	0.01	15.78
1	South Dakota	55.94	32.77	−0.08	7.87	Central African Rep.	108.20	82.80	0.05	16.70
1	Wisconsin	74.00	50.83	−0.01	10.60	Mali	58.03	32.64	0.32	5.65
1	Arkansas	91.37	68.21	0.00	15.73	Mauritania	47.62	22.23	0.26	3.71
1	Louisiana	88.51	65.34	0.01	12.47	Niger	54.13	28.74	0.22	4.11
1	Mississippi	99.72	76.55	−0.01	18.89	Nigeria	78.12	52.73	0.06	11.52
1	Kansas	62.87	39.70	−0.06	10.78	Guinea	73.87	48.48	0.03	10.00
1	Nebraska	57.94	34.77	−0.12	9.80	Ghana	78.16	52.77	0.09	13.48
1	Oklahoma	61.91	38.74	0.02	9.60	Australia	38.22	–	−0.95	–
1	Texas	54.86	31.69	0.08	7.80	Guatemala	83.69	59.31	−0.03	15.71
1	Arizona	103.74	80.57	−0.02	14.70	Honduras	75.62	51.24	−0.01	7.50
1	New Mexico	62.49	39.32	−0.11	9.99	Panama	124.89	100.52	0.00	12.26
1	Colorado	63.54	40.37	−0.09	12.61	Colombia	84.18	59.81	−0.12	12.91
1	Idaho	89.66	66.49	0.00	13.33	Venezuela	66.58	42.20	−0.01	9.33
1	Montana	64.82	41.65	−0.07	9.21	Guyana	76.71	52.33	0.00	15.39
1	Nevada	108.64	85.47	0.00	18.07	Guyane	74.41	50.03	0.01	16.65
1	Oregon	93.08	69.91	−0.01	11.94	Suriname	72.72	48.34	0.01	16.58
1	Utah	106.83	83.66	−0.01	15.76	Ecuador	67.77	43.39	0.00	15.66
1	Washington	97.77	74.60	0.01	12.23	Peru	62.89	38.52	0.00	10.81
1	Wyoming	57.62	34.45	−0.11	7.62	Bolivia	79.29	54.92	0.22	8.68
1	California	83.90	60.73	−0.02	10.80	Brazil	47.74	23.37	−0.18	3.84
1	Manitoba	47.98	24.81	0.03	3.75	Chile	36.77	12.40	−0.01	1.08
1	Saskatchewan	61.35	38.18	0.00	7.00	Argentina	36.70	12.32	0.38	1.47
1	Alberta	68.51	45.34	−0.02	8.35	Uruguay	67.65	43.27	−0.01	8.80
1						Paraguay	80.75	56.38	0.01	9.11

Note: 1) 1-Country/Province/State, 2-Sub-region, 3-Region, 4-Continent, 5-Inter-continent, 6-Global. 2) Reduction is calculated by the CV of Continent minus that of Country, e.g., the CV of Germany is 71.77% (onshore) and the CV of corresponding continent Europe is 30.13%, thus the difference is 41.65%. 3) Reduction’ is calculated by the STD of Continent minus that of Country.

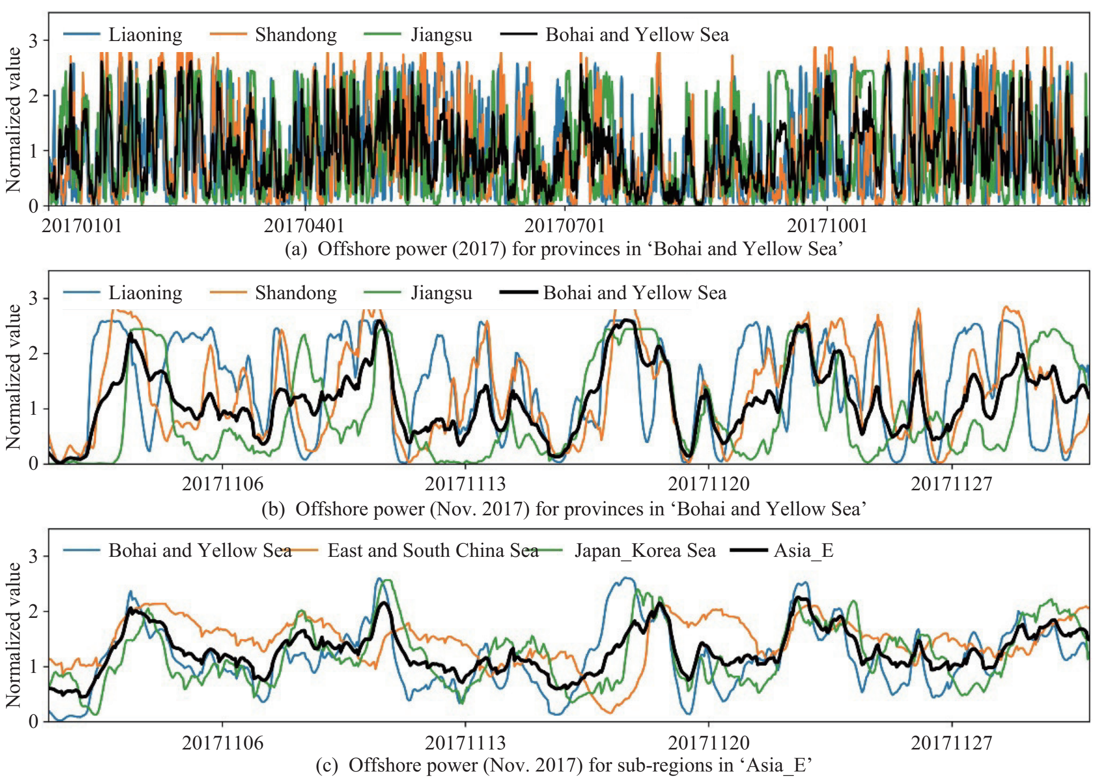
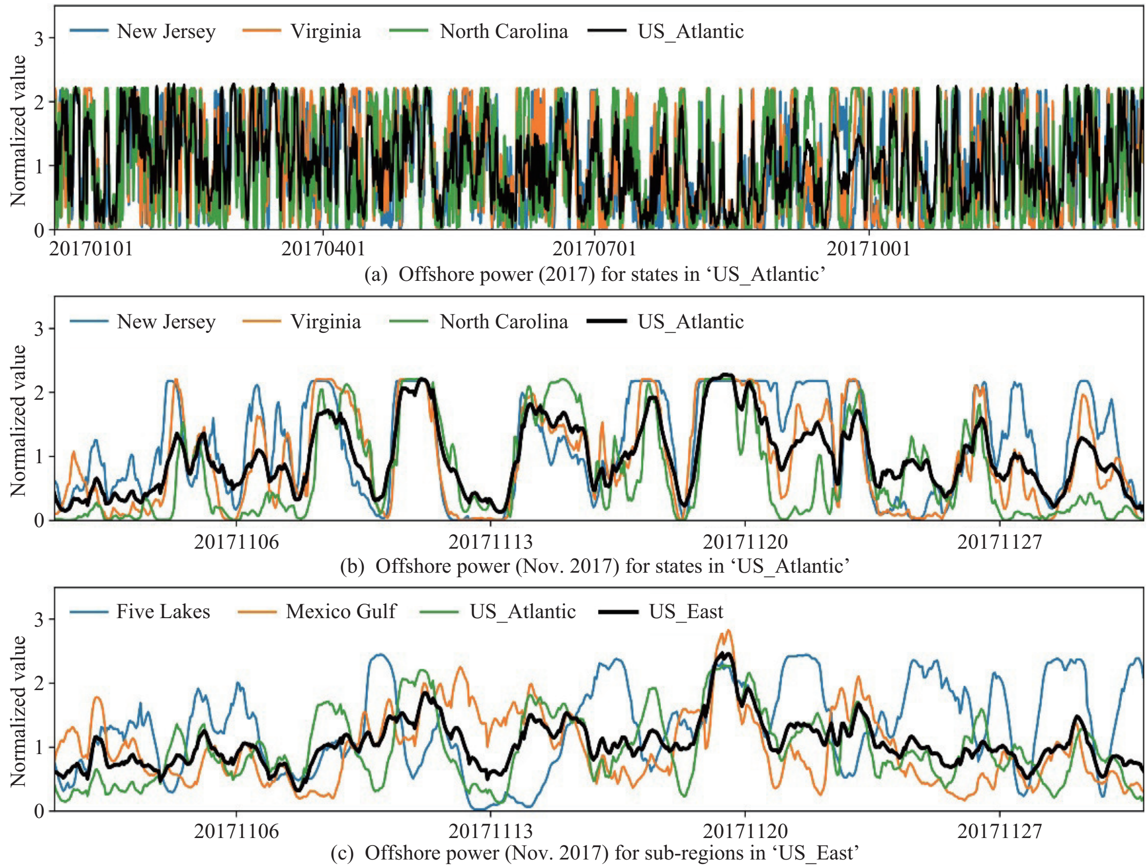


Fig. A1. Offshore wind power series of selected provinces/sub-regions within region Asia_E.



(a) Offshore power (2017) for states in 'US_Atlantic'

(b) Offshore power (Nov. 2017) for states in 'US_Atlantic'

(c) Offshore power (Nov. 2017) for sub-regions in 'US_East'

Fig. A2. Offshore wind power series of selected states/sub-regions within region US_East.

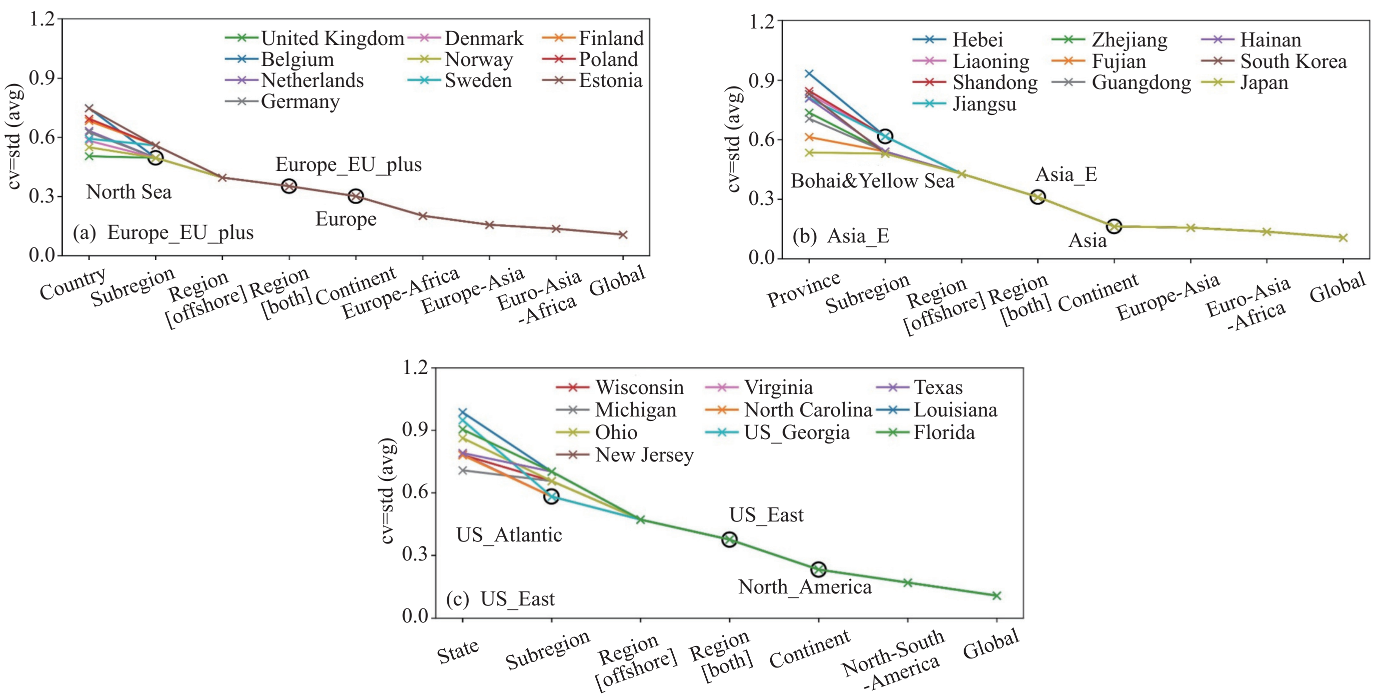


Fig. A3. CV of 7-year offshore power series for three typical regions at different aggregation levels.

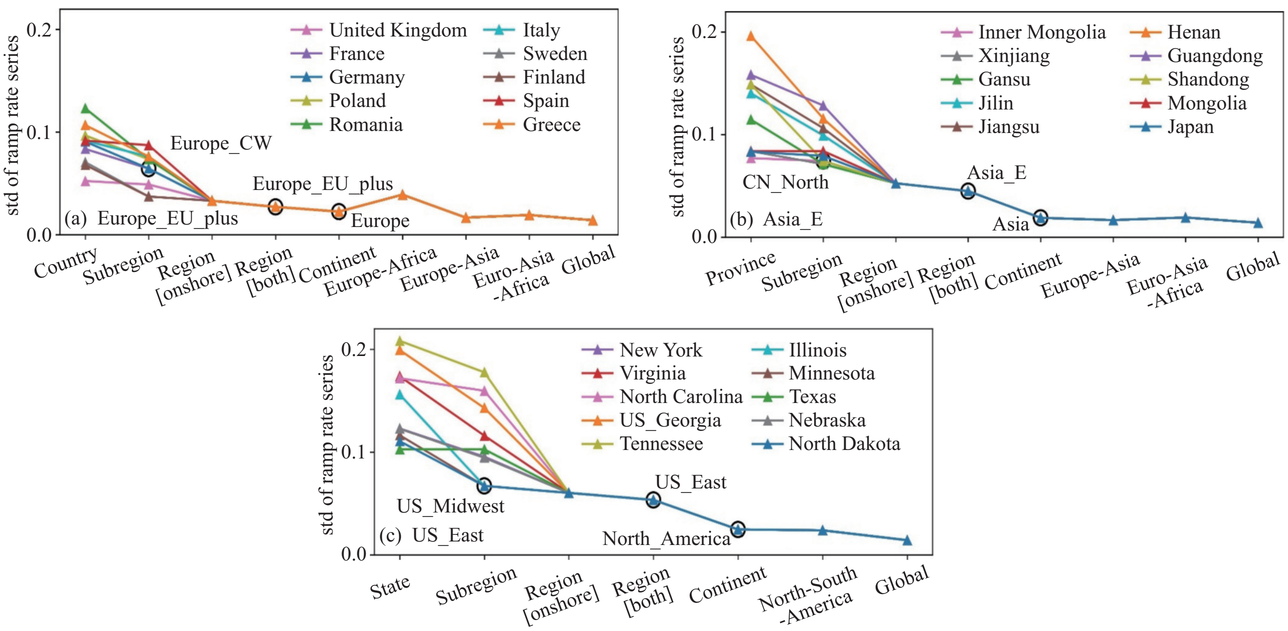
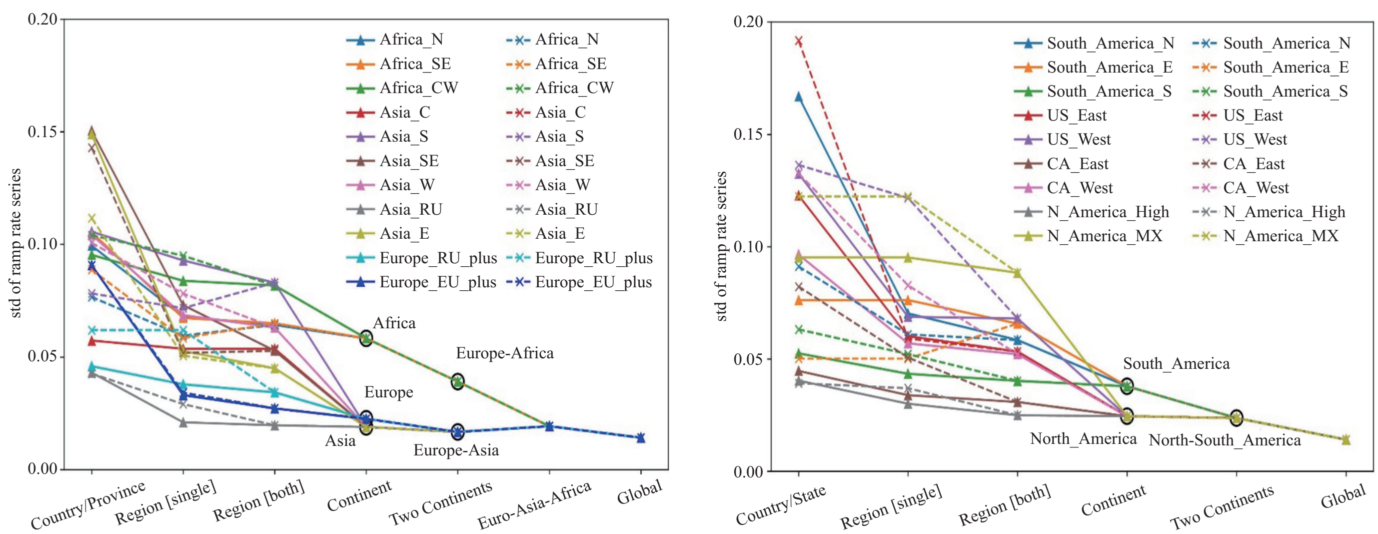


Fig. A4. CV of onshore ramping power series for three typical regions at different aggregation levels.



(a) Regions in Europe, Asia and Africa

(b) Regions in North_America and South_America

Fig. A5. CV of 7-year onshore ramping power series for all regions at different aggregation levels.

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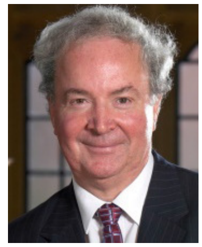

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