Supplementary Information

Inherent Spatiotemporal Uncertainty of Renewable Power in China

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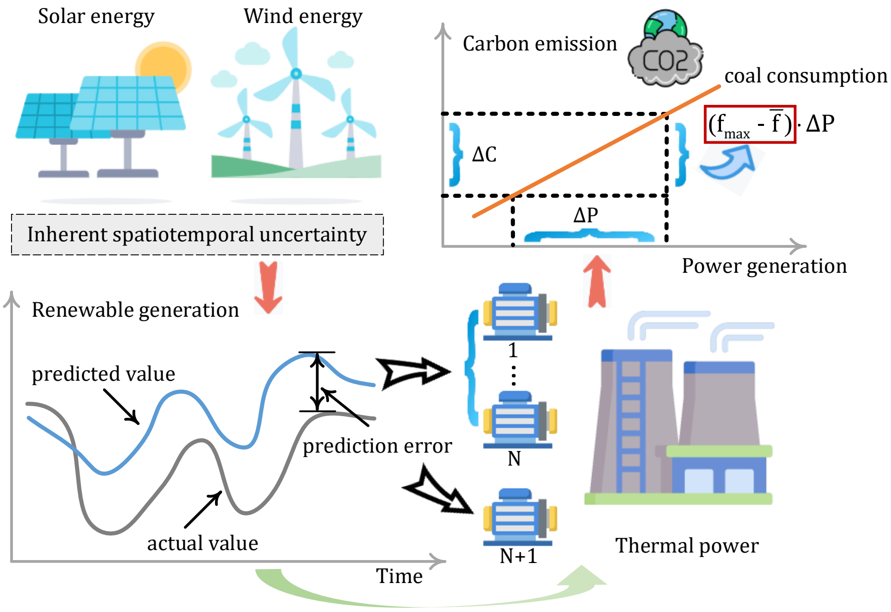
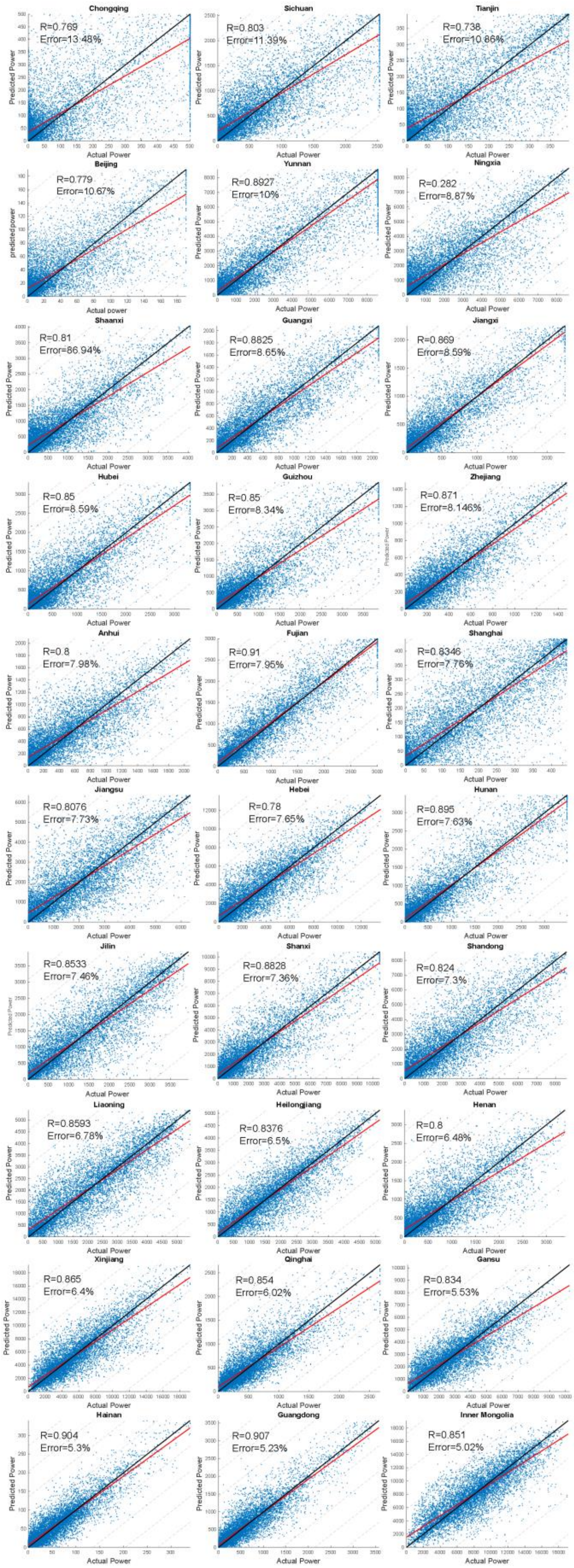
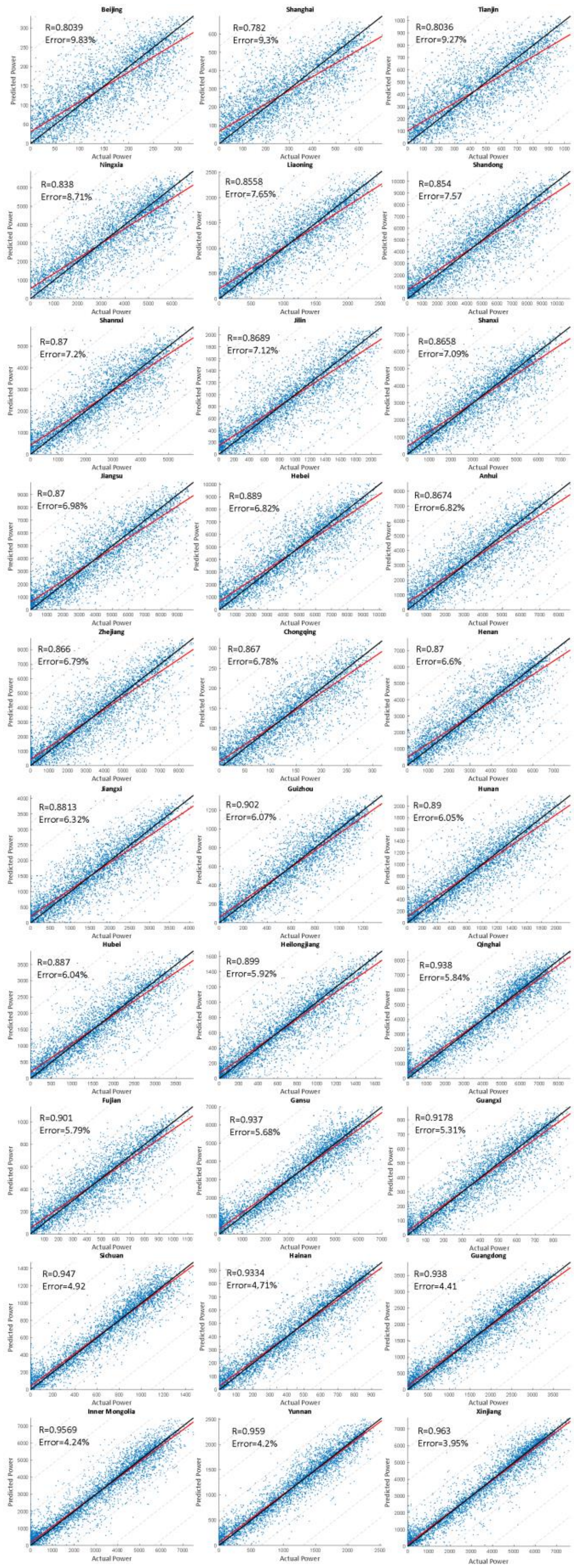


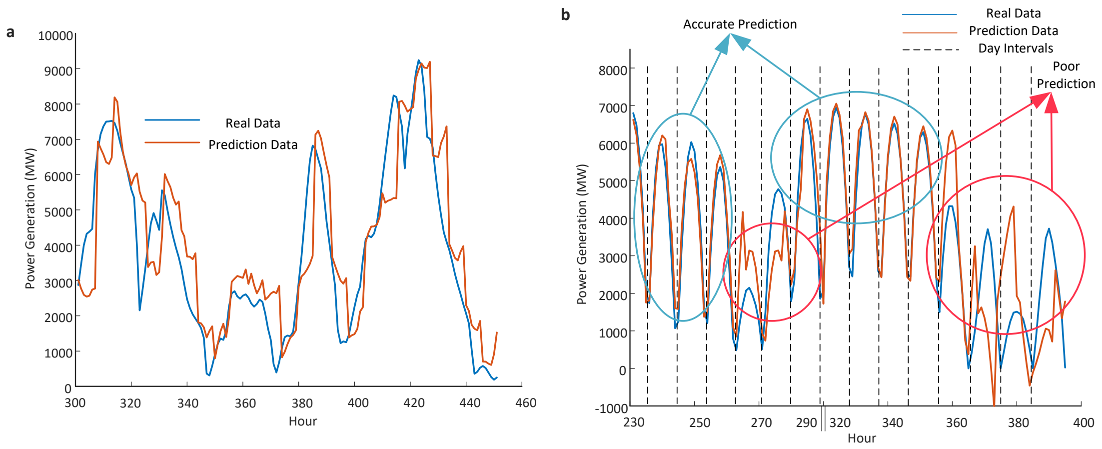
Supplementary Figure 1. Additional carbon emissions caused by renewable prediction errors. The uncertainty of renewable energy forces the power system operator to start on (N+1)st generator (even N+2, N+3, etc.) at the minimal output level to provide spinning reserve capacity, where "N" denotes the number of the marginal generator satisfying the last-MWh electric load. Due to load balance constraints, the (N+1)st generator would lead to additional carbon emissions since this unit is of stronger carbon intensity. Here we make an aggressive estimation of a province's additional carbon emissions from renewable prediction errors as $(f_{\max} - \bar{f}) \times \Delta P$, where $f_{\max}$ denotes the maximum of provincial thermal plants' carbon emission rates; $\bar{f}$ is provincial average carbon emission rate of thermal power plants; and ΔP is the renewable energy deviation caused by the average prediction error.



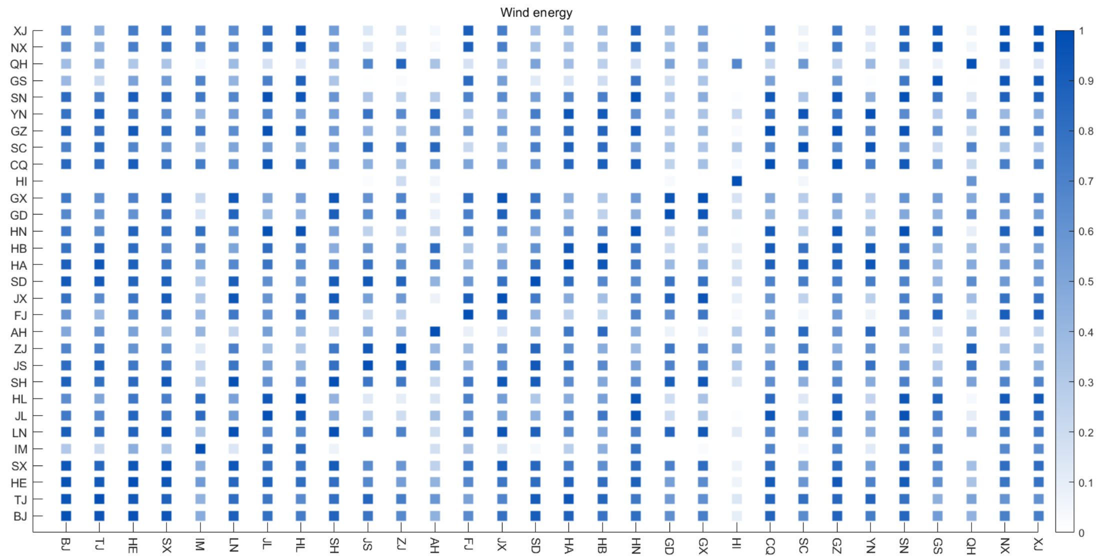
Supplementary Figure 2. Wind prediction error analysis of 30 provinces of China.



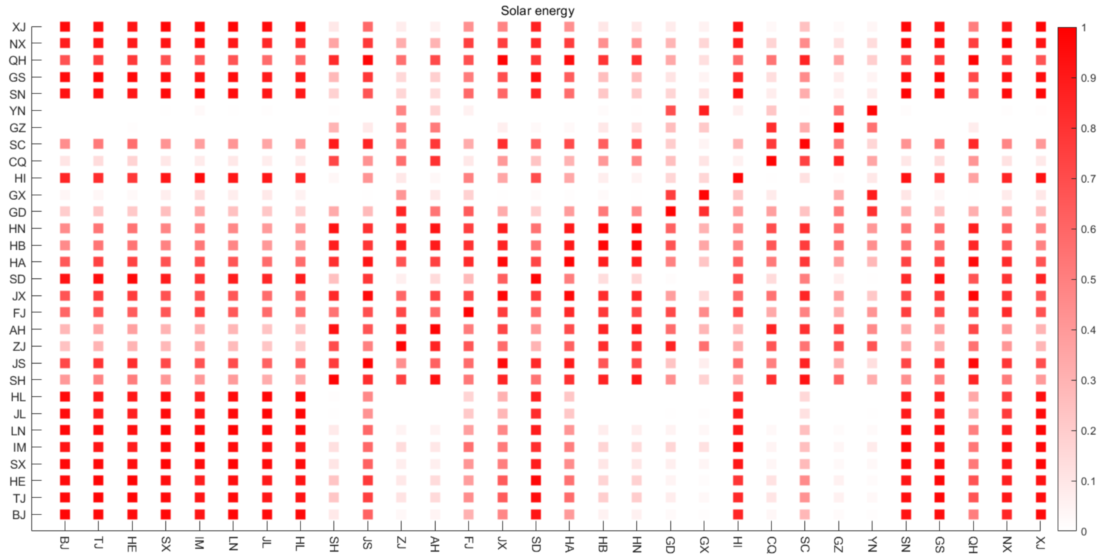
Supplementary Figure 3. Solar prediction error analysis of 30 provinces of China.



Supplementary Figure 4. Analysis of different wind and solar power generation characteristics. **a**, Wind power generation of Shanxi (SX) Province from 300~450 hours (total is 8760 hours) in 2018. **b**, Solar energy generation of SX from 230~290 hours and 320~400 hours. The black dot line separates each day in the time horizon, and the short vertical line in the Hour axis indicates the abruption, the data from 290~320 hour is ignored due to the similar distribution with other parts.



Supplementary Figure 5. Correlation of wind prediction error between provinces.



Supplementary Figure 6. Correlation of solar prediction error between provinces.

Supplementary Tables

Supplementary Table 1 Data Distribution for each interval of the box diagram in Fig. 4

Province	Interval	Max value	Min value	Average value
Beijing wind	1	0.205	0	0.074
	2	0.281	0	0.097
	3	0.376	0	0.121
	4	0.468	0	0.141
	5	0.504	0	0.151
	6	0.606	0	0.178
	7	0.640	0	0.187
	8	0.681	0	0.202
	9	0.741	0	0.218
	10	0.740	0	0.227
	Total	0.741	0	0.227
Guizhou wind	1	0.157	0	0.050
	2	0.180	0	0.066
	3	0.267	0	0.088
	4	0.370	0	0.119
	5	0.449	0	0.150
	6	0.546	0	0.186
	7	0.574	0	0.174
	8	0.477	0	0.174
	9	0.691	0	0.209
	10	0.423	0	0.162
	Total	0.691	0	0.209
Fujian wind	1	0.132	0	0.046
	2	0.216	0	0.071
	3	0.257	0	0.083
	4	0.275	0	0.090
	5	0.298	0	0.097
	6	0.380	0	0.123
	7	0.336	0	0.117
	8	0.388	0	0.124
	9	0.375	0	0.132
	10	0.265	0	0.097
	Total	0.388	0	0.132
Inner Mongolia wind	1	0.169	0	0.053
	2	0.160	0	0.051
	3	0.153	0	0.048
	4	0.154	0	0.049
	5	0.159	0	0.049
	6	0.197	0	0.061
	7	0.168	0	0.086
	8	0	0	0
	9	0	0	0
	10	0	0	0
	Total	0.197	0	0.086
Beijing solar	1	0.313	0	0.098
	2	0.288	0	0.099
	3	0.276	0	0.088
	4	0.333	0	0.100

	5	0.293	0	0.097
	6	0.283	0	0.096
	7	0.327	0	0.101
	8	0.331	0	0.117
	9	0.463	0	0.144
	10	0	0	0
	Total	0.463	0	0.144
Jilin solar	1	0.171	0	0.064
	2	0.171	0	0.065
	3	0.182	0	0.063
	4	0.192	0	0.065
	5	0.219	0	0.075
	6	0.244	0	0.081
	7	0.261	0	0.095
	8	0.280	0	0.090
	9	0	0	0
	10	0	0	0
	Total	0.280	0	0.090
Chongqing solar	1	0.160	0	0.054
	2	0.176	0	0.058
	3	0.206	0	0.067
	4	0.227	0	0.070
	5	0.238	0	0.072
	6	0.251	0	0.083
	7	0.267	0	0.093
	8	0.199	0	0.109
	9	0	0	0
	10	0	0	0
	Total	0.267	0	0.109
Inner Mongolia solar	1	0.093	0	0.035
	2	0.095	0	0.038
	3	0.115	0	0.040
	4	0.156	0	0.051
	5	0.138	0	0.043
	6	0.148	0	0.046
	7	0.161	0	0.050
	8	0.219	0	0.058
	9	0	0	0
	10	0	0	0
	Total	0.219	0	0.058

Supplementary Table 2 Detailed ARIMA parameters for each province

Province	Wind energy			Solar energy		
	p	q	d	p	q	d
BJ	6	7	1	8	8	1
TJ	6	6	1	8	9	1
HE	9	8	1	9	7	1
SX	6	7	1	9	8	1
IM	9	9	1	9	8	1
LN	9	9	1	9	9	1
JL	9	8	1	9	8	1
HL	7	9	1	9	9	1
SH	7	7	1	7	8	1
JS	6	9	1	9	8	1
ZJ	6	8	1	9	6	1
AH	9	6	1	9	9	1
FJ	8	7	1	9	9	1
JX	9	9	1	9	9	1
SD	8	8	1	9	7	1
HA	6	9	1	9	8	1
HB	9	8	1	9	9	1
HN	6	7	1	8	9	1
GD	7	6	1	9	8	1
GX	7	9	1	9	9	1
HI	6	9	1	9	9	1
CQ	9	6	1	9	6	1
SC	9	6	1	9	8	1
GZ	6	6	1	9	9	1
YN	8	6	1	9	9	1
SN	8	9	1	9	9	1
GS	8	8	1	7	9	1
QH	6	9	1	9	8	1
NX	8	6	1	9	7	1
XJ	8	6	1	9	9	1

Supplementary Table 3 Peak ratios in each power generation interval

Interval	Wind energy		Solar energy	
	Peaks' ratio of provinces with large prediction error	Peaks' ratio of provinces with low prediction error	Peaks' ratio of provinces with large prediction error	Peaks' ratio of provinces with low prediction error
1	0.032	0.025	0.001	0.000
2	0.045	0.025	0.007	0.002
3	0.058	0.030	0.019	0.005
4	0.066	0.029	0.038	0.021
5	0.073	0.030	0.064	0.058
6	0.076	0.052	0.135	0.155
7	0.076	0.050	0.240	0.240
8	0.076	0.015	0.408	0.000
9	0.101	0.099	0.000	0.000
10	0.032	0.025	0.000	0.000

Note 1: The provinces with large prediction error includes the first three groups, i.e., prediction error larger than 6.5% for wind energy and larger than 6% for solar energy, and provinces with low prediction error includes the last group, i.e., prediction error lower than 6.5% for wind energy and lower than 6% for solar energy. The ratio is the average value of all provinces.

Note 2: In provinces with large prediction error, the peaks' ratio is higher in high power generation interval, while in provinces with low prediction error, the peaks' ratio distributes evenly in each interval. The phenomenon is more obvious for wind energy. The reason is that there are fewer data points for solar energy since power generation is zero for nearly half of the day, so the difference in the peaks' distribution is less significant

Supplementary Note 1: Abbreviation of 30 provinces in China

This study focusses on 30 provinces of China, excepting Xizang, Taiwan, Hong Kong, and Macao province, due to the data limited and unsuitable to build wind energy, including: Beijing (BJ), Tianjin (TJ), Hebei (HE), Shanxi (SX), Inner Mongolia (IM), Liaoning (LN), Jilin (JL), Heilongjiang (HL), Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Anhui (AH), Fujian (FJ), Jiangxi (JX), Shandong (SD), Henan (HA), Hubei (HB), Hunan (HN), Guangdong (GD), Guangxi (GX), Hainan (HI), Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN), Shaanxi (SN), Gansu (GS), Qinghai (QH), Ningxia (NX), Xinjiang (XJ).

Supplementary Note 2: Detailed content of each category divided by prediction error

We divide four categories for wind and solar energy, respectively, according to the prediction error. For the wind energy, the four categories and their content are expressed as follows:

i) >9.5%, including CQ, SC, TJ, BJ, YN;

ii) 8%~9.5%, including NX, SN, GX, JX, HB, GZ, ZJ;

iii) 6.5%~8%, including AH, FJ, SH, JS, HE, HN, JL, SX, SD;

iv) <6.5%, including LN, HL, HA, XJ, QH, GS, HI, GD, IM.

For solar energy, the four categories and their content are expressed as follow:

i) >8%, including BJ, SH, TJ, NX;

ii) 7%~8%, including LN, SD, SN, JL, SX;

iii) 6%~7%, including JS, HE, AH, ZJ, CQ, HA, JX, GZ, HN, HB;

iv) <6%, including HL, QH, FJ, GS, GX, SC, HI, GD, IM, YN, XJ.

Supplementary Note 3: Detailed content of North, East, Central, and Southeast area of China

To analyze the nationwide distribution of prediction error, we specify four areas of China, which is shown as follows:

i) North area of China: BJ, TJ, LN, SD, JL, SX, HE;

ii) East area of China: SH, JS, AH, ZJ;

iii) Central area of China: NX, SN, HA, HB, JX, HN;

iv) Southeast area of China: CQ, SC, YN, GX, GZ.

Supplementary Note 4: Explanation of hourly wind energy and daily solar energy

We analyze the data feature, concluding the characteristic of wind and solar output: the wind output fluctuates greatly, and presents irregular distribution on the hourly scale, while the solar output distribute regularly in daily scale, increasing from average 2000MW to average 6000MW, then drop to average 2000MW in a day, as shown in Supplementary Fig. 3, after excluding the near zero output of solar energy (The reason is that the solar output is near zero at nighttime, which is unnecessary to predict and will greatly affect the prediction results). These differences are attributed to the properties of sun and wind, with irregular wind throughout the day, while the sun rise and sets each day, and its radiation varies accordingly. Based on these characteristics, hourly prediction for solar power is more accuracy than wind power most of the time. The reason for the inaccurate solar energy prediction is the difference between each day. For example, the peak of several consecutive days (230-263 hour in Fig. 3b), with the difference within 1000MW, drops to a lower peak (264-272 hour in Fig. 3b), with the difference more than 3500MW (such as cloudy days), and the average prediction error also increase from 3.86% to 12.79%. Thus, the solar power fluctuation that affects prediction should be seen from the daily scale. In this work, we use hourly power generation data and daily power generation data to analyze the wind and solar prediction error, respectively.