COBEM 2021
26th International Congress of Mechanical Engineering

An Improved Ensemble Learning Model for Multi-Step Ahead Wind Power Generation Forecasting

COBEM2021-0166

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Wind Power Data Set

- 15 Wind Turbines (WT);
- 2000kW rated power each;
- Rotor Diameter 90m;
- Rotor height 80m;
- August, 1st up to November, 20th, 2020;
- Installed Capacity 30000kW.

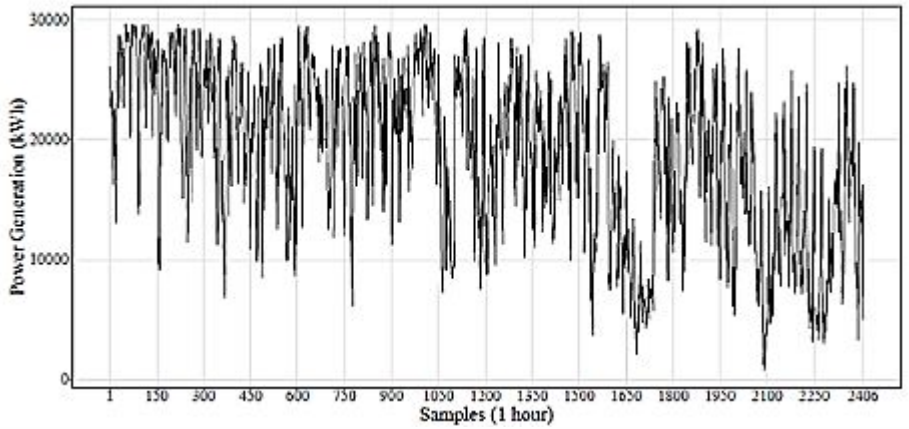


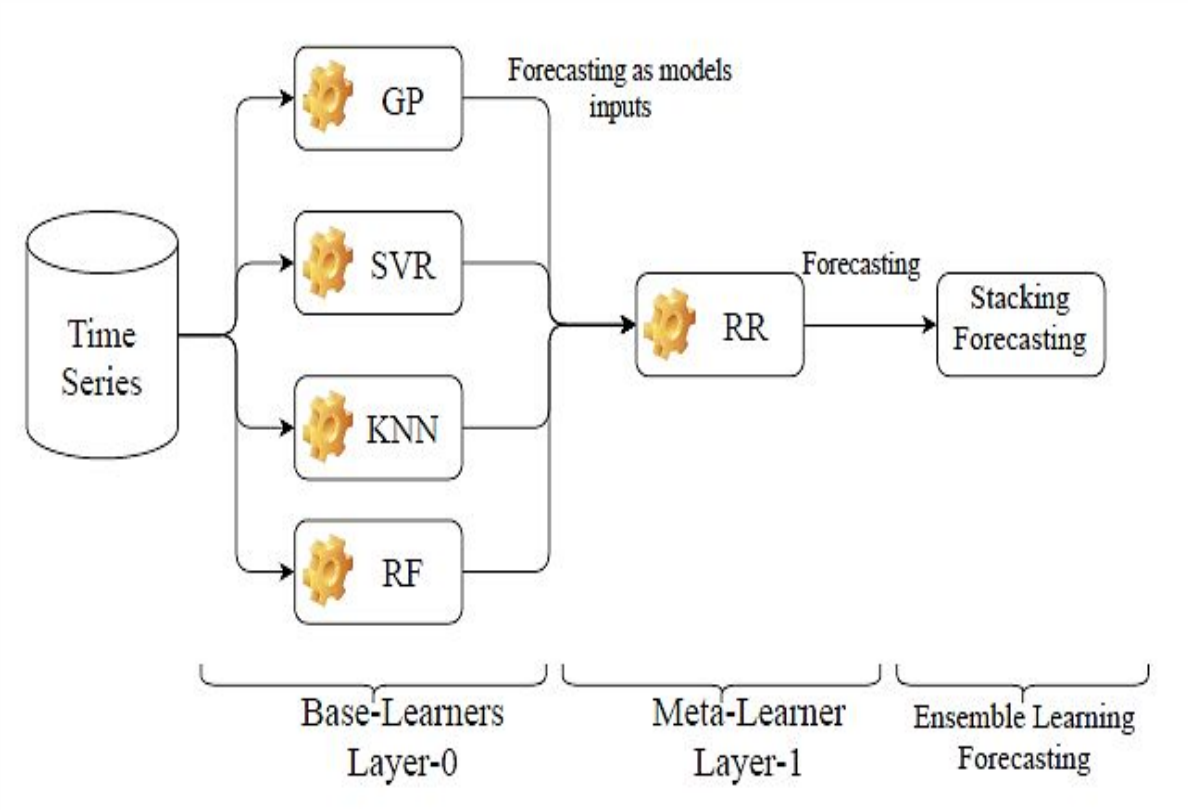
Table 1: Statistical indicators of wind power generation time series.

Dataset	Statistical Indicator					
	Minimum	Median	Mean	Maximum	Standard Deviation	# Samples
Whole	810.88	20093.76	19079.59	29627.22	6889.61	2406
Training	2108.69	22335.07	21100.39	29627.22	6000.78	1684
Test	810.88	14200.27	14366.25	29146.23	6518.65	722

Proposed Method

Stacking Learning Ensemble

- Base Learners Layer-0:
  - Gaussian process (GP);
  - Support Vector Regression with linear kernel (SVR);
  - k-Nearest Neighbor (kNN); and
  - Random Forests (RF).
- Meta Learner Layer-1
  - Ridge Regression (RR)
- Forecasting Horizon
  - 1 up to 12 hours-ahead
- Metrics
  - Root Mean Squared Error (RMSE);
  - Normalized RMSE (nRMSE);
  - Mean Absolute Error (MAE); and
  - Theil's U Index (UT)



Results and Conclusion

Table 2: Performance measures of compared models for wind power generation forecasting.

Forecasting Horizon	Criteria	Stack	Stack + 10 Bootstraps		Stack + 30 Bootstraps		Stack + 50 Bootstraps		Stack + 100 Bootstraps	
		Original	Average	Median	Average	Median	Average	Median	Average	Median
1	RMSE	**2828.28**	3263.56	3269.56	3282.41	3281.12	3249.62	3247.45	3234.27	3230.37
	nRMSE	**19.69%**	22.72%	22.76%	22.85%	22.84%	22.62%	22.60%	22.51%	22.49%
	MAE	**2143.38**	2658.33	2654.99	2666.80	2667.84	2650.65	2645.63	2624.77	2616.27
	UT	**0.1757**	0.2088	0.2082	0.2104	0.2096	0.2084	0.2073	0.2073	0.2061
2	RMSE	3619.77	3627.37	3633.27	3619.22	3601.62	3615.68	3614.11	3589.65	**3587.29**
	nRMSE	25.20%	25.25%	25.29%	25.19%	25.07%	25.17%	25.16%	24.99%	**24.97%**
	MAE	**2794.92**	2948.79	2953.97	2950.43	2935.89	2953.71	2949.19	2927.37	2919.55
	UT	**0.2228**	0.2309	0.2305	0.2309	0.2293	0.2308	0.2296	0.2290	0.2279
3	RMSE	3965.14	3843.91	3831.81	3847.81	3832.02	3851.32	3850.22	3819.64	**3816.36**
	nRMSE	27.60%	26.76%	26.67%	26.78%	26.67%	26.81%	26.80%	26.59%	**26.56%**
	MAE	**3106.56**	3150.51	3149.94	3133.94	3112.65	3156.10	3149.30	3121.94	3116.57
	UT	0.2442	0.2446	0.2431	0.2457	0.2443	0.2456	0.2448	0.2436	**0.2426**
4	RMSE	4299.16	4038.70	4020.25	4036.19	4021.39	4031.32	4024.26	4017.22	**4015.05**
	nRMSE	29.93%	28.11%	27.98%	28.09%	27.99%	28.06%	28.01%	27.96%	**27.95%**
	MAE	3439.89	3307.92	3306.61	3281.34	**3268.64**	3303.48	3291.35	3287.81	3285.06
	UT	0.2655	0.2571	0.2558	0.2574	0.2561	0.2576	0.2559	0.2563	**0.2554**
5	RMSE	4745.92	4311.46	4298.85	4253.71	**4237.61**	4262.42	4267.57	4275.31	4279.48
	nRMSE	33.04%	30.01%	29.92%	29.61%	**29.50%**	29.67%	29.71%	29.76%	29.79%
	MAE	3753.23	3563.41	3553.66	3485.50	**3472.47**	3524.86	3523.52	3523.55	3519.53
	UT	0.2857	0.2705	0.2694	0.2679	**0.2666**	0.2676	0.2672	0.2679	0.2673
6	RMSE	4980.08	4431.71	4422.91	4407.80	4396.45	4405.82	4414.56	**4380.39**	4381.94
	nRMSE	34.67%	30.85%	30.79%	30.68%	30.60%	30.67%	30.73%	**30.49%**	30.50%
	MAE	4068.44	3629.18	3630.24	3600.70	3583.04	3613.53	3615.79	3588.88	**3580.12**
	UT	0.3048	0.2845	0.2830	0.2844	0.2834	0.2834	0.2831	0.2813	**0.2807**

Table 3: Performance measures of compared models for wind power generation forecasting.

Forecasting Horizon	Criteria	Stack	Stack + 10 Bootstraps		Stack + 30 Bootstraps		Stack + 50 Bootstraps		Stack + 100 Bootstraps	
		Original	Average	Median	Average	Median	Average	Median	Average	Median
7	RMSE	5270.26	4617.50	4628.60	**4533.12**	4542.79	4580.91	4594.23	4581.73	4559.18
	nRMSE	36.69%	32.14%	32.22%	**31.55%**	31.62%	31.89%	31.98%	31.89%	31.74%
	MAE	4330.83	3815.19	3820.15	**3715.38**	3724.50	3770.34	3772.40	3756.30	3738.98
	UT	0.3090	0.2888	0.2884	**0.2827**	0.2831	0.2856	0.2858	0.2855	0.2836
8	RMSE	5642.22	4944.71	4947.58	4886.27	4876.31	4885.22	4893.83	**4871.47**	4881.43
	nRMSE	39.27%	34.42%	34.44%	34.01%	33.94%	34.00%	34.06%	**33.91%**	33.98%
	MAE	4623.75	4078.54	4088.49	**3976.37**	3977.77	4012.46	4013.49	4001.76	4010.42
	UT	0.3342	0.3080	0.3072	0.3073	0.3062	0.3060	0.3054	0.3049	**0.3046**
9	RMSE	5630.98	5013.70	5027.65	**4976.59**	4989.36	5008.38	5020.91	5021.83	5018.92
	nRMSE	39.20%	34.90%	35.00%	**34.64%**	34.73%	34.86%	34.95%	34.96%	34.94%
	MAE	4572.41	4131.90	4157.31	**4102.29**	4107.94	4132.87	4129.94	4139.83	4131.96
	UT	0.3334	0.3106	0.3105	0.3103	**0.3101**	0.3110	0.3110	0.3122	0.3111
10	RMSE	5672.43	5088.86	5110.29	**5022.55**	5029.13	5042.02	5058.06	5033.94	5038.41
	nRMSE	39.48%	35.42%	35.57%	**34.96%**	35.01%	35.10%	35.21%	35.04%	35.07%
	MAE	4565.26	4213.07	4237.94	**4134.96**	4142.64	4171.57	4183.56	4159.95	4162.16
	UT	0.3336	0.3136	0.3145	0.3116	0.3116	0.3105	0.3105	0.3106	**0.3100**
11	RMSE	5851.22	5206.03	5193.34	**5132.27**	5137.94	5146.48	5162.33	5150.96	5167.22
	nRMSE	40.73%	36.24%	36.15%	**35.72%**	35.76%	35.82%	35.93%	35.85%	35.97%
	MAE	4703.26	4275.71	4266.79	**4194.70**	4206.75	4227.47	4238.53	4217.68	4229.88
	UT	0.3352	0.3201	0.3175	0.3177	0.3172	0.3158	**0.3158**	0.3166	0.3166
12	RMSE	6004.80	5419.08	5385.52	5469.57	5473.68	**5380.41**	5404.83	5410.85	5424.00
	nRMSE	41.80%	37.72%	37.49%	38.07%	38.10%	**37.45%**	37.62%	37.66%	37.76%
	MAE	4968.50	4470.93	4451.70	4486.47	4484.83	**4413.89**	4436.98	4446.02	4451.88
	UT	0.3569	0.3424	**0.3397**	0.3476	0.3480	0.3410	0.3413	0.3424	0.3423

Table 4: Frequency distribution of best results according to the compared methods.

Aggregation	Stacking	Stacking + 10 Bootstraps	Stacking +30 Bootstraps	Stacking +50 Bootstraps	Stacking + 100 Bootstraps	Total
-	14.58%	-	-	-	-	14.58%
Average	-	0.00%	29.17%	6.25%	8.33%	43.75%
Median	-	2.08%	12.50%	2.08%	25%	41.67%
Total	14.58%	2.08%	41.67%	8.33%	33.33%	100.00%

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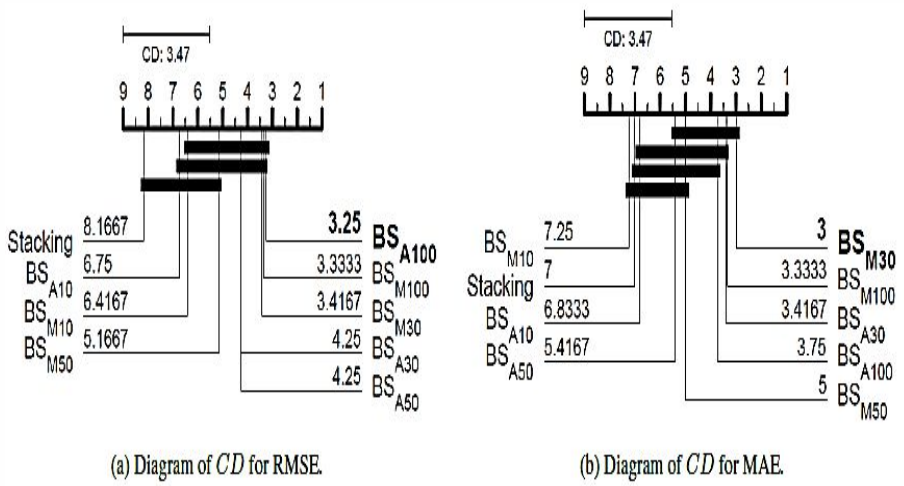
Results and Conclusion



(a) Diagram of *CD* for RMSE. (b) Diagram of *CD* for MAE.

- Accuracy and Forecasting Horizon:
  - In 85.42% of all comparisons, the stacking combined with bagging ensemble has better accuracy than the stacking ensemble learning model;
  - For one-hour-ahead forecasting, the stacking ensemble learning achieves forecasting errors lower than the combination of stacking with bagging ensemble approach according to all performance criteria;
  - These two approaches have competitive results concerning the forecasting horizons of two and three-hours-ahead;

- Bootstrapping Samples
  - Better forecasting results regarding the performance measures are achieved when 30 bootstrap samples are considered in the ensemble structure, followed by 100, 50, and 10;
- Aggregation strategy
  - Similar accuracy