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Including Wind Power Generation in Brazil's Long-Term Optimization Model for Energy Planning

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Paula Medina Maçaira (DEI, PUC-Rio)
Yasmin Monteiro Cyrillo (ONS)
Fernando Luiz Cyrino Oliveira (DEI, PUC-Rio)
Reinaldo Castro Souza (DEI, PUC-Rio)

Coordenação: CCEE

Assessoria Técnica: Eletrobras Cepel

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Introdução

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Article

Including Wind Power Generation in Brazil's Long-Term Optimization Model for Energy Planning

Paula Medina Maçaira [1,*], Yasmin Monteiro Cyrillo [2], Fernando Luiz Cyrino Oliveira [1] and Reinaldo Castro Souza [1]

1 Industrial Engineering Department, PUC-Rio, Rio de Janeiro-RJ 22451-900, Brazil; cyrino@puc-rio.br (F.L.C.O.); reinaldo@puc-rio.br (R.C.S.)
2 Electrical Engineering Department, PUC-Rio, Rio de Janeiro-RJ 22451-900, Brazil; yasmin.cyrillo@engenharia.ufjf.br
* Correspondence: paulamacaira@esp.puc-rio.br

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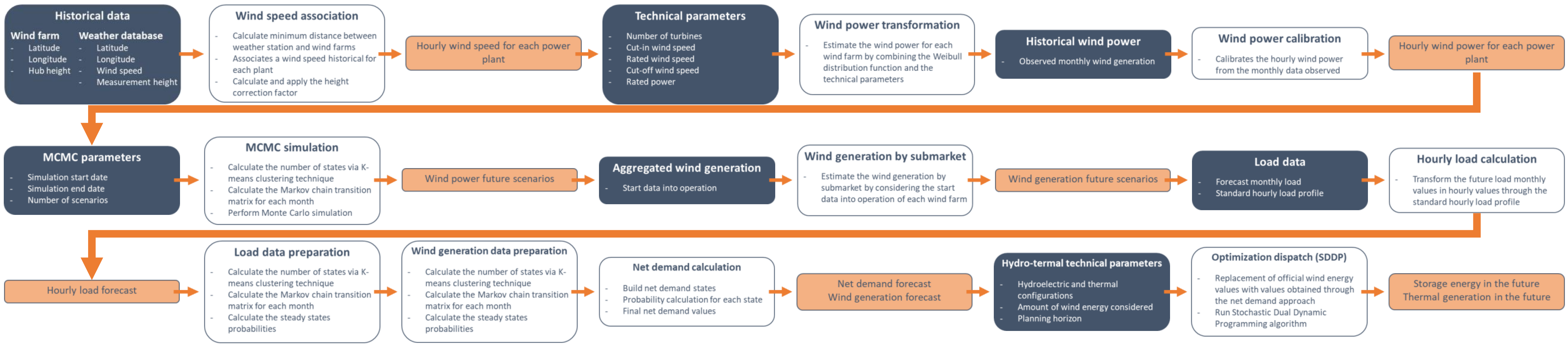
Objetivo

- Besides wind generation, modeling and forecasting, this work aims to integrate these results in the current Brazilian hydro-thermal dispatch model, without the need of any structural change in the optimization model, by updating the calculation of the non-dispatched plants
- The Frequency and Duration (F&D) methodological principle is used, combining via Markov chain Monte Carlo method the states of generation and load capacity to determine those ones of net demand and the corresponding probabilities

Metodologia



Criação das séries históricas

1. Obtaining a full year history of hourly wind speed series at the selected location
   - Through the CFSR it is possible to obtain the desired information according to geographic coordinates, with a spatial resolution of 0.25° by 0.25°
2. The association of a wind speed series to a wind farm was carried out by searching for the measurement point that minimizes the distance between them

Criação das séries históricas

3. As a consequence of the difference in height between the measurement of wind speed (10 m) and the height of the turbines, it is necessary to consider a height correction factor

$$HF_i = \frac{\log(HT_i)}{\log(HM_i)}$$

HF_i: height correction factor
HT_i: turbine height
HM_i: measurement height

4. The final wind speed, associated with the wind farms is the result of multiplying the height correction factor by the original wind speed

$$WS_{h,d,m.i} = HF_i \times OWS_{h,d,m,i}$$

$WS_{h,d,m,i}$: final wind speed
$OWS_{h,d,m,i}$: original wind speed

Criação das séries históricas

5. The transformation of wind speed into wind power is made by a parametric model of the power curve of wind turbine

$$WPA_{h,d,m,i} = \begin{cases} 0 & WS_{h,d,m,i} < v_{ci}, WS_{h,d,m,i} > v_{co} \\ q(v) & v_{ci} < WS_{h,d,m,i} < v_r \\ P_r & v_r \leq WS_{h,d,m,i} \leq v_{co} \end{cases}$$

$WPA_{h,d,m,i}$: total wind power
v_{ci}: cut in velocity
v_r: rated velocity
v_{co}: cut off velocity
P_r: rated Power

6. Weibull distribution function to the wind speed data from each month (parameter k is estimated through ML)

$$q(v) = \left(\frac{v_{ci}^{k_m}}{v_{ci}^{k_m} - v_r^{k_m}} + \frac{{WS_{h,d,m,i}}^{k_m}}{v_{co}^{k_m} - v_{ci}^{k_m}} \right) P_r$$

Criação das séries históricas

7. The calibration factor will be calculated from the observed monthly wind generation values and also the calculated monthly wind generation values

$$WP_{h,d,m,i} = WPA_{h,d,m,i} \times \frac{O_{m,i}}{WP_{m,i}}$$

$WP_{h,d,m,i}$: calibrated wind power
$O_{m,i}$: observed wind generation

Simulação e obtenção de cenários futuros

1. Application of the K-means clustering technique to transform the wind power data into a finite number of states

$$WPS_{h,d,m,i} = \begin{cases} c_1, & \text{if } WP_{h,d,m,i} \in c_1 \\ c_2, & \text{if } WP_{h,d,m,i} \in c_2 \\ & \vdots \\ c_k, & \text{if } WP_{h,d,m,i} \in c_k \end{cases}$$

c_k: centroid value of cluster k

2. Creation of transitions matrices by month

$$P_{ind} = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,k} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ p_{k,1} & p_{k,2} & \cdots & p_{k,k} \end{bmatrix}$$

$$p_{a,b} = \frac{n_{a,b}}{\sum_k n_{a,b}}$$

Simulação e obtenção de cenários futuros

3. The transition probability from state a to b, for all indices $1 \leq (a, b) \leq k$, can be calculated by

$$p_{a,b} = \frac{n_{a,b}}{\sum_k n_{a,b}}$$

$n_{a,b}$ is the number of transitions from a to b

4. Cumulative matrices can be created, so that its last column is equal to one for every row and month

$$P_{cum} = \begin{bmatrix} p_{1,1} & p_{1,1} + p_{1,2} & \cdots & p_{1,1} + p_{1,2} + \cdots + p_{1,k} \\ p_{2,1} & p_{2,1} + p_{2,2} & \cdots & p_{2,1} + p_{2,2} + \cdots + p_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ p_{k,1} & p_{k,1} + p_{k,2} & \cdots & p_{k,1} + p_{k,2} + \cdots + p_{k,k} \end{bmatrix}$$

Simulação e obtenção de cenários futuros

5. Randomly select the initial state z and a value between $[0,1]$ (uniform distribution)
6. Obtain the next state by comparing the value of the random number with the elements of the zth row of the cumulative probability transition
7. This procedure is repeated in order to simulate wind power data (by hour)

$$WSIM_{h,d,m,y,i,s} = c_k \qquad if \quad c_{k-1} < p_{unif\ [0,1]} \leq c_k$$

$WSIM_{h,d,my,i,s}$ simulated wind power for hour

Simulação e obtenção de cenários futuros

8. To create the wind generation data by submarket, it is first necessary to consider the starting date of operation in the wind power simulated in the previous step and then sum the wind farms corresponding to each submarket

$$G_{h,d,m,y,i,s} = \begin{cases} 0, & \text{if } d < d_{initial}, m < m_{initial}, y < y_{initial} \\ WSIM_{h,d,m,y,i,s} & \text{otherwise} \end{cases}$$

$$G_{h,d,m,y,j,s} = \sum_{i \in j} G_{h,d,m,y,i,s}$$

$G_{h,d,my,i,s}$ simulated wind power for a given submarket

Simulação e obtenção de cenários futuros

9. After obtain the hourly load data for each submarket the K-means algorithm is used again to discretize both the wind power generation and load series into states
10. In addition, in a subsequent step, the Markov chain transition matrices for each month (and scenario) are created, following the same steps described before

The need to recalculate the states and transition matrices for the wind generation series comes from the fact that the series originated in the previous step has changed with the input of the starting dates of operation and the transformation into submarkets.

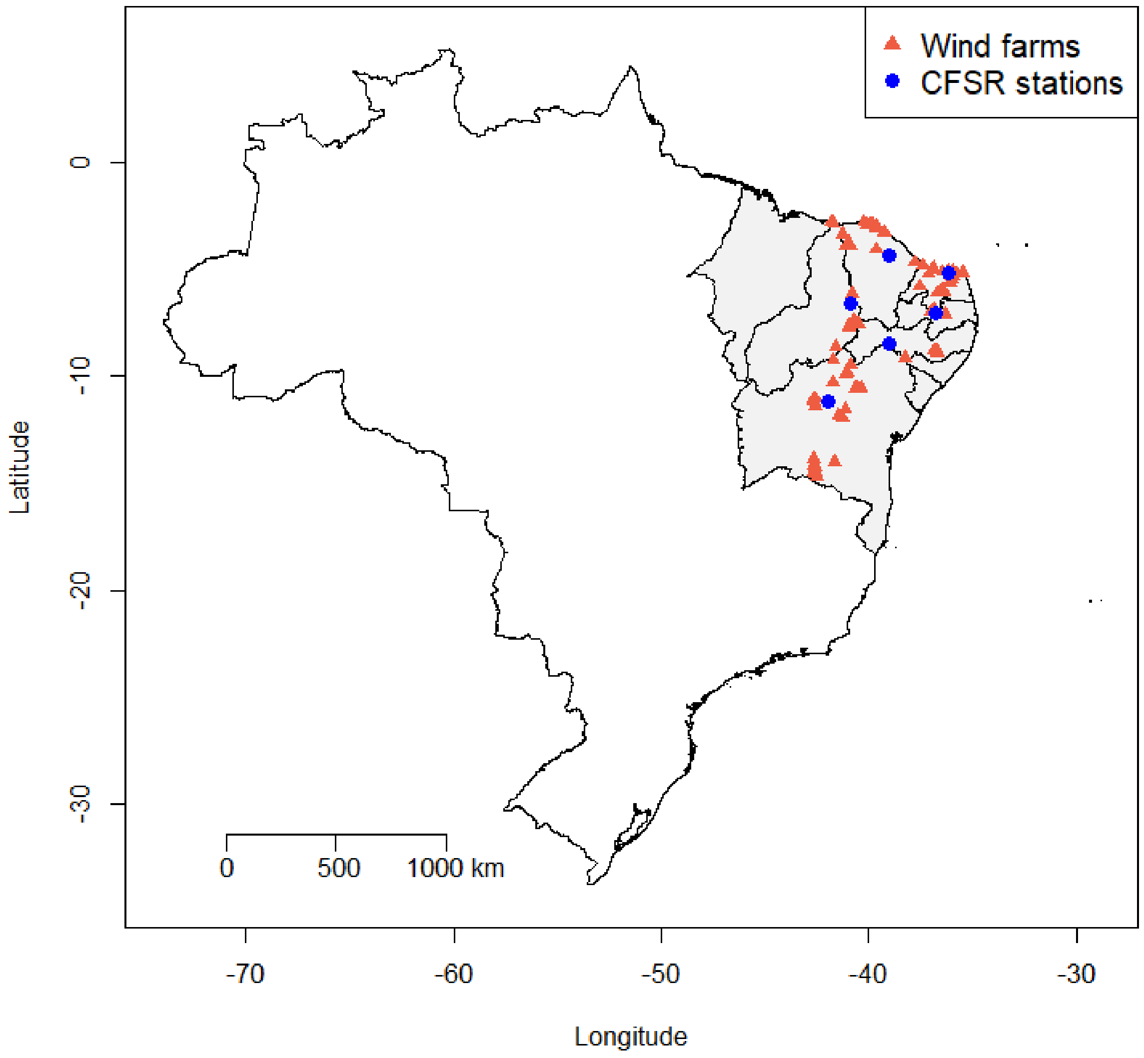
Simulação e obtenção de cenários futuros

11. The steady-state probability represents the occurrence of each state and is used to obtain the Net Demand states
12. The final output of this system is a value for each month and year in the forecasted period

Caso exemplo

- The proposed methodology is applied to the Brazilian Northeast region in order to forecast the wind power generation from July 2017 to December 2021
- The year 2016 is used as the base year, so the wind speed series extracted from CFSR are hourly from 1 January to 31 December (2016) and the standard load profile is built based on the hourly load for 2016, obtained from the National System Operator

Caso exemplo



Caso exemplo

- Only 6 measurement points were needed and the maximum distance found was approximately 12 km

Station	Latitude	Longitude
NASA 1362	−4.40	−39.07
NASA 1628	−5.21	−36.20
NASA 2046	−6.64	−40.91
NASA 2192	−7.05	−36.82
NASA 2622	−8.48	−39.07
NASA 3427	−11.14	−41.93

Caso exemplo

- Only 7 turbine manufacturers serve this region with 12 models

Manufacturer	Model	Hub Height (m)	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut-Off Wind Speed (m/s)	Rated Power (kW)
Acciona	AW-3000/116	120	3	10.6	20	3000
Alstom	ECO-122/2700	139	3	10	25	2700
Alstom	ECO-86/1670	80	3	10	25	1670
Gamesa	G106/2500	93	2	12	24	2500
Gamesa	G97/2000	120	3	14	25	2000
GE	1.6-100	100	3.5	11	25	1600
GE	1.85-82.5	80	3	13	25	1850
GE	1.7-103	96	3	10	23	1700
GE	1.68-100	100	3.5	11	25	1680
Siemens	SWT-2.3-101	100	3	12	20	2300
Weg	AWG 110/2.1	120	2.5	11	20	2100
Wobben	E92/2350	138	2	13	25	2350

- The maximum wind turbine height found was 139 m and the minimum was 80 m, so the height correction factor varies from 1.90 to 2.14

Caso exemplo

- Transition matrix example

State a (MW)	State b (MW)													
	0	0,32	1,20	2,18	3,32	4,47	5,71	7,03	8,57	10,20	11,77	13,55	15,53	17,60
0	0,50	0,50	0	0	0	0	0	0	0	0	0	0	0	0
0,32	0,01	0,84	0,13	0,02	0	0	0	0	0	0	0	0	0	0
1,20	0	0,14	0,58	0,25	0,03	0	0	0	0	0	0	0	0	0
2,18	0	0,04	0,21	0,41	0,28	0,04	0,03	0	0	0	0	0	0	0
3,32	0	0	0,05	0,20	0,34	0,23	0,06	0,08	0,02	0,02	0	0	0	0
4,47	0	0	0,02	0,07	0,22	0,31	0,24	0,10	0,03	0,00	0	0	0	0
5,71	0	0	0	0,04	0,07	0,21	0,29	0,21	0,09	0,07	0,02	0	0	0
7,03	0	0	0	0,03	0,03	0,10	0,24	0,32	0,15	0,06	0,05	0,02	0	0
8,57	0	0	0	0,00	0,02	0,06	0,04	0,21	0,31	0,17	0,08	0,08	0,04	0
10,20	0	0	0	0,00	0	0	0,04	0,09	0,26	0,24	0,26	0,07	0	0,04
11,77	0	0	0	0,02	0	0,02	0,02	0,05	0,11	0,30	0,23	0,11	0,11	0,02
13,55	0	0	0	0	0	0	0	0	0,08	0,04	0,31	0,31	0,15	0,12
15,53	0	0	0	0,04	0	0	0	0	0	0,11	0,19	0,11	0,30	0,26
17,60	0	0	0	0	0	0	0	0,03	0	0	0,02	0,03	0,14	0,78

Caso exemplo

- Cumulative transition matrix example

State a (MW)	State b (MW)													
	0	0,32	1,20	2,18	3,32	4,47	5,71	7,03	8,57	10,20	11,77	13,55	15,53	17,60
0	0,50	1	1	1	1	1	1	1	1	1	1	1	1	1
0,32	0,01	0,85	0,98	1	1	1	1	1	1	1	1	1	1	1
1,20	0	0,14	0,72	0,97	1	1	1	1	1	1	1	1	1	1
2,18	0	0,04	0,25	0,66	0,93	0,97	1	1	1	1	1	1	1	1
3,32	0	0	0,05	0,25	0,59	0,83	0,89	0,97	0,98	1	1	1	1	1
4,47	0	0	0,02	0,09	0,31	0,62	0,86	0,97	1	1	1	1	1	1
5,71	0	0	0	0,04	0,11	0,32	0,61	0,82	0,91	0,98	1	1	1	1
7,03	0	0	0	0,03	0,06	0,16	0,40	0,73	0,87	0,94	0,98	1	1	1
8,57	0	0	0	0	0,02	0,08	0,12	0,33	0,63	0,81	0,88	0,96	1	1
10,20	0	0	0	0	0	0	0,04	0,13	0,39	0,63	0,89	0,96	0,96	1
11,77	0	0	0	0,02	0,02	0,05	0,07	0,11	0,23	0,52	0,75	0,86	0,98	1
13,55	0	0	0	0	0	0	0	0	0,08	0,12	0,42	0,73	0,88	1
15,53	0	0	0	0,04	0,04	0,04	0,04	0,04	0,04	0,15	0,33	0,44	0,74	1
17,60	0	0	0	0	0	0	0	0,03	0,03	0,03	0,05	0,08	0,22	1

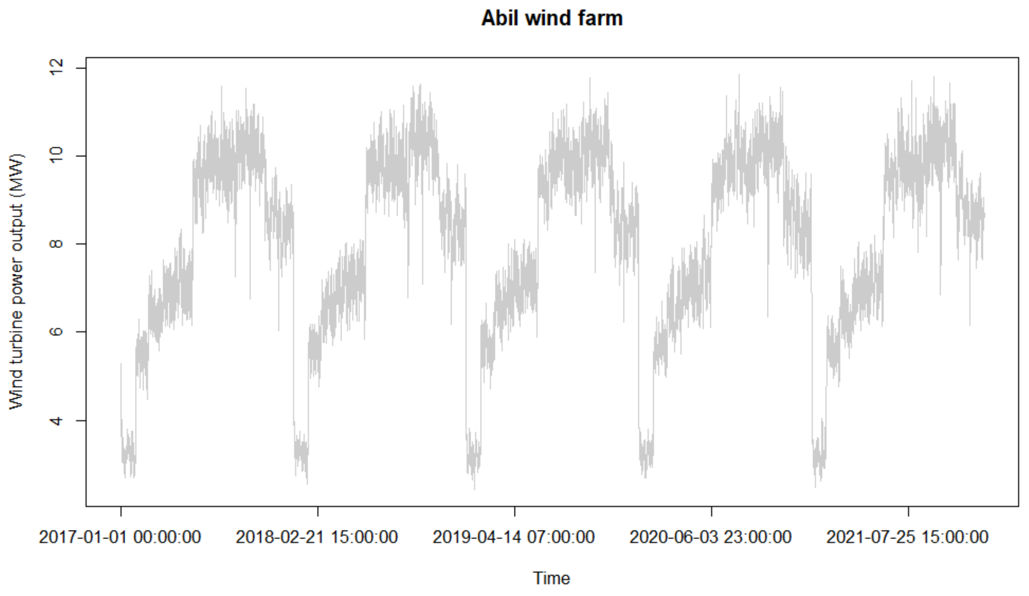
Caso exemplo

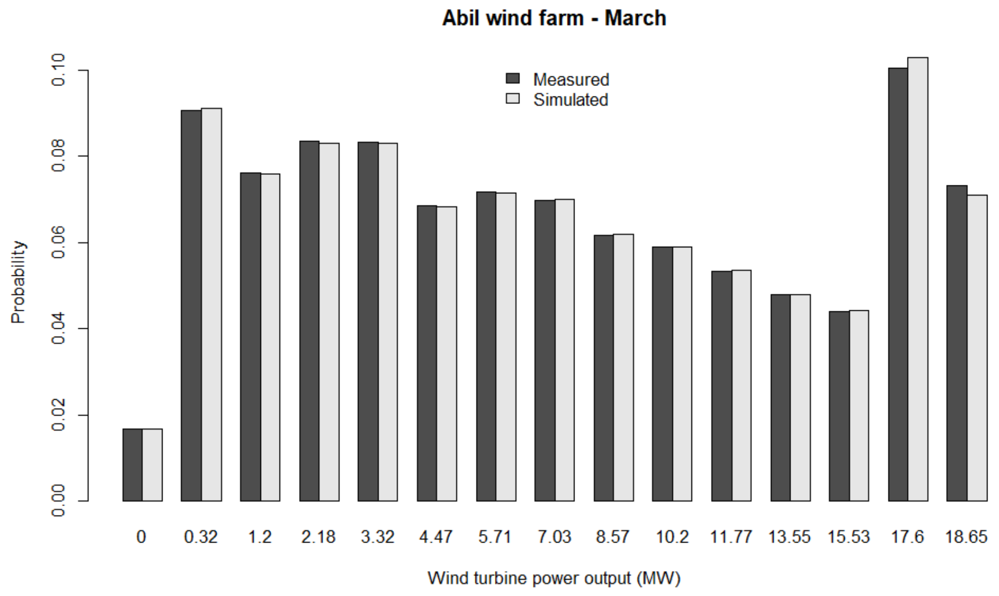
- Cumulative transition matrix example

State a (MW)	State b (MW)													
	0	0,32	1,20	2,18	3,32	4,47	5,71	7,03	8,57	10,20	11,77	13,55	15,53	17,60
0	0,50	1	1	1	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0,32	0,01	0,85	0,98	1	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1,20	0	0,14	0,72	0,97	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2,18	0	0,04	0,25	0,66	0,93	0,97	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3,32	0	0	0,05	0,25	0,59	0,83	0,89	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4,47	0	0	0,02	0,09	0,31	0,62	0,86	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5,71	0	0	0	0,04	0,11	0,32	0,61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7,03	0	0	0	0,03	0,06	0,16	0,40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8,57	0	0	0	0	0,02	0,08	0,12	0,33	0,63	0,81	0,88	0,96	1	1
10,20	0	0	0	0	0	0	0,04	0,13	0,39	0,63	0,89	0,96	0,96	1
11,77	0	0	0	0,02	0,02	0,05	0,07	0,11	0,23	0,52	0,75	0,86	0,98	1
13,55	0	0	0	0	0	0	0	0	0,08	0,12	0,42	0,73	0,88	1
15,53	0	0	0	0,04	0,04	0,04	0,04	0,04	0,04	0,15	0,33	0,44	0,74	1
17,60	0	0	0	0	0	0	0	0,03	0,03	0,03	0,05	0,08	0,22	1

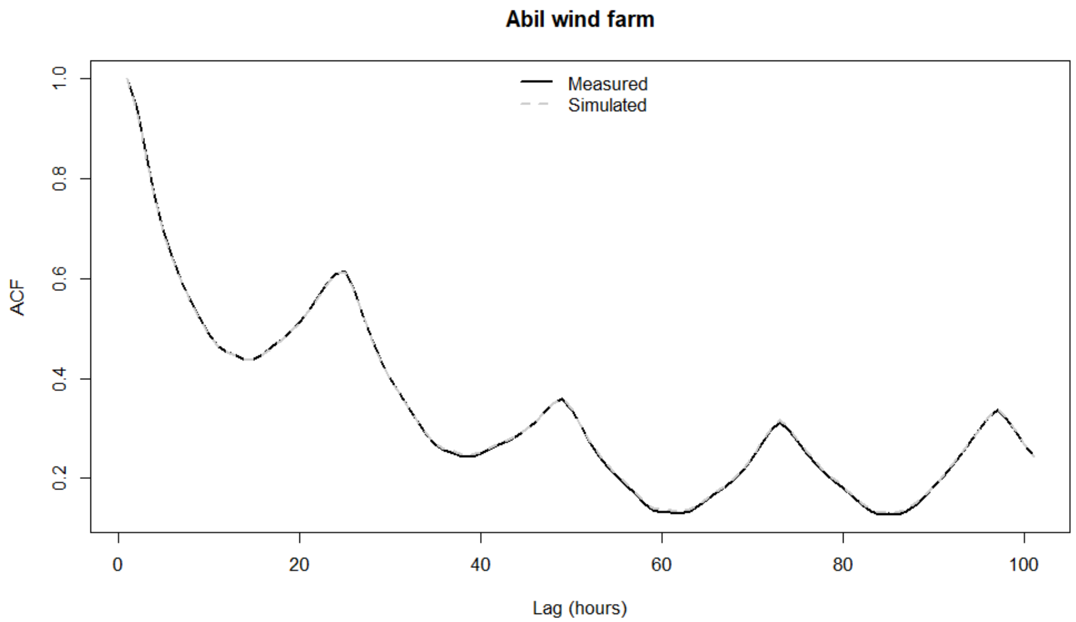
To simulate the hourly wind power values, it is first necessary to randomly select the initial state, for instance, state 3 (1.20 MW in the example) and then to choose a value from the uniform [0,1] distribution. Assume it is 0.92. This means that the first simulated value is 1.20 MW and the second is 2.18 MW, since 0.92 is more than 0.72 (state 3) and less than 0.97 (state 4)

Caso exemplo

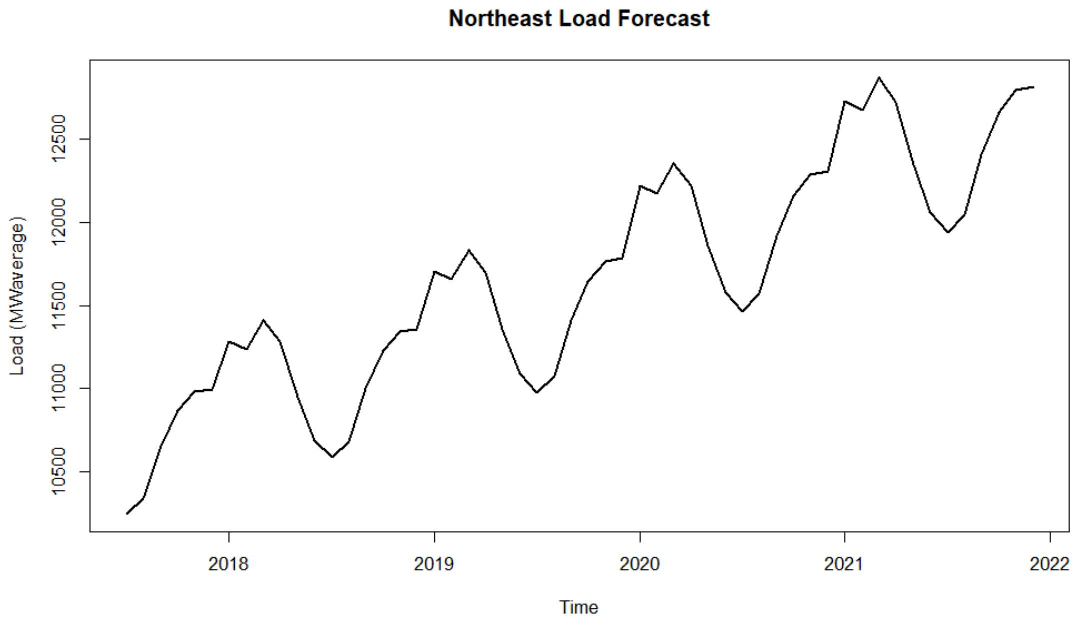


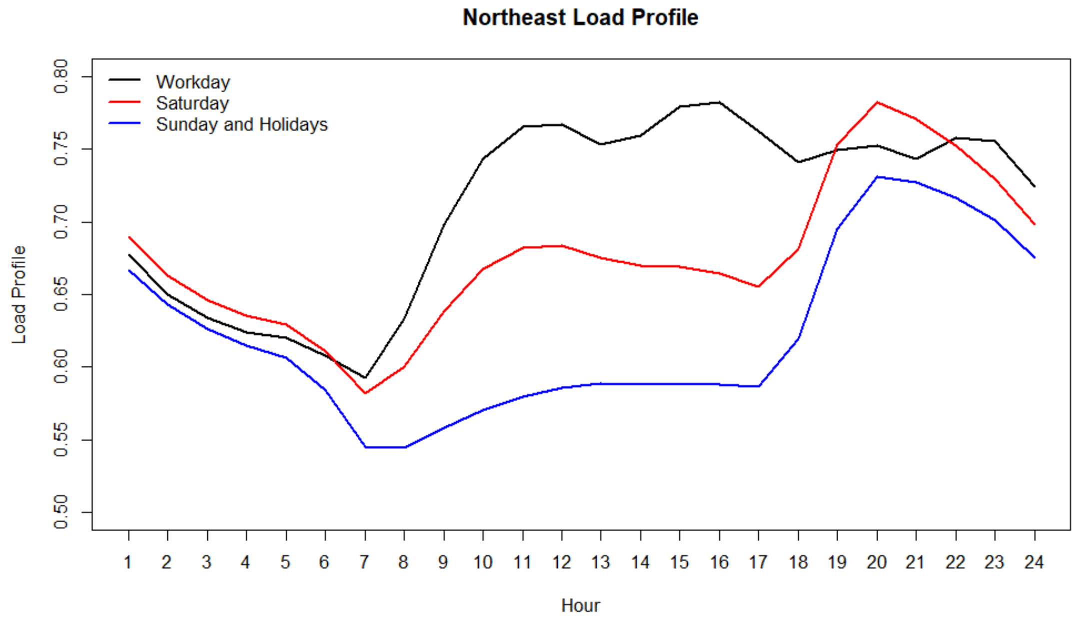


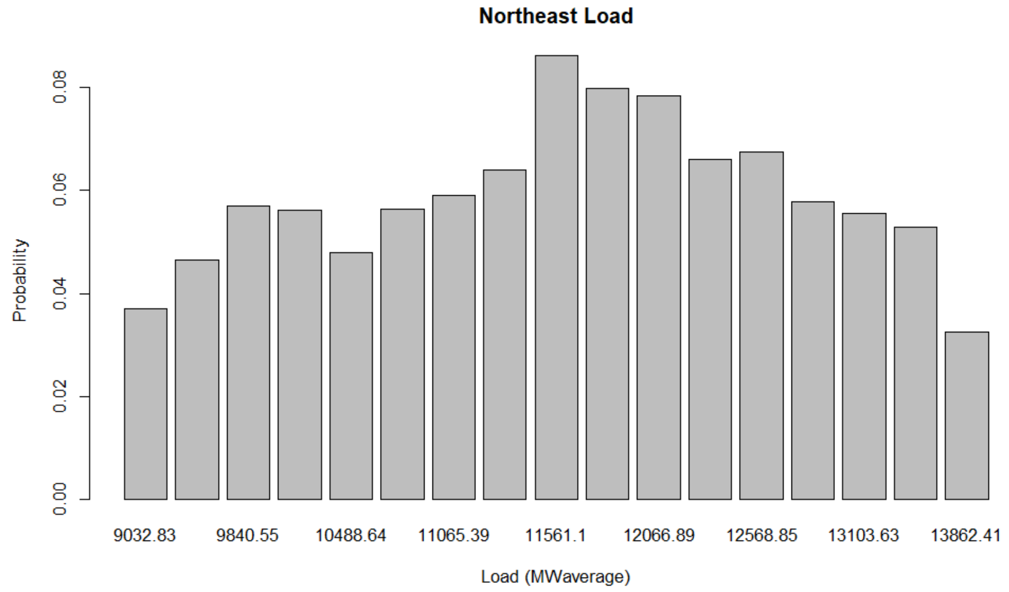
Month	Mean (MW)		Standard Deviation (MW)	
	Measured Data	Simulated Data	Measured Data	Simulated Data
Jan	3.2204	3.2727	3.5331	3.5668
Feb	5.6109	5.5751	4.2978	4.3025
Mar	6.3998	6.4795	5.3218	5.3187
Apr	7.0073	6.9852	5.6116	5.6165
May	7.1462	7.1800	5.8127	5.8084
Jun	9.0496	9.3804	6.3166	6.3166
Jul	9.9104	9.9181	6.0918	6.1196
Aug	9.6687	9.7155	6.2547	6.2793
Sep	10.5886	10.2190	6.5827	6.6192
Oct	10.1114	10.2143	6.3178	6.3066
Nov	9.1185	8.7986	6.7229	6.6391
Dec	8.2729	8.3653	6.3252	6.3179



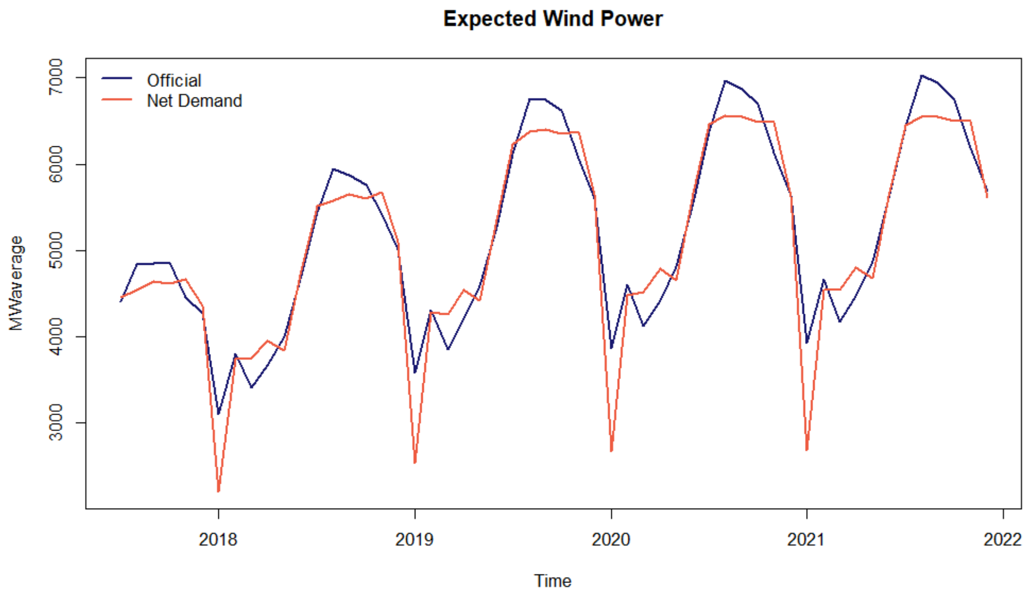
Caso exemplo

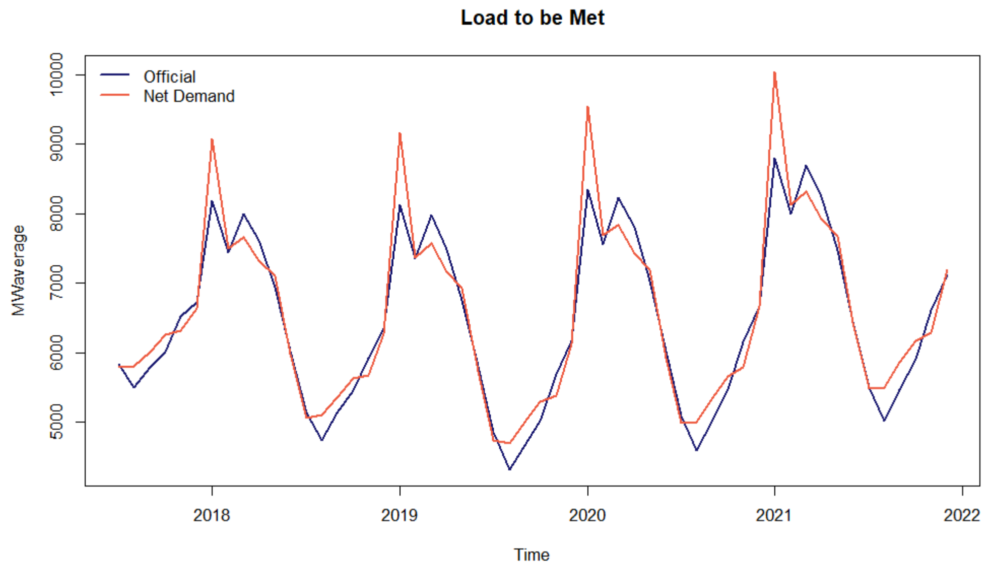


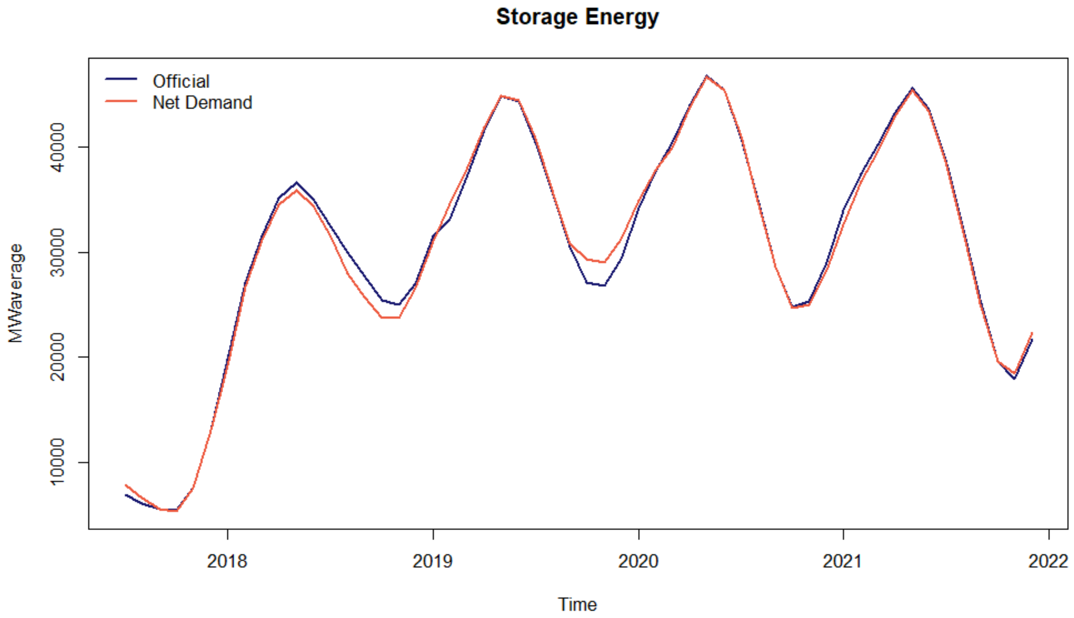




Caso exemplo







Conclusões

- The results obtained confirm that the expected wind power forecast using the proposed methodology is more conservative than the official expectations
- That is, in periods of higher wind power generation in the Northeast, the net demand approach expects less generation than the government, with the same for periods with smaller generation
- These values indicate a lower expectation of water storage in the future, translated into energy storage, and also higher generation from thermal plants
- The main consequences of such differences between what is expected by the government and the forecast calculated here are the depletion of hydroelectric reservoirs and also the "non-optimization" of dispatch
- Therefore, we can conclude that the consideration of probabilistic scenarios of wind energy generation as proposed in the net demand approach can mitigate errors in decision making by the Brazilian National Electric System Operator

Direcionamentos futuros

- For future research, we suggest:
  - Using other databases to provide wind speed series in addition to obtain a history of more than one year in order to capture yearly variability
  - Application of other techniques to forecast wind power generation and consideration of different approaches for insertion of such generation in a mainly water and thermal dispatch
  - Application of methods that specifically consider the night/day effects of wind time series
  - Construct confidence intervals to increase the reliability of the applied simulation method
  - Apply the proposed approach to other renewable sources, such as photovoltaic

Paula Maçaira
paulamacaira@puc-rio.br

Coordenação do GT Metodologia
gtmet.cpamp@ccee.org.br

Assessoria Técnica: