IEEE Hrvatska sekcija Croatia Section

STATICAL AND DYNAMICAL PROPERTIES OF ELECTRICITY GENERATION FROM A LARGE SYSTEM OF WIND PLANTS – A CASE STUDY

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HOPS

Goal

- to obtain <u>**simple**</u> theoretic distribution functions to model actual statistical distributions of wind generation-related phenomena with sufficient accuracy,
- so that they can be used for various analyses in either power system operation, or power system economics/policy.

Source of data

- Bonneville Power Administration (BPA)
  - federal nonprofit agency based in the Pacific Northwest region of the United States of America.
- Excel files with historic data of wind generation in 5-minute increments from 2007 on are available at the address: http://transmission.bpa.gov/business/operations/wind/
- More info on BPA: http://www.bpa.gov

BPA-controlled wind plant system

Year	Total installed capacity at the end of the year [MW]
2006	722
2007	1,301
2008	1,599
2009	2,617
2010	3,372
2011	3,788
2012	4,711
2013	4,515

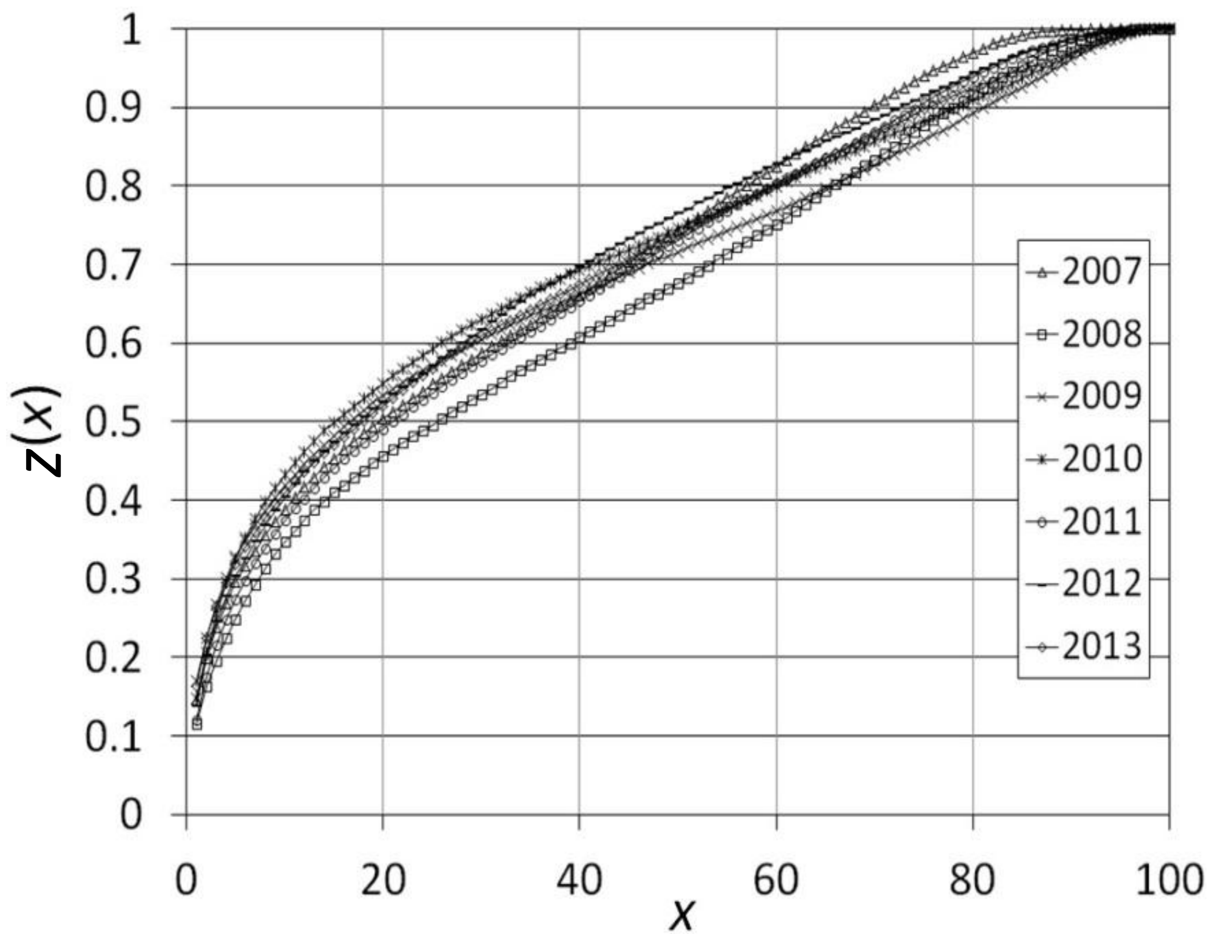
More detailed schedule:

http://transmission.bpa.gov/business/operations/wind/WIND_InstalledCapacity_DATA.pdf

The distributions studied:

- From the 5-minute readings, recorded from the beginning of 2007 to the end of 2013:
  - total generation as percentage of total installed capacity;
  - change in total generation power in 5, 10, 15, 20, 25, 30, 45, and 60 minutes as percentage of total installed capacity;
  - Limitation of total installed wind plant capacity, when it is determined by regulation demand from wind plants;
  - duration of intervals with total generated power, expressed as percentage of total installed capacity, lower than certain pre-specified level.
- All checked by rigorous tests of goodness-of-fit.

TOTAL POWER
expressed as percentage of total installed capacity

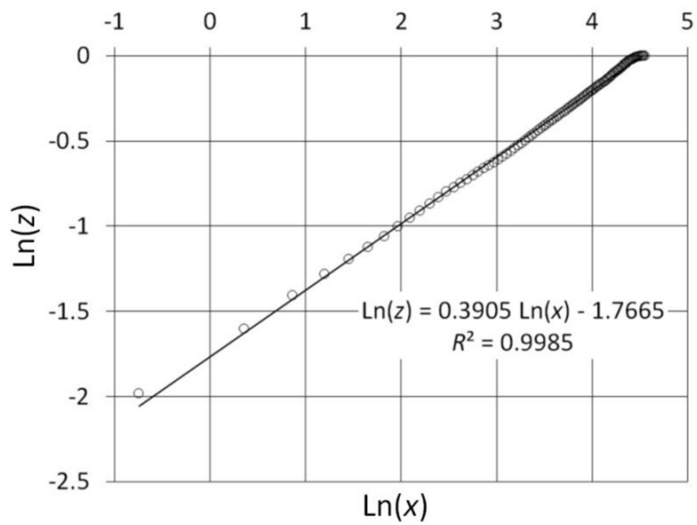


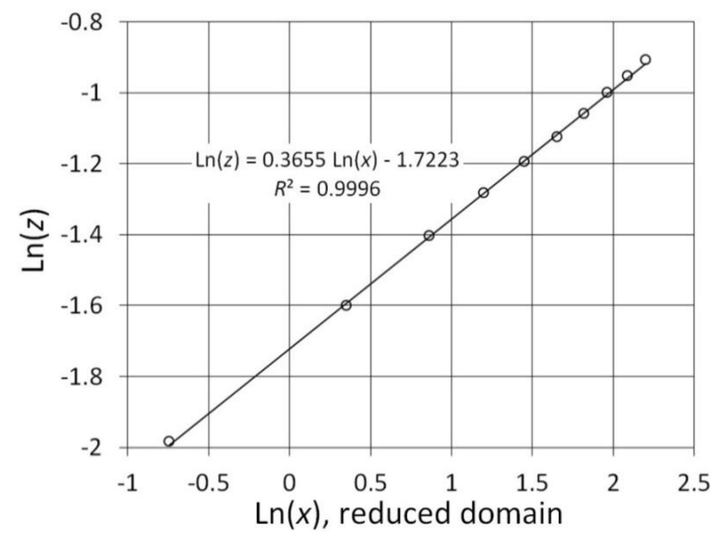
$z(x) = e^B x^A$

TOTAL POWER
expressed as percentage of total installed capacity

Figs: 2012

$$\mathrm{Ln}(z) = A\ \mathrm{Ln}x + B$$



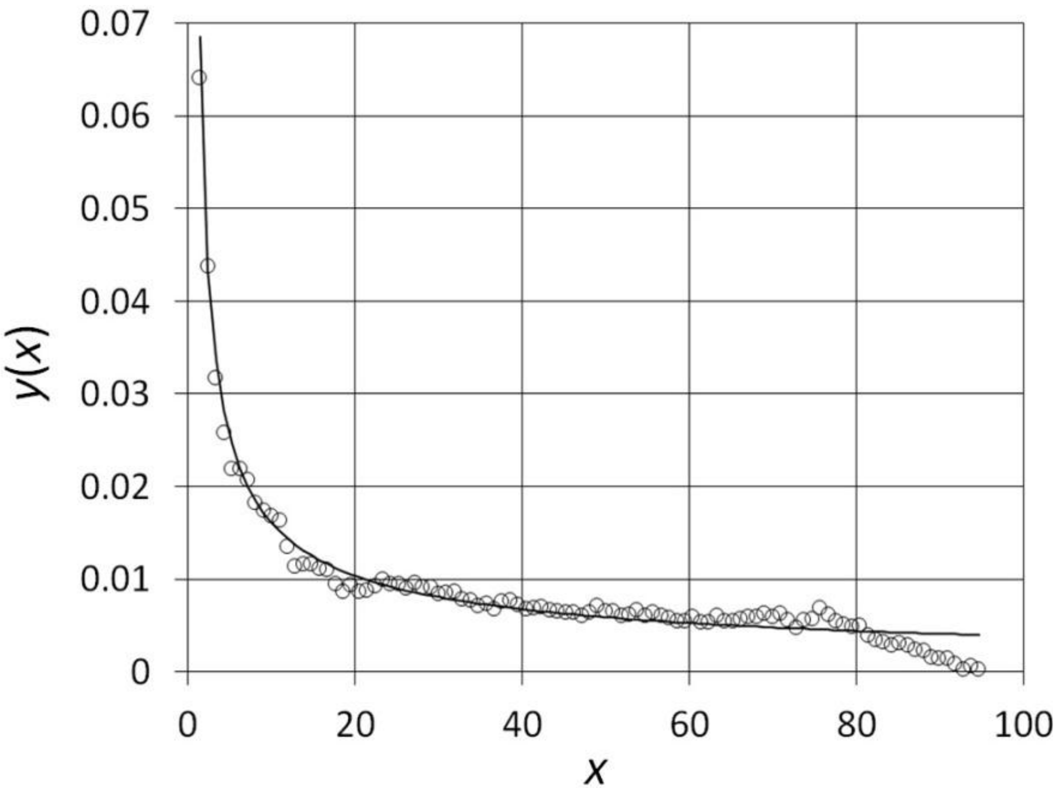


Complete domain: $x \in [0, 100\%]$							
Parameter	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
A	0.402838	0.439875	0.347887	0.35989	0.422034	0.390461	0.365416
B	-1.87783	-2.06074	-1.64213	-1.6616	-1.93211	-1.76643	-1.69203
Reduced domain: $x \in [0, 10\%]$							
Parameter	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
A	0.337334	0.379821	0.314231	0.376816	0.390471	0.365449	0.314955
B	-1.75044	-1.9419	-1.5758	-1.6763	-1.86602	-1.72231	-1.59877

TOTAL POWER
expressed as percentage of total installed capacity

Probability density: $y(x) = \mathrm{d}z(x)/\mathrm{d}x = A\ e^{B}\ x^{A-1}$

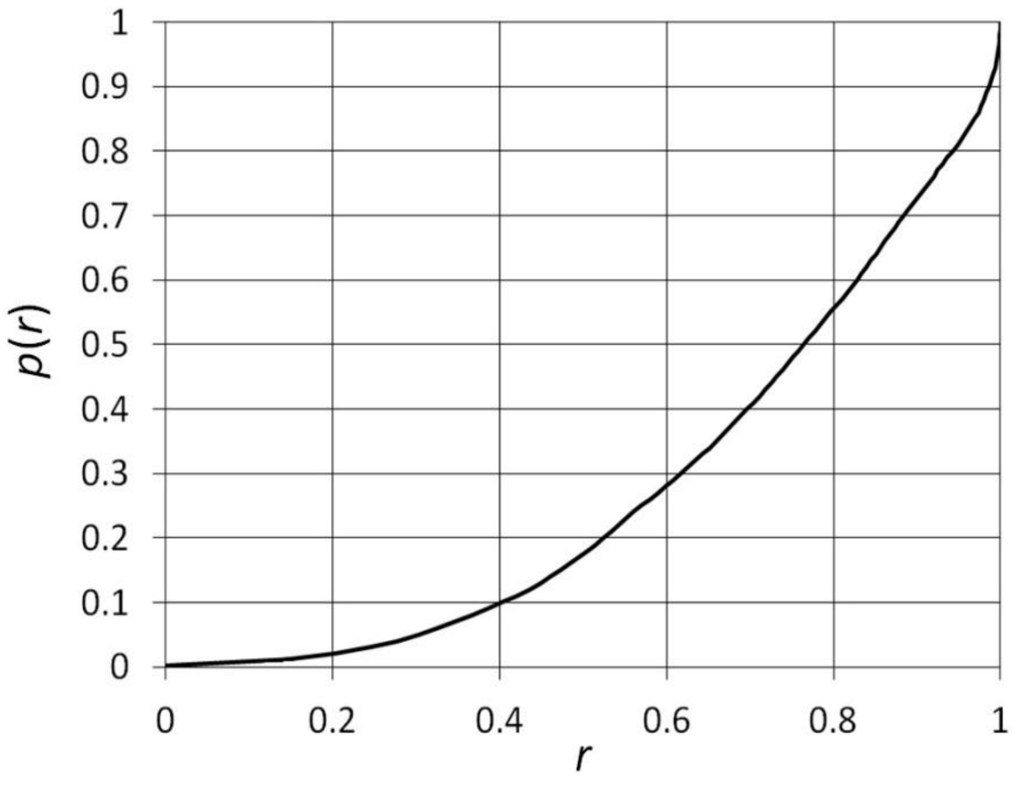
A fat-tailed power-distribution, indicating that extreme values are quite frequent (much more that they would be if distribution was, say, Gaussian).



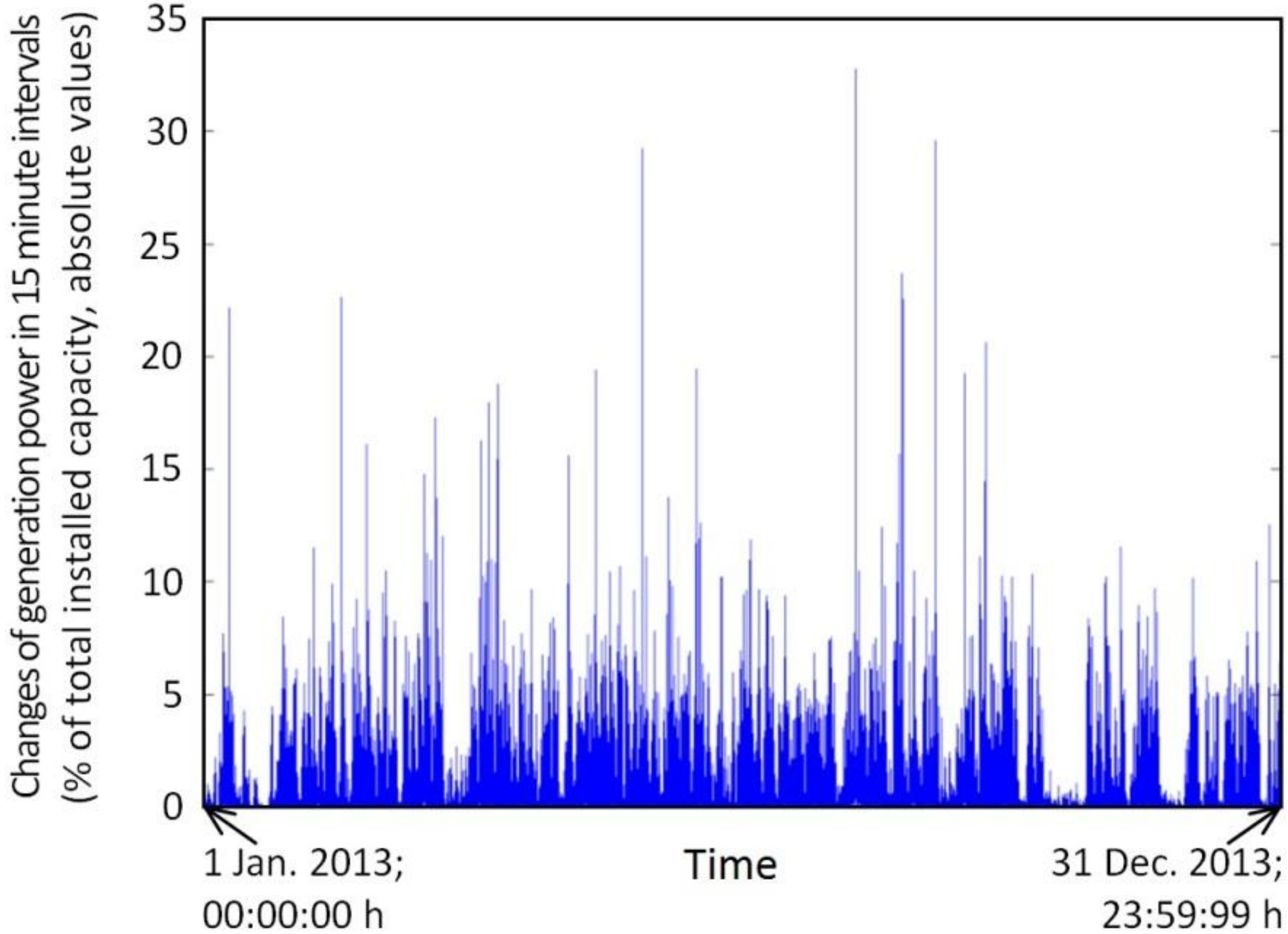
TOTAL POWER
expressed as percentage of total installed capacity

VAR function: $p(r) = e^{-B/A}\, r^{1/A}$ – just an inverse of prob. distr.

VaR increases slowly with risk, which is generally a feature most unusual for VaR functions, pointing at unfavorable long-term statistics of wind generation



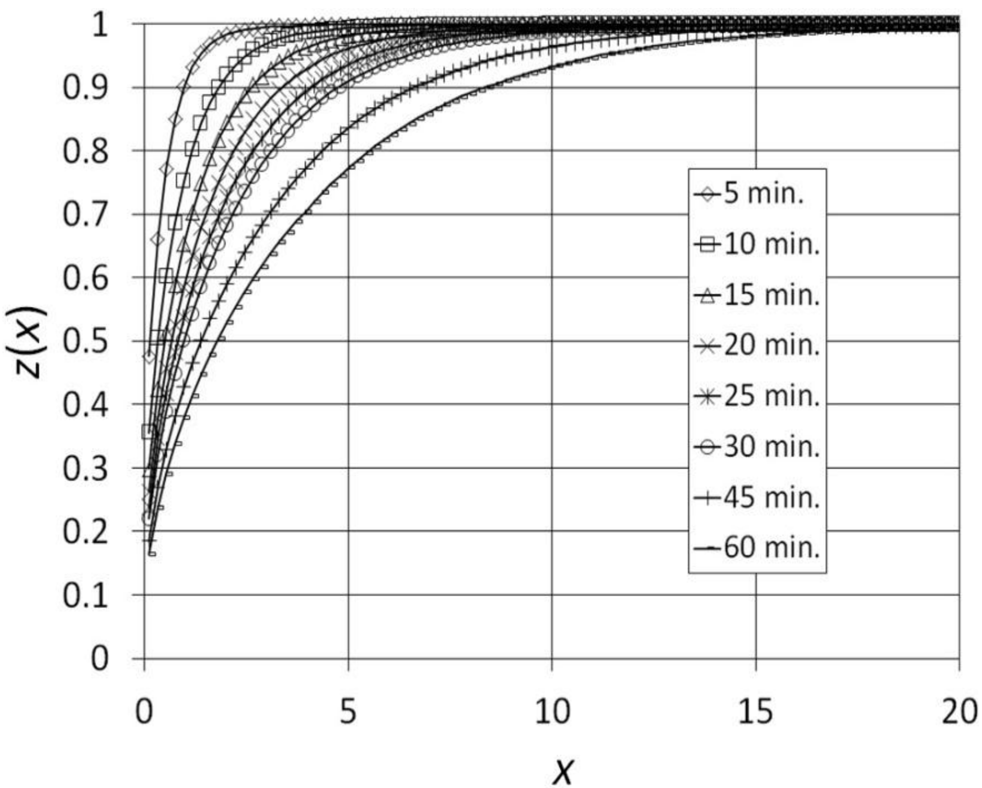
TEMPORAL CHANGES IN POWER
in short intervals (intra-hour)



TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

Experimental probability distribution functions, $z(x)$, of short-time changes of wind generation power (2013). Curves are experimental, and the candidate theoretical function is:

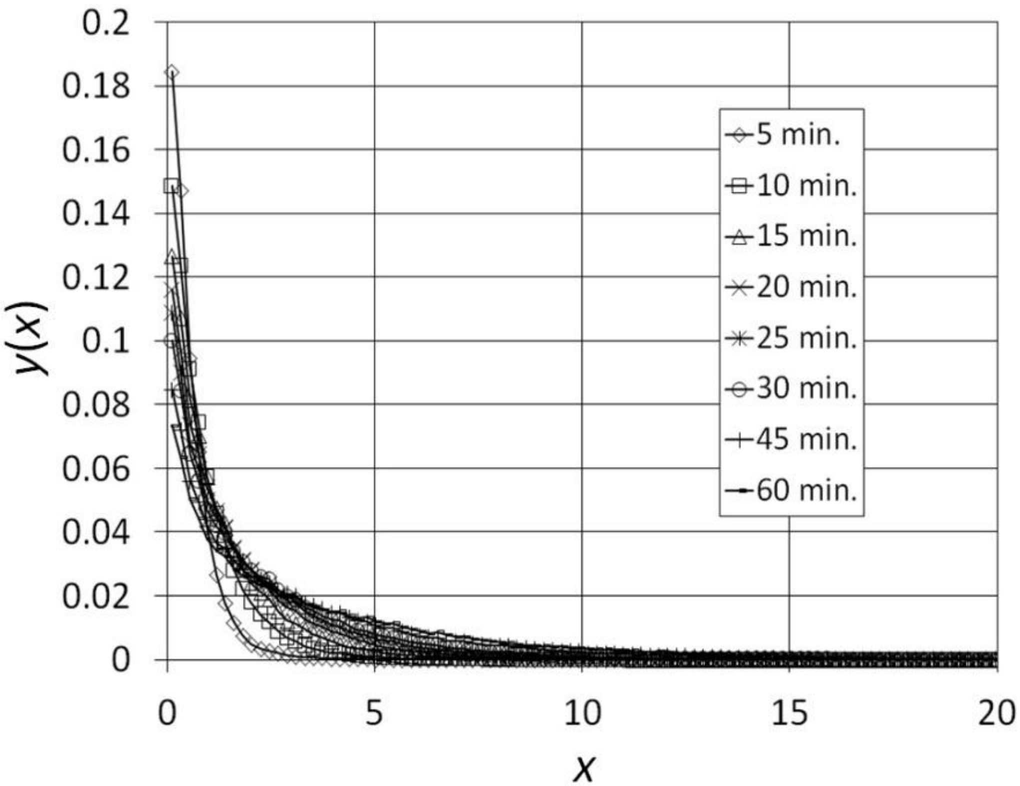
$$z(x) = \mathrm{Ln}[1 + (e - 1)(1 - e^{-x/B})^A]$$



TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

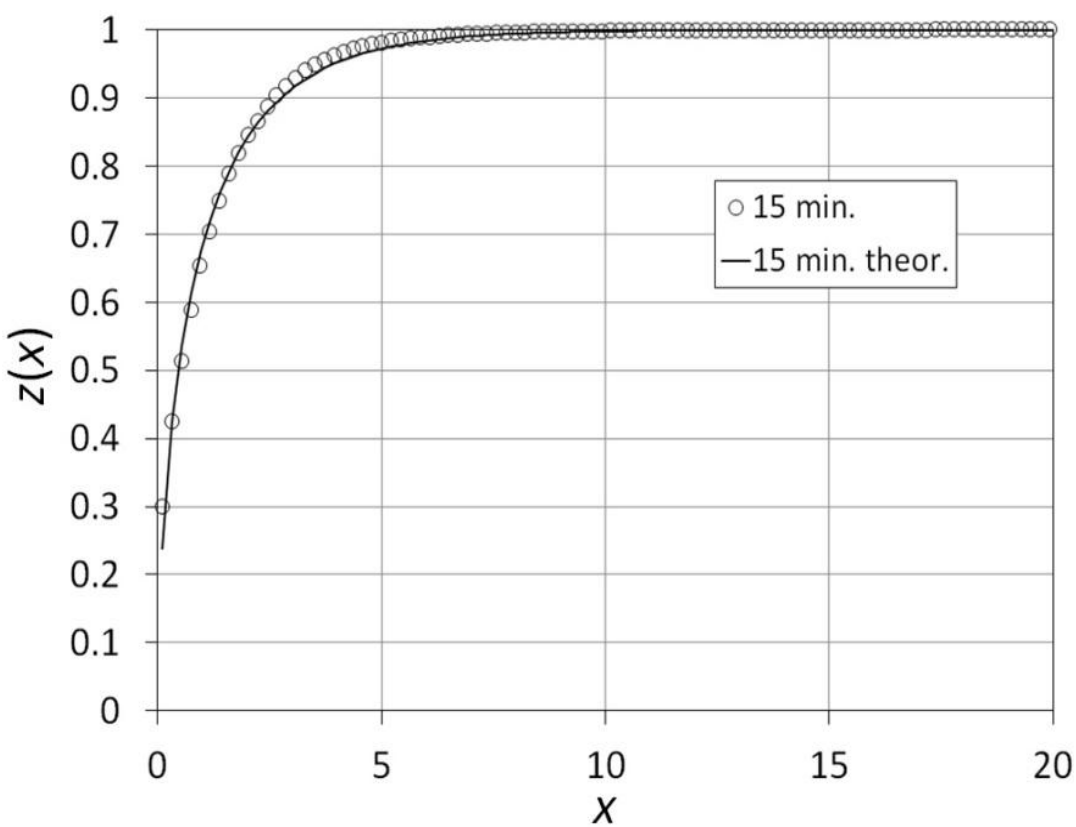
Experimental probability density functions, $y(x)$, of short-time changes of wind generation power (2013). Curves are experimental, and the candidate theoretical function is:

$$y(x) = (e - 1)(A/B)\,(1 - e^{-x/B})^{A-1}/[1 + (e - 1)(1 - e^{-x/B})^{A}].$$



TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

Example of goodnes-of-fit (theoretical to experimental):



2013

TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

Parameter *A*							
***k* (min.)**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
5	0.6899	0.5513	0.5567	0.5889	0.4967	0.5018	0.5401
10	0.7440	0.6294	0.6143	0.6525	0.5802	0.5756	0.6057
15	0.7703	0.6755	0.6474	0.6858	0.6297	0.6233	0.6443
20	0.7855	0.7099	0.6687	0.7054	0.6670	0.6553	0.6691
25	0.7960	0.7371	0.6826	0.7189	0.6968	0.6813	0.6852
30	0.8041	0.7587	0.6927	0.7306	0.7210	0.7026	0.6998
45	0.8228	0.7996	0.7153	0.7549	0.7777	0.7517	0.7290
60	0.8366	0.8331	0.7353	0.7623	0.8155	0.7816	0.7478
Parameter *B*							
***k* (min.)**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
5	1.0970	0.9390	0.8573	0.7738	0.8918	0.8247	0.7397
10	1.7679	1.6681	1.5002	1.3513	1.5398	1.4505	1.3206
15	2.3606	2.2911	2.0711	1.8687	2.0992	1.9831	1.8325
20	2.8945	2.8349	2.5954	2.3529	2.5971	2.4651	2.3029
25	3.3816	3.3178	3.0887	2.8077	3.0527	2.9040	2.7479
30	3.8311	3.7620	3.5529	3.2337	3.4758	3.3082	3.1597
45	5.0266	4.9486	4.8127	4.4073	4.5916	4.3739	4.2911
60	6.0686	5.9435	5.9262	5.5109	5.5367	5.3480	5.3179

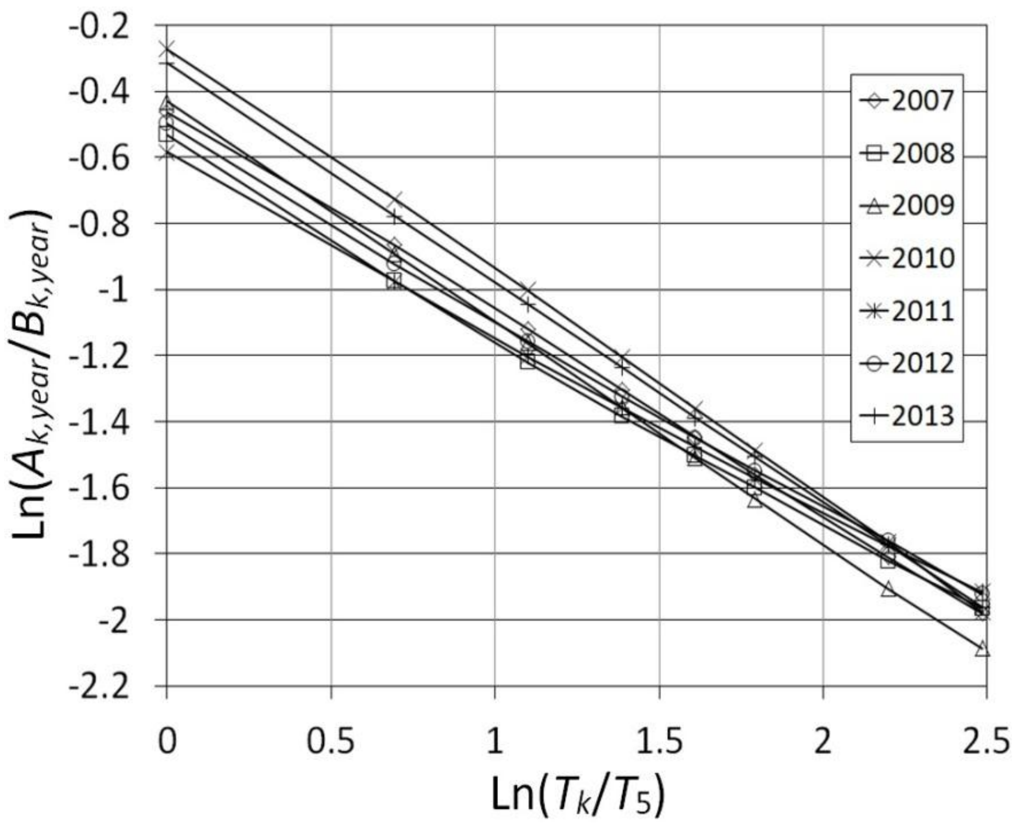
TEMPORAL CHANGES IN POWER
in short intervals (intra-hour)

Additional relations between *A* and *B* parameters

$\mathrm{Ln}(A_{k,year}/B_{k,year}) = -\,C_{year}\,\mathrm{Ln}(T_k/T_5) - D_{year}$
$k \in \{5,10,15,20,25,30,45,60\}; \quad C_{year}, D_{year} > 0.$

or simply: $B_k = A_k\, e^D\, (T_k/T_5)^C$

Theoretic model.



Experimental relations.

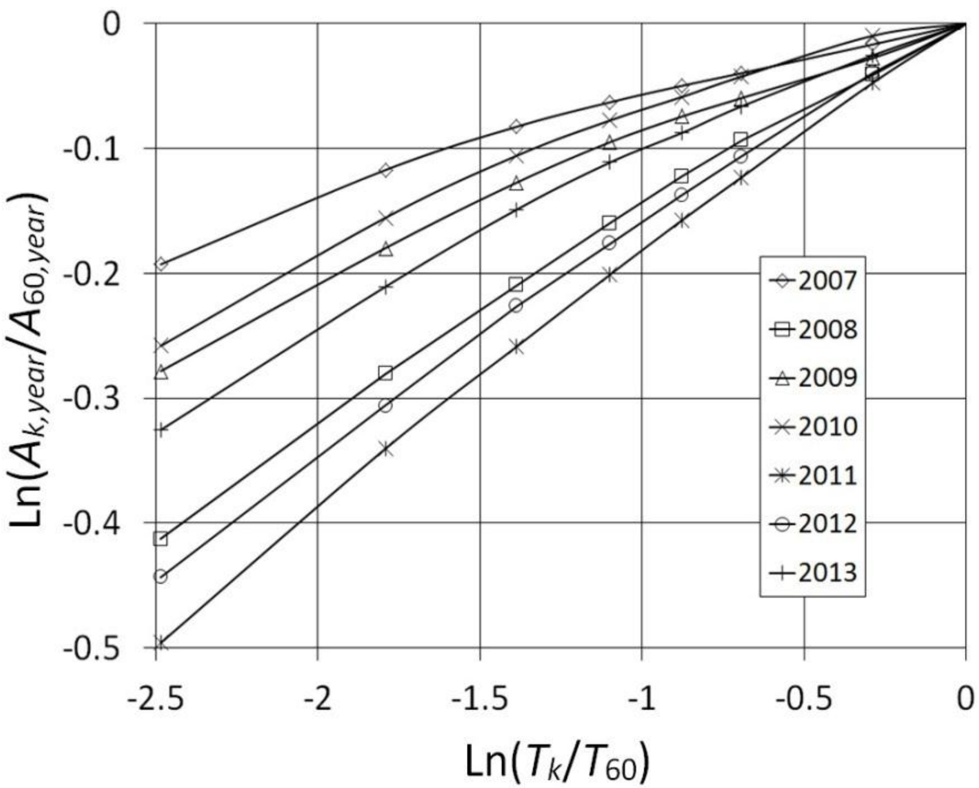
TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

Recalculation of *A*'s and *B*'s

$\mathrm{Ln}(A_{k,year}/A_{60,year}) = -P_{year}\,\mathrm{Ln}^2(T_k/T_{60}) + Q_{year}\,\mathrm{Ln}(T_k/T_{60})$.

or $A_k \approx A_{60}\,(T_k/T_{60})^Q \exp[-P\,\mathrm{Ln}^2(T_k/T_{60})]$

Theoretic model.



Experimental relations.

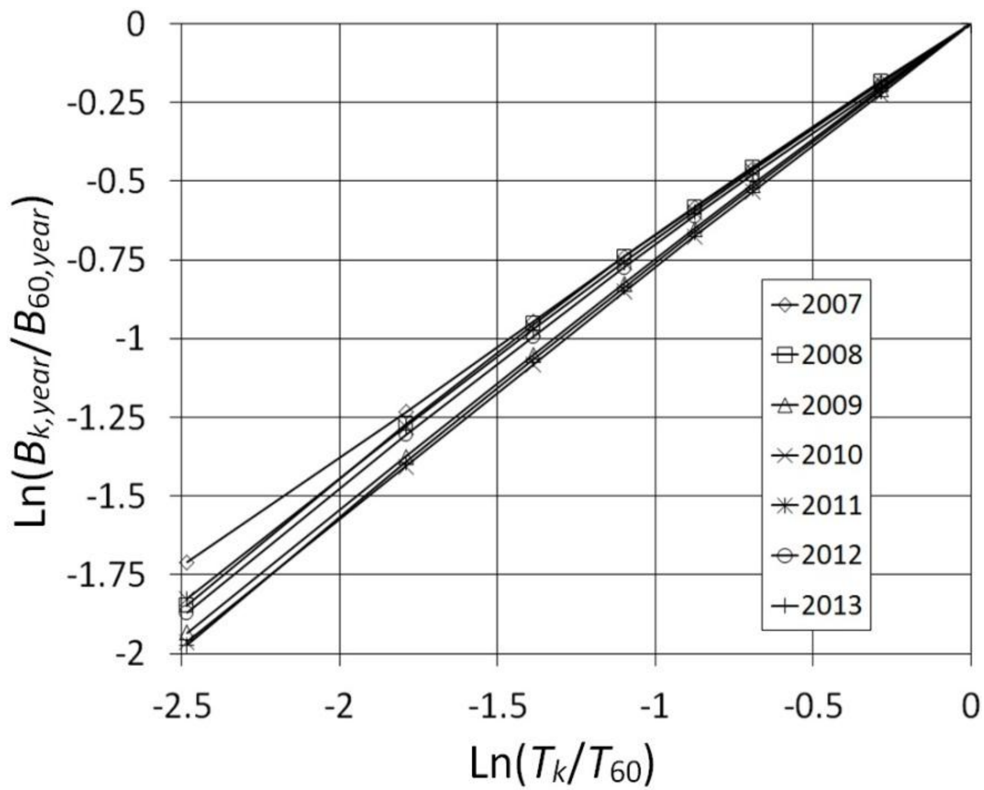
TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

Recalculation of *A*'s and *B*'s

$\mathrm{Ln}(B_{k,year}/B_{60,year}) = R\ \mathrm{Ln}(T_{k,year}/T_{60,year})$

or $B_k \approx B_{60}\ (T_k/T_{60})^R$

Theoretic model.



Experimental relations.

TEMPORAL CHANGES IN POWER in short intervals (intra-hour)

Recalculation of *A*'s and *B*'s

What's the use of these recalculation formulae?

- How often have you found, say, 15-minute readings of wind plant's generation?
- The 60-minute dana are far more available on the Internet.
- However, they're not exactly relevant if you wish to study regulation-related issues.
- So, if you want to go there, you may use recalculation rules to obtain fair approximations to 15-minute readings from 60-minute ones.
- So, it's just about being practical.

$$A_{15} \approx A_{60}\ 0.25^{Q} \exp[-1.9218\ P] \qquad B_{15} \approx B_{60}\ (T_{15}/T_{60})^{R}$$

Year	2007	2008	2009	2010	2011	2012	2013	Avg.	St.dev./Avg. (%)
P	0.0137	0.0152	0.0165	0.0244	0.0124	0.0136	0.0203	0.0166	25.99
Q	0.0427	0.1288	0.0706	0.0432	0.1678	0.1449	0.0804	0.0969	51.82
A_{15}/A_{60}	0.9180	0.8124	0.8785	0.8987	0.7738	0.7969	0.8603	0.8484	6.45
R	0.6839	0.7135	0.7668	0.7841	0.7154	0.7321	0.7798	0.7394	5.17
B_{15}/B_{60}	0.3875	0.3719	0.3454	0.3372	0.3709	0.3624	0.3392	0.3592	5.31

Contribution of the wind plant system to the DEMAND FOR REGULATION

Let us introduce a concept of REGULATION MULTIPLIER, M_{reg}:
How many times can the total installed wind plant power exceede the available fast (secondary) regulation reserve, given certain level of default risk?

- Here we shall stick to the wind generation only as a variable parameter, so to grasp at the regulation demand coming from wind generation alone. In reality, one should take into account load variability, too. But then, the wind generation effect would be harder to evaluate separately.
- We present here a simplified analysis, assuming the secondary reserve, when needed, is fully cleared by the tertiary one, i.e. fully available at its capacity level.

If we kept regulation reserve at x, we would perceive any occurrence of deviation larger than x as a default situation. Therefore, we are interested in:
$w(x) = 1 - z(x) = 1 - \mathrm{Ln}[1 + (e - 1)(1 - e^{-x/B})^A]$. This function has an inverse:

$w^{-1}(r) = - B\ \mathrm{Ln}\{1 - [(e^{1 - r/100} - 1)/(e - 1)]^{1/A}\}$.

We formally replaced x by r to denote the risk variable. Finally, we can define the M_{Reg} simply as $100/w^{-1}(x)$, or:

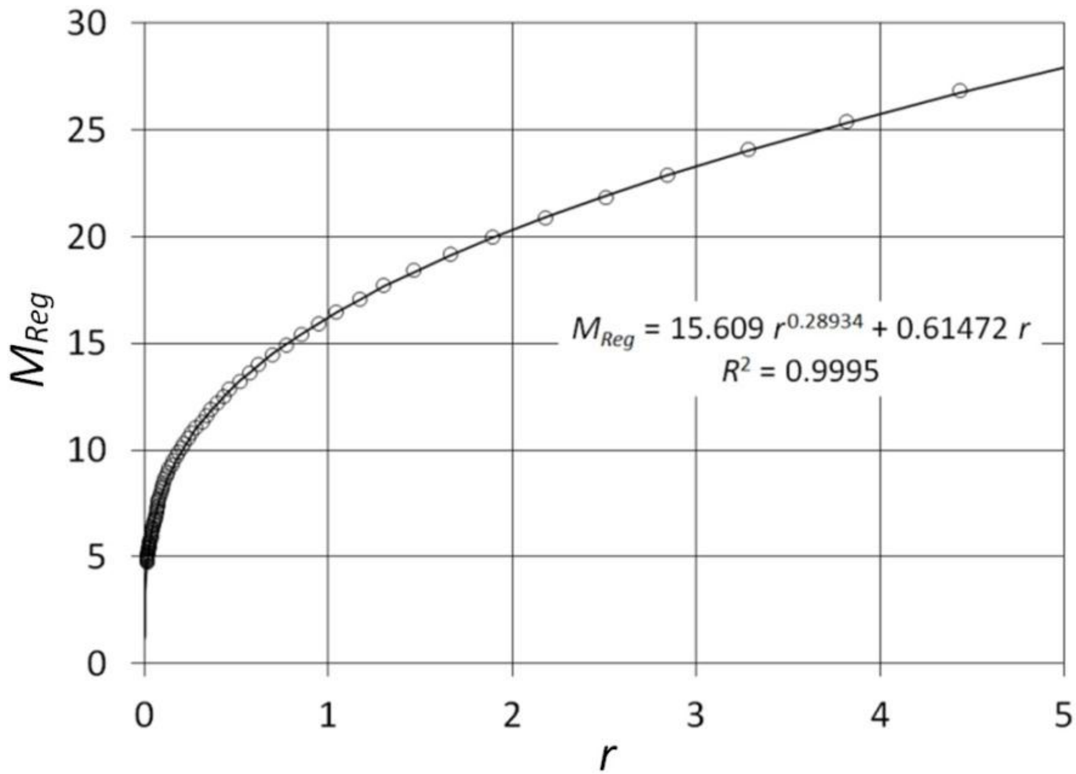
$$\boldsymbol{M_{Reg} = -100/\mathrm{Ln}\{1 - [(e^{1 - r/100} - 1)/(e - 1)]^{1/A}\}^B}$$

This is the VaR function for M_{reg}.

A's and B's are from the distribution function of temporal changes of generated power.

Contribution of the wind plant system to the DEMAND FOR REGULATION

However, due to very complex mathematical operations, it proved a better strategy to first calculate **experimental M_{reg} values**, $100/[1 - z_{exper}(r)]$, and then to use least-squares fit to find appropriate theoretical models.



Theoretical model:

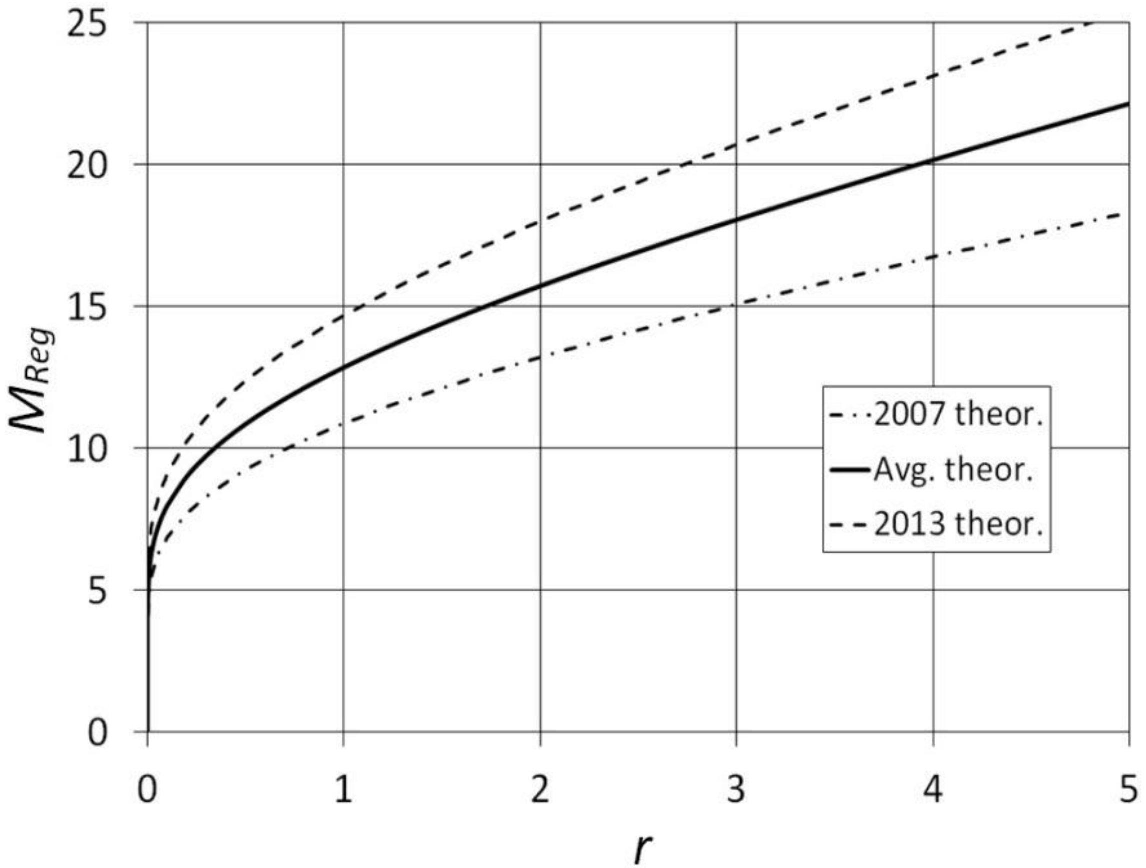
$M_{Reg} = (U/V)r^V + W\,r$

Obviously, the fit is excelent.

Note: In this **simplified** model it is assumed that the secondary regulation is fully available, that is, fully cleared by the tertiary reserve.

Contribution of the wind plant system to the DEMAND FOR REGULATION

Theoretic M_{Reg} functions for 2007, and 2013,
and the geometric mean between them.



DISCUSSION
A few teaser questions…

What about allowing one's self to get short of regulation during certain (ample) percentage of time?

Can one count on good neighbour's help?

What if the neighbour is short, too, at the same time?

There are ideas here in Croatia about allowing the system to be left short of regulation in 2% of the time.

Theoretically, the limitation for new wind capacity could then exceed available fast regulation reserves by factor or ten, or so.

Croatia, 2015:
- +/- (75 secodary + 120 fast tertiary);
- about 400 MW of installed wind;
- plus rest of the system.

Thank you for your attention!