More on Wind Generation in the US

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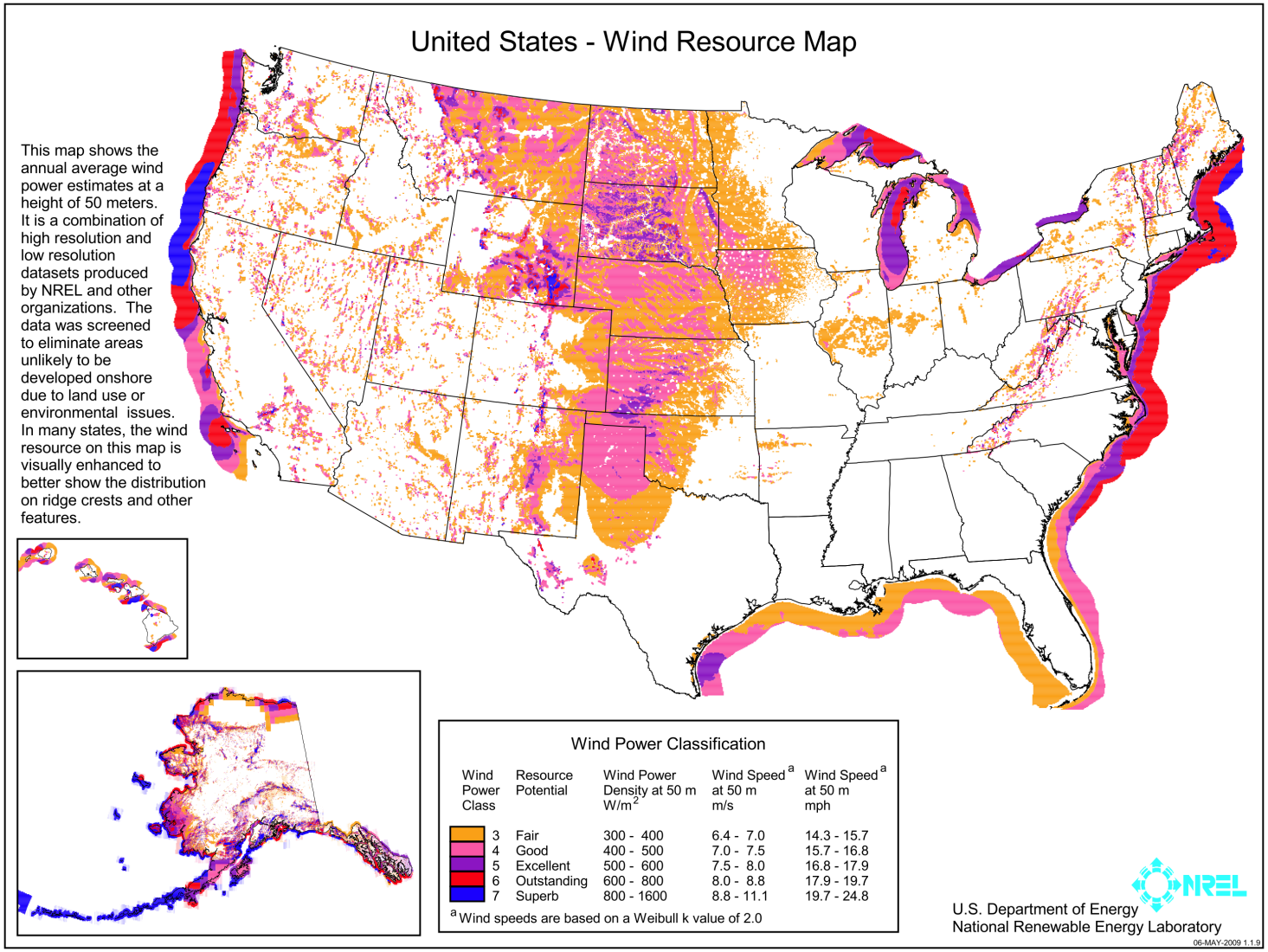
US wind resources



Generating capacity (MW) by state (2007)

	AK	AL	AR	AZ	CA	CO	CT	DC	DE	FL	GA	HI	IA	ID	IL	IN	KS
All capacity	2163	33230	16462	28730	68522	13735	8561	868	3525	63145	39767	2674	13389	3518	48654	30050	12200
Wind capacity	3	0	0	0	2318	1065	0	0	0	0	0	64	1170	75	740	0	363
Wind percent	0.139	0.000	0.000	0.000	3.383	7.754	0.000	0.000	0.000	0.000	0.000	2.393	8.739	2.132	1.521	0.000	2.975

	KY	LA	MA	MD	ME	MI	MN	MO	MS	MT	NC	ND	NE	NH	NJ	NM	NV
All capacity	23351	30158	15299	13442	4522	33037	13984	22195	18184	5658	29654	5346	7422	4494	20154	7934	11526
Wind capacity	0	0	2	0	42	2	1139	57	0	165	0	383	71	0	8	494	425
Wind percent	0.000	0.000	0.013	0.000	0.929	0.006	8.145	0.257	0.000	2.916	0.000	7.164	0.957	0.000	0.040	6.226	3.687

	NY	OH	OK	OR	PA	RI	SC	SD	TN	**TX**	UT	VA	VT	WA	WI	WV	WY
All capacity	42769	36707	21901	13802	49176	2022	25078	3127	22962	**111098**	7521	25270	1090	28720	16976	16986	7036
Wind capacity	0	7	689	886	293	0	0	43	29	**4490**	0	0	6	1163	53	66	287
Wind percent	0.000	0.019	3.146	6.419	0.596	0.000	0.000	1.375	0.126	**4.041**	0.000	0.000	0.550	4.049	0.312	0.389	4.079

Source: EPA State Historical Tables

Wind capacity utilization in ERCOT

- Analysis based on hourly data from ERCOT for 2007, 2008, 2009
- Summary statistics:

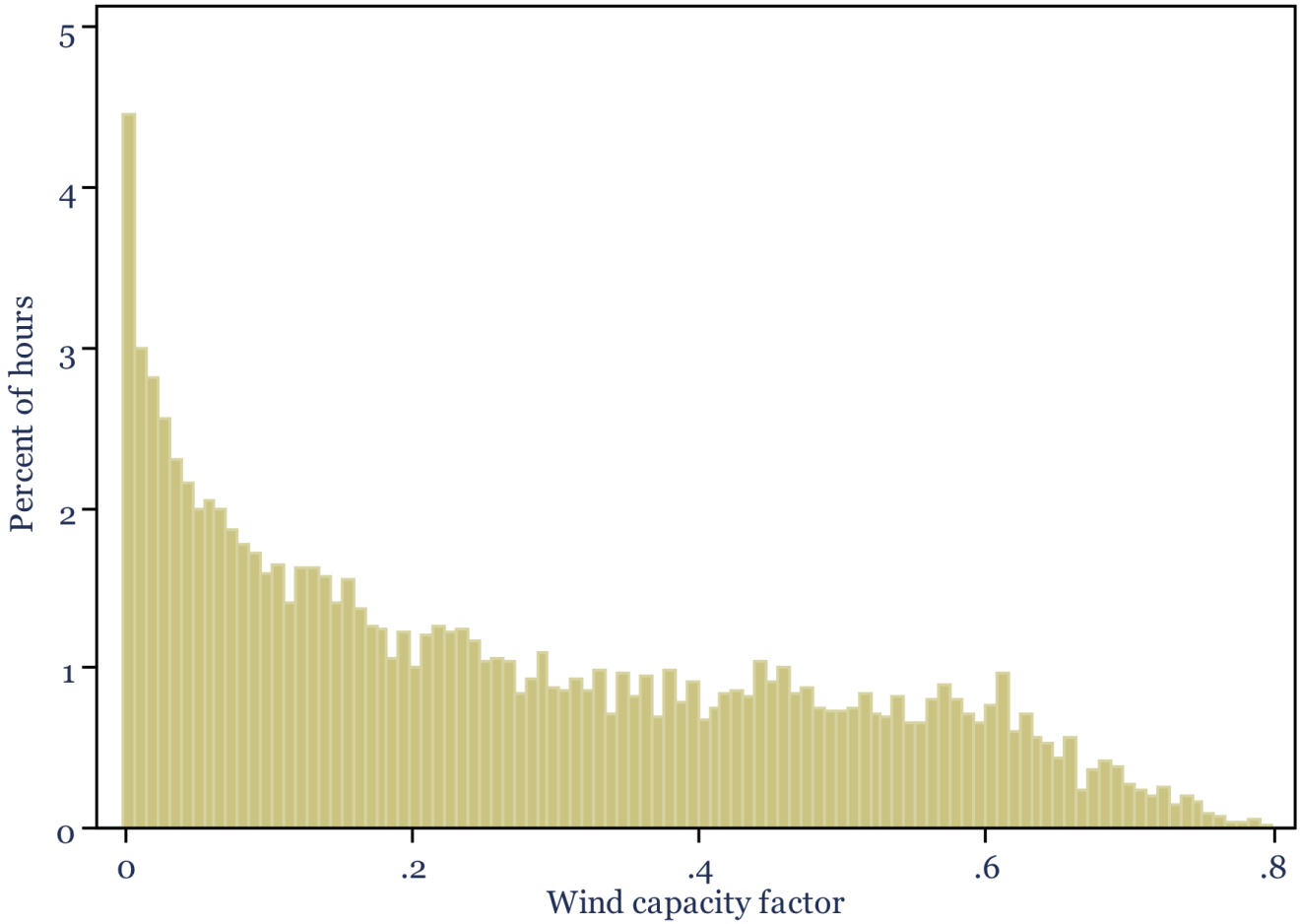
	Mean	Standard deviation	Min	Percentiles 1	5	10	25	50	75	90	95	99	Max
2007	.2630	.2075	-.0013	-.0003	.0078	.0215	.0777	.2175	.4319	.5791	.6350	.7208	.7989
2008	.2966	.2019	-.0016	.0018	.0122	.0286	.1076	.2925	.4613	.5717	.6267	.7103	.7932
2009	.2445	.1441	.0016	0.0122	.0348	.0518	.1147	.2414	.3641	.4368	.4713	.5400	.6793

Wind capacity utilization in MISO

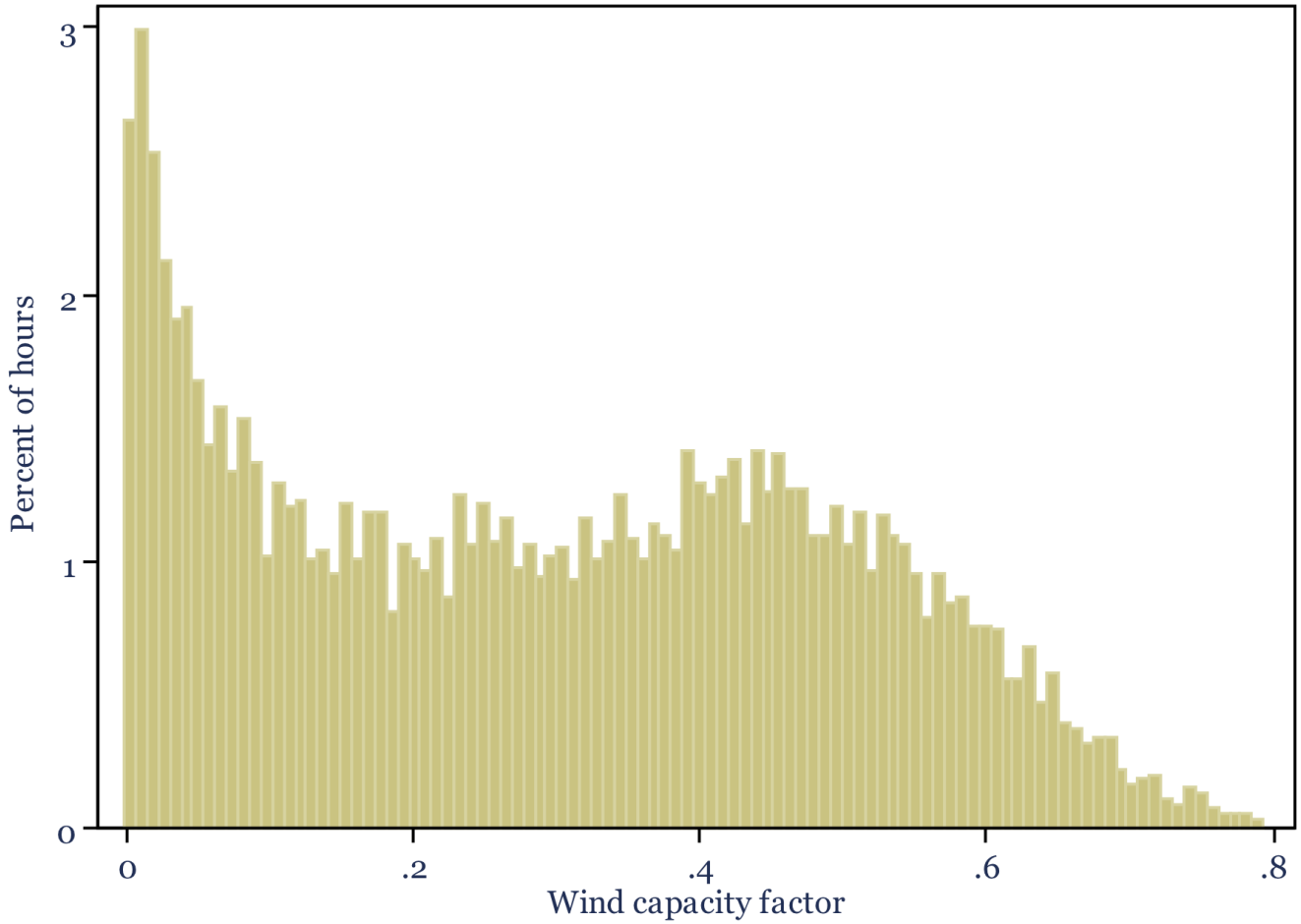
- Analysis based on hourly data from MISO for 2008, 2009
- Summary statistics:

	Mean	Standard deviation	Min	Percentiles 1	5	10	25	50	75	90	95	99	Max
2008	.3413	.2152	.0020	.0220	.0561	.0840	.1521	.3039	.5123	.6578	.7221	.8280	.9576
2009	.2889	.1776	-.0007	0.0122	.0146	.0434	.1395	.2612	.4236	.5549	.6042	.6690	.7513

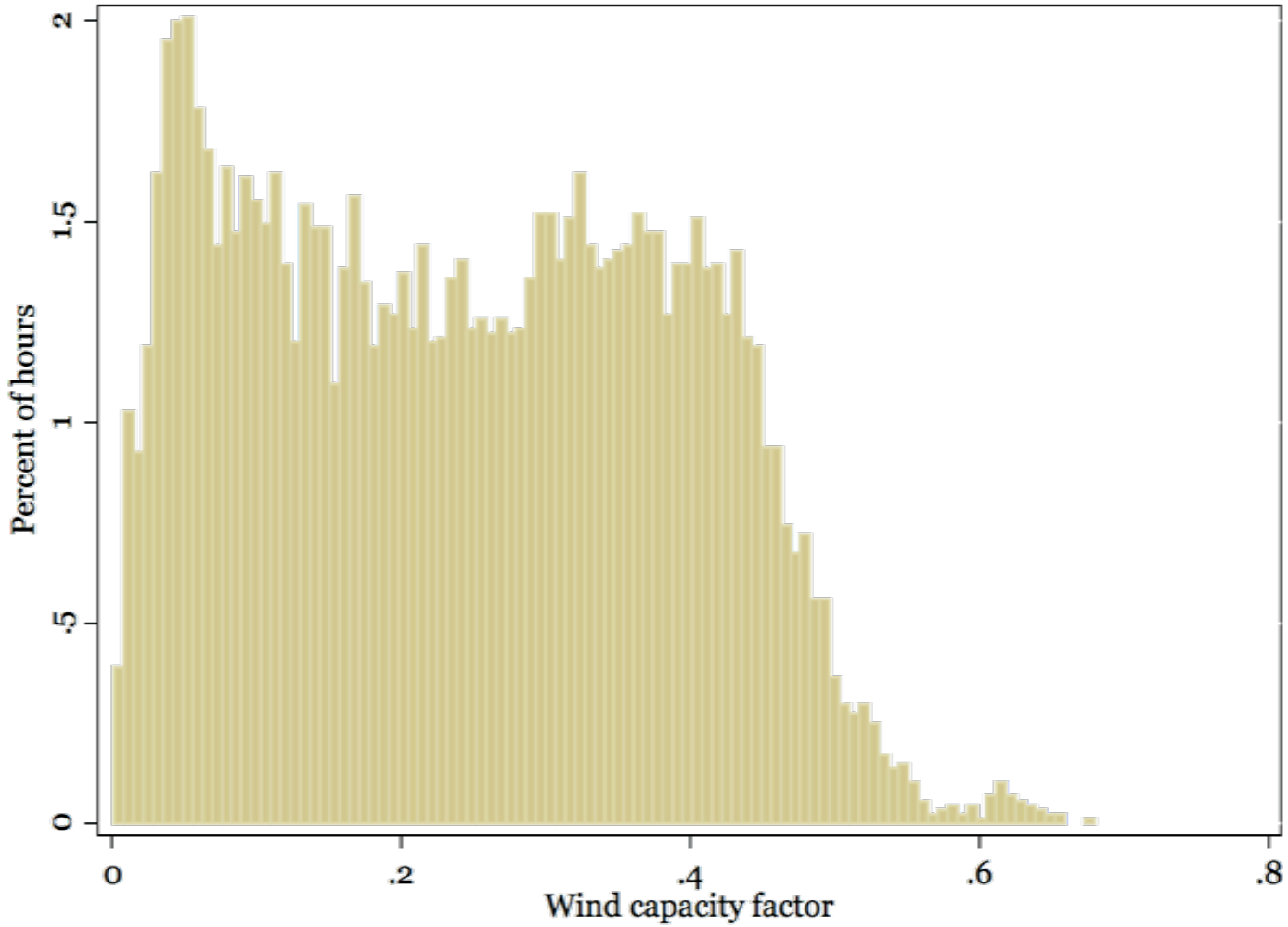
ERCOT wind capacity utilization 2007



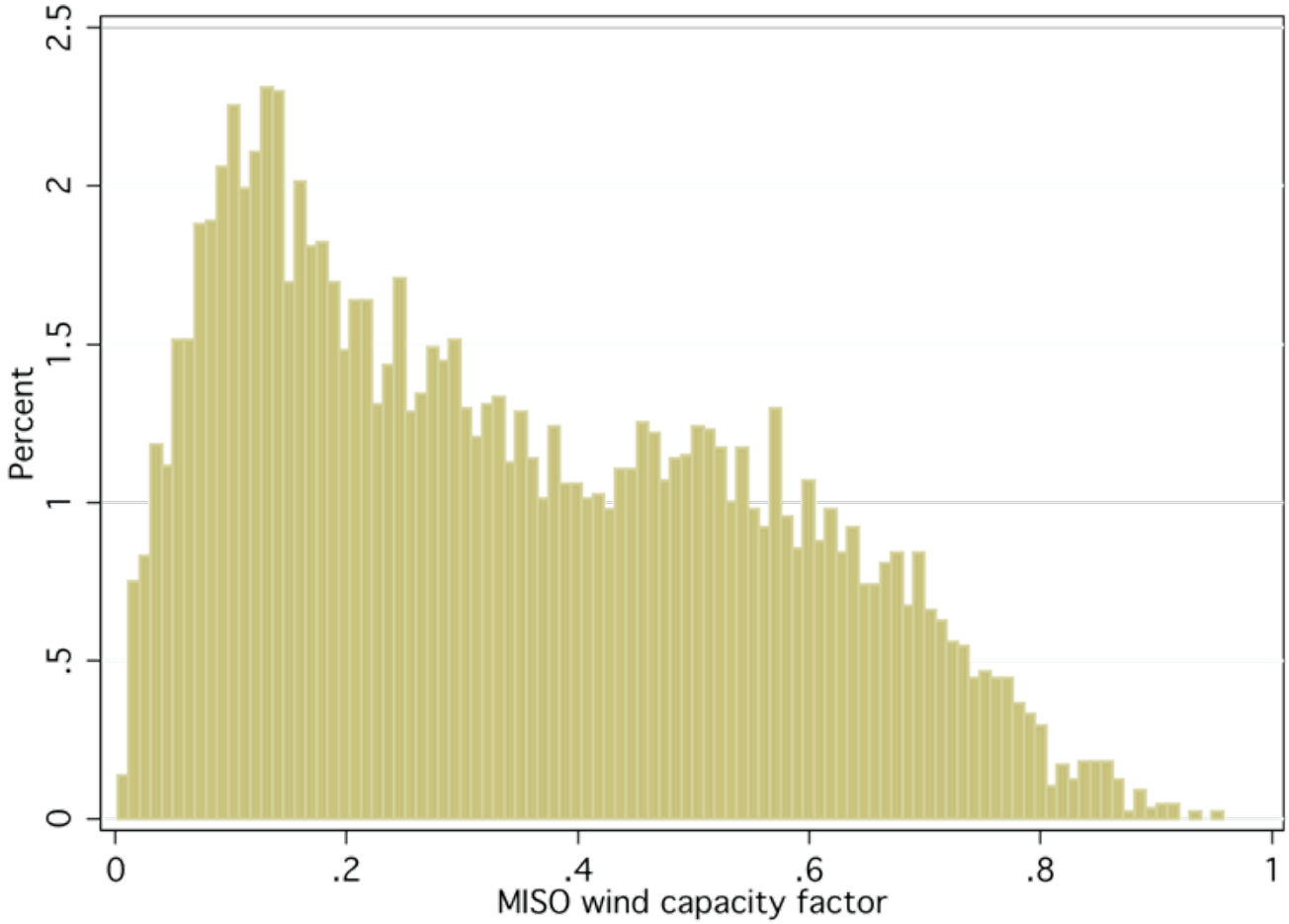
ERCOT wind capacity utilization 2008



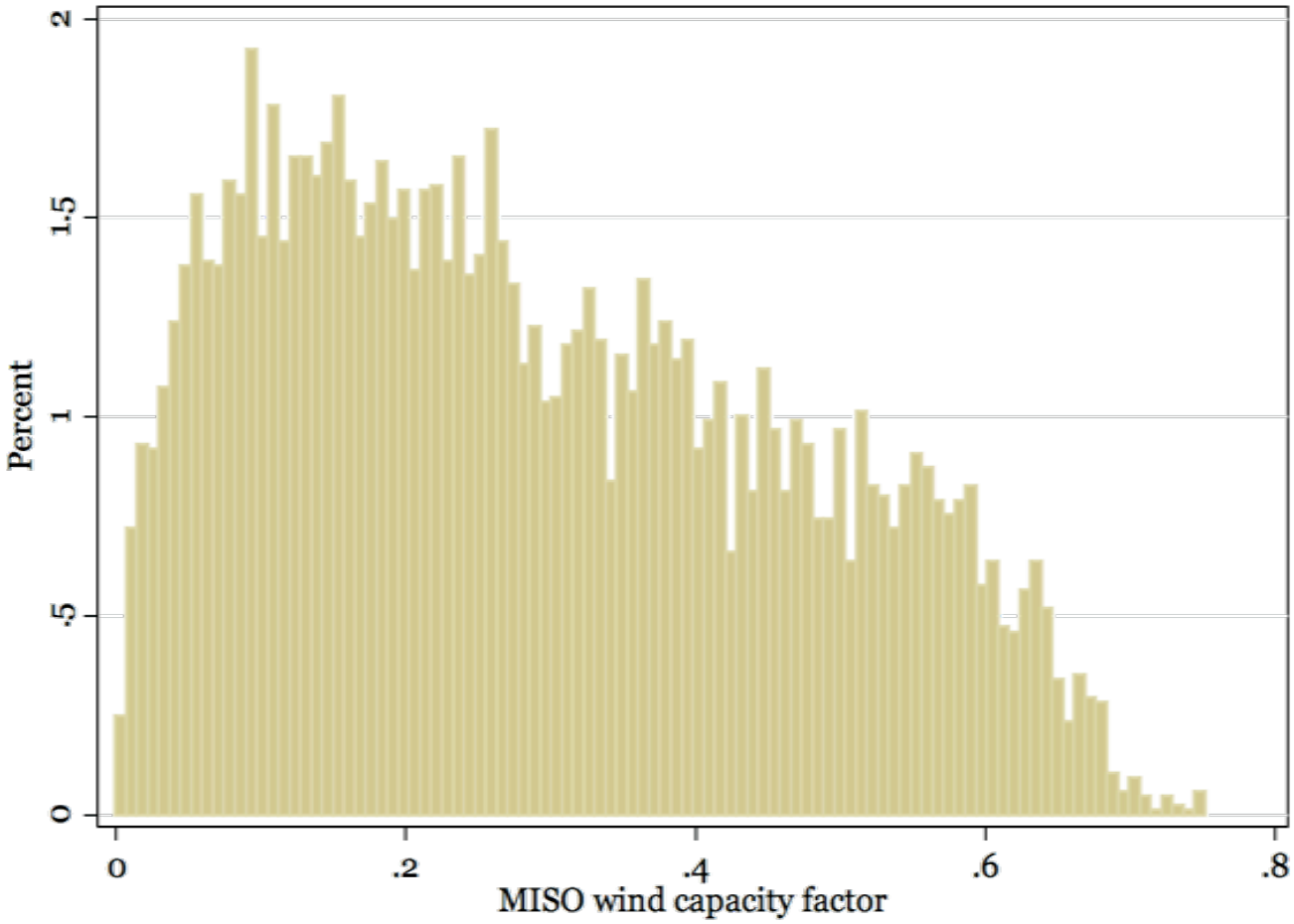
ERCOT wind capacity utilization 2009



MISO wind capacity utilization 2008



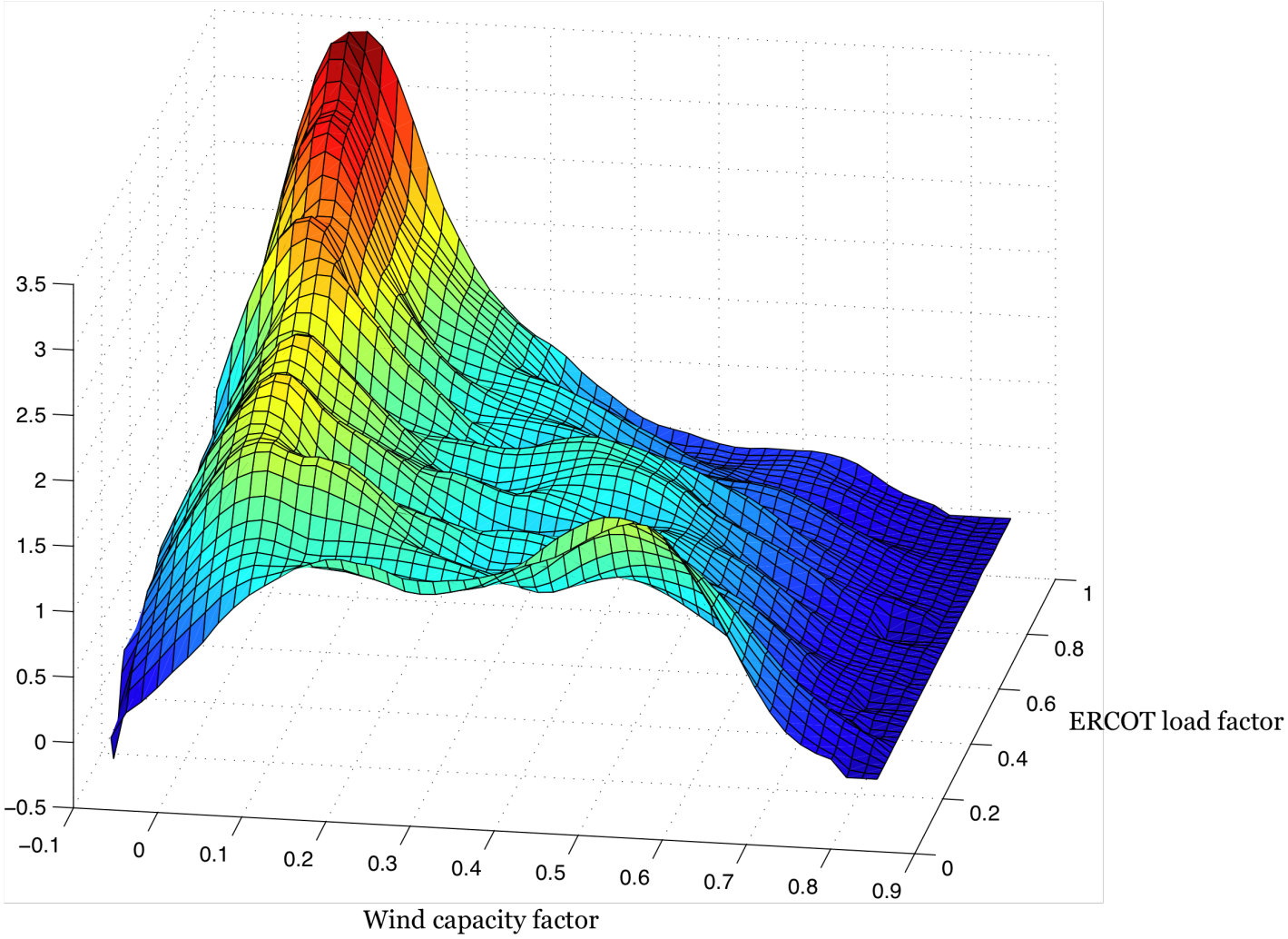
MISO wind capacity utilization 2009



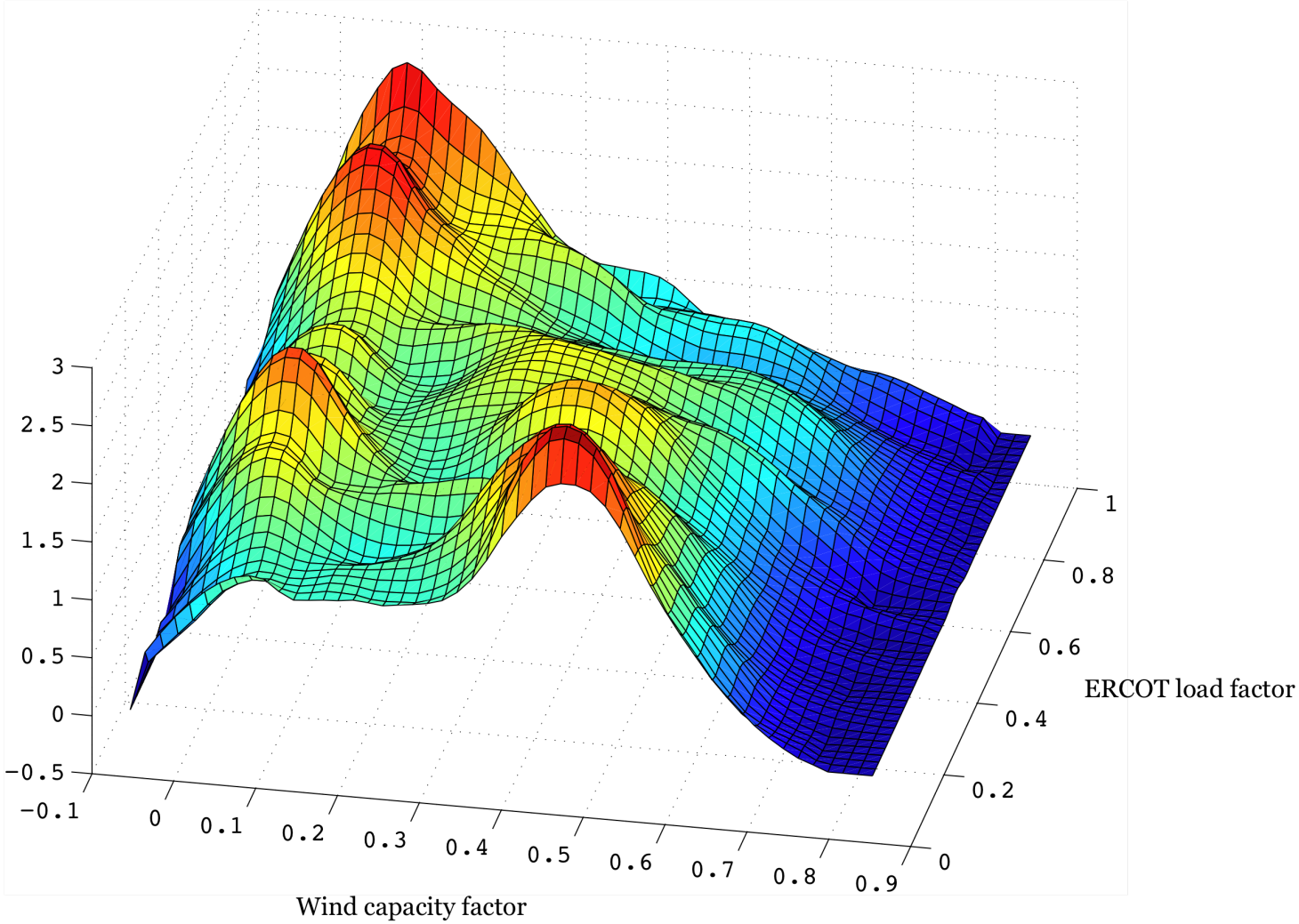
Valuing wind power output

- The average capacity factor of wind determines how much electricity is available for sale to recoup the up-front capital costs
- Assuming no reverse power flow to west Texas, the average capacity factor also determines how much the transmission lines will be used
- However, revenue also depends on the *price* of electricity when the wind is blowing, which is largely determined by the overall system load
- Similarly, the implicit "capacity value" of wind generation depends on how closely wind output tracks overall system load
- To investigate further, we calculated the pattern of wind capacity utilization as a function of the ERCOT system load

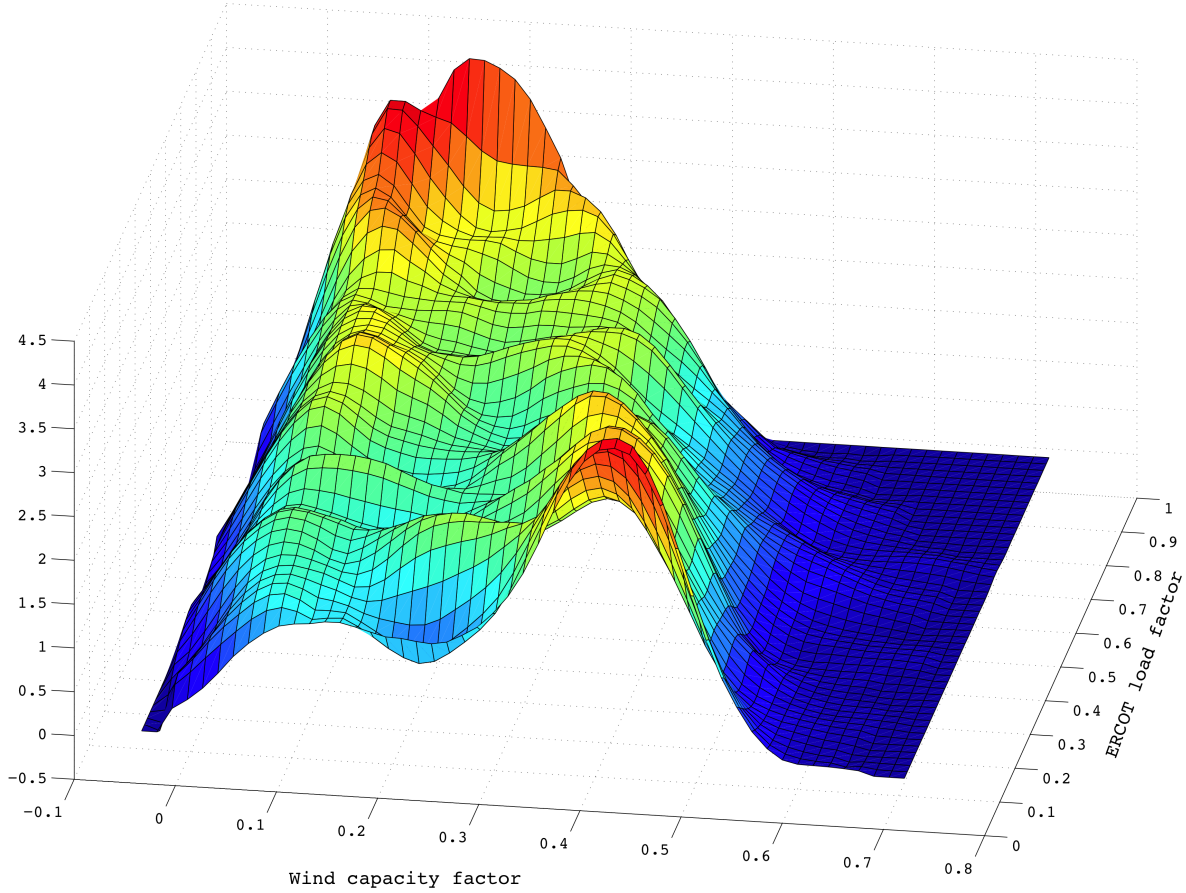
Wind capacity factor and ERCOT load, 2007



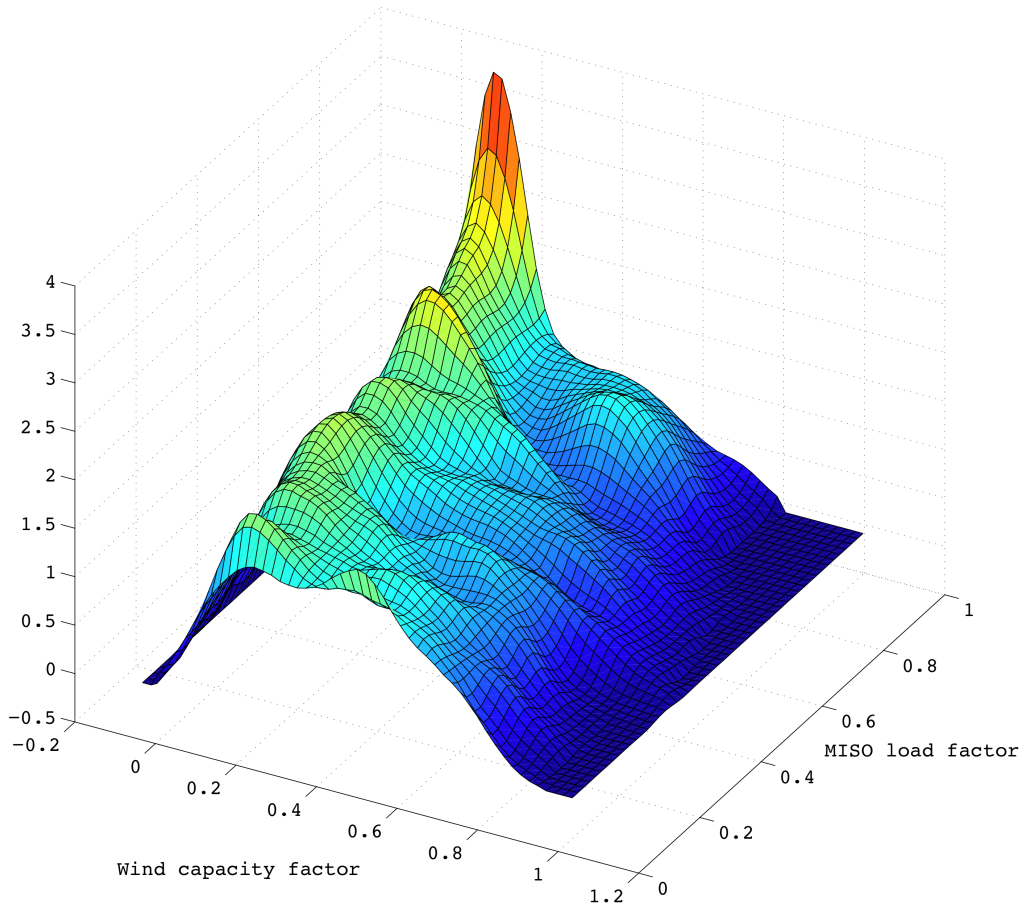
Wind capacity factor and ERCOT load, 2008



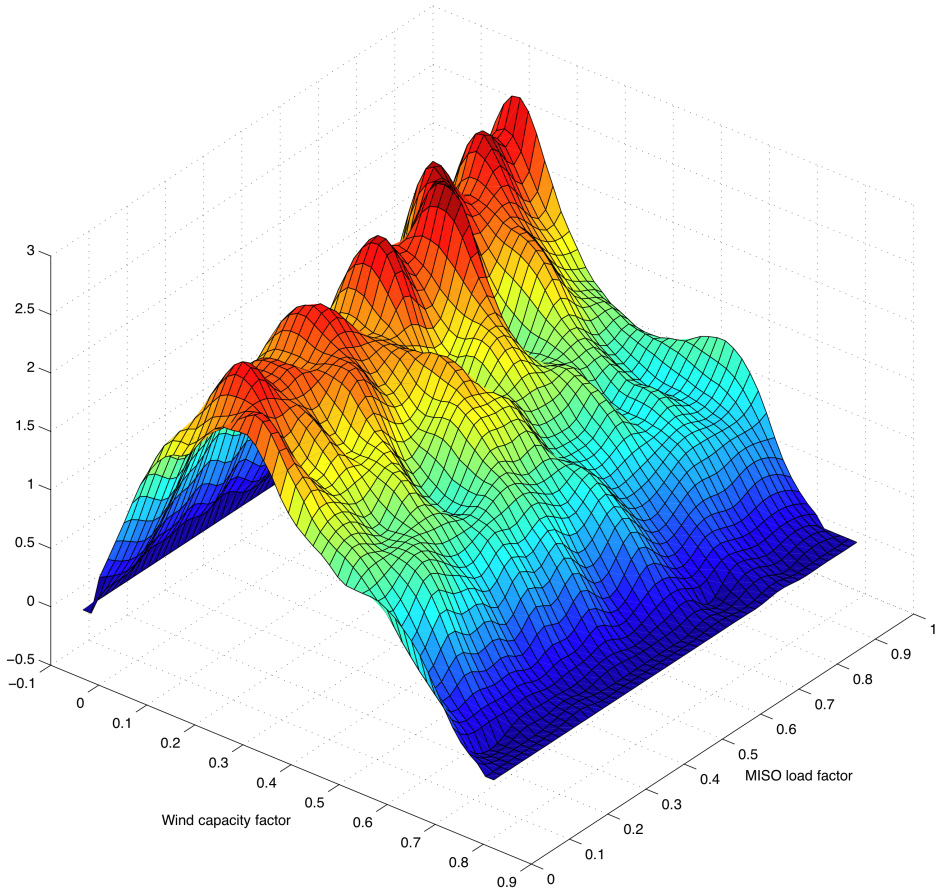
Wind capacity factor and ERCOT load, 2009



Wind capacity factor and MISO load, 2008



Wind capacity factor and MISO load, 2009



Systematic daily pattern in ERCOT wind output

2007 data

windcapf	Coef.	OPG Std. Err.	z	P>|z|	[95% Conf.	Interval]
windcapf						
_Ihour_1	-.0018536	.0026343	-0.70	0.482	-.0070167	.0033095
_Ihour_2	-.009009	.0042213	-2.13	0.033	-.0172826	-.0007354
_Ihour_3	-.02072	.0054422	-3.81	0.000	-.0313865	-.0100536
_Ihour_4	-.0321016	.0064003	-5.02	0.000	-.0446459	-.0195573
_Ihour_5	-.0449911	.0072219	-6.23	0.000	-.0591458	-.0308364
_Ihour_6	-.0557725	.0079092	-7.05	0.000	-.0712743	-.0402708
_Ihour_7	-.0718472	.0084013	-8.55	0.000	-.0883135	-.0553808
_Ihour_8	-.0895515	.0086963	-10.30	0.000	-.1065959	-.0725071
_Ihour_9	-.1028928	.0088724	-11.60	0.000	-.1202823	-.0855033
_Ihour_10	-.1127387	.0089716	-12.57	0.000	-.1303227	-.0951547
_Ihour_11	-.1234337	.0090276	-13.67	0.000	-.1411275	-.1057399
_Ihour_12	-.1309192	.0090475	-14.47	0.000	-.1486519	-.1131864
_Ihour_13	-.1361745	.0090462	-15.05	0.000	-.1539047	-.1184443
_Ihour_14	-.139032	.008919	-15.59	0.000	-.156513	-.1215511
_Ihour_15	-.1393946	.0086428	-16.13	0.000	-.1563341	-.122455
_Ihour_16	-.1365793	.0083455	-16.37	0.000	-.1529361	-.1202225
_Ihour_17	-.1326055	.0078521	-16.89	0.000	-.1479954	-.1172155
_Ihour_18	-.1286089	.0074018	-17.38	0.000	-.1431162	-.1141016
_Ihour_19	-.108529	.0068139	-15.93	0.000	-.121884	-.0951739
_Ihour_20	-.0707997	.0060878	-11.63	0.000	-.0827316	-.0588677
_Ihour_21	-.0348511	.0050681	-6.88	0.000	-.0447844	-.0249178
_Ihour_22	-.0119944	.003941	-3.04	0.002	-.0197187	-.0042702
_Ihour_23	.0004864	.0023612	0.21	0.837	-.0041414	.0051142
_cons	.3397349	.0150293	22.60	0.000	.310278	.3691918
ARMA						
ar						
L1.	1.254581	.0074467	168.47	0.000	1.239985	1.269176
L2.	-.296615	.0068248	-43.46	0.000	-.3099913	-.2832386
ma						
L24.	.0570291	.0097662	5.84	0.000	.0378878	.0761704
/sigma	.0475944	.0002143	222.09	0.000	.0471743	.0480144

2008 data

windcapf	Coef.	OPG Std. Err.	z	P>|z|	[95% Conf.	Interval]
windcapf						
_Ihour_1	.0027822	.0028412	0.98	0.327	-.0027864	.0083508
_Ihour_2	.0002797	.0045341	0.06	0.951	-.0086069	.0091664
_Ihour_3	-.0054225	.0058215	-0.93	0.352	-.0168325	.0059876
_Ihour_4	-.0142872	.0068255	-2.09	0.036	-.0276651	-.0009094
_Ihour_5	-.0239001	.0075329	-3.17	0.002	-.0386644	-.0091358
_Ihour_6	-.0366257	.0081116	-4.52	0.000	-.0525242	-.0207273
_Ihour_7	-.0501049	.0085472	-5.86	0.000	-.0668571	-.0333526
_Ihour_8	-.0677501	.008781	-7.72	0.000	-.0849605	-.0505397
_Ihour_9	-.0851137	.008925	-9.54	0.000	-.1026064	-.067621
_Ihour_10	-.1010894	.0090353	-11.19	0.000	-.1187982	-.0833806
_Ihour_11	-.1115758	.0091282	-12.22	0.000	-.1294668	-.0936848
_Ihour_12	-.1190387	.0091975	-12.94	0.000	-.1370655	-.1010119
_Ihour_13	-.1223346	.0091406	-13.38	0.000	-.1402498	-.1044193
_Ihour_14	-.123572	.0089481	-13.81	0.000	-.14111	-.1060341
_Ihour_15	-.1232514	.0086293	-14.28	0.000	-.1401645	-.1063382
_Ihour_16	-.1186124	.0082107	-14.45	0.000	-.1347051	-.1025198
_Ihour_17	-.1165187	.0076779	-15.18	0.000	-.131567	-.1014703
_Ihour_18	-.1112412	.0071381	-15.58	0.000	-.1252316	-.0972508
_Ihour_19	-.0990561	.0065493	-15.12	0.000	-.1118924	-.0862198
_Ihour_20	-.0698331	.0058598	-11.92	0.000	-.0813181	-.0583481
_Ihour_21	-.0419448	.0049869	-8.41	0.000	-.0517189	-.0321706
_Ihour_22	-.0150872	.003851	-3.92	0.000	-.0226351	-.0075394
_Ihour_23	-.0078471	.00254	-3.09	0.002	-.0128254	-.0028689
_cons	.361696	.0149454	24.20	0.000	.3324036	.3909883
ARMA						
ar						
L1.	1.203352	.0076306	157.70	0.000	1.188396	1.218307
L2.	-.2467094	.0069429	-35.53	0.000	-.2603173	-.2331016
ma						
L12.	-.0436322	.0101712	-4.29	0.000	-.0635673	-.0236971
L24.	.0482166	.0094283	5.11	0.000	.0297374	.0666959
/sigma	.0499354	.0002471	202.11	0.000	.0494512	.0504197

Systematic daily pattern in ERCOT wind output

2009 data

windcapf	Coef.	OPG Std. Err.	z	P>|z|	[95% Conf.	Interval]
windcapf						
_Ihour_1	.0062733	.0019676	3.19	0.001	.0024169	.0101297
_Ihour_2	.0070804	.0030652	2.31	0.021	.0010728	.0130881
_Ihour_3	.0038654	.0040067	0.96	0.335	-.0039876	.0117184
_Ihour_4	.001873	.0047215	0.40	0.692	-.0073809	.0111269
_Ihour_5	-.0060739	.0053063	-1.14	0.252	-.0164741	.0043262
_Ihour_6	-.0106403	.005774	-1.84	0.065	-.0219572	.0006765
_Ihour_7	-.0146536	.0061191	-2.39	0.017	-.0266468	-.0026604
_Ihour_8	-.0271477	.0063862	-4.25	0.000	-.0396643	-.014631
_Ihour_9	-.036207	.0065538	-5.52	0.000	-.0490523	-.0233617
_Ihour_10	-.0495123	.0066251	-7.47	0.000	-.0624972	-.0365274
_Ihour_11	-.0627278	.0066511	-9.43	0.000	-.0757638	-.0496919
_Ihour_12	-.0752365	.0066573	-11.30	0.000	-.0882846	-.0621885
_Ihour_13	-.0851194	.0066195	-12.86	0.000	-.0980935	-.0721454
_Ihour_14	-.0867464	.006533	-13.28	0.000	-.0995509	-.0739418
_Ihour_15	-.0850341	.0063865	-13.31	0.000	-.0975515	-.0725167
_Ihour_16	-.0805977	.0061397	-13.13	0.000	-.0926314	-.0685641
_Ihour_17	-.0767598	.0058017	-13.23	0.000	-.0881309	-.0653888
_Ihour_18	-.0762292	.0053877	-14.15	0.000	-.0867888	-.0656695
_Ihour_19	-.0703643	.0049677	-14.16	0.000	-.0801009	-.0606277
_Ihour_20	-.0584854	.0045061	-12.98	0.000	-.0673172	-.0496536
_Ihour_21	-.0392986	.0038416	-10.23	0.000	-.046828	-.0317692
_Ihour_22	-.0171443	.0031007	-5.53	0.000	-.0232215	-.0110671
_Ihour_23	-.0059577	.0019278	-3.09	0.002	-.009736	-.0021794
_cons	.2838462	.0103588	27.40	0.000	.2635434	.3041491
ARMA						
ar						
L1.	1.177857	.0075825	155.34	0.000	1.162995	1.192718
L2.	-.2256977	.007156	-31.54	0.000	-.2397232	-.2116722
ma						
L12.	-.0230617	.0103449	-2.23	0.026	-.0433374	-.002786
L24.	.0569449	.0101987	5.58	0.000	.0369558	.0769339
/sigma	.0375156	.0001875	200.07	0.000	.0371481	.0378832

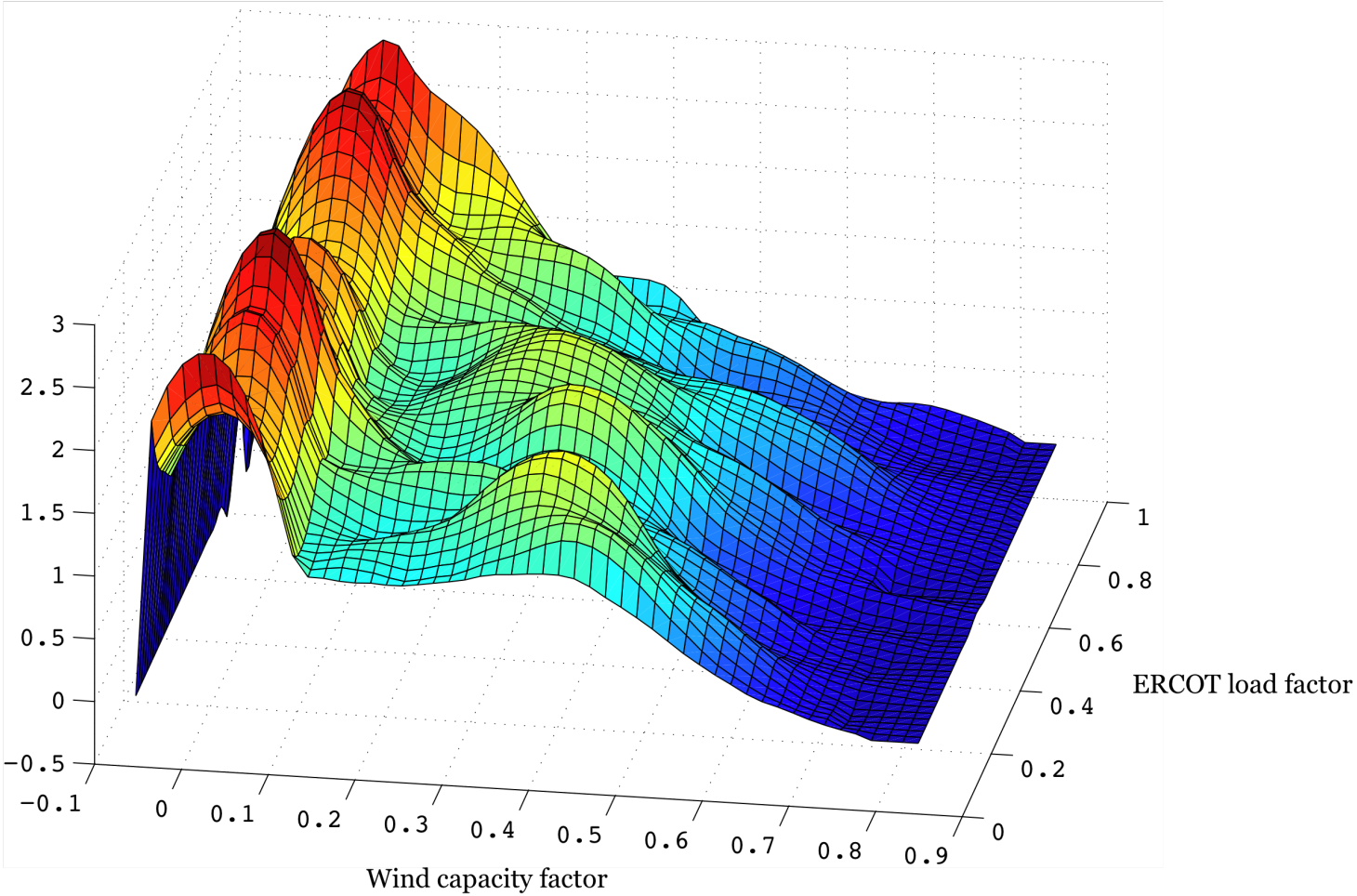
Systematic daily pattern in MISO wind output

wind_lf	Coef.	OPG Std. Err.	z	P>|z|	[95% Conf.	Interval]
wind_lf						
_Ihour_1	.001984	.002126	0.93	0.351	-.0021829	.0061509
_Ihour_2	-.0016285	.0037099	-0.44	0.661	-.0088998	.0056428
_Ihour_3	-.0041615	.005059	-0.82	0.411	-.0140769	.0057539
_Ihour_4	-.0080453	.0061676	-1.30	0.192	-.0201336	.0040429
_Ihour_5	-.008031	.0070417	-1.14	0.254	-.0218323	.0057704
_Ihour_6	-.0094962	.0077171	-1.23	0.218	-.0246214	.005629
_Ihour_7	-.012427	.0082327	-1.51	0.131	-.0285628	.0037088
_Ihour_8	-.0215346	.0086197	-2.50	0.012	-.0384288	-.0046403
_Ihour_9	-.0392264	.0088927	-4.41	0.000	-.0566557	-.0217971
_Ihour_10	-.0512045	.0090533	-5.66	0.000	-.0689486	-.0334603
_Ihour_11	-.0471143	.009108	-5.17	0.000	-.0649656	-.029263
_Ihour_12	-.0384465	.0090779	-4.24	0.000	-.0562389	-.0206542
_Ihour_13	-.0330773	.0089905	-3.68	0.000	-.0506984	-.0154561
_Ihour_14	-.0278963	.008796	-3.17	0.002	-.0451361	-.0106565
_Ihour_15	-.0214404	.0085308	-2.51	0.012	-.0381604	-.0047203
_Ihour_16	-.0169363	.0081214	-2.09	0.037	-.0328538	-.0010187
_Ihour_17	-.0186309	.0075887	-2.46	0.014	-.0335044	-.0037574
_Ihour_18	-.0242172	.0069781	-3.47	0.001	-.037894	-.0105404
_Ihour_19	-.0309852	.0063726	-4.86	0.000	-.0434752	-.0184951
_Ihour_20	-.0347822	.0057486	-6.05	0.000	-.0460493	-.0235151
_Ihour_21	-.0293441	.0048658	-6.03	0.000	-.038881	-.0198073
_Ihour_22	-.0157807	.0037051	-4.26	0.000	-.0230426	-.0085188
_Ihour_23	-.0053569	.0021706	-2.47	0.014	-.0096113	-.0011026
_cons	.3629932	.0164574	22.06	0.000	.3307372	.3952491
ARMA						
ar						
L1.	1.517765	.0069326	218.93	0.000	1.504177	1.531352
L2.	-.5431038	.006636	-81.84	0.000	-.5561101	-.5300975
ma						
L12.	.0083736	.0094129	0.89	0.374	-.0100754	.0268226
L24.	.0894375	.0095411	9.37	0.000	.0707373	.1081376
/sigma	.0317296	.0001622	195.58	0.000	.0314116	.0320475

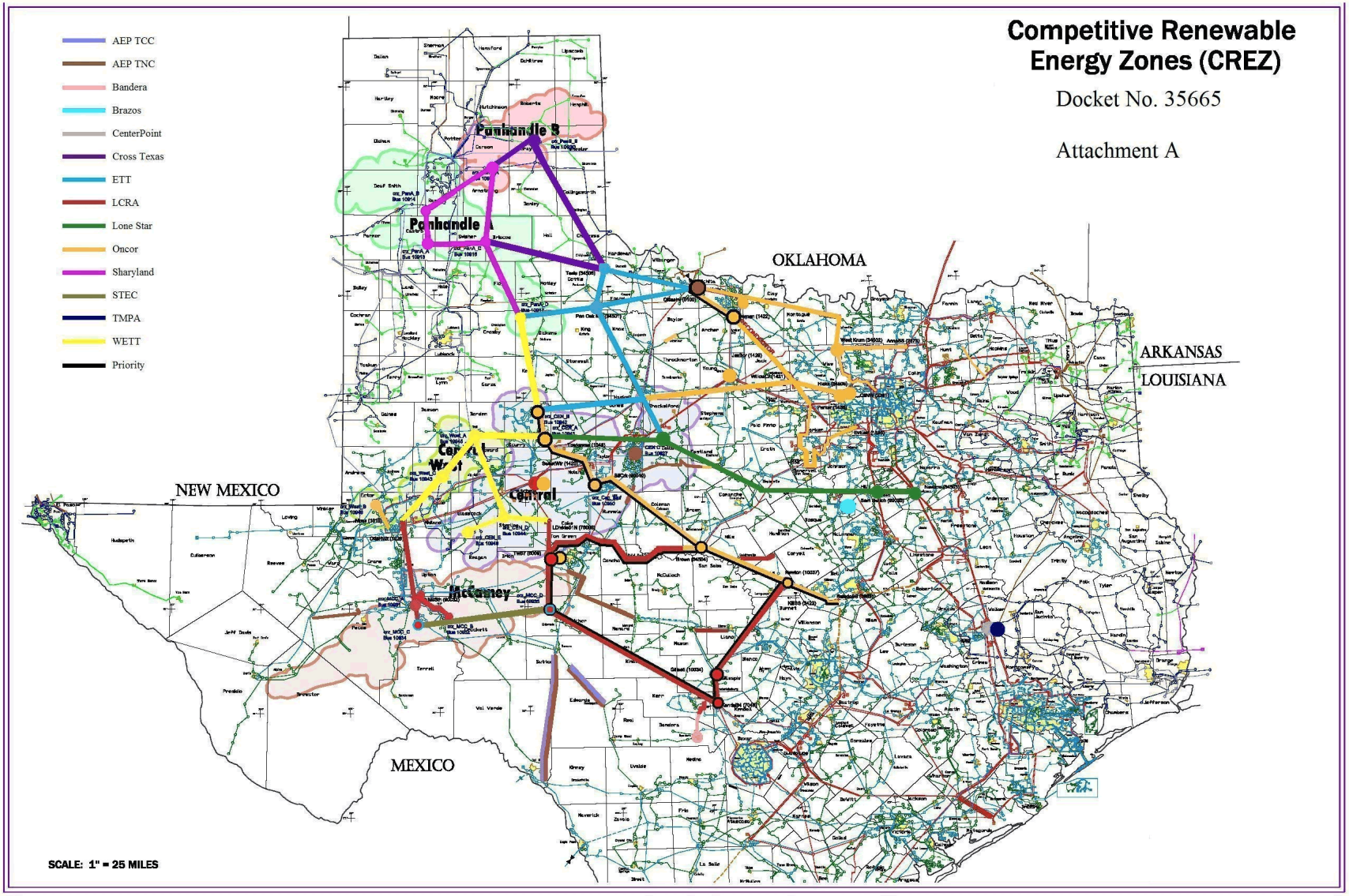
Negative prices

- In recent years, prices for down regulation in the ERCOT balancing market have sometimes been negative, especially in the west zone
  - In 2007, the minimum 15-minute price was –$999.01 and 0.965% of prices were < 0
  - In 2008, the minimum 15-minute price was –$1981.81 and 13.94% of prices were < 0
  - In 2009, the minimum 15-minute price was –$1000.00 and 8.76% of prices were < 0
- Negative prices effectively mean that suppliers are demanding a payment to cut back output, or equivalently are willing to pay money in order to supply more
- In other wholesale markets, this can occur when base load plants have large costs of re-starting and thus would prefer to avoid shutting down
- It would appear that the large negative prices recently seen in ERCOT, however, are largely the result of wind generation
  - The negative prices are more concentrated in the west zone where the wind generation also is to be found and transmission bottlenecks prevent exports
  - Given PTCs and RECs, wind generators need to be paid to shut down output

Positively valued wind output & ERCOT load, 2008



Planned transmission upgrades



Wind capacity availability at ERCOT peak

- Probability distributions of wind capacity availability for the top 5% or top 1% of hourly loads in 2008:

ERCOT load	Mean	Standard deviation	Min	Percentiles 1	5	10	25	50	75	90	95	99	Max
Top 5%	.2183	.1835	.0013	.0031	.0109	.0230	.0720	.1664	.3343	.4790	.6129	.7290	.7531
Top 1%	.1441	.1305	.0035	.0035	.0079	.0110	.0448	.1079	.2092	.3735	.4021	.5696	.5696

- Probability distributions of wind capacity availability for the top 5% or top 1% of hourly loads in 2009:

ERCOT load	Mean	Standard deviation	Min	Percentiles 1	5	10	25	50	75	90	95	99	Max
Top 5%	.1584	.0823	.0177	.0243	.0350	.0492	.0931	.1578	.2172	.2763	.3069	.3365	.3835
Top 1%	.1448	.0708	.0294	.0294	.0350	.0473	.0892	.1478	.1852	.2446	.2705	.3077	.3077

Wind capacity availability at MISO peak

- Probability distributions of wind capacity availability for the top 5% or top 1% of hourly loads in 2008:

ERCOT load	Mean	Standard deviation	Min	Percentiles 1	5	10	25	50	75	90	95	99	Max
Top 5%	.2275	.1924	.0084	.0180	.0389	.0558	.0942	.1444	.3207	.5620	.6666	.7525	.7720
Top 1%	.1289	.0733	.0333	.0333	.0469	.0553	.0913	.1104	.1446	.1923	.3114	.4328	.4328

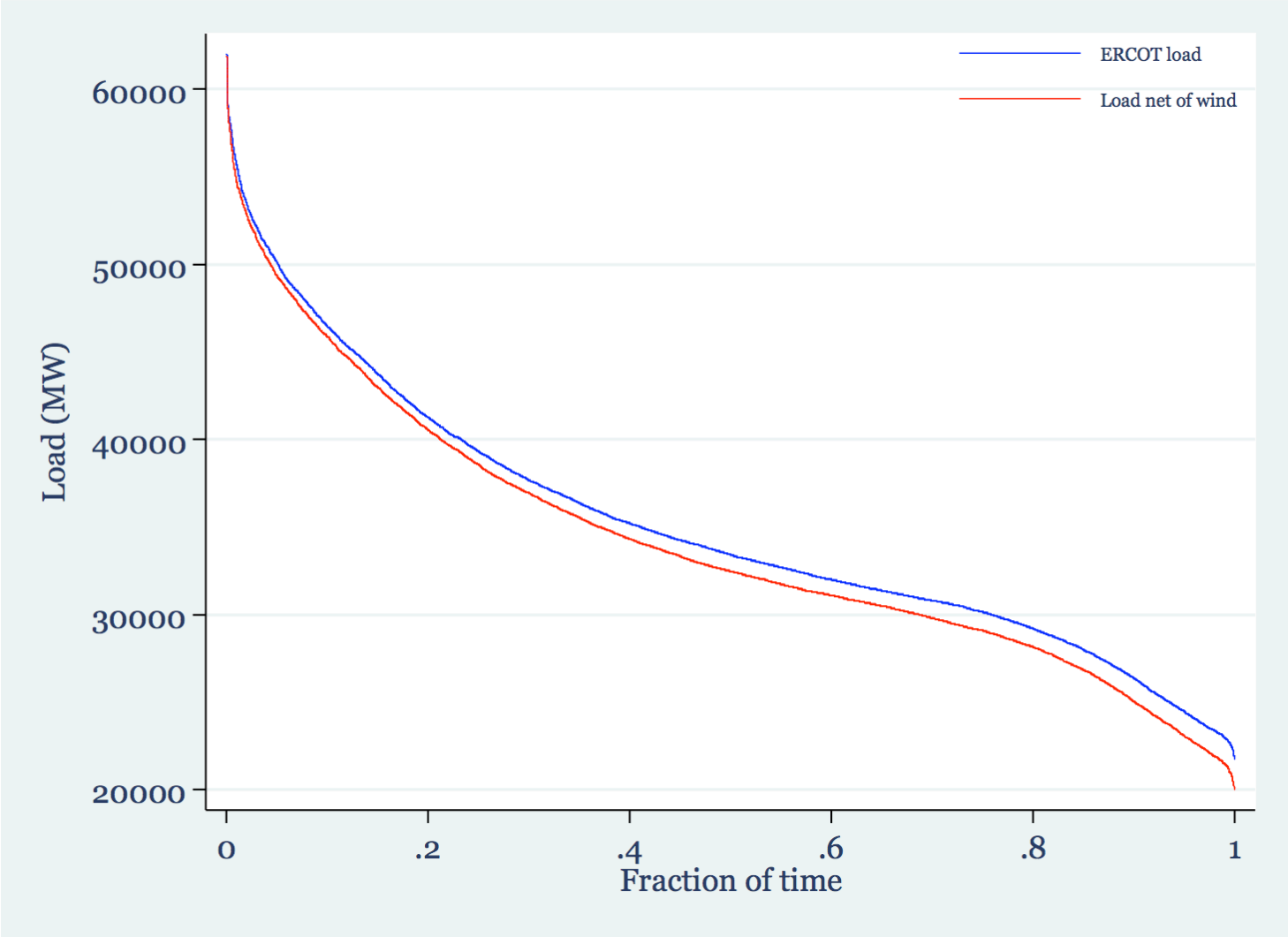
- Probability distributions of wind capacity availability for the top 5% or top 1% of hourly loads in 2009 (*incomplete data*):

ERCOT load	Mean	Standard deviation	Min	Percentiles 1	5	10	25	50	75	90	95	99	Max
Top 5%	.2572	.1912	.0058	.0146	.0349	.0454	.0830	.2083	.4309	.5473	.5784	.6376	.6688
Top 1%	.2008	. 1666	.0172	.0172	.0354	.0403	.0573	.1386	.3082	.5113	.5213	.5771	.5771

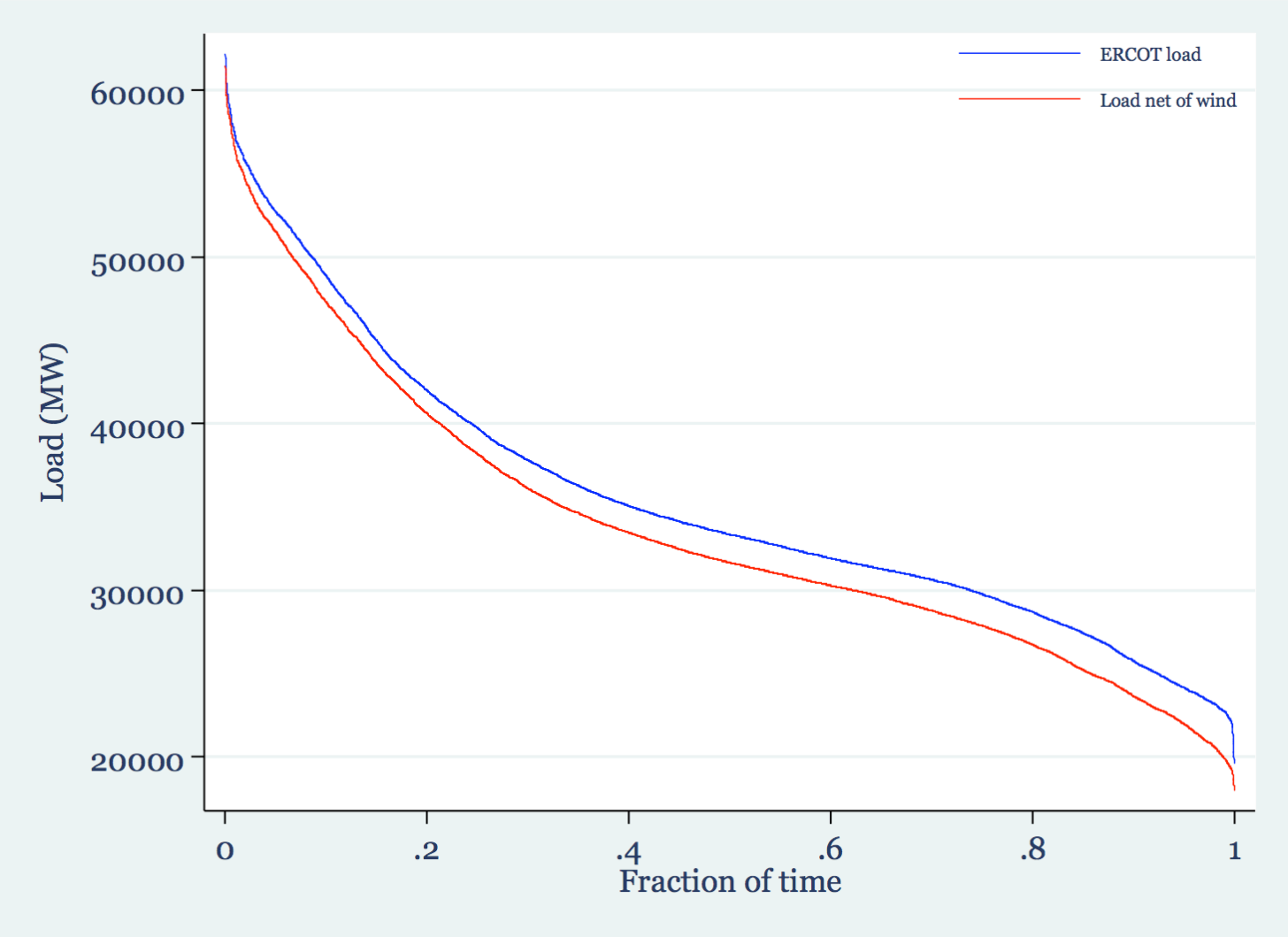
Wind output as negative demand

- Wind (or other exogenous production) can also be thought of as "negative demand"
  - The remaining system has to meet the overall demand *less* the exogenous contribution from wind
  - Wind output typically will increase the variability of demand on the rest of the system
    - In 2008, mean overall ERCOT load = 35365.98MW, std dev = 8357.114, while the mean load *net of wind* = 33650.35MW, std dev = 8639.491
    - In 2009, mean overall ERCOT load = 35073.38MW, std dev = 8763.766, while the mean load *net of wind* = 33022.11MW, std dev = 9179.48
- Thinking of wind output as negative demand is useful for thinking about the implications of increased wind capacity for the likely configuration of the rest of the system – including forecasting the effects on demands for other fuels

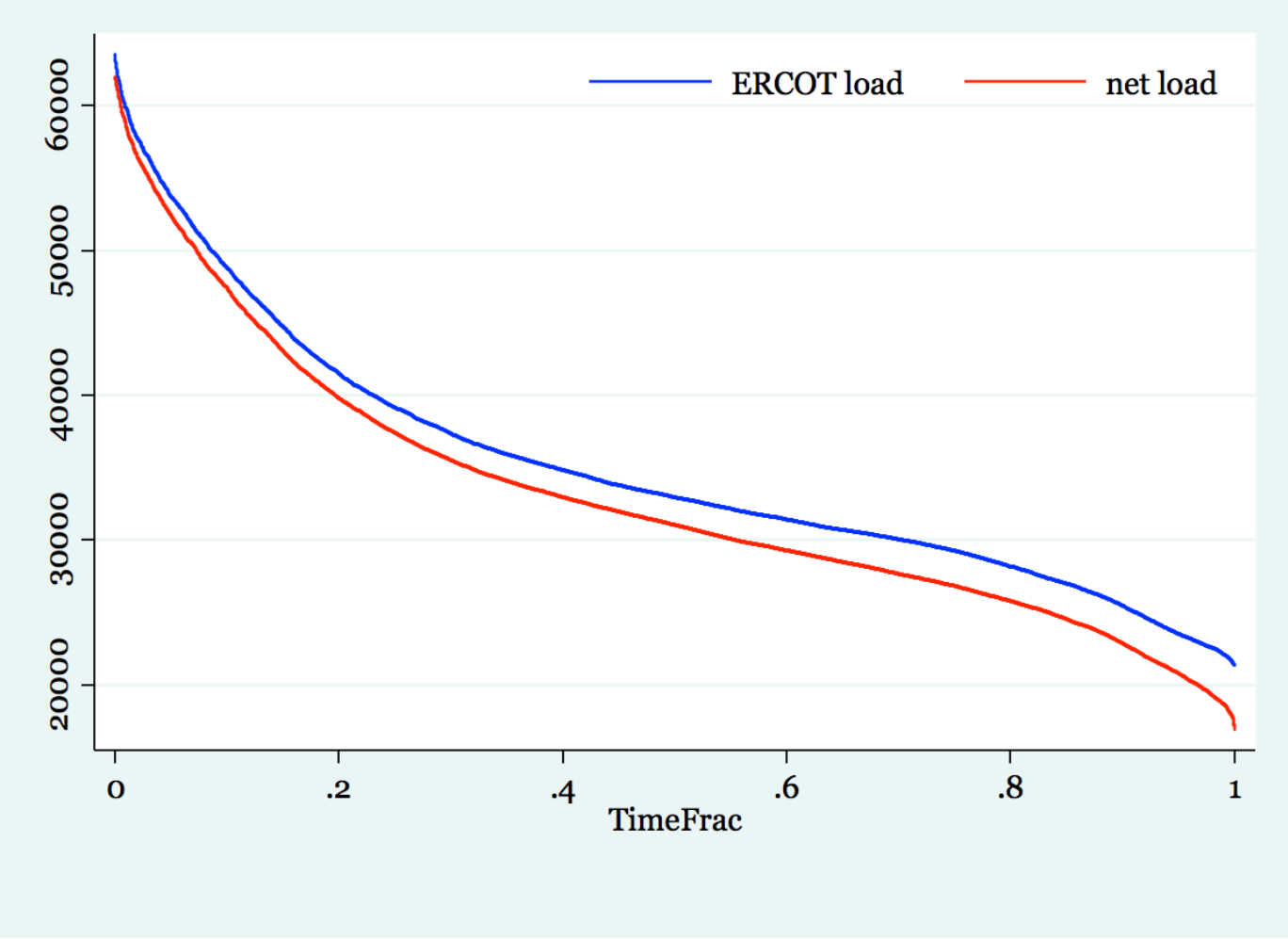
Load, and net load, duration curves, 2007



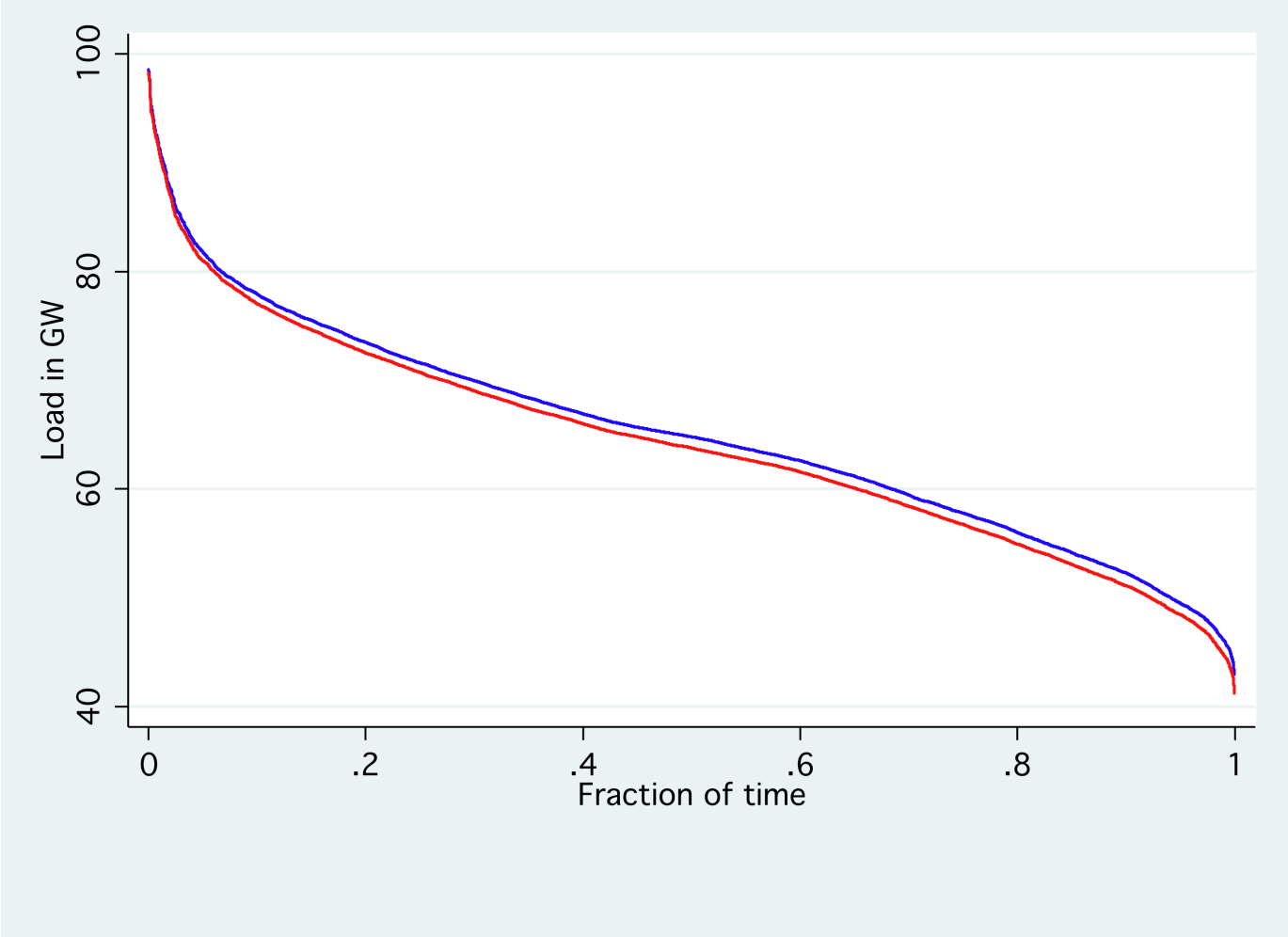
Load, and net load, duration curves, 2008



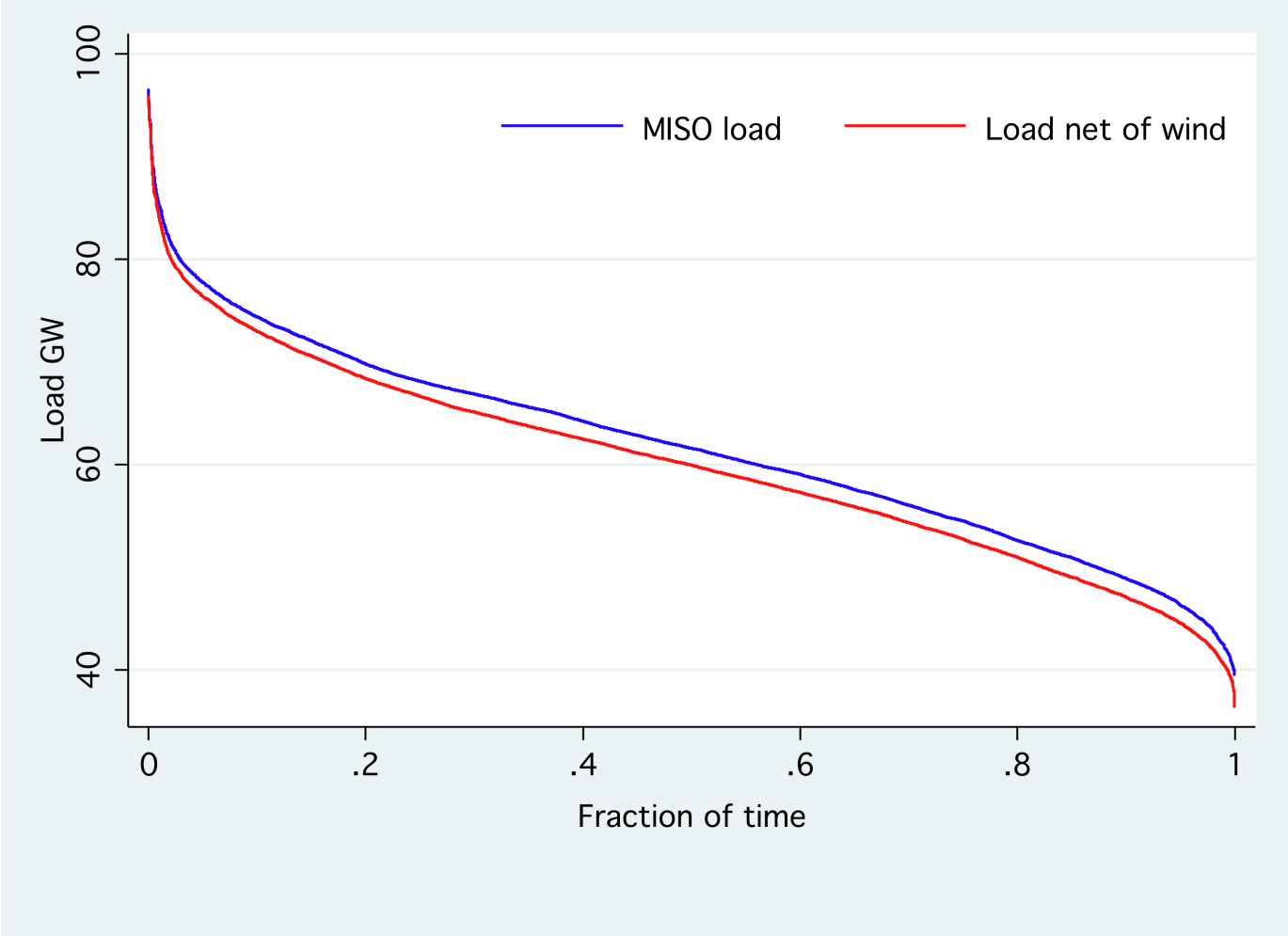
Load, and net load, duration curves, 2009



MISO load, and net load, duration curves, 2008



MISO load, and net load, duration curves, 2009



Conclusions

- Continuation, or extension, of current policies is likely to increase the proportion of wind generation in both ERCOT and MISO
  - An increase in the dispersion of wind generation sites reduces the correlation in output and makes *aggregate* wind supply less variable
  - It also reduces the maximum, and increases the minimum, wind capacity factor
  - The mean wind capacity factor also appears to decline somewhat
- Increased wind production comes at the expense of natural gas in the short run, but in the longer run it may increase natural gas demand
  - A steeper load duration curve disadvantages base more than other loads
  - Natural gas plants with quick-start capability are also a better complement for the short run intermittency of wind generation
- For system planning *or* day ahead scheduling purposes, wind can be thought of as negative demand with other plants required to meet load *net* of wind output
  - This essentially requires wind levels to be forecast along with other weather variables