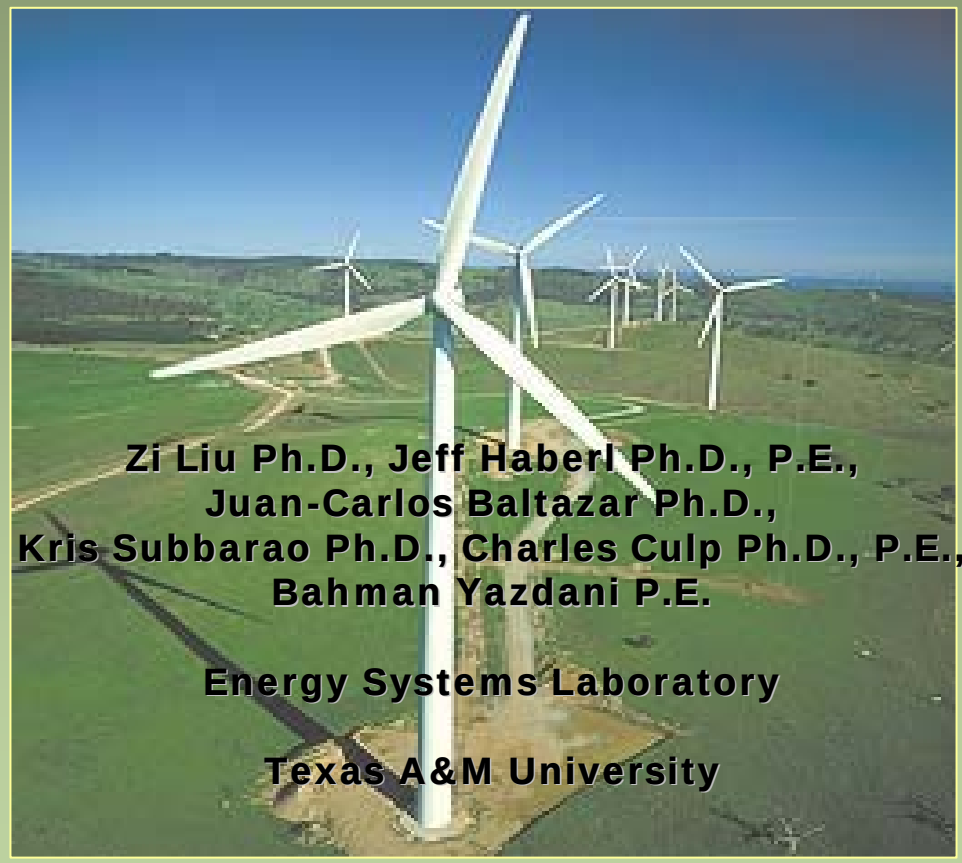
A METHODOLOGY FOR CALCULATING EMISSIONS REDUCTIONS FROM RENEWABLE ENERGY PROGRAMS AND ITS APPLICATION TO THE WIND FARMS IN THE TEXAS ERCOT REGION



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Outline

- Introduction
- Methodology
  - Daily Modeling Procedure
  - Analysis on Sweetwater I Wind Farm
  - Capacity Factor Analysis
- Application to All Wind Farms
- Uncertainty Analysis
- Emissions Reduction
- Summary

Background

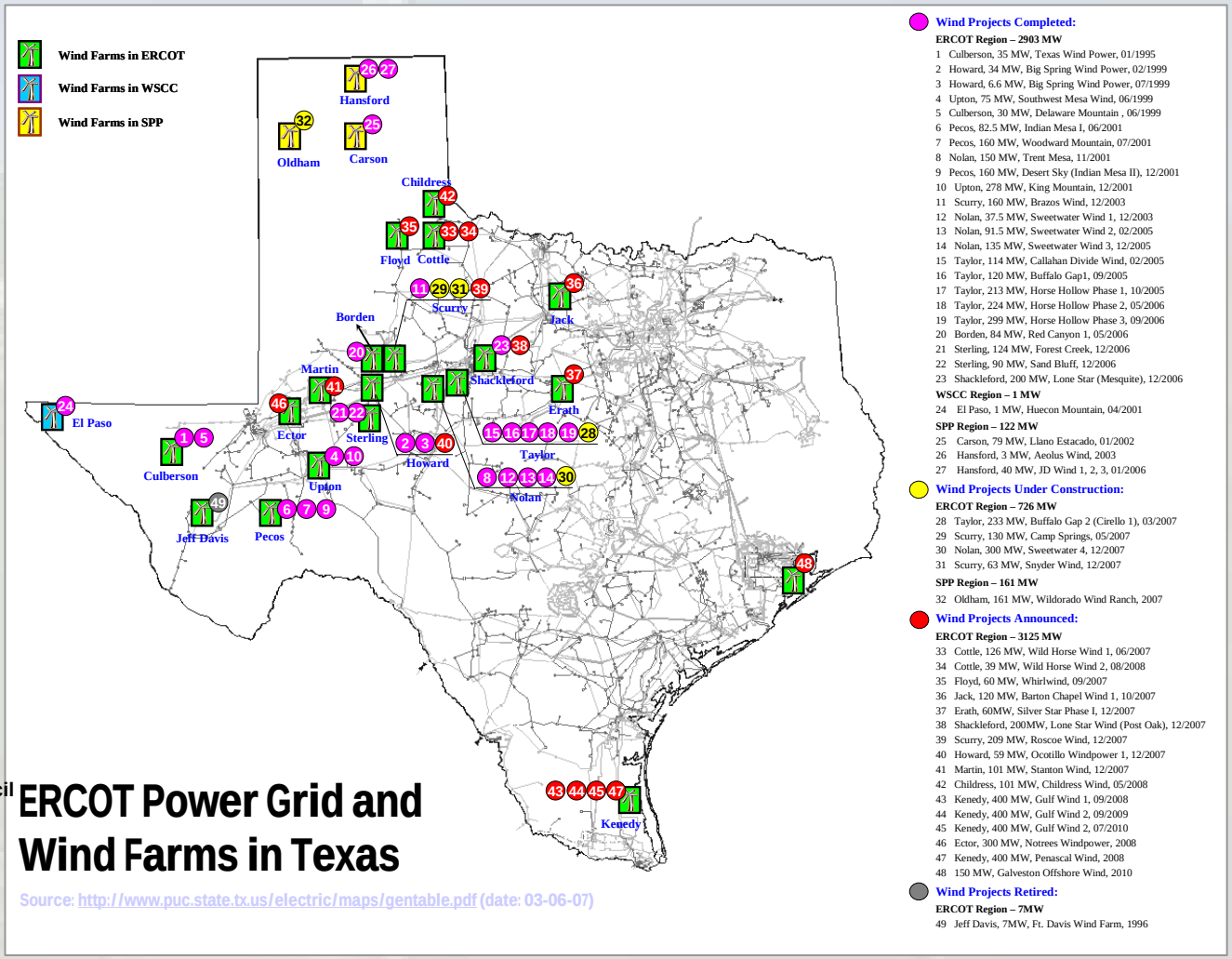
- Texas Legislature Requirement
  - Adding 5,880 MW of generating capacity from renewable energy by 2015, 500 MW from non-wind renewables.
  - PUCT: A target of 10,000 MW by 2025
  - TCEQ: Required creditable methodology for computing emissions reductions from renewables to report to the US EPA
- Energy Systems Laboratory
  - Assist TCEQ to develop SIP-creditable calculations for EE/RE to report to the US EPA.
  - Developing procedures to calculate emissions reduction from all wind farms in ERCOT area
  - Weather normalization of the daily wind power multiple base years selected by TCEQ and US EPA

Wind Farms in Texas

- **Completed**
  - ERCOT: 2903 MW
  - WSCC: 1 MW
  - SPP: 122 MW
- **Construction**
  - ERCOT: 726 MW
  - SPP: 161 MW
- **Announced**
  - ERCOT: 3125 MW

ERCOT: Electric Reliability Council of Texas
SPP: Southwest Power Pool
WSCC: Western Systems Coordinating Council

Source: http://www.puc.state.tx.us/electric/maps/gentable.pdf (date: 03-06-07)



Texas Wind Power Generation

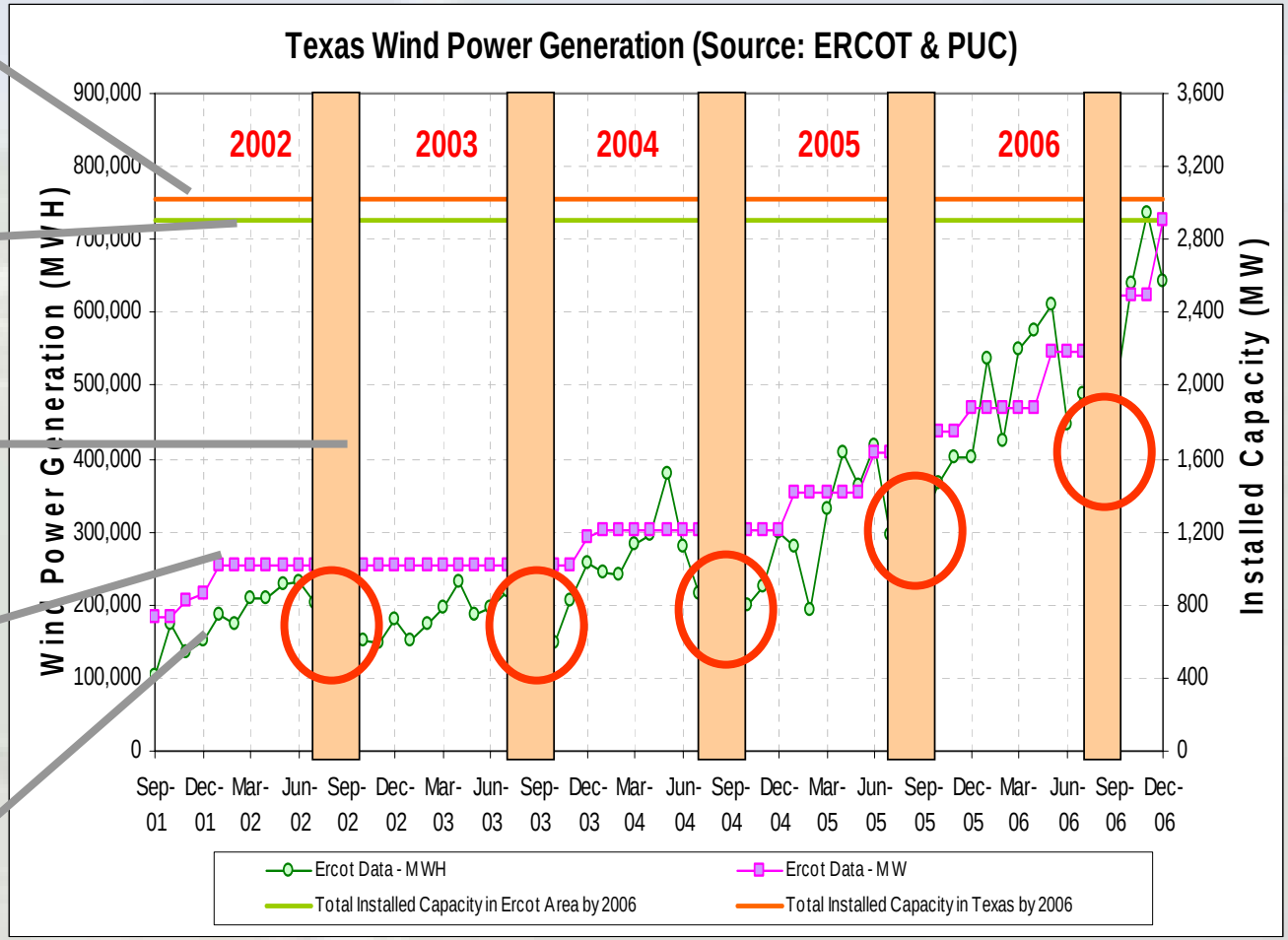
Installed Capacity as of 03/07 – All Texas

Installed Capacity as of 03/07 - ERCOT

Ozone Season Period (Jul. – Sep.)

Measured Capacity in ERCOT (MW)

Measured Power Generation in ERCOT (MWh)



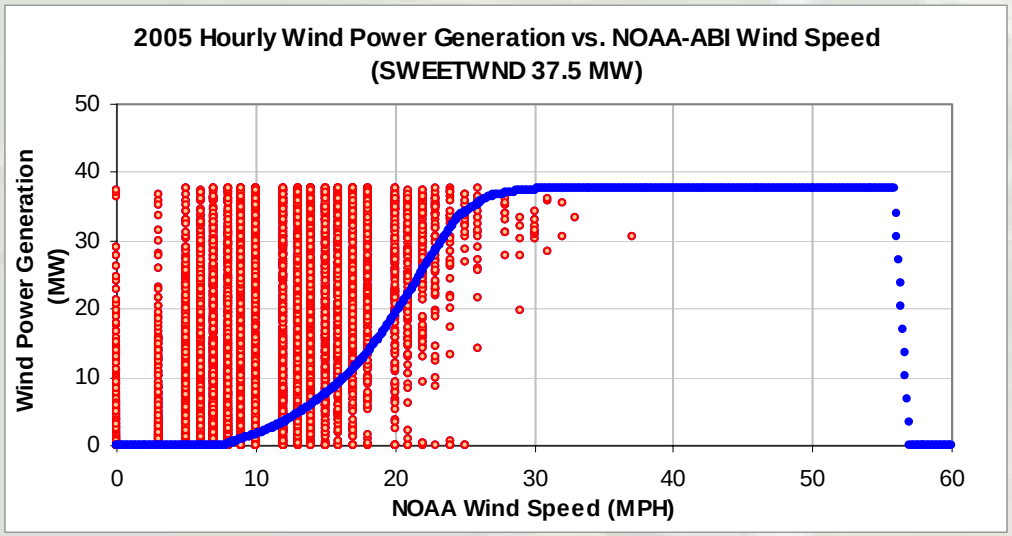
Modeling Procedure Overview

- **Hourly Wind Data**
  - On-site hourly wind data not available for the base year (not available or the wind farms not existing)
  - NOAA's network of weather stations – hourly wind speed data at 10 meter height available
- **Hourly Wind Power Generation Data**
  - 15-minute data obtained from ERCOT for each wind farm since 2001
- **Modeling Procedure**
  - NOAA hourly wind speed and measured power for the base year and study year (i.e. 1999 and 2005) converted to daily data
  - Daily performance curve developed – regressed the daily power generation against the daily average wind speed using ASHRAE's Inverse Model Toolkit (IMT)
  - Weather Normalization:
    - Coefficients from 2005 IMT regression applied to the 1999 average daily NOAA wind speed
    - ***Predicts the daily electricity the wind farm would have produced in 1999 "base year".***

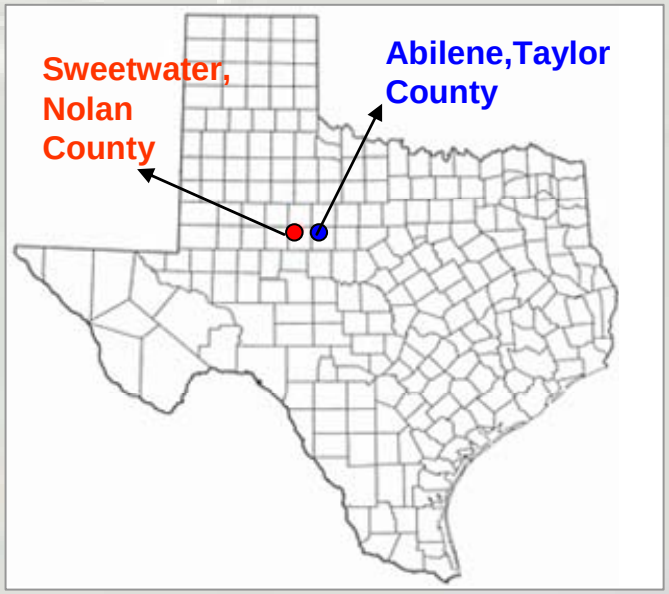
Analysis on Sweetwater I Wind Farm

- Located in Nolan County, Texas
- Nearest NOAA station - Abilene Regional Airport –ABI
- 37.5 MW Capacity, 25 GE 1.5s Wind Turbines
- Using hourly model to predict wind power production in baseyear (1999) impractical.

GE 1.5s Wind Turbine Specifications	
Manufacture	GE
Nameplate Capacity	1,500 kW
Cut-in speed	4 m/s
Cut-out speed	25 m/s
Rotor diameter	70.5 m
Tower height at hub	80 m
Swept area	3904 m^2
Rotor speed	12.0-22.2 rpm

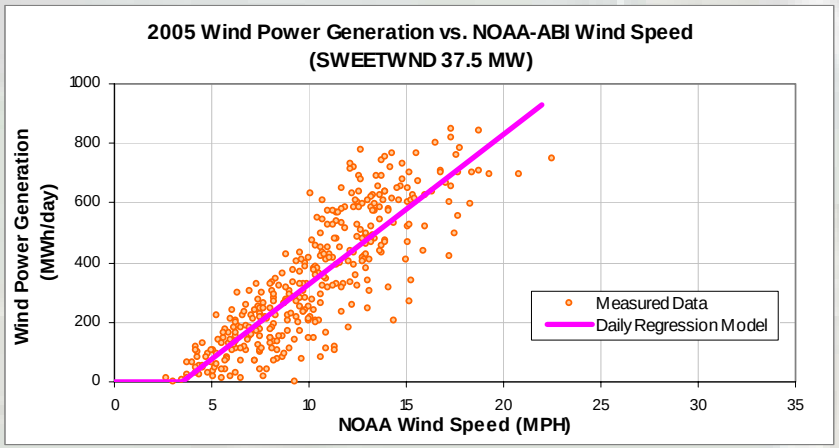


2005 Hourly wind power plotted against NOAA-ABI wind & manufacture's power curve



Sweetwater I – Predicted vs. Measured Power in 2005

- Daily data more appropriate for modeling
- Daily model performed well for the entire year and OSP tracking the measured wind power production
- July – the biggest error (-19.34%)



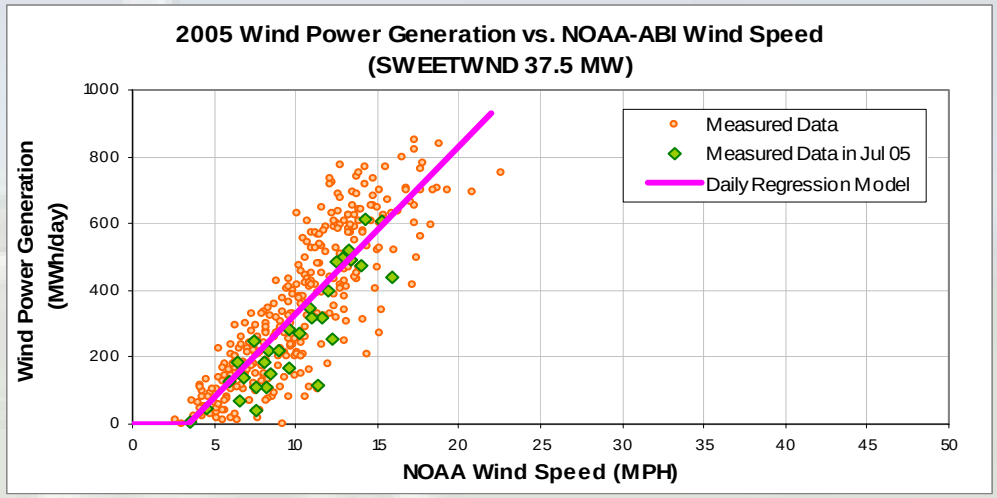
Daily Wind Power vs. NOAA-ABI Wind (2005)

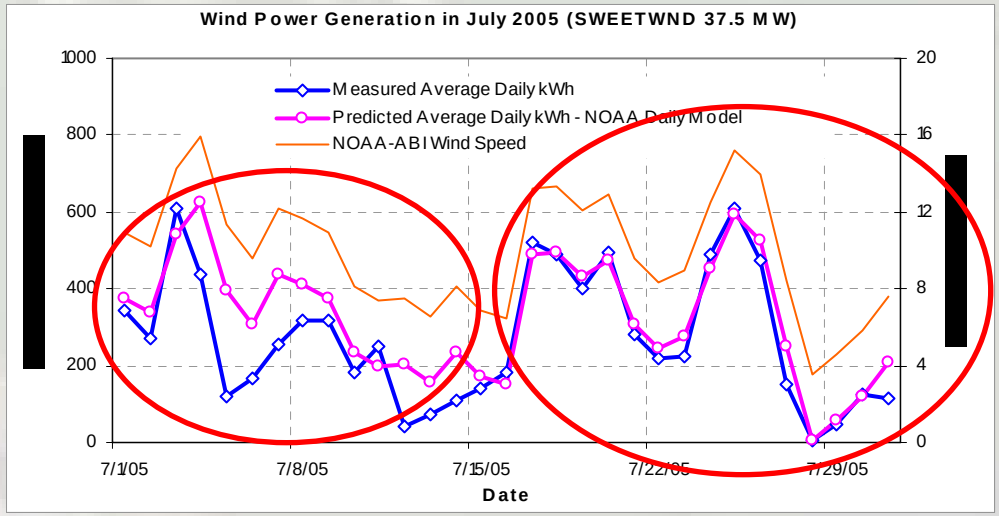
IMT Coefficients	
Ycp (MWh/day)	-172.9893
Left Slope (MWh/mph-day)	50.1761
RMSE (MWh/day)	112.8012
R2	0.7237
CV-RMSE	32.80%

Month	No. Of Days	Average Daily Wind Speed (MPH)	Measured Power Generation (MWh)	Predicted Power Generation Using Daily Model (MWh)	Diff.	CV-RMSE
Jan-05	31	10.34	11,105	10,726	3.41%	42.79%
Feb-05	28	8.92	7,130	7,729	-8.40%	43.40%
Mar-05	31	11.54	11,611	12,584	-8.38%	32.27%
Apr-05	30	12.97	13,597	14,331	-5.40%	22.98%
May-05	30	11.03	11,029	11,417	-3.51%	30.15%
Jun-05	30	11.86	13,323	12,660	4.97%	20.98%
Jul-05	31	9.94	8,465	10,102	-19.34%	35.09%
Aug-05	31	8.26	7,882	7,489	4.98%	31.71%
Sep-05	30	9.29	9,062	8,789	3.01%	36.16%
Oct-05	30	9.26	9,167	8,428	8.06%	35.57%
Nov-05	30	10.33	11,094	10,364	6.57%	37.64%
Dec-05	31	10.02	11,322	10,227	9.66%	34.43%
Total	363	10.32	124,787	124,846	-0.05%	32.76%
Total in OSP (07/15-09/15)	63	8.98	18,131	17,485	3.56%	24.02%

Sweetwater I – Predicted vs. Measured Power in July 05

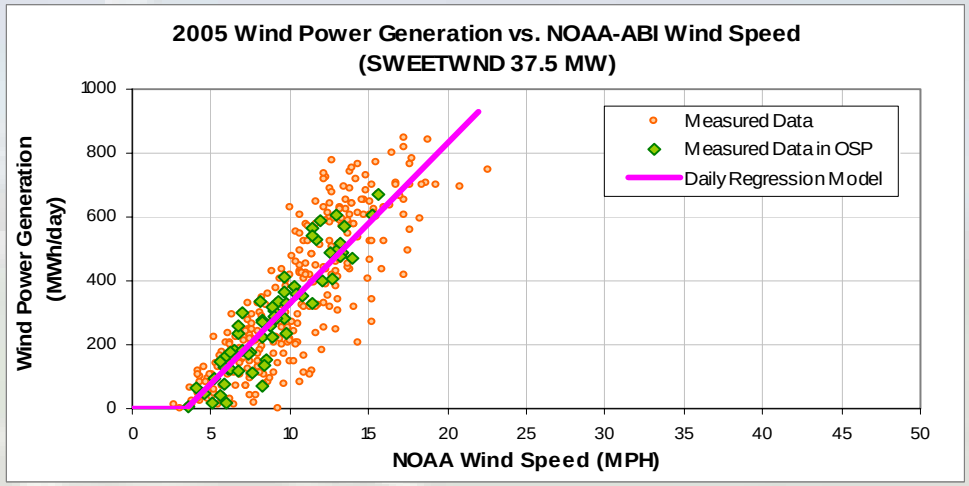
- Measured power not evenly distributed around the prediction
- Overestimation for the first half of the month
- Model fit data well in second half of the month
- Reason unknown
- *Possible causes:*
  - *Curtailment?*
  - *Maintenance?*
  - *Others?*

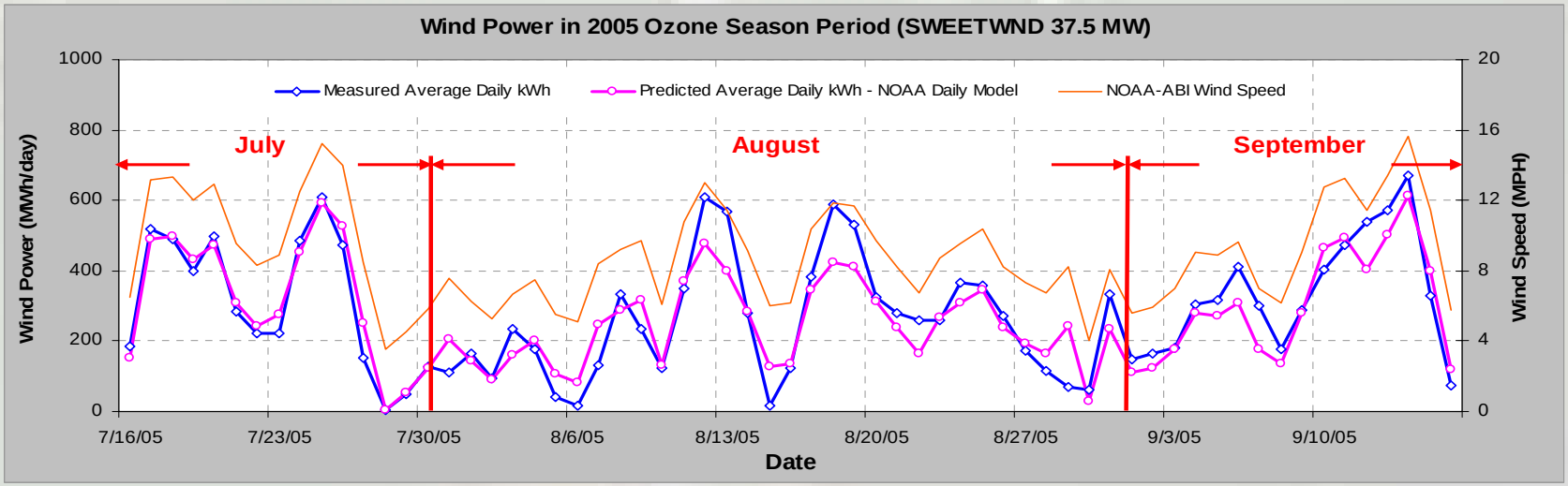




Sweetwater I – Predicted vs. Measured Power in OSP 05

- Daily model performing well in OSP
- Predicted vs. measured: 3.56%

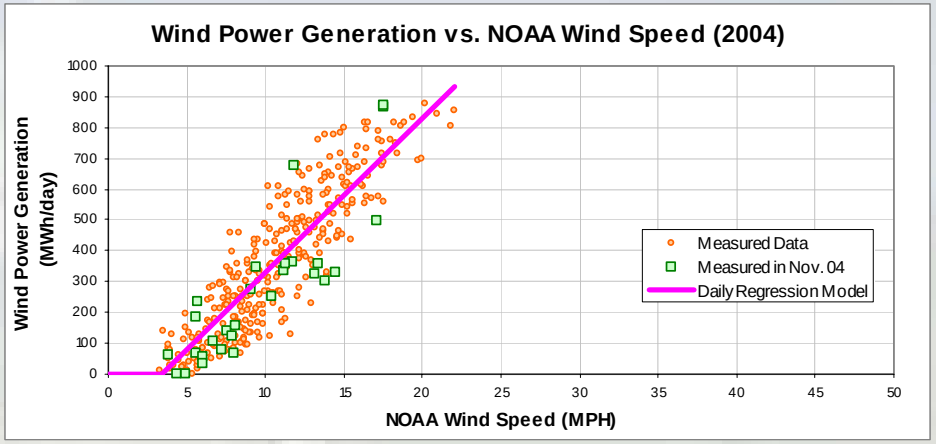


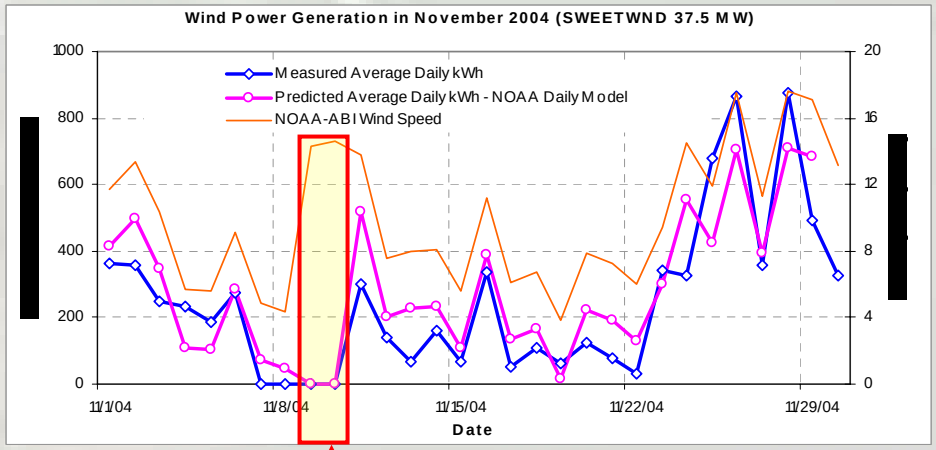


Sweetwater I – Testing of the Model

- **Used:**
  - **2004 measured power output and 2004 NOAA wind speed vs 2005 daily model coefficients**
- ***Model sufficiently robust for predicting MWh in base year***
- **Nov – 16.3% diff.**

Month	2004 Predicted MWh/mo Daily Model	2004 Measured-ERCOT MWh/mo	2004 Diff. Daily Model
Jan	11,914	11,898	-0.1%
Feb	11,303	11,073	-2.1%
Mar	11,813	12,625	6.4%
Apr	12,869	12,238	-5.2%
May	14,886	16,017	7.1%
Jun	12,063	11,049	-9.2%
Jul	10,595	10,055	-5.4%
Aug	8,645	8,375	-3.2%
Sep	7,989	8,067	1.0%
Oct	8,798	9,974	11.8%
Nov	8,673	7,456	-16.3%
Dec	9,553	10,543	9.4%
Total	129,103	129,371	0.2%





Two days data missing

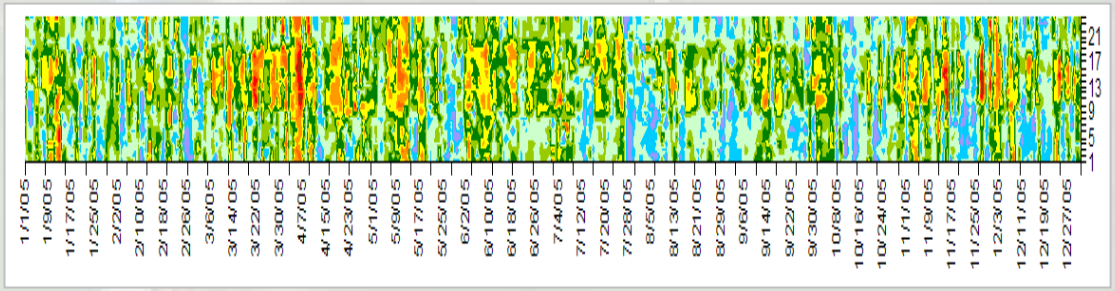
Sweetwater I – Predicted Wind Power in 1999

- 1999 hourly NOAA-ABI wind speed converted to average daily wind speed
- Used 2005 daily model coefficients
- Estimated annual power increased about **15 %** when compared against 2005, OSP power increased **9 %**
- Reason: 1999 windier than 2005
- ***Shows importance of a weather normalization procedure for a more accurate estimation***

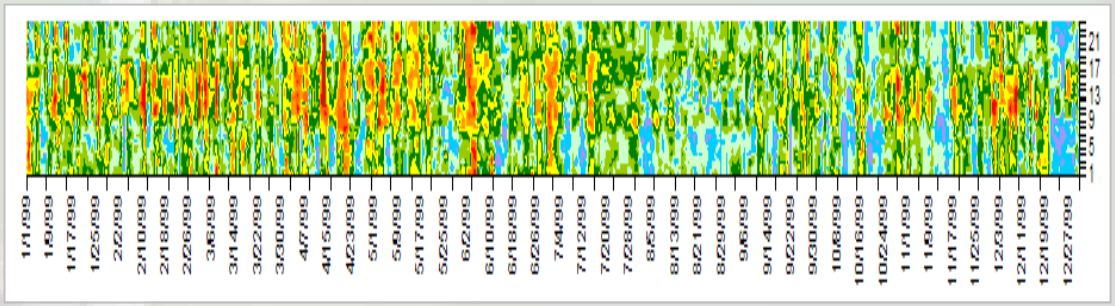
1999 Estimated MWh/yr	2005 Measured MWh/yr
143,711 ←	125,249
1999 OSP Estimated MWh/day	**2005 OSP Measured MWh/day**
314 ←	288

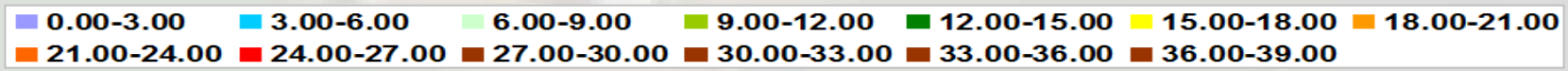
Surface plots for comparing ABI 1999 and 2005 hourly wind speeds

2005



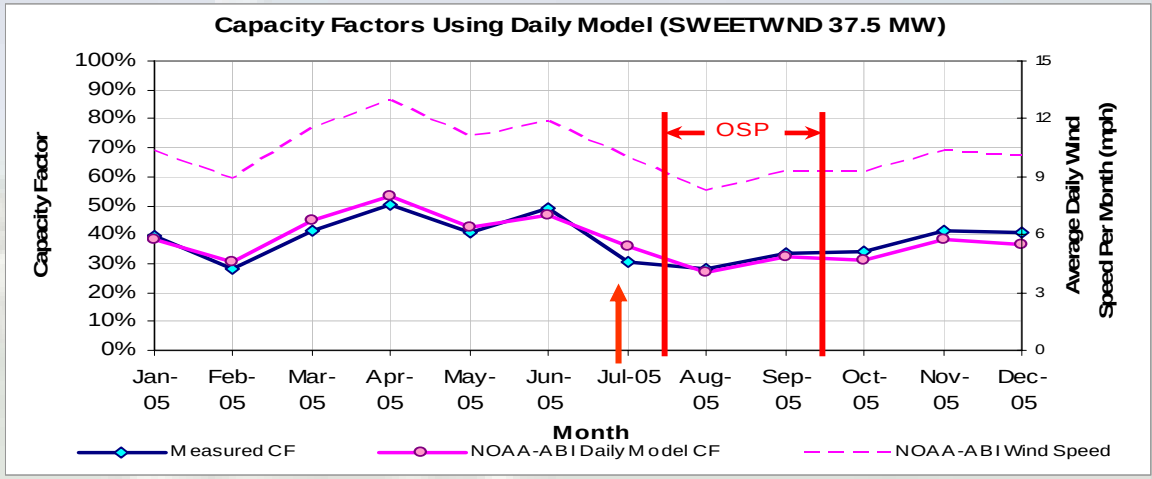
1999

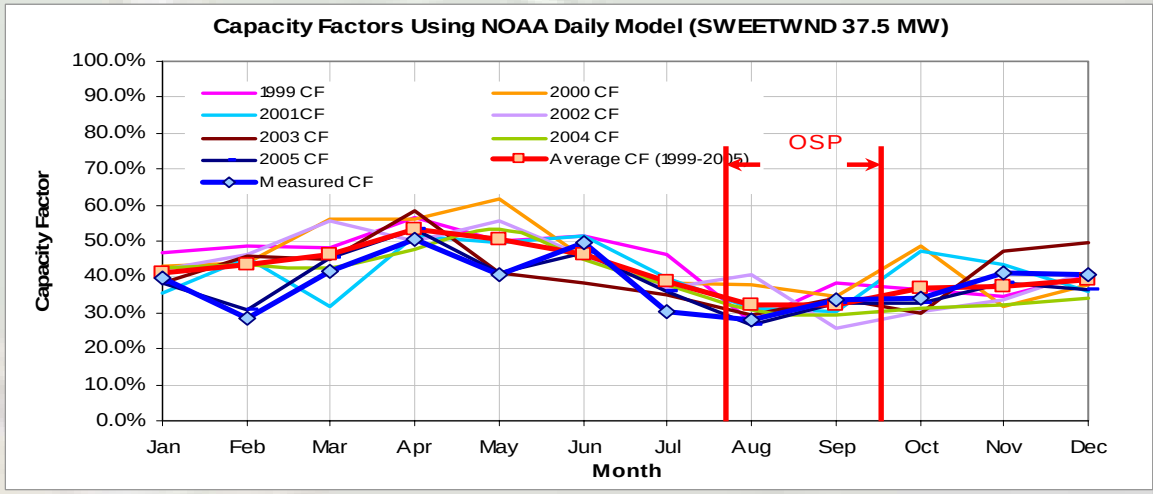




Sweetwater I – Capacity Factor

- **Predicted 2005 capacity factor using 2005 daily model vs. measured capacity factor:**
  - **The daily model performing well in predicting annual and OSP capacity factors (1% error).**
  - **The biggest error in July (6%).**
- **Predicted capacity factor using 2005 model for 1999 through 2005**
  - **More variation in the year-to-year wind speeds than the uncertainty from the model**
  - ***Showed importance of a weather normalizing wind speed back to the base year***





Estimated Power Production in 1999 for Each Wind Farm in ERCOT

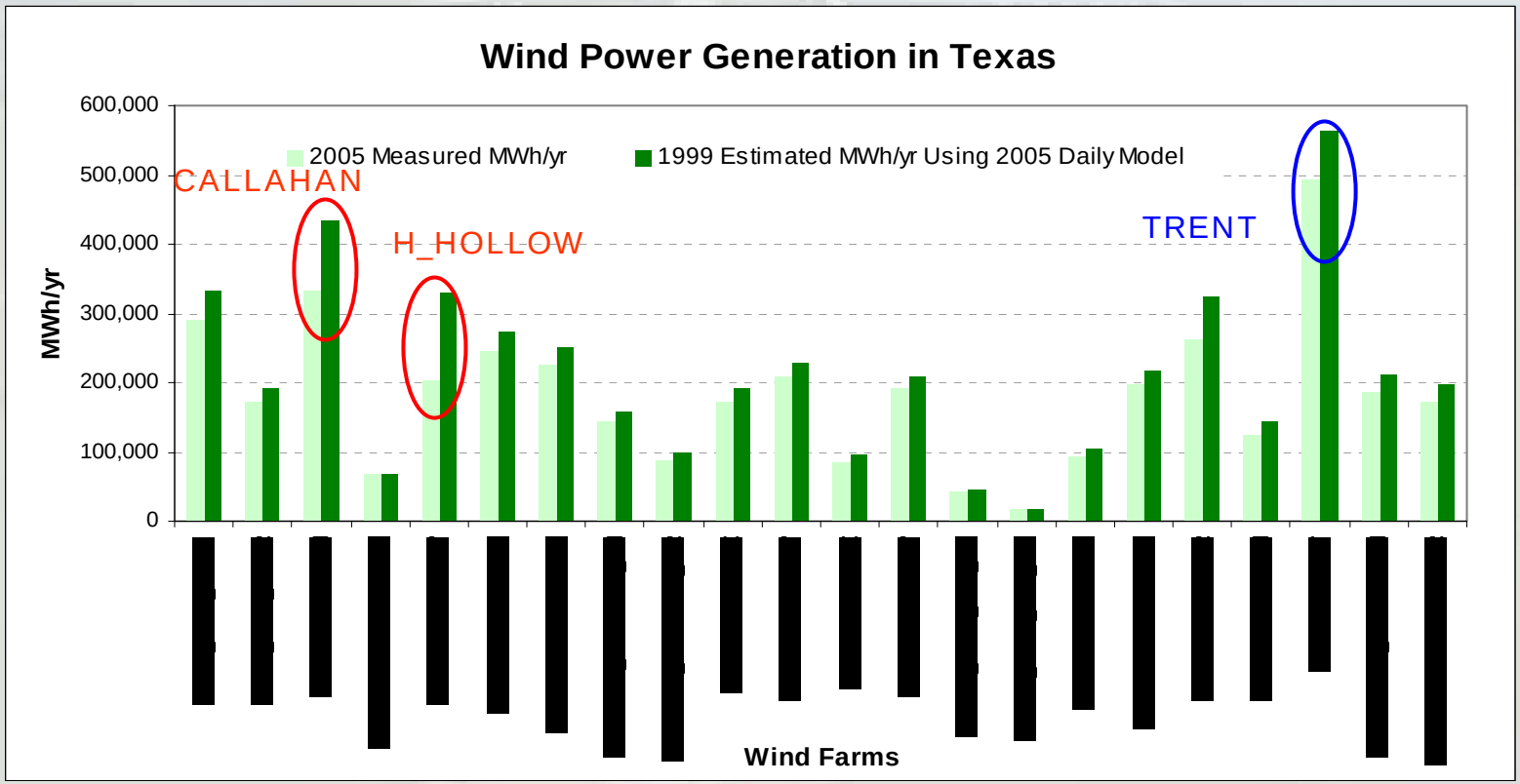
- 1999 estimated annual MWh using 2005 coeff: all sites increased
- 1999 estimated OSP MWh/day using 2005 coeff: 6 sites decreased, all other sites increased.

Wind Unit Name	County	NOAA Weather Station	Capacity (MW)	2005 Measured (MWh/yr)	1999 Estimated Using Daily Model (MWh/yr)	Increase - 1999 vs. 2005 (MWhyr)	2005 OSP Measured (MWh/day)	1999 OSP Estimated (MWh/day)	Increase - 1999 vs. 2005 (MWh/day)
BRAZ_WND_WND1	SCURRY	ABI	160	290,411	331,570	41,159	641	724	83
BRAZ_WND_WND2	SCURRY	ABI		170,608	191,907	21,299	368	420	52
CALLAHAN_WND1	TAYLOR	ABI	114	332,572	433,697	101,125	831	955	124
DELAWARE_WIND_NWP	CULBERSON	GDP	30	66,267	68,298	2,031	103	114	11
H_HOLLOW_WND1 *	TAYLOR	ABI	220.5	203,673	267,691	64,018	550	1,354	804
INDNENR_INDNENR	PECOS	FST	160.5	246,131	273,888	27,757	625	639	14
INDNENR_INDNENR_2	PECOS	FST		224,842	250,714	25,872	585	583	-2
INDNNWP_INDNNWP	PECOS	FST	82.5	142,264	158,580	16,316	372	369	-3
INDNNWP_INDNNWP	PECOS	FST		87,914	97,971	10,057	230	228	-2
KING_NE_KINGNE	UPTON	MAF	80	172,198	192,701	20,503	378	417	39
KING_NW_KINGNW	UPTON	MAF	80	207,634	227,493	19,859	534	515	-19
KING_SE_KINGSE	UPTON	MAF	40	85,097	95,931	10,834	182	204	22
KING_SW_KINGSW	UPTON	MAF	80	190,202	209,671	19,469	474	469	-5
KUNITZ_WIND_LGE	CULBERSON	GDP	35	42,119	43,855	1,736	40	67	27
KUNITZ_WIND_LGE	CULBERSON	GDP		17,210	17,913	703	16	27	11
SGMTN_SIGNALMT	HOWARD	MAF	41	93,939	103,431	9,492	217	232	15
SW_MESA_SW_MESA	UPTON	MAF	74.9	197,694	217,416	19,722	522	488	-34
SWEETWN2_WND2	NOLAN	ABI	91.5	262,537	323,218	60,681	623	717	94
SWEETWND_WND1	NOLAN	ABI	37.5	125,259	143,711	18,452	288	314	26
TRENT_TRENT	NOLAN	ABI	150	492,444	563,714	71,270	1,095	1,227	132
WOODWRD1_WOODWRD1	PECOS	FST	80	185,149	211,627	26,478	401	474	73
WOODWRD2_WOODWRD2	PECOS	FST	80	172,532	196,032	23,500	424	442	18
TOTAL			1,763	4,030,820	4,643,153	612,333	9,499	11,555	2,056

Note: Blue text shows the wind farms built before 09/2001.

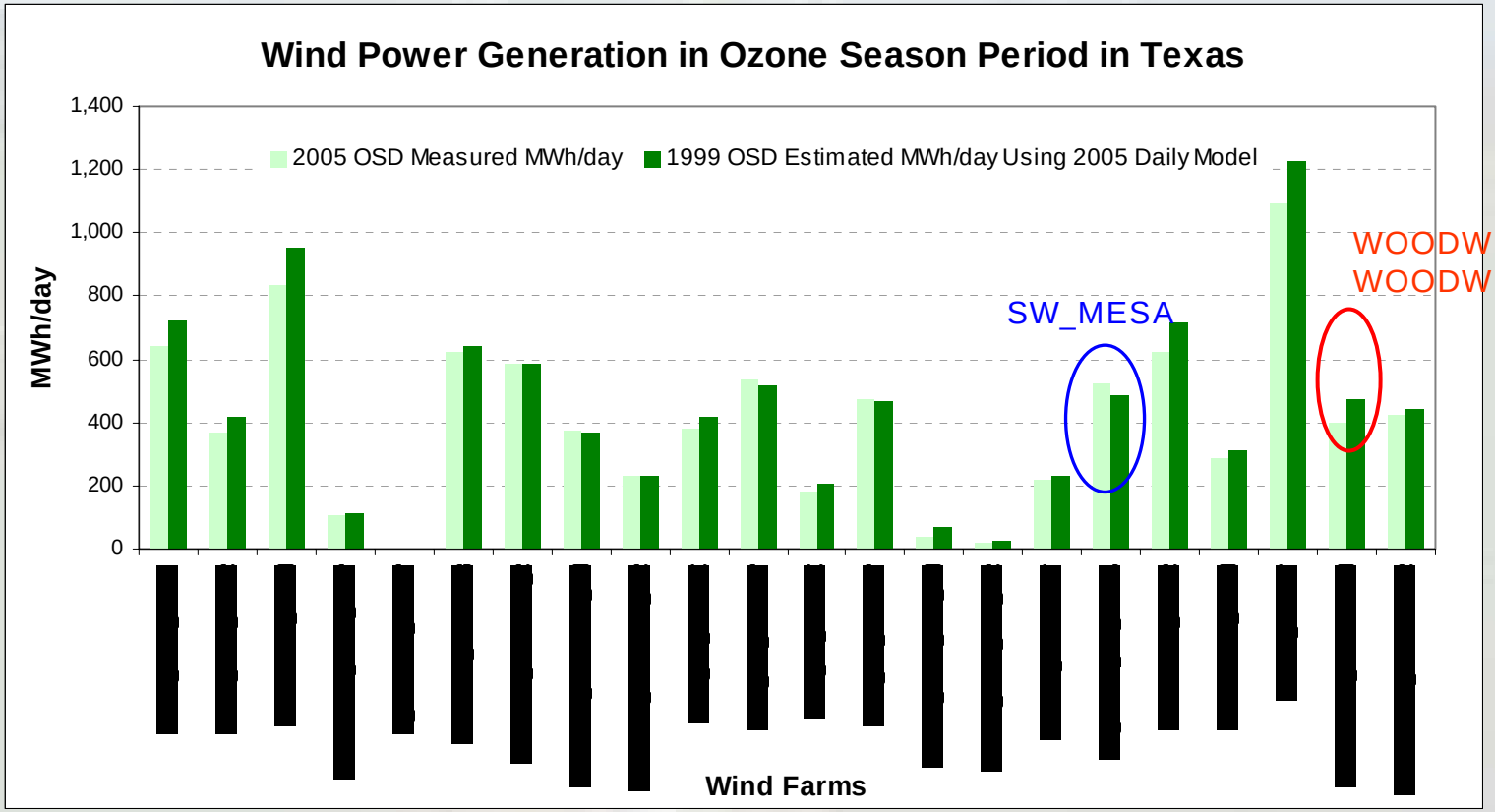
Comparison of Annual 1999 Estimated vs. 2005 Measured

- **1999 estimated annual MWh using 2005 coeff: <u>all sites increased</u>**
  - **Biggest increase: CALLAHAN +30%, H_HOLLOW +31%**
  - **Highest annual production: TRENT**



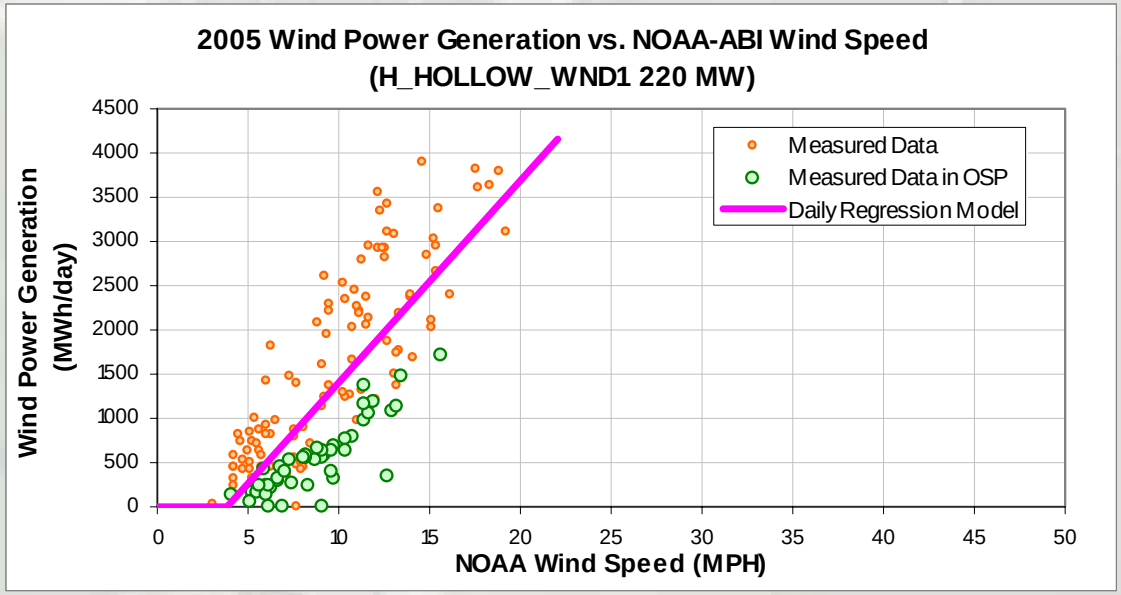
Comparison of 1999 Estimated 2005 Measured in OSP

- 1999 OSP MWh/day: 6 sites decreased, all other sites increased
- Biggest decrease: SW_MESA, -7%
- Biggest increase: WOODWRD1_WOODWRD1



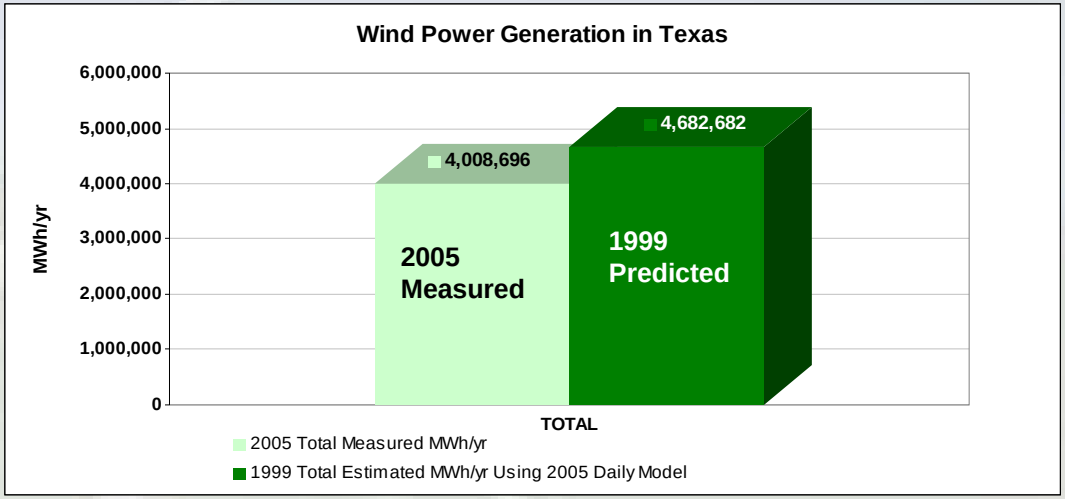
Horse Hollow Wind Farm (220 MW)

- Started operation in July 2005
- Power production during the testing period (July through September) excluded from the analysis
- 2005 model using 3 months data from October to December

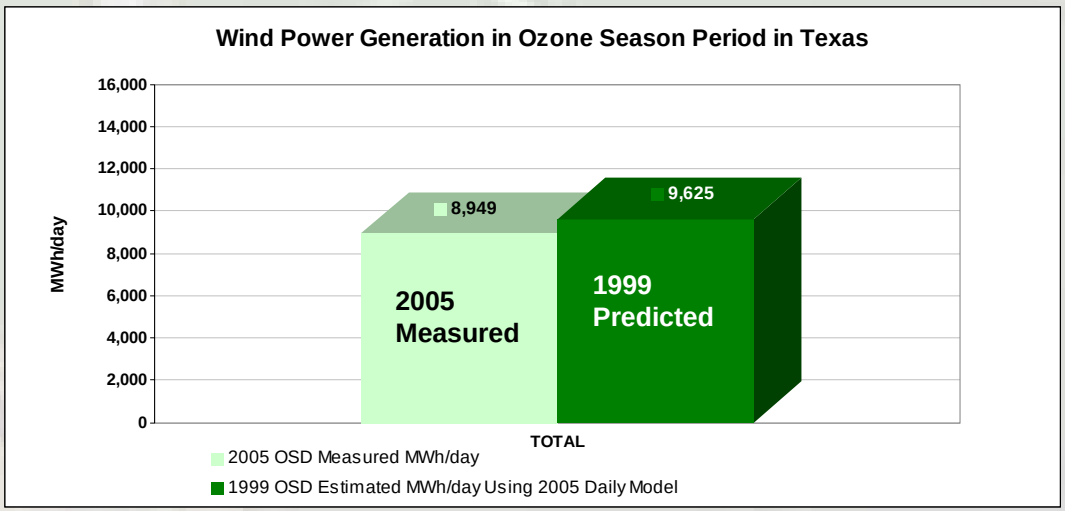


Comparison 1999 vs. 2005 For All Wind Farms

Annual Total: Increased 17 %

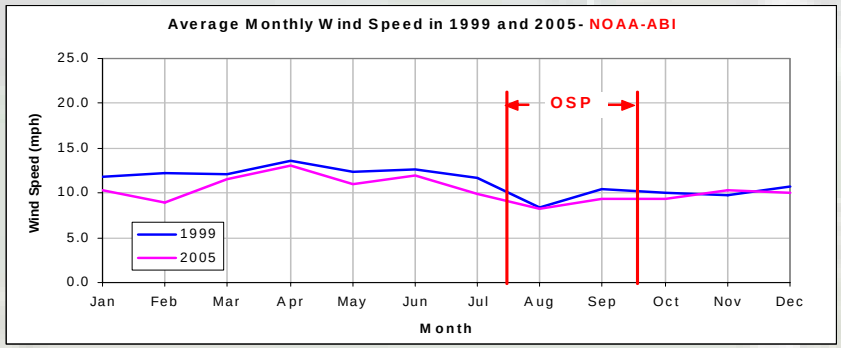


OSP: Increased 26 %

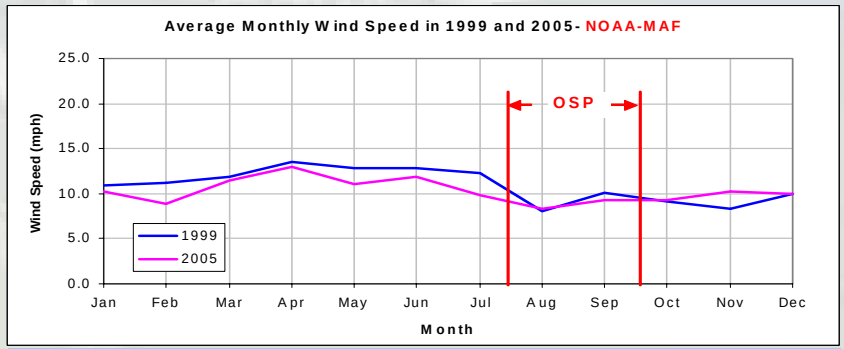


Comparison of 1999 and 2005 Wind Speed

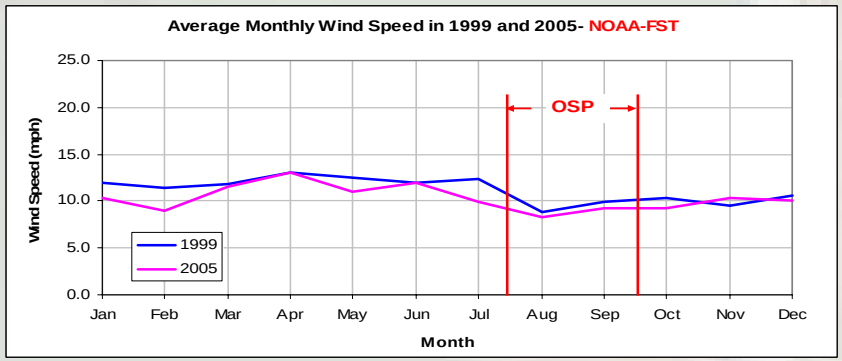
- Four weather stations used in the modeling
- Annually, 1999 windier than 2005 for all four weather stations
- In OSP, 1999 windier than 2005 for ABI and FST
- In OSP, 2005 windier than 1999 for MAF and GDP



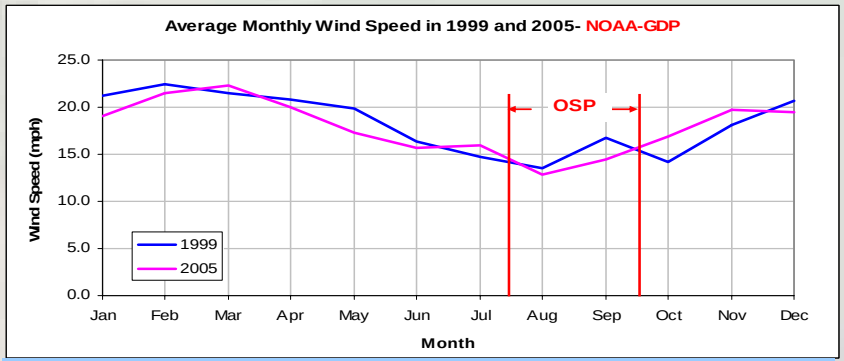
ABI: 10% windier in 1999 8% windier in 1999 OSP



MAF: 7% windier in 1999 2% windier in 2005 OSP



FST: 9% windier in 1999 8% windier in 1999 OSP



GDP: 2% windier in 1999 4% windier in 2005 OSP

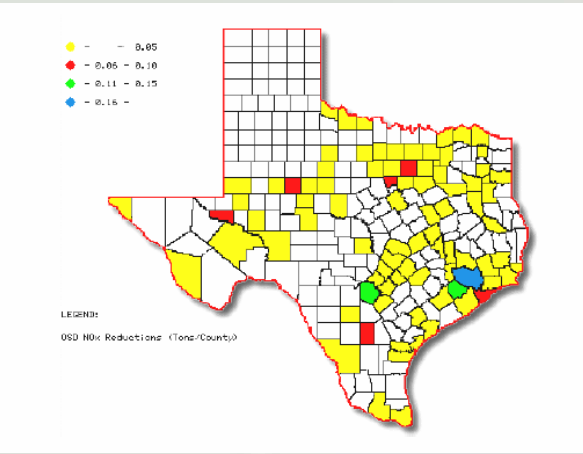
1999 Annual and OSP Uncertainty of the Power Prediction

- The uncertainty of applying the daily models to predict the 1999 annual wind power ranged from 2.4% to 5.5% (Reddy et al. 1992).
- Daily models reasonably reliable for predicting the performance of the wind farm in the base year within the same range of wind conditions.
- The uncertainty related to predicting 1999 OSP wind power using annual model are higher than the annual values (7.1 – 23.1%).
- A model developed using only the measured power in the OSP would improve the reliability of the wind power prediction in the OSP.

Wind Farm	1999 Annual				1999 Ozone Season Period (OSP)			
	Pred Days	Total Variance	Total Estimated	Rel Uncer	Pred Days	Total Variance	Total Estimated	Rel Uncer
BRAZ_WND_WND1	365	12,549	331,570	3.80%	63	5,208	45,617	11.40%
BRAZ_WND_WND2	365	7,148	191,907	3.70%	63	2,967	26,458	11.20%
CALLAHAN_WND1	365	10,364	433,697	2.40%	63	4,301	60,173	7.10%
H_HOLLOW_WND1 *	365	23,949	626,846	3.80%	63	9,917	85,292	11.60%
INDNENR_INDNENR	363	11,155	273,888	4.10%	63	4,642	40,256	11.50%
INDNENR_INDNENR_2	365	10,904	249,340	4.40%	63	4,525	36,733	12.30%
KING_NE_KINGNE	365	6,721	192,701	3.50%	63	2,789	26,266	10.60%
KING_NW_KINGNW	365	9,112	227,493	4.00%	63	3,781	32,451	11.70%
KING_SE_KINGSE	365	3,492	95,931	3.60%	63	1,449	12,878	11.30%
KING_SW_KINGSW	365	7,906	209,671	3.80%	63	3,280	29,521	11.10%
SWEETWN2_WND2	365	8,895	323,218	2.80%	63	3,691	45,168	8.20%
SWEETWND_WND1	365	4,231	143,711	2.90%	63	1,756	19,794	8.90%
TRENT_TRENT	365	16,487	563,714	2.90%	63	6,843	77,287	8.90%
DELAWARE_WIND_NWP	365	2,864	68,298	4.20%	61	1,171	7,201	16.30%
INDNNWP_INDNNWP	363	7,183	157,711	4.60%	63	2,989	23,239	12.90%
INDNNWP_INDNNWP2	363	4,436	97,434	4.60%	63	1,846	14,354	12.90%
KUNITZ_WIND_LGE	365	2,393	43,856	5.50%	60	970	4,201	23.10%
KUNITZ_WIND_LGE2	365	976	17,913	5.40%	60	396	1,717	23.00%
SGMTN_SIGNALMT	365	4,361	103,431	4.20%	63	1,809	14,602	12.40%
SW_MESA_SW_MESA	365	9,106	217,416	4.20%	63	3,778	30,765	12.30%
WOODWRD1_WOODWRD1	363	8,193	210,468	3.90%	63	3,410	29,882	11.40%
WOODWRD2_WOODWRD2	363	6,829	196,032	3.50%	63	2,842	27,851	10.20%

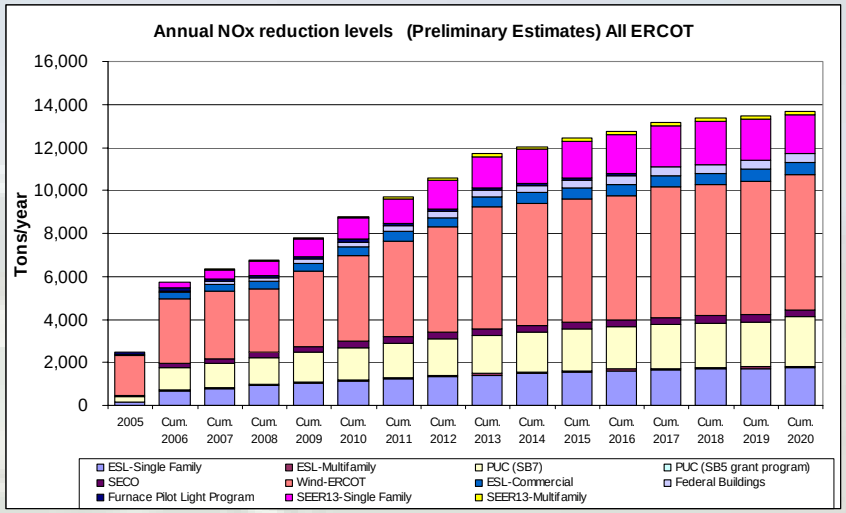
Emissions Reduction from Wind Power in Texas

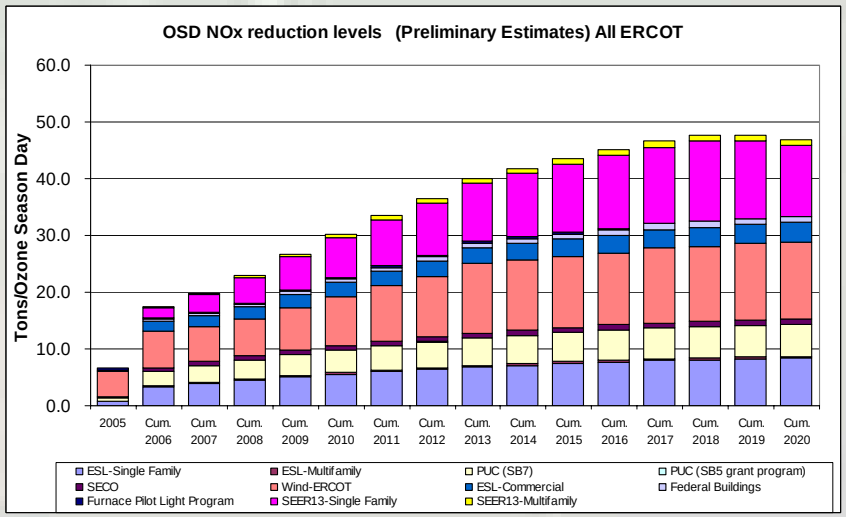
- Using 2007 annual and OSD eGRID
- Total MWh savings for each Power Control Area used to calculate the NOx emissions reduction for each of the different county through the USA-EPA prescribed emission fractions.
- Total MWh savings in the base year 1999 for the wind farms built before September 2001 within the ERCOT region:
  - 2,674,858 MWh/yr and
  - 6,652 MWh/day in the Ozone Season Period.
- Total NOx emissions reductions across all the counties:
  - 1,639 tons/yr
  - 4.08 tons/day for the Ozone Season Period.



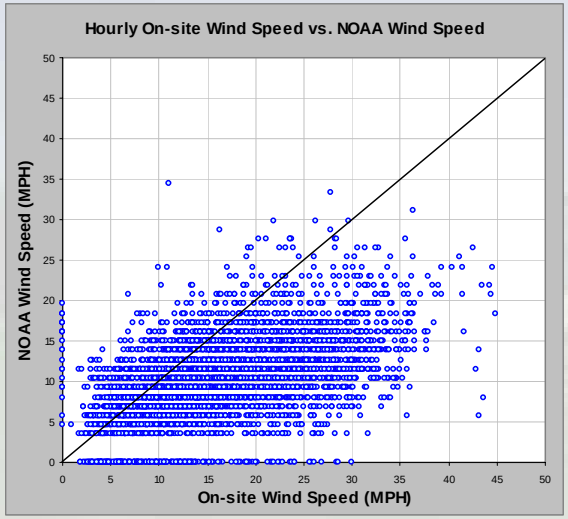
Summary

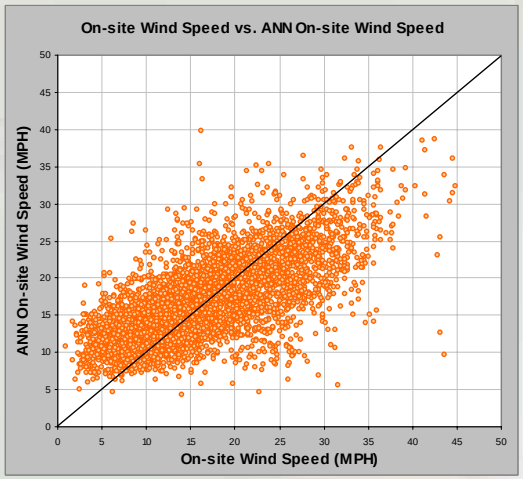
- **Methodology for predicting electricity from wind farms in the 1999 base year using 2005 measured electricity and NOAA wind data.**
- **The total wind power production in the base year (1999) and the corresponding emissions reduction calculated from all the wind farms in the ERCOT region using this procedure**
- **Result: Improvement of the accuracy of base year predictions using normalization procedure compared to the non-weather normalization procedure.**
- **The uncertainty analysis showed that the daily regression models are sufficiently reliable to allow for their use in projecting wind production into other weather base years.**
- **Results now combined with EE/RE for integrated NOx emissions reductions**

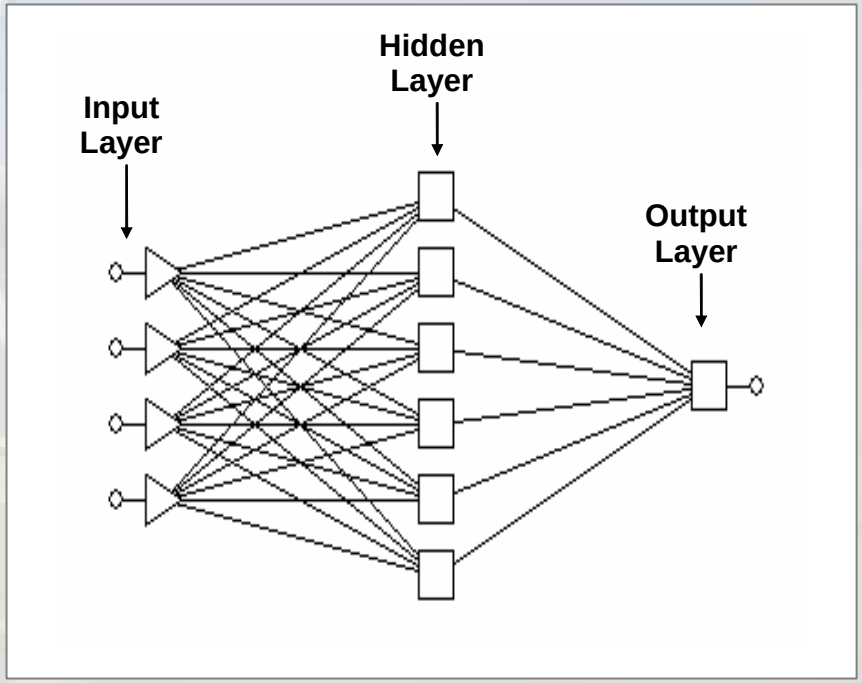




Future Work - ANNs





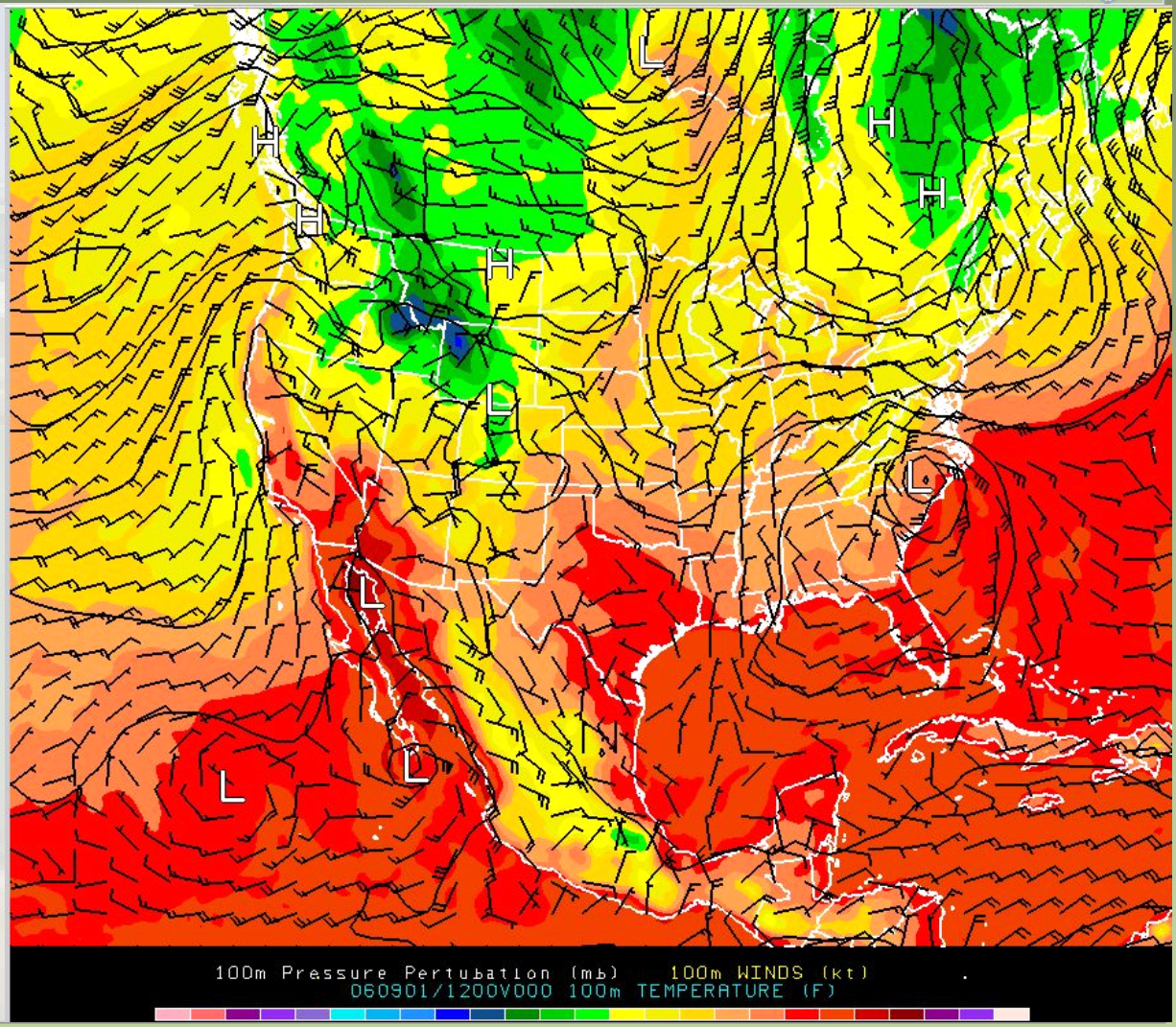


Multilayer perceptron neural net architecture for relating site wind (output) to (input) variables measured at the NOAA weather site: wind speed, wind direction, dew point temperature and dry bulb temperature

Future Work

MORE ACCURATE WIND DATA

- On-site 50 meter and 100 meter wind speed data
- Texas Mesonet, Academy for Advanced Telecommunications and Learning Technology (AATLT)
- Goal: Hourly analysis, curtailment factors, forecasting, etc.



Questions?