ANALYSIS OF WIND POWER GENERATION OF TEXAS

April 2007

Zi "Betty" Liu, Ph.D., Jeff Haberl, Ph.D., P.E.,
Kris Subbarao, Ph.D., P.E., Juan-Carlos Baltazar, Ph.D.

Energy Systems Laboratory

REVIEW OF OCT 06 MEETING

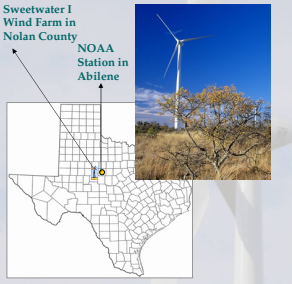
- Comparison of Method 0 vs. Method 1
  - Year to year variation decreased using Method 1.
- Curtailment Analysis
  - 34% curtailment and maintenance factor observed for Indian Mesa from Jul 2002 to Jan 2003
- Degradation Analysis
  - On average, no degradation observed for nine wind farms analyzed over 4-year period.
- Application of Method 1 to New Site- Sweetwater I Wind Farm

OUTLINE

- Application of Method 1 – Prediction of Power Production in Base Year Using Daily Regression Model for Each Wind Farm (22 subsites).
- Method 1 Improvement – Daily Regression Model Based on Synthesized On-site Wind Using Artificial Neural Nets (ANN).
- Future Work

APPLICATION: Method 1 – Sweetwater I Wind Farm

Example: Sweetwater I Wind Farm (37.5 MW)

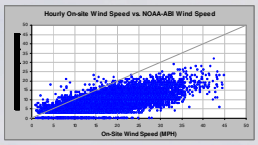


- Completed and commenced operation in late December 2003.
- Wind Turbines : GE Wind Energy 1.5s 1500 kW
- Tower Height: 80 m
- Rotor Diameter: 70.5 m
- Rotor Speed: 11-22 rpm
- Number of Turbines :25
- Projected Annual Output: 141,748 mph
- Nearest NOAA Station: Abilene Regional Airport -ABI

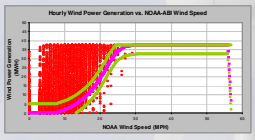
WHY NOT Use Hourly NOAA Wind and Power Curve ?
Sweetwater I Wind Farm

Hourly Power Generation and Wind Speed (2004 Hourly Data):

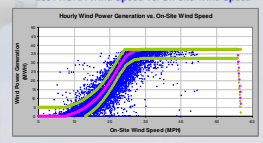
- NOAA wind:
  - Significant lower than on-site wind
  - Not appropriate for predicting hourly power using power curve
- On-site wind:
  - Measured power vs. on-site wind following well the power curve prediction
  - No curtailment at this site
- Green curves showing a band of 5 MW from the power curve



2004 NOAA Wind Speed vs. On-site Wind Speed



2004 Power vs. NOAA Wind Speed (MPH)

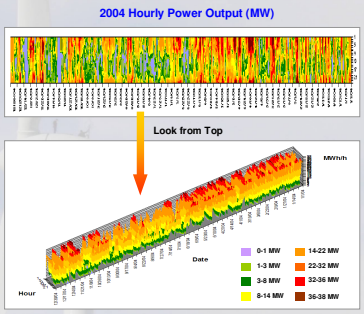


2004 Power vs. On-site Wind Speed (MPH)

WHY NOT Use Hourly NOAA Wind and Power Curve ?
Sweetwater I Wind Farm

Introduction to the 3D color map surface plot:

- 3D color map surface plot:
  - Use to evaluate relationships between three variables at once
  - Different colors representing different range of power output for each hour of the year.
- Top contour:
  - Another projection of the 3D color map surface graph, which is from the top.
- An example:
  - 2004 hourly power output for Sweetwater I wind farm.

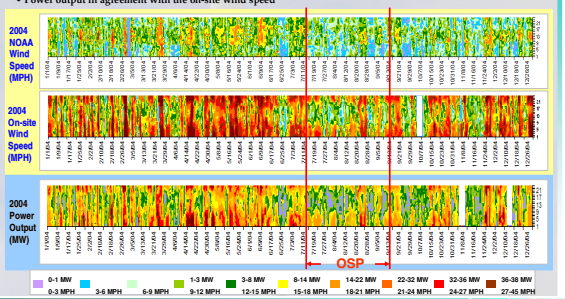


WHY NOT Use Hourly NOAA Wind and Power Curve ?

Sweetwater I Wind Farm

Comparison of Hourly NOAA, On-site Wind and Power Generation (2004):

- NOAA wind speed significantly different from the on-site wind for this site
- The color settings for the power 3D surface plot were correlated to the wind speed 3D surface plot using power curve
- Power output in agreement with the on-site wind speed



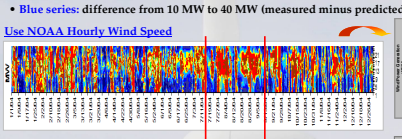
WHY NOT Use Hourly NOAA Wind and Power Curve ?

Sweetwater I Wind Farm

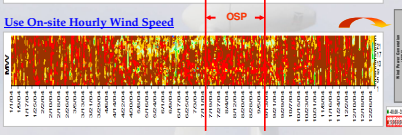
Comparison of Measured Hourly MW and Predicted MW Using Power Curve (2004)

- 3D surface plot: showing the difference between measured and predicted MW
- Brown and red: difference within 5 MW
- Blue series: difference from 10 MW to 40 MW (measured minus predicted)

Use NOAA Hourly Wind Speed



Use On-site Hourly Wind Speed



Conclusion: Hourly NOAA wind may not be appropriate for predicting power production with power curve for Sweetwater I Wind Farm

APPLICATION – Method 1

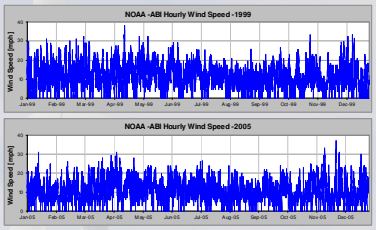
Procedure

- 2005 measured hourly wind power production obtained from ERCOT.
- 2005 and 1999 hourly wind speed data obtained for the nearest NOAA weather station.
- Hourly wind speed and power production data converted to daily data.
- Daily performance curves developed by regressing the 2005 daily electricity production against the 2005 daily average NOAA wind.
- The coefficients from the 2005 regression and 1999 wind data used to predict the daily electricity the wind farm would have produced in 1999.

APPLICATION: Method 1 – Sweetwater I Wind Farm

Weather Data: NOAA- ABI 1999 and 2005 Hourly Wind Speed

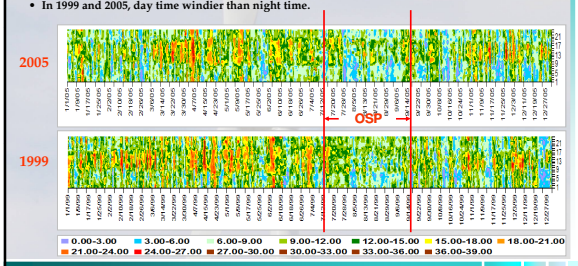
- 2005 Wind Speed
  - 16 hours wind speed data missing
  - Annual average: 10.3 mph
- 1999 Wind Speed
  - 6 hours wind speed data missing
  - Annual average: 11.3 mph
- 1999 Windier than 2005



APPLICATION: Method 1 – Sweetwater I Wind Farm

NOAA- ABI 1999 and 2005 Hourly Wind Speed in MPH

- 3D surface plots – top contour for comparing 1999 and 2005 hourly wind speeds
- 1999 windier than 2005.
- In 1999 and 2005, winter and spring months windier than summer months.
- In 1999 and 2005, OSP less windier than other months, for example, Apr. to Jun., and Nov. to Dec.
- In 1999 and 2005, day time windier than night time.

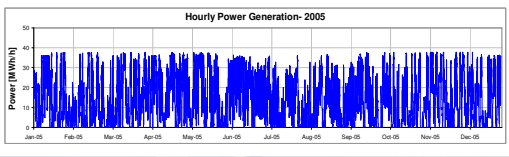


APPLICATION: Method 1 – Sweetwater I Wind Farm

2005 Hourly Measured Wind Power Data from ERCOT:

Observations:

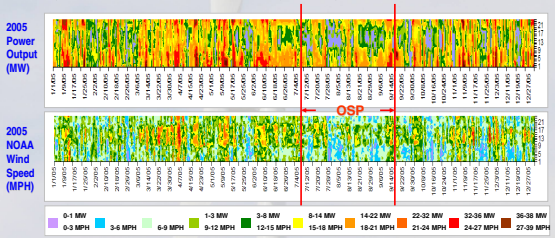
- Total capacity: 37.5 MW
- Maximum hourly output in 2005: 37.0 MW
- No missing hours



APPLICATION: Method 1 – Sweetwater I Wind Farm

Hourly NOAA Wind Speed and Power Generation (2005):

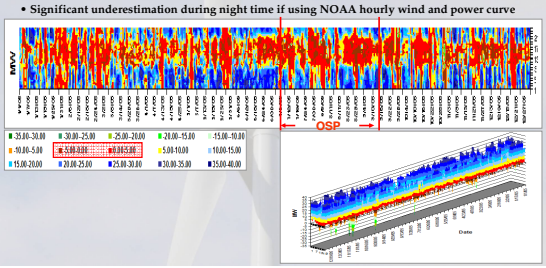
- Power generation: higher during the night time; lower during the summer and OSP.
- NOAA wind speed: higher during the day time; lower during the OSP.
- The color settings for the power 3D surface plot were correlated to the wind plot using power curve.
- Measured power generation not in agreement with NOAA wind speed.
- Original NOAA data not appropriate for hourly modeling.



APPLICATION: Method 1 – Sweetwater I Wind Farm

Comparison of Measured MW and Predicted MW Using Power Curve and Hourly NOAA Wind (2005)

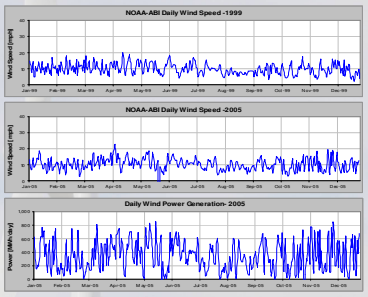
- 3D surface plot: showing the difference (measured MW minus predicted MW)
- Brown and red: difference within 5 MW
- Blue series: difference from 10 MW to 40MW
- Significant underestimation during night time if using NOAA hourly wind and power curve



APPLICATION: Method 1 – Sweetwater I Wind Farm

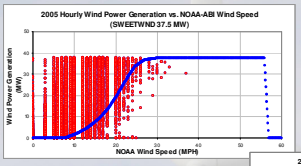
Hourly Data Converted to Daily Data

- 2005 and 1999 hourly wind speed averaged to daily wind speed
  - Criteria: missing hours (more than 6) excluded as a missing day
  - 2005: total of 2 days wind speed data missing
  - 1999: no missing days
- 2005 hourly power production summed to daily power
  - No missing days



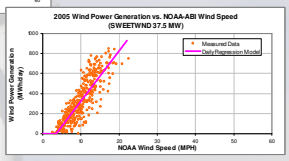
APPLICATION: Method 1 – Sweetwater I Wind Farm

Modeling of Daily Turbine Power vs. Daily Wind Speed (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%

- Hourly Data
  - Discretization, scatter
- Daily Data
  - More appropriate for modeling



APPLICATION: Method 1 – Sweetwater I Wind Farm

Predicted Wind Power Using 2005 Daily Model vs. Measured MWH

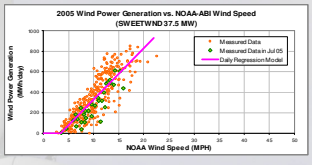
- Daily model performing well for the entire year and OSP
- July – the biggest error (-19.34%)

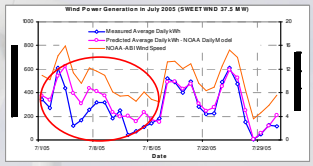
Month	No. Of Days	Average Daily Wind Speed (MPH) NOAA	Measured Power Generation (MWh) NOAA	Predicted Power Generation Using Daily Model (MWh) NOAA	Diff. NOAA	Measured Capacity Factor	Capacity Factor Using Daily Model NOAA
Jan-05	31	10.34	11,105	10,726	3.41%	40%	38%
Feb-05	28	8.92	7,130	7,729	-8.40%	28%	31%
Mar-05	31	11.54	11,611	12,584	-8.38%	42%	45%
Apr-05	30	12.97	13,597	14,331	-5.40%	50%	53%
May-05	30	11.03	11,029	11,417	-3.51%	41%	42%
Jun-05	30	11.86	13,323	12,660	4.97%	49%	47%
Jul-05	31	9.94	8,465	10,102	-19.34%	30%	36%
Aug-05	31	8.26	7,882	7,489	4.98%	28%	27%
Sep-05	30	9.29	9,062	8,789	3.01%	34%	33%
Oct-05	30	9.26	9,167	8,428	8.06%	34%	31%
Nov-05	30	10.33	11,094	10,364	6.57%	41%	38%
Dec-05	31	10.62	11,322	10,227	9.66%	41%	37%
Total	363	10.32	124,787	124,846	-0.05%	38%	38%
Total in OSP (07/15-09/15)	63	8.98	18,131	17,485	3.56%	32%	31%

APPLICATION: Method 1 – Sweetwater I Wind Farm

Predicted vs. Measured in July 2005

- Measured power not evenly distributed around the prediction
- Overestimation for the first half of the month
- Reason unknown:
  - Curtailment?
  - Maintenance?
  - Others?

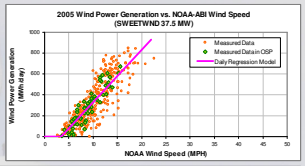


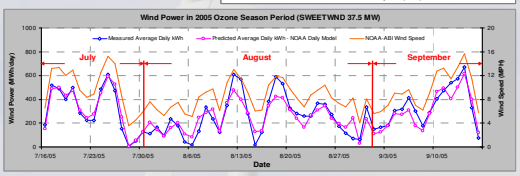


APPLICATION: Method 1 – Sweetwater I Wind Farm

Predicted vs. Measured in 2005 Ozone Season Period

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

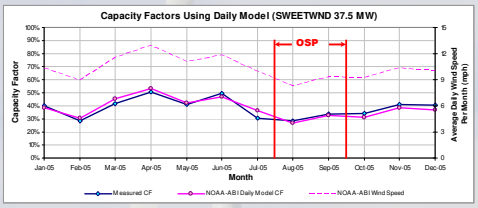




APPLICATION: Method 1 – Sweetwater I Wind Farm

Predicted 2005 Capacity Factor Using 2005 Daily Model vs. Measured Capacity Factor:

- The daily model performing well in predicting annual (0% error) and OSP capacity factors (1% error).
- The biggest error in July (6%).



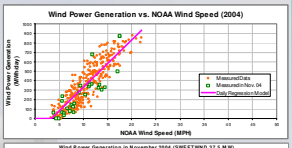
APPLICATION: Method 1 – Sweetwater I Wind Farm

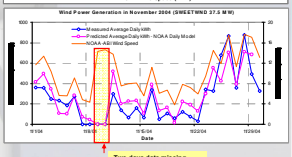
Testing of the 2005 Model with 2004 Data

- 2004 measured power output and 2004 wind speed
- 2005 daily model coefficients

Conclusions:

- 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	12,669	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%

APPLICATION: Method 1 – Sweetwater I Wind Farm

Predicted Power Production in 1999 for Sweetwater I Wind Farm:

Method 0: Uses daily average for OSP
Does not correct for base-year weather conditions

Method 1: Uses daily regression model
Corrects for base-year weather conditions

Method 0: 2005 Measured: 125,259 MWh/yr
2005 OSP Measured: 288 MWh/day

Method 1: 1999 Estimated with 2005 Model: 143,711 MWh/yr, a 15% increase
1999 OSP Estimated with 2005 Model: 314 MWh/day, a 9% increase

APPLICATION: Summary for All Wind Farms

Estimated Power Production in 1999 for Each Wind Farm in ERCOT:

- 1999 estimated annual MWh with 2005 model: all sites increase.
- 1999 estimated OSP MWh/day with 2005 model: 6 sites decrease, all other sites increase.

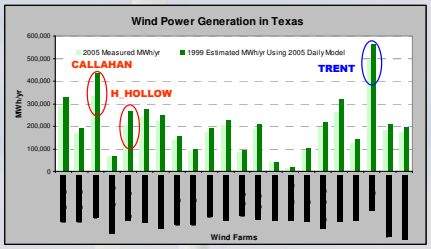
Wind Unit Name	County	NOAA Weather Station	Capacity (MW)	2005 Measured (MWh/yr)	1999 Estimated Using Daily Model (MWh/yr)	Increase 1999 vs. 2005 (MWh/yr)	2005 OSP Measured (MWh/day)	1999 OSP Estimated (MWh/day)	Increase 1999 vs. 2005 (MWh/day)
BRAZ_WND_WND1	SCURRY	ABI	160	286,411	331,578	45,169	641	724	83
BRAZ_WND_WND2	SCURRY	ABI		170,606	191,967	21,360	368	420	52
CALLAHAN_WND1	TAYLOR	ABI	114	332,572	433,697	101,125	831	955	124
DELAWARE_WND_NWP	CULBERSON	GDP	30	66,267	68,298	2,031	103	114	11
H_HOLLOW_WND1 *	TAYLOR	ABI	220.5	283,673	367,691	84,018	550	1,354	804
INDNENR_INDNENR	PECOS	FST	160.5	246,131	273,888	27,757	625	639	14
INDNENR_INDNENR_2	PECOS	FST		224,642	250,714	26,072	585	583	-2
INDNWP_INDNWP	PECOS	FST	82.5	142,264	156,586	16,316	372	369	-3
INDNWP_INDNWP	PECOS	FST		87,914	97,971	10,057	230	228	-2
KING_NE_KINGNE	UPTON	MAF	80	172,198	192,791	20,593	378	417	39
KING_NW_KINGNW	UPTON	MAF	80	207,634	227,493	19,859	534	515	-19
KING_SE_KINGSE	UPTON	MAF	40	85,697	95,931	10,234	182	204	22
KING_SW_KINGSW	UPTON	MAF	80	195,202	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	197,094	217,418	19,722	522	468	-54
SWEETWND_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
WOODWND1_WOODWND1	PECOS	FST	80	185,149	211,827	26,678	401	474	73
WOODWND2_WOODWND2	PECOS	FST	80	172,532	196,032	23,500	424	442	18
TOTAL			1,760	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.

APPLICATION: Comparison 1999 vs. 2005

Comparison of Annual 1999 Estimated (Method 1) vs. 2005 Measured (Method 0) For Each Wind Farm

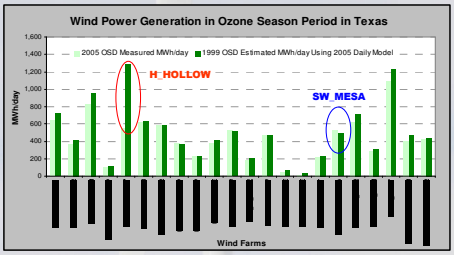
- 1999 annual MWh: all sites increase.
- Biggest increase: CALLAHAN - 30%, H_HOLLOW – 31%
- Highest annual production: TRENT



APPLICATION: Comparison 1999 vs. 2005

Comparison of 1999 Estimated (Method 1) vs. 2005 Measured (Method 0) in OSP :

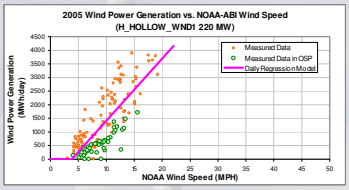
- 1999 OSP MWh/day: 6 sites decrease, the other sites increase.
- Biggest increase: H_HOLLOW, 146%
- Biggest degrease: SW_MESA, -7%



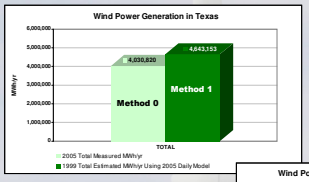
H_HOLLOW: Why Does the Predicted Power Generation in OSP Increase 146% vs. Measured?

H_HOLLOW (220 MW) :

- Started operation in August 2005.
- Not running full capacity in OSP.
- 2005 model using 5 months data from August to December.
- Partial data used to predict the power production in OSP.



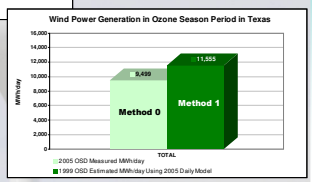
APPLICATION: Comparison 1999 vs. 2005



Comparison of 1999 Predicted Using 2005 Daily Model (Method 1) vs. 2005 Measured (Method 0)

Annual Total: Increased 15.2%

OSP: Increased 21.6%



Why 1999 Estimated MWH Higher than 2005 Measured MWH?

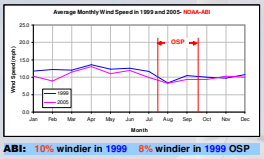
Comparison of 1999 and 2005 Wind Speed for the NOAA Weather Stations

- 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

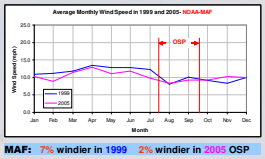
Month	Wind Speed ABI (mph)		Wind Speed MAF (mph)		Wind Speed FST (mph)		Wind Speed GDP (mph)	
	1999	2005	1999	2005	1999	2005	1999	2005
Jan	11.8	10.3	10.9	9.7	12.0	10.2	21.2	19.1
Feb	12.2	8.9	11.2	8.9	11.4	9.2	22.4	21.5
Mar	12.1	11.5	11.8	11.1	11.8	11.1	21.5	22.3
Apr	13.6	13	13.5	12.1	13.1	12.5	20.9	19.9
May	12.4	11	12.8	10.8	12.6	11.7	19.9	17.3
Jun	12.7	11.9	12.8	12.1	12.0	12.4	16.3	15.7
Jul	11.7	9.9	12.3	10.4	12.3	10.6	14.8	16.0
Aug	8.4	8.3	8.0	9.2	8.8	8.5	13.5	12.9
Sep	10.4	9.3	10.1	9.7	9.9	9.2	16.8	14.5
Oct	10	9.3	9.1	9.3	10.4	9.7	14.2	16.8
Nov	9.7	10.3	8.3	9.4	9.5	10.3	18.2	19.8
Dec	10.7	10	10.0	9.5	10.6	8.6	20.6	19.5
Annual Average	11.3	10.3	10.9	10.2	11.2	10.3	18.3	18.0
OSP Average	9.7	9.0	9.5	9.7	10.0	9.3	13.9	14.5

Why 1999 Estimated MWH Higher than 2005 Measured MWH?

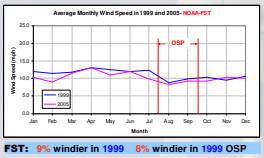
Monthly Average Wind Speed in 1999 and 2005 for the NOAA Weather Stations



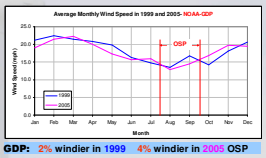
ABI: 10% windier in 1999 8% windier in 1999 OSP



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

CONCLUSIONS

Conclusions

- Predicted annual and OSP power production using NOAA daily regression model (Method 1) for all wind farms in ERCOT area increased by 15% and 21% respectively compared to method 0.

Recommendations:

- Use weather normalization for predicting 1999 base year power production for each wind farm.
- Use of weather normalization should allow the reduction of discount factor used in the previous calculation.

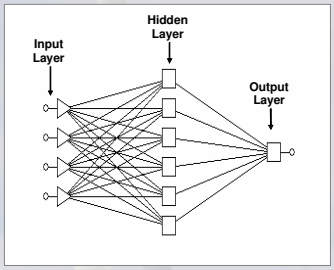
OUTLINE

- Application of Method 1 – Prediction of Power Production in Base Year Using Daily Regression Model for All Wind Farms
- Method 1 Improvement – Daily Regression Model Based on Synthesized On-site Wind Using Artificial Neural Nets
- Future Work

METHOD 1 IMPROVEMENT-ANN

- NOAA variables used in Artificial Neural Nets (ANN):
  - Wind speeds
  - Wind directions, account for terrain effects
  - Dry bulb temperatures, account for weather fronts
  - Dew point temperatures, account for clouds
- Determination of the architecture of the neural nets
  - Automatic routines performed through a search process resulting in the most parsimonious architecture
  - Best network - multilayer perceptron with a hidden layer of six nodes
- The data set divided into three random groups
  - Training set
  - Verification set
  - Test set

METHOD 1 IMPROVEMENT-ANN



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

ANN APPLICATION – Procedure

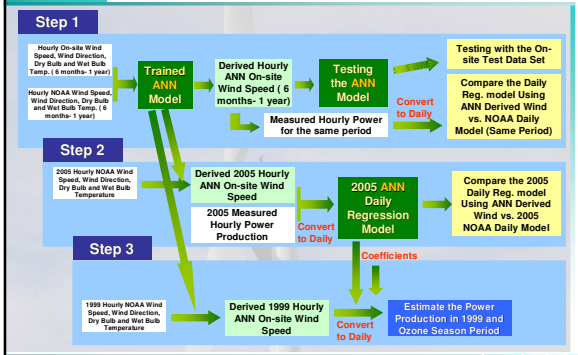
Procedure:

Step 1:
1.1 Development and testing of the ANN model using on-site and NOAA hourly wind speed, wind direction, dry bulb and wet bulb temp. for a same period for a site.
1.2 Conversion of the hourly ANN on-site wind and power output to daily data and development of the ANN daily regression model and comparing it against NOAA daily model for the same period.

Step 2:
2.1 Application of the ANN model to the 2005 NOAA hourly wind speed, wind direction, dry bulb, and wet bulb temp. for this site to derive 2005 ANN hourly on-site wind speed.
2.2 Conversion of the 2005 hourly ANN on-site wind to daily data and development of the 2005 ANN daily regression model using the measured 2005 daily power and ANN daily on-site wind.

Step 3:
3.1 Application of the ANN model to the 1999 NOAA hourly wind speed, wind direction, wet bulb, and dry bulb temp. for this site to derive 1999 ANN hourly on-site wind speed.
3.2 Conversion of the 1999 hourly ANN on-site wind to daily data and application of the coefficients of ANN daily regression model to the 1999 daily wind speed to predict the power production in 1999 and 1999 OSP.

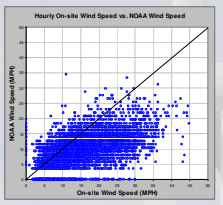
ANN APPLICATION – Procedure



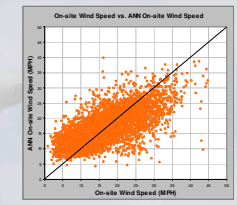
ANN APPLICATION – Indian Mesa Wind Farm

Step 1.1 Indian Mesa Wind Farm (Jul 2002 to Jan 2003) – Hourly Data

- Development of ANN Model:
  - 4 input variables (wind speed, wind direction, dry bulb and dew point temp.).
  - 6 nodes for the hidden layer.
- ANN improves the prediction of hourly on-site wind speed



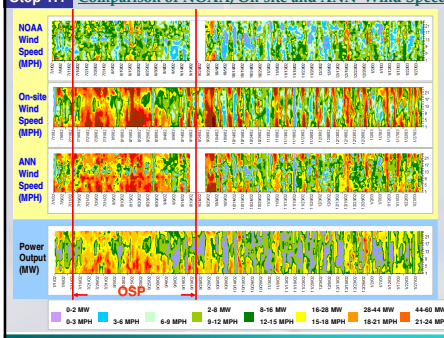
Hourly On-site Wind Speed vs. NOAA Wind Speed



Hourly On-site Wind Speed vs. ANN Synthesized Wind Speed

ANN APPLICATION – Indian Mesa Wind Farm

Step 1.1 Comparison of NOAA, On-site and ANN Wind Speed (2002-2003):



Observations:

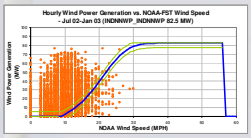
- NOAA wind much lower than on-site wind.
- ANN providing much better prediction on on-site wind than NOAA.
- The color settings in the power plot correlated to the wind plot using power curve.
- The color in the power plot one to several classes lower than the wind plot indicating curtailment or maintenance.

ANN APPLICATION – Indian Mesa Wind Farm

Step 1.1

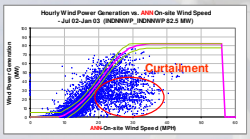
Indian Mesa Wind Farm (Jul 2002 to Jan 2003)

- ANN significantly improves the prediction of on-site wind speed compared to NOAA.
- Green curves showing a band of 5 MW from the power curve



Measured MW Plotted Against Hourly NOAA Wind Speed

Measured MW Plotted Against Hourly On-site Wind Speed

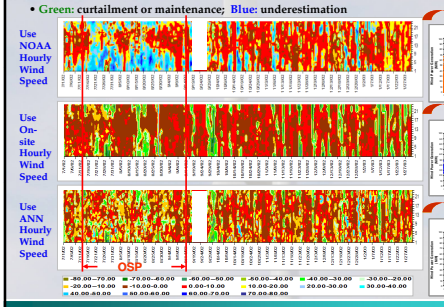


Measured MW Plotted Against Hourly ANN On-site Wind Speed

ANN APPLICATION – Indian Mesa Wind Farm

Step 1.1 Comparison of Measured and Predicted MW Using Power Curve (2004)

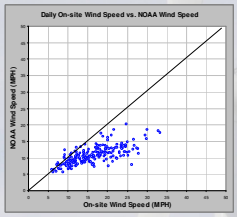
- 3D Surface plot: showing the difference (measured minus predicted)
- Brown and red: difference within 5 MW
- Green: curtailment or maintenance; Blue: underestimation



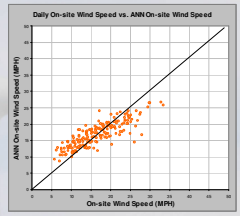
ANN APPLICATION – Indian Mesa Wind Farm

Step 1.2 Indian Mesa Wind Farm (Jul 2002 to Jan 2003) – Daily Data

- NOAA wind speed is ok for predicting on-site wind speed for low wind speed range, but underestimates significantly at higher wind speed.
- ANN predicts the on-site wind speed more accurately



Daily On-site Wind Speed vs. NOAA Wind Speed

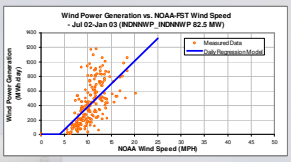


Daily On-site Wind Speed vs. ANN Synthesized Wind Speed

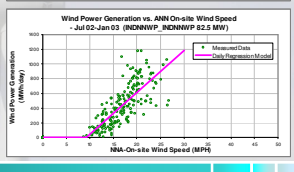
ANN APPLICATION – Indian Mesa Wind Farm

Step 1.2 Indian Mesa Wind Farm (Jul 2002 to Jan 2003) – Daily Data

- NOAA model vs. ANN model
  - Slopes are similar: 62.9 for NOAA and 56.9 for ANN
  - Offsets significantly different: 3.9 mph for NOAA and 9.2 mph for ANN
- ANN – Improves the model especially in low wind speeds
- ANN - Monthly errors and error in OSP decrease significantly



Measured MWh/day Plotted Against Daily NOAA Wind Speed



Measured MWh/day Plotted Against Daily ANN On-site Wind Speed

ANN APPLICATION – Indian Mesa Wind Farm

Step 1.2 Indian Mesa Wind Farm (Jul 2002 to Jan 2003)

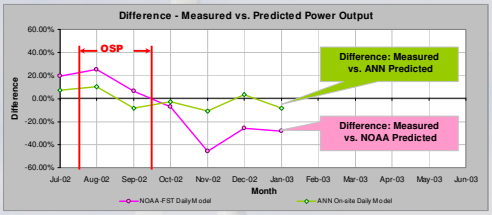
- Both NOAA and ANN models perform well for predicting annual power production
- ANN - Monthly errors and error in OSP decrease significantly

	Monthly Summary Using NOAA Wind					Monthly Summary Using ANN On-site Wind			
Month	No. Of Days	Average Daily Wind Speed (MPH) NOAA	Measured Power Generation (MWh/Mo) NOAA	Predicted Power Generation Using Daily Model (MWh/mo) NOAA	Diff. NOAA	Average Daily Wind Speed (MPH) NNA-On-site	Measured Power Generation (MWh/Mo) NNA-On-site	Predicted Power Generation Using Daily Model (MWh/mo) NNA-On-site	Diff. NNA-On-site
Jul-02	30	11.47	17,821	14,302	19.75%	19.03	17,821	16,799	7.14%
Aug-02	30	12.25	20,996	15,766	24.91%	20.53	20,996	19,348	10.46%
Sep-02	21	10.11	8,793	8,212	6.61%	17.14	8,793	9,484	-8.53%
Oct-02	29	10.43	11,152	11,924	-6.92%	16.17	11,152	11,516	-3.06%
Nov-02	27	9.73	6,815	9,912	-45.45%	14.34	6,815	7,916	-13.11%
Dec-02	30	11.12	10,862	13,639	-25.56%	15.25	10,862	10,370	3.61%
Jan-03	30	10.33	9,468	12,152	-28.36%	15.34	9,468	10,495	-8.45%
Total	197	10.83	85,907	85,907	0.00%	16.86	85,907	85,937	-0.03%
OSP	62	11.36	38,678	29,137	24.67%	19.20	38,678	35,296	11.91%

ANN APPLICATION – Indian Mesa Wind Farm

Step 1.2 Indian Mesa Wind Farm (Jul 2002 to Jan 2003) – Monthly Comparison

- Difference between the Measured and Predicted Power Output for Each Month = (Measured– Predicted)/Measured
- Positive: Underestimation Negative: Overestimation
- ANN model predicts the monthly power production more accurately
- Both models underestimate for July and August and overestimate in Oct, Nov.

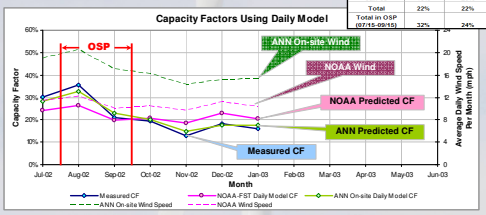


ANN APPLICATION – Indian Mesa Wind Farm

Step 1.2 Indian Mesa Wind Farm (Jul 2002 to Jan 2003) Monthly Capacity Factors

- ANN model: more accurate prediction on monthly and OSP capacity factor

Month	Measured Capacity Factor (NOAA)	Capacity Factor Using NOAA Daily Model	Capacity Factor Using WAA On-site Daily Model
Jul-02	30%	24%	28%
Aug-02	35%	27%	33%
Sep-02	21%	20%	23%
Oct-02	19%	21%	20%
Nov-02	13%	19%	15%
Dec-02	18%	23%	17%
Jan-03	16%	20%	16%
Total	22%	22%	22%
Total in OSP (07/15-09/15)	32%	24%	29%



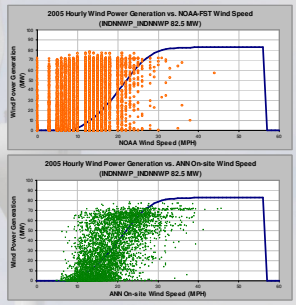
ANN APPLICATION – Indian Mesa Wind Farm

Step 2.1 Indian Mesa Wind Farm (2005 Hourly Data)

- Application of the ANN model to derive the 2005 ANN on-site wind.
- ANN significantly improves the prediction of on-site wind speed compared to NOAA.

Measured MW Plotted Against Hourly NOAA-FST Wind Speed

Measured MW Plotted Against Hourly ANN On-site Wind Speed



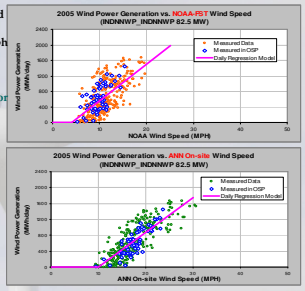
ANN APPLICATION – Indian Mesa Wind Farm

Step 2.2 Indian Mesa Wind Farm (2005 Daily Data)

- Development of 2005 ANN daily reg. model
- NOAA daily model vs. ANN daily model
  - Slopes are similar: 94.9 for NOAA and 86.9 for ANN
  - Offsets significantly different: 4.1 mph for NOAA and 10.0 mph for ANN
- ANN wind – Improves the daily model in low wind speed
- ANN daily model - Monthly errors and error in OSP decrease significantly

Measured MWh/day Plotted Against Daily On-site Wind Speed

Measured MWh/day Plotted Against Daily ANN On-site Wind Speed



ANN APPLICATION – Indian Mesa Wind Farm

Step 2.2 Indian Mesa Wind Farm (2005 Model)

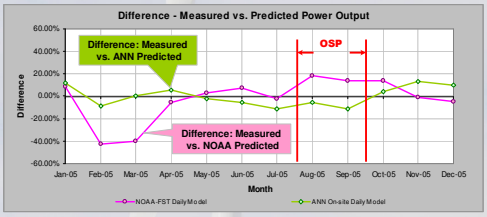
- Both NOAA and ANN models perform well for predicting annual power production
- ANN - Monthly errors and error in OSP decrease significantly

	Monthly Summary Using NOAA Wind					Using ANN On-site Wind			
Month	No. Of Days	Average Daily Wind Speed (MPH) NOAA	Measured Power Generation (MWh/day) NOAA	Predicted Power Generation Using Daily Model (MWh/mo) NOAA	Diff. NOAA	Average Daily Wind Speed (MPH) ANN-On-site	Measured Power Generation (MWh/Mo) ANN-On-site	Predicted Power Generation Using Daily Model (MWh/mo) ANN-On-site	Diff. ANN-On-site
Jan-05	30	10.59	20,259	18,508	8.64%	16.89	20,259	18,085	11.74%
Feb-05	26	9.80	9,887	14,099	-42.60%	14.82	9,887	11,064	-8.36%
Mar-05	30	11.44	14,950	20,942	-40.08%	15.64	14,950	14,834	0.55%
Apr-05	29	12.85	22,835	24,107	-5.57%	18.51	22,835	21,674	5.23%
May-05	29	11.98	22,439	21,721	3.20%	19.04	22,439	22,961	-2.41%
Jun-05	29	12.87	26,162	24,168	7.65%	20.82	26,162	27,412	-5.17%
Jul-05	29	11.33	19,466	19,942	-2.50%	18.54	19,466	21,641	-10.96%
Aug-05	30	8.96	16,970	13,867	18.29%	16.73	16,970	17,726	-5.46%
Sep-05	28	9.73	17,361	14,986	13.68%	17.78	17,361	19,054	-11.36%
Oct-05	29	10.18	19,412	16,768	13.62%	17.38	19,412	18,742	4.09%
Nov-05	24	10.99	15,607	15,726	-0.76%	16.46	15,607	13,672	10.50%
Dec-05	19	10.70	11,402	11,915	-4.50%	16.15	11,402	10,238	9.77%
Total	332	10.97	216,740	216,740	0.00%	17.46	216,740	216,904	-0.08%
OSP	59	9.87	37,078	32,353	12.74%	17.64	37,078	39,468	-7.39%

ANN APPLICATION – Indian Mesa Wind Farm

Step 2.2 Indian Mesa Wind Farm (2005 Model)

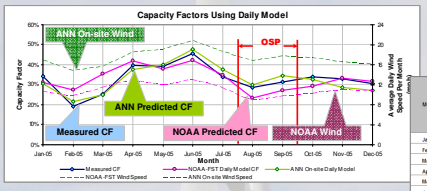
- Difference between the Measured and Predicted Power Output for Each Month = (Measured– Predicted)/Measured
- Positive: Underestimation Negative: Overestimation
- ANN model predicts the monthly power production more accurately
- ANN model overestimates the power in OSP; NOAA underestimates the power in OSP



ANN APPLICATION – Indian Mesa Wind Farm

Step 2.2 Indian Mesa Wind Farm (2005 Model)

- ANN model: more accurate prediction on monthly and OSP capacity factors



Month	Measured Capacity Factor (ROA)	Capacity Factor Using NOAA Daily Model	Capacity Factor Using ANN On-site Daily Model
Jan-05	34%	31%	30%
Feb-05	19%	27%	21%
Mar-05	25%	35%	25%
Apr-05	40%	42%	39%
May-05	39%	38%	40%
Jun-05	46%	42%	48%
Jul-05	34%	35%	30%
Aug-05	29%	23%	30%
Sep-05	31%	27%	34%
Oct-05	34%	29%	33%
Nov-05	33%	33%	29%
Dec-05	30%	32%	27%
Total	33%	33%	33%
Total in OSP (07/15-09/15)	32%	28%	34%

ANN APPLICATION – Indian Mesa Wind Farm

Indian Mesa Wind Farm (2005 Model)

Step 3.1
- Derive the 1999 ANN on-site wind using the ANN model

Step 3.2
- Apply the coefficients from 2005 ANN and NOAA daily models to 1999 ANN wind and NOAA wind, respectively.
- Estimated Power Production in 1999 with 2005 Model
  - Both NOAA and ANN models perform well for predicting annual power production
  - ANN - more accurate prediction for monthly and OSP power production

Summary

Annual - ANN On-site Wind Data

1999 Estimated MWh/yr (2005 Daily Model)	2005 Measured MWh/yr	2005 Predicted MWh/yr (2005 Daily Model)
246,921	238,283	238,283

OSP - ANN On-site Wind Data

1999 OSD Estimated MWh/day (2005 Daily Model)	2005 OSD Measured MWh/day	2005 OSD Predicted MWh/day (2005 Daily Model)
702	628	669

Annual - NOAA-FST Wind Data

1999 Estimated MWh/yr (2005 Daily Model)	2005 Measured MWh/yr	2005 Predicted MWh/yr (2005 Daily Model)
245,966	238,283	238,283

OSP - NOAA-FST Wind Data

1999 OSD Estimated MWh/day (2005 Daily Model)	2005 OSD Measured MWh/day	2005 OSD Predicted MWh/day (2005 Daily Model)
557	628	548

CONCLUSIONS

Conclusions:
- Both NOAA and ANN daily models providing acceptable annual prediction on wind power generation.
- ANN models providing more accurate prediction on monthly and OSP power generation.

Recommendations:
- Potential of underestimation of OSP power production could be more than 10% if using NOAA wind speed.
- Continue the study on ANN for predicting more accurate on-site wind speed.

FUTURE WORK

Summary
- Method 1 (weather normalization using NOAA daily model) increases the predicted annual and OSP power production by 15% and 21% respectively for all the wind farms in ERCOT area.
- ANN on-site wind speed improves the performance of daily regression model.

Future Work:
- More on-site wind speed data needed for the ongoing research.
- Improve the ANN model for predicting more accurate on-site wind speed for hourly model.
- Other methodologies for predicting on-site wind speed at hub height for hourly model.