INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the
Research and Development of Wind Turbine Systems
ANNEX XI

33 Meeting of Experts

Wind Forecasting Techniques

Boulder, U.S.A., April 4-5, 2000

Organised by: NREL

Scientific Coordination:

Sven-Erik Thor
FFA, The Aeronautical Research
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CONTENTS

INTRODUCTORY NOTE TO IEA EXPERT MEETING ON WIND FORECASTING TECHNIQUES

Marc Schwartz, NREL, USA

As wind energy makes significant penetration into electric grids in various places around the world, the need for accurate predictions of available wind electric potential for a variety of time scales is increasing in importance. Accurate wind forecasts are required to best integrate wind electric potential into scheduling and dispatch decisions made by an energy provider.

Accurate wind forecasts will also help overcome the perceived barriers of wind intermittence and unpredictability that make some energy providers reluctant to pursue wind as an energy resource. Furthermore, the move towards electric industry deregulation is likely to increase the importance of accurate wind forecasts. The IEA believes now is an opportune time to assess the current state-of-the-art of wind forecasting techniques. Therefore, the IEA is arranging an expert meeting on wind forecasting techniques.

A primary goal of the meeting is to give the participants a good overall view of the current status of wind forecasting efforts. To this end, the expert meeting will welcome participation from parties who have had experience in wind forecasting projects and those who have an interest in starting wind forecasting projects. Experienced wind forecasting participants should discuss a variety of technical topics including but not limited to:

- the wind forecast methodology used in the project
- the structure of wind forecast products being currently supplied to clients
- summaries of past forecasting project results
- descriptions of present and planned wind forecasting projects
- and any particular problems and/or success noted in the project

Those participants who are interested in beginning a wind forecasting project should discuss where the forecasting project will take place, the structure of the utility/energy provider in the area of interest, and the perceived benefits of accurate forecasts for that area.

Another goal of the meeting is to discuss what forecasting methodologies may hold promise for developing the most accurate future wind forecasting tools and what type of research and applications may be the most beneficial to create confidence in the electricity industry of the predictability of wind energy.

The outcome of the meeting should be a decision on whether the participants will proceed to establish an IEA wind forecasting annex. If there is a decision to proceed with the annex, a general outline of the annex and its timetable will be reviewed.

WIND FORECASTING ACTIVITIES AT THE U.S. NATIONAL RENEWABLE ENERGY LABORATORY

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USA

BACKGROUND

The wind energy industry and electricity producers can benefit in a number of ways from increased wind forecast accuracy. Higher confidence in the reliability of wind forecasts can help persuade an electric utility to increase the penetration of wind energy into its operating system and to augment the capacity value of wind electric generation. Reliable forecasts can also assist daily energy traders employed by utilities in marketing the available and anticipated wind energy to power pools and other energy users. As the number of utilities with wind energy experience grows, and wind energy penetration levels increase, the need for reliable wind forecasts will likely grow as well. This period of wind energy growth also coincides with advances in computer weather prediction technology that could lead to more accurate wind forecasts. The challenge in this field is to develop advanced wind forecasting techniques that will result in useful products being supplied to utilities or other energy generating entities. This paper presents a summary of recent wind forecasting activities both under the direct auspices of the National Renewable Energy Laboratory (NREL) with emphasis on a series of utility interviews conducted during the past few years.

UTILITY INTERVIEWS

The focus of this initiative was to learn firsthand about the needs of prospective utility users of wind forecast information (Schwartz and Bailey, 1998). NREL and its representatives conducted a series of on-site interviews with key utility staff, usually schedulers and research planners, at seven U.S. utilities. The purpose was to ascertain information on actual scheduling and trading procedures, and how utilities could integrate wind forecasting into these activities. Representatives of the Electric Power Research Institute, who have been involved with a European wind forecasting initiative (Landberg, 1997) with Riso (Denmark) National Laboratory also attended most of these interviews.

The interview process consisted of several steps including the development of a pre-interview written questionnaire, the mailing of this questionnaire to the selected utilities, and the on-site interviews. A representative sample of seven utilities with emphasis on diverse geographical and size criteria was included in this survey. In addition, a utility had to have some prior experience with wind energy or future plans to use wind energy in order to be considered for these interviews.

The written questionnaire was designed to guide and document all the discussion points at the on-site interviews. It consists of 25 questions covering three broad topic areas: wind forecasts, general information, and background information. The following is a sample of questions from the wind forecasting, and general information areas:

Wind Forecasts

- Where within your scheduling hierarchy would wind forecasts be of use?
- When are forecasts needed, and how often should they be updated?
- What is the forecast lead-time; the outlook period; the time resolution?
- What is the desired forecast product format?
- How should forecast uncertainty be expressed?

General Information

- How much wind generation on your system is necessary to become incorporated into scheduling?
- What value would wind forecasts have when important wind penetration is reached?
- What are the operational concerns over significant wind penetration?
- How might restructuring impact the value of wind forecasts?

The utility personnel identified most often as being appropriate for a wind forecasting discussion were schedulers. The investigators interviewed one or more schedulers plus the research planner at each utility. Dispatchers and energy traders were also included in the interviews at some of the utilities.

RESULTS OF FORECASTING INTERVIEWS

The responses of the seven utilities to the questions in the wind forecasting section contained more similarities than contrasts. All agreed that "next day," defined as the period from midnight to midnight the following day, was an important forecast period. Reliable wind forecasts would aid in planning the utility's unit commitment schedule and its energy trading (buy/sell) activities. The next day forecast is usually needed by early morning (0600 to 0900 local time) in order to meet the mid- to late-morning (1000 to 1200 local time) deadline for the next day's plan. There was also consensus among the utilities that forecast products would be most useful if they were computer-based and expressed as on-line wind-based generation, in units of megawatts. Most utilities want the "next day" forecasts in hourly increments, though some would accept increments in 3 hourly or 6 hourly blocks. Another area where there was strong agreement among the utilities was how the forecast uncertainty should be expressed. The preferred way to express forecast uncertainty is a range of the maximum and minimum wind generation values. Utilities would most likely use the minimum forecasted wind generation value for scheduling/trading purposes since it's the most conservative, until utility staff gain confidence in the reliability of forecasts. Some utilities also stated that putting a confidence level on a forecast would be quite useful with a 70% to 80% confidence level being a key milestone.

Same day forecasts would be most valuable for dispatching decisions if the forecasts were extremely accurate or could reliably predict significant changes in available wind power. The longest forecast time frame that dispatchers would want is an hourly forecast. The forecast would have to be presented to them at least one-half hour prior to the start of the forecast period. The dispatchers we interviewed were more conservative than the schedulers were in their attitudes towards using wind forecasts. A dispatcher mentioned that a forecast with a 95% confidence level would not be accurate enough to be useful.

Longer range 3 to 7 day outlooks would be used for two purposes: (1) scheduling at utilities where staff does not work on holidays or weekends; and (2) anticipating the availability (or lack thereof) of all generation sources, especially during critical peak demand periods. The forecast resolution for these outlooks would not have to be hourly; daily trends or averages would suffice in most cases.

There was strong agreement among the utilities that wind forecasts would be important when the installed wind capacity enabled potential wind generation to reach a significant penetration level within their systems. This level ranged from 20 MW to 65 MW depending on the particular utility. The major concern that utility staff expressed about the integration of wind energy into their system was its intermittent nature. They emphasized the importance, to them, of significant wind generation impact on system reliability and spinning reserve requirements and that forecasts are necessary for each wind plant within a utility system. Their concerns with the reliability of wind forecasts also increased their uneasiness of integrating wind generation into their systems. Their experience with using meteorological forecasts, primarily temperature, to forecast loads have not always been satisfactory and this skepticism extended to the reliability of wind forecasts. A summary of the results follows the body of this paper.

COOPERATIVE ACTIVITIES

NREL is working with the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory (FSL) to help test the accuracy of wind forecasts produced the Rapid Update Cycle (RUC) numerical weather prediction model. The RUC was developed by FSL and is one of the package of forecast models routinely run and disseminated to the public by the National Centers for Environmental Prediction. The RUC is updated more frequently (every 3 hours) than the other forecast models (every 12 hours) and also produces wind forecasts for levels above ground near wind turbine hub-heights. RUC wind forecasts are being made for several regions of the United States including the Great Plains.

CONCLUSION

The utility interviews laid the groundwork for the design of future wind forecasting systems and research. The help of the utility staff clarified their needs and operating constraints and also established relationships that may prove invaluable when developing and testing wind forecasting tools.

ACKNOWLEDGEMENTS

The participation of the following utilities is greatly appreciated: Central and South West, Green Mountain Power, Niagara Mohawk, Northern State Power, Public Service of Colorado, and Texas utilities. I would like to thank representatives of AWS Scientific, Inc. and the Electric Power Research Institute for their participation in the interviews. This paper was written at the National Renewable Energy Laboratory in support of the U.S. Department of Energy under contract number DE-AC36-98-GO10337.

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Schwartz, M.N.; Bailey, B.H. (1998). "Wind Forecasting Objectives for Utility Schedulers and Energy Traders." *Windpower '98 Proceedings, Washington D.C. : American Wind Energy Association,* pp. 369-373.

Results of Forecasting Interviews

- Concepts with strong agreement
  - "Next day" time frame is an important wind forecasting period
  - Products should predict wind generation in units of MW
  - Forecast uncertainty as a range of predicted wind generation
  - Importance of accurate forecasts will likely increase after restructuring

Results of Forecasting Interviews

- Additional issues
  - 20 to 65 MW (depending on utility) wind power generation on system needed to incorporate into scheduling/dispatching operations
  - concerns about system reliability and variability with significant wind penetration
  - skepticism about the reliability of any meteorological forecast

Results of Forecasting Interviews

- Concepts with general consensus
  - Confidence level for wind forecasts could be useful
  - Schedulers would be very conservative when faced with a large forecast uncertainty
  - Same day forecasts would be most valuable if:
    - » extremely accurate
    - » reliably predict significant changes in available wind power

Towards wind forecasts at hub height

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senior meteorologist
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Introduction

$P \propto U^3$

and

P dependent on U_{ci}, U_{rated}, U_{co} (*cf. Verheij et al.*)

→ precision requirement higher than in normal wind forecast

U needed at hub height and at wind turbine site, but

→ normal forecasting procedures yield 'regional' wind or 'station' wind at 10m

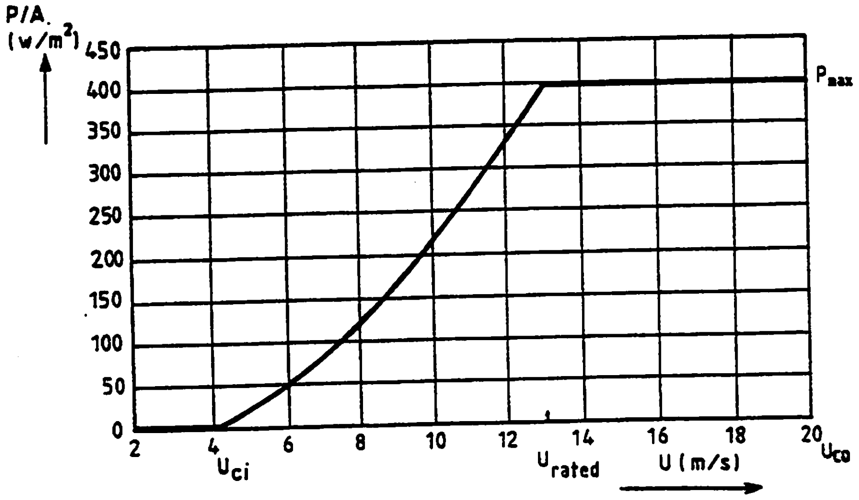
Current sources of wind forecasts

Some examples of operational wind forecast products

What do we need for wind (energy) forecasting?

Some meteorological remarks

Suggestion for future developments



Figuur 7.2 Voorbeeld van een theoretische vermogenskarakteristiek.

Current sources of wind forecasts

- direct model output (DMO), *cf. fig. 1*

grid point output of
  wind at 10m (or e.g. wind at 1000 hPa)
    global model
      coarse mesh (50-100 km), smoothed topography
      medium range to long range forecasts (HH +48 till +144/240)
    regional/mesoscale model
      fine mesh (10-50 km), increased resolution of small scale wind extremes and increased resolution of topography (sea, land, mountains)
      short range forecasts (HH +1 till +36/48)

- model output statistics (MOS), *cf. fig. 2*

station output of
  wind at 10m
  prob. of wind (gusts) exceeding threshold values
  error statistics

- man/machine methods

nowcasting, based on near real-time analysis of observations
  (surface -> geostrophic/gradient wind, upper air, radar & satellite information), HH +1 till HH +6
local forecasts (interpolation, local database)
ensemble techniques,
  based on 1 model, *cf. fig. 3*,
  or based on several models
severe weather warning?

Some examples of operational wind forecast products

MOS wind forecasts *(fig. 4)*

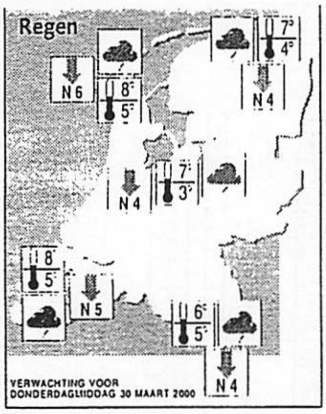
general wind forecasts (news papers, TV)
45° wind direction, wind speed in Bft

regional wind forecasts (road weather, agro meteorology)
10° wind direction, 10m winds in m/s, gusts

special projects (construction)
10-22,5° wind direction, 10/50m winds in m/s (neutral stability), gusts

marine forecasts (North Sea)
10-22,5° wind direction, 10/50m winds in kts (neutral stability)

verification results of MOS wind forecasts (March 2000, quite changeable, winds observed 0-20 m/s), *table 1*



VERWACHTING VOOR DONDERDAGMIDDAG 30 MAART 2000

Regio: Schakel

De lente is vaak een seizoen met twee gezichten net als de herfst. Beide vormen de schakel tussen winter en zomer en andersom. Het weer kan daarom van week tot week erg wisselen. Vorige week bijvoorbeeld werd het met ruggesteun van veel zon plaatselijk 18 graden, terwijl deze week het kwik serieus moet inleveren en gisteren bijvoorbeeld niet boven 5 graden klom. Voorlopig zit er geen ommekeer naar heerlijk lenteweer in de weerkaarten. Integendeel, een complex lagedrukgebied nabij de Alpen houdt een groot deel van Europa, inclusief Nederland in de tang. Bewolking domineert derhalve met van tijd tot tijd wat lichte regen of motregen. Het wordt wel geleidelijk droger in de loop van de avond en nacht. Het kwik fluctueert niet veel en 's nachts daalt het niet onder de 4 graden. De matige tot vrij krachtige noordoostenwind is nog altijd van de partij en maakt het voor het gevoel nog een stuk kouder. Morgen passeert een lagedrukgebied oost van onze regio. Dat betekent dat het bewolkt blijft en er perioden met regen zijn. Het wordt opnieuw een waterkoude dag met temperaturen van om en bij de 7 graden bij een nog altijd stevige wind die geleidelijk naar het noorden draait. In de nacht van donderdag op vrijdag blijven de wolkenvelden in de meerderheid en kan er nog wat regen vallen. Vrijdag wordt het droger van het westen uit en zijn er zelfs enkele opklaringen bij circa 8 graden. Het weekeinde is meest droog bij iets hogere temperaturen van 10 tot 12 graden.

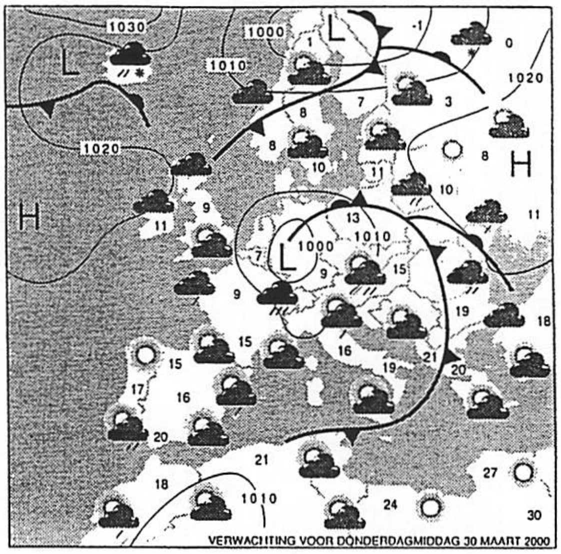
PLAATS	WEER-TYPE	WIND m/sec	TEMP min	TEMP 12 uur	NEER SLAG
Amsterdam	zwaar bew	nno 8	4	4	0.0
De Bilt	zwaar bew	nno 5	3	4	0.1
Deelen	motregen	nno 6	2	4	0.0
Lelystad	zwaar bew	nno 6	4	4	0.0
Maastricht	zwaar bew	nno 6	3	4	0.0
Rotterdam	motregen	nno 6	2	5	0.0
Terschelling	zwaar bew	nno 12	4	4	0.1
Twente	regen	nno 6	2	3	0.5
Vlissingen	zwaar bew	nno 7	3	6	0.0
Alicante	zwaar bew	zzw 1	13	12	0.9
Athene	zwaar bew	zzw 3	10	18	0.0
Barcelona	zwaar bew	w 2	8	11	3.0
Berlijn	regen	n 2	3	6	2.0
Bordeaux	half bew	n 5	4	9	0.0
Brussel	zwaar bew	n 6	3	5	0.0
Edinburgh	zwaar bew	ono 3	2	8	0.0
Faro	zwaar bew	wnw 5	11	18	0.0
Frankfurt	zwaar bew	no 5	3	6	0.0
Genève	zwaar bew	ono 5	0	6	0.0
Hamburg	zwaar bew	no 7	2	4	0.4
Helsinki	onbewolkt	wnw 1	-9	4	0.0
Heraklion	zwaar bew	no 4	15	18	0.0
Innsbruck	licht bew	o 3	2	9	0.0
Istanbul	onbewolkt	zw 5	10	17	0.0
Kopenhagen	zwaar bew	no 7	-1	4	2.0
Las Palmas	zwaar bew	no 11	17	20	0.0
Locarno	regenbui	wnw 3	5	11	0.0
Londen	zwaar bew	nno 6	4	7	0.0
Luxemburg	zwaar bew	no 4	4	5	0.0
Lyon	zwaar bew	no 2	2	6	0.0
Mallorca	regen	no 6	11	11	0.0
Málaga	licht bew	nw 10	12	19	0.0
Milaan	zwaar bew	zo 4	4	10	0.0
Moskou	licht bew	no 2	-7	2	0.0
München	zwaar bew	var 0	3	5	3.0
Nice	zwaar bew	wnw 2	8	9	2.0
Oslo	onbewolkt	var 0	-8	3	0.0
Parijs	zwaar bew	nno 6	5	6	0.0
Praag	zwaar bew	n 4	2	4	0.3
Rome	zwaar bew	zo 6	10	16	5.0
Stockholm	onbewolkt	o 4	-6	2	0.0
Toulouse	zwaar bew	nnw 3	3	9	0.0
Wenen	zwaar bew	wnw 7	6	10	2.0
Bangkok	zwaar bew	z 3	27	30	0.0
Casablanca	half bew	ono 2	10	17	0.0
Chicago	zwaar bew	nw 6	1	1	1.0
San Francisco	half bew	w 5	8	8	0.0
Jakarta	zwaar bew	nno 4	24	27	1.0
Johannesburg	zwaar bew	nnw 4	14	19	1.0
Los Angeles	zwaar bew	nw 3	13	13	0.0
Melbourne	licht bew	nw 4	12	12	0.0
Miami	half bew	w 3	18	19	0.0
Montreal	regen	nno 7	6	7	3.0
Nairobi	zwaar bew	ono 9	15	28	2.0
Nassau	zwaar bew	zzw 7	20	23	0.0
New York	zwaar bew	w 5	12	12	0.0
Peking	onbewolkt	n 4	9	13	0.0
Tel Aviv	half bew	wnw 7	13	21	0.0
Tokyo	regenbui	zo 3	8	13	16.0
Vancouver	zwaar bew	w 7	7	7	0.4

Europa: Regentol

Boven het midden en westen van Europa bevindt zich hoog in de atmosfeer een bel met koude lucht die al dagenlang een beetje ligt rond te tollen. Aan de grond heeft zich op die plaats een lagedrukgebied gevormd dat gevuld is met allerlei regen- en buiengebieden. Het is dan ook nauwelijks een verrassing dat in de Benelux, Frankrijk, de Alpenlanden, delen van Polen en Duitsland de lente op dit moment ver te zoeken is. De bewolking voert er nagenoeg overal de boventoon, vooral in het noordoosten van Frankrijk en in Zwitserland valt veel neerslag en het is met temperaturen dichter bij 5 dan bij 10 graden koud. Boven 1000 meter valt vooral in de Zwitserse Alpen opnieuw veel sneeuw op de toch al indrukwekkende laag die zich de laatste weken heeft opgebouwd. Het betere weer bevindt zich in de gebieden rondom het Centraal-Europese laag. Zo krijgt vooral Spanje de zon uitbundig te zien. In het zuiden wordt het daarbij ruim 20 graden. Naast zon is er in het zuiden van Portugal ook kans op een enkele bui, vooral in de tweede helft van middag. In Italië blijft het op een enkele bui in het uiterste noorden na droog. Er zijn flinke perioden met zon en de temperaturen schommelen op de meeste plaatsen tussen 15 en 20 graden.

Legenda kaart Europa

L Lagedrukgebied	Koufront
H Hogedrukgebied	Warmtefront
1030 Isobar	Samengesteld front



VERWACHTING VOOR DONDERDAGMIDDAG 30 MAART 2000

	donderdag	vrijdag	zaterdag	zondag	maandag
weer	🌧	🌧	🌦	⛅	☁
max.	7°	9°	10°	11°	12°
min.	3°	5°	3°	3°	4°
wind	N 4	W 3	W 3	ZW 3	ZW 4

☀
op: 7.16 uur
onder: 20.08 uur

◑
op: 5.18 uur
onder: 13.59 uur

Achtergrond:

Noodweer Italië

De Noord-Italiaanse havenstad Genua is in de nacht van zaterdag op zondag getroffen door een spectaculair noodweer. Tijdens de passage van een koufront deed een buiengebied de stad aan dat in minder dan twee uur tijd zo'n 150 millimeter neerslag achterliet, een absoluut record voor de regio. Een groot deel van die neerslag kwam omlaag als fijne hagel.
Omdat bovendien veel water door de straten stroomde en er veel wind was, werd de hagel plaatselijk tot een laag van een halve meter opgestuwd.
Auto's en huizen raakten hierbij soms flink beschadigd.
Sneeuwploegen moesten er aan te pas komen om delen van de stad en bij voorbeeld de grote wegen richting Middellandse Zee weer vrij te maken.
Daarbij werd een groot aantal vrijwilligers ingezet om de klus zo snel mogelijk te klaren. Hulp was ook hard nodig in het grootste ziekenhuis van de stad, San Martino. Het noodweer veroorzaakte er onder meer in de Intensive Care afdeling enkele malen kortsluiting. In het ziekenhuis moesten zo'n 200 patiënten tijdelijk verplaatst worden. Het slechte weer werd veroorzaakt door een koufront dat Italië van west naar oost passeerde.
In het front, dat op grote hoogte erg koude lucht bij zich had, ontwikkelde zich boven het warme water van de Middellandse Zee een aparte storing die met veel geweld over het noorden van Italië trok. Het slechte weer in de regio is overigens nog niet voorbij. Een groot deel van de week wordt er veel neerslag verwacht. Vooral hogerop in de bergen valt zelfs een dikke laag verse sneeuw. Verder is het er relatief koud.

```
Aan                 : Meteo Consult
T.a.v.              : wegbeheerder
Betreft             : weerbericht t.b.v. gladheidsbewaking
Regio               : Noord-Holland Noord
Opgesteld           : woensdag 29 maart 2000   10.36 uur


--------------- A. REGIONALE KORTE TERMIJN VERWACHTING --------------------

dag      temperatuur  vochtigheid       wind        bewolking    neerslag
uur     150 cm   weg  dauwpt  rel richting snelheid    in      kans hoev vorm
         in graden    graden   %           10 m Bft achtsten    %    mm
------  -----  -----  ----------- -------- -------- --------  -------------
Wo 10u    5.3    6.9    3.4    88    ono          5      8      10  0.0    -*
Wo 11u    5.7    8.2    3.5    86    ono          5      8      10  0.0    -
Wo 12u    6.1    9.5    3.6    84    ono          5      8      10  0.0    -
Wo 13u    6.5   10.6    3.7    82     no          5      7       5  0.0    -
Wo 14u    6.7   11.2    3.8    82     no          5      7       5  0.0    -
Wo 15u    6.9   11.7    3.9    81     no        5-6      6       5  0.0    -
Wo 16u    6.9   11.9    4.0    82     no        5-6      6       5  0.0    -
Wo 17u    6.3   10.9    3.9    85     no        5-6      6       5  0.0    -
Wo 18u    5.8    9.7    3.7    86     no        5-6      6       5  0.0    -
Wo 19u    5.5    8.4    3.6    88     no        5-6      6       5  0.0    -
Wo 20u    5.3    7.1    3.4    88    nno        5-6      6       5  0.0    -
Wo 21u    5.2    6.4    3.3    88    nno        5-6      6       5  0.0    -
Wo 22u    5.1    5.9    3.1    87    nno        5-6      6       5  0.0    -
Wo 23u    5.0    5.5    3.0    87    nno        5-6      6       5  0.0    -
Do 00u    5.0    5.3    3.0    87    nno        5-6      6       5  0.0    -
Do 01u    5.0    5.1    3.0    87    nno        5-6      6       5  0.0    -
Do 02u    5.0    5.0    3.0    87    nno        5-6      6       5  0.0    -
Do 03u    5.0    4.9    3.0    87    nno        5-6      6       5  0.0    -
Do 04u    5.0    4.8    3.0    87    nno        5-6      6       5  0.0    -
Do 05u    5.0    4.7    3.0    87    nno        5-6      6       5  0.0    -
Do 06u    5.0    4.7    3.0    87    nno        5-6      6       5  0.0    -
Do 07u    5.0    5.0    3.0    87      n        5-6      6       5  0.0    -
Do 08u    5.0    5.1    3.0    87      n        5-6      6       5  0.0    -
Do 09u    5.6    6.6    3.3    85      n        5-6      6       5  0.0    -
Do 10u    6.1    8.2    3.5    83      n        5-6      6      10  0.0    -
------  -----  -----  ----------- -------- -------- --------  -------------
* MO = motregen   RE = regen   RB = regenbuien  SN = sneeuw  SB = sneeuwbuien
  HA = hagel      MI = mist    YZ = ijzel
```

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-page 1/1-

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T.a.v.	: HCB Barendrecht / Peter Kortekaas / Piet Sinke
Telefax	: 0180623082
Van	: Meteo Consult, Wageningen
Betreft	: Windverwachting Oude Maas/Nieuwe Waterweg
Opgesteld	: Donderdag 9 December 1999 13.53 uur

KORTE TERMIJN

dag	uur	windsnelheid Bft 10m	m/s 10m	km/u 10m	Bft 50m	m/s 50m	km/u 50m	max. stoot m/s	windrichting
Do 9/12	10u	5	9	32	6	12	44	13	zw
Do 9/12	13u	5-6	11	39	7	15	55	16	zw
Do 9/12	16u	5-6	11	39	7	15	54	17	zw
Do 9/12	19u	5-6	11	38	7	15	54	18	zw
Do 9/12	22u	5-6	11	38	7	15	53	18	zzw
Vr 10/12	1u	5	10	37	6-7	14	51	16	zzw
Vr 10/12	4u	5	10	35	6-7	14	49	15	zw
Vr 10/12	7u	5	9	34	6	13	47	14	zw
Vr 10/12	10u	5	9	32	6	13	45	14	zw
Vr 10/12	13u	4-5	8	30	6	12	42	13	wzw
Vr 10/12	16u	4-5	7	27	5-6	10	37	11	w

Speciaal voor deze locatie:

Max. do: 8 graden	Zicht do: 20-30 km
Min. do/vr: 6 graden	zicht do/vr: 5-15 km
Max. vr: 8 graden	zicht vr: 10-20 km

LANGE TERMIJN

dag	windsnelheid Bft 10m	m/s 10m	km/u 10m	Bft 50m	m/s 50m	km/u 50m	windrichting
Za 11/12	4	7	25	5	10	34	zzw
Zo 12/12	5	9	33	6	13	46	wzw
Ma 13/12	4	7	25	5	10	34	wnw
Di 14/12	3	5	19	4-5	7	27	wzw

Met vriendelijke groeten,
Phil van Haren

To :
Attn : [illegible]
Fax : 070-3424700 (PGA)
cc : 072-5406857
Subj. : Cluster offshore weather forecast
Info. : Duty forecaster at +31-(0)317-423300
Issued: Wednesday, 29-MAR-2000 06:00 UTC

SYNOPSIS:
03 UTC - High (1029 hPa) centered over Scotland retrieving westward. Low (1000 hPa) over southern Germany slowly moving north the coming 24 hours. Weak frontal system is lingering over the southerly North Sea.
A strong NE-ly wind slightly increasing to strong to near gale, force 6 to 7 during this morning. Until Thursday morning no significant changes are expected. Occasional rain. Moderate to good visibility.

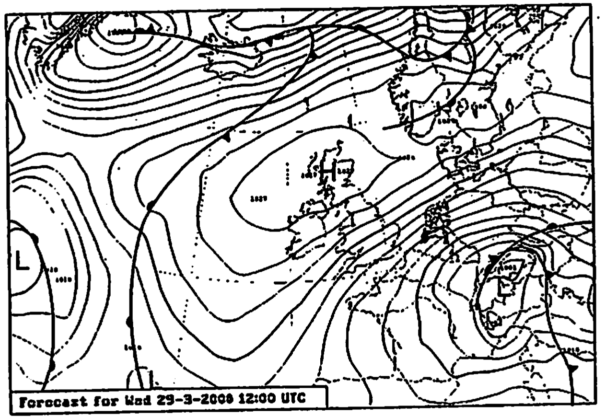
GALE WARNINGS (next 24 hours):
None.

LOCATION: BLOCKS-P&Q POSITION: 52.3 N. 4.0 E

Time utc	Wind/Gusts at 10m Kn	at 50m Kn	Wave height sign. / max. m / m	Sea height per. m s	Swell height per. m s	Temp C	Vis. n.m.
We 12	NE 27/35	32/38	2.2 / 3.7	NE 2.2 6	//	7	3-5
We 18	NE 29/38	35/42	2.5 / 4.2	NE 2.5 6	//	8	3-5
Th 00	NE 28/36	34/41	2.5 / 4.2	NE 2.5 6	//	8	3-5
Th 06	NNE 26/34	31/37	2.2 / 3.7	NNE 2.2 6	//	7	3-5
Th 12	NNE 22-26/31	26-31/35	2.0 / 3.5	NNE 2.0 6	//	7	3-5
Fr 00	N 16-20/23	19-24/26	2.0 / 2.5	N 1.5 4	NNE 1.0 5	7	5+
Fr 12	WNW 11-17/19	13-20/20	1.5 / 2.5	WNW 1.5 4	NNE 0.5 5	7	5+
Sa 12	WSW 9-15/17	11-18/17	1.0 / 1.5	WSW 1.0 3	//	8	5+
Su 12	S 8-16/18	10-19/18	1.0 / 1.5	S 1.0 3	//	8	5+

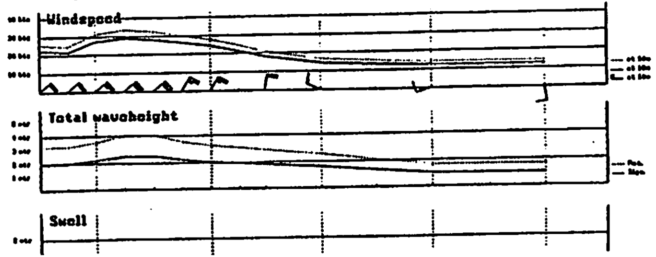
FURTHER OUTLOOK:
Thursday wind will gradually back to northerly direction during the day, decreasing to fresh, force 5. High is moving away to the Atlantic and low is moving towards Scandinavia. Occasional drizzle. Friday at the westflank of the low a gentle to moderate wind, force 3 to 4, backing to NW is expected over the forecast area.
Towards the end of the forecast period shallow low pressure will be situated over the North Sea area giving relative calm conditions with a gentle to moderate wind from varying directions.

Regards, Hans Kleingeld



Forecast for Wed 29-3-2000 12:00 UTC

Graphforecast for BLOCKS-P&Q (position: 52.30 N 4.00 E)



What do we need for wind (energy) forecasting?

agreement on the time scale, accuracy and type of wind forecasting:

- HH + 1 (site, semi real time wind energy)?
- HH +1 till HH +24 (site, regional; 24h wind energy production)?
- risk analysis and severe weather warning (thunder, icing, gusts)?
- HH +24 till HH +144/240 (regional average of long term wind energy production)?
- forecast of wind energy production relative to climatological forecast of wind energy production at a specific site?

general accepted method for objective automatic transformation of wind forecast (DMO, MOS, manual) to hub height including stability, topography and roughness (season!) corrections;
two possibilities:

- downward transformation of geostrophic (better: gradient) or model (950 hPa?, 100m level?) wind speed
- upward transformation from surface (model: 10m level?) wind with '1/7 power law'
  (but: 1/7 in fact dependent on z_0 and hub height!, *cf. Wieringa p 54 formula 3.10*)
  or logarithmic formula
  agreement necessary about the choice of z_0 (cf. Wind Atlas with 4 categories and 'Davenport revised' with 8 categories *cf. Wieringa 1992*)

- two sources of wind forecast data are possible:
  - use of gridded wind forecasts (based on DMO output)
    accuracy depending on model resolution (horizontal, vertical) and boundary layer model physics
  - use of station based forecasts (MOS, manual)
    accurate for the station itself, but perhaps not for its surrounding

- method of downscaling of model forecasts and/or interpolation of MOS/manual forecasts to wind turbine site

Table 4.
Davenport roughness classification (revised).

z_0 (m)	Landscape description
1: 0.0002 "Sea"	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2: 0.005 "Smooth"	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, morass, and snow-covered or fallow open country.
3: 0.03 "Open"	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4: 0.10 "Roughly open"	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g. low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5: 0.25 "Rough"	Recently-developed "young" landscape with high crops or crops of varying height, and scattered obstacles (e.g. dense shelterbelts, vineyards) at relative distances of about 15 obstacle heights.
6: 0.5 "Very rough"	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces, such as bushland, orchards, young densely-planted forest.
7: 1.0 "Closed"	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g. mature regular forests, homogeneous cities or villages.
8: ≥ 2 "Chaotic"	Centres of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

(Wieringa, 1992)

Some meteorological remarks

- a good forecast of thermally induced local wind regimes (e.g. sea breeze) is not very important because of low wind speeds (less than 5 m/s in general, *cf. Tijm* and *cf. Coelingh et al.*); exception: mountain/valley winds

- forecasts of other mesoscale events may be necessary for short term power management (coastal front *cf. Van den Berg p 8*, squall line)

- in stead of only forecasting V it is also possible to forecast ρ V [(note that ρ = p/RT may change with -5 % (warm, low pressure) to +10% (cold, high pressure)]; without correction for p,T wind energy will be up to 5% overpredicted in summer and up to 10% underpredicted in winter

- in general no correction is needed to the gustiness of the wind (turbulence), but in cases with strong surface heating or rough terrain this may be necessary (*cf. European Wind Atlas p 98*)

- with moderate winds it may be important to include stability corrections in the forecast: in unstable conditions the wind increases slowly with height, in stable conditions the increase is steeper especially in the case of a nocturnal boundary layer with supergeostrophic winds at 100-150m (*cf. Wieringa et al. p 40-43*); with increasing hub heights it is important to include this in the forecast

- special attention is needed in cases with an internal boundary layer because of a upstream (<10 km) roughness/stability change (*cf. Verkaik*)

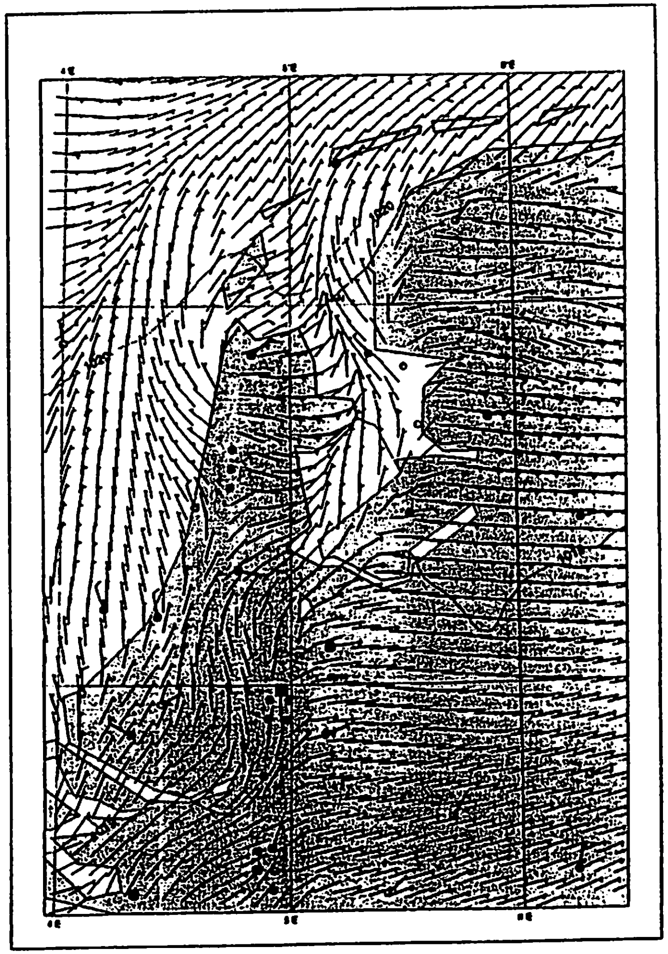


Figure 1.4: *Horizontal wind field and surface-pressure distribution over the Netherlands at 15 UTC on 29 July, 1995, as calculated with the doubly-nested version VHiRLAM with semi-lagrangian advection. The observations at 10 m height are shown also. The circles indicate model points with zero wind. The observed as well as the modelled 10m wind are plotted in the standard synoptic way. Cabauw lies at 51°58′N and 4°56′E indicated by a black square*

(Van den Berg, 1987)

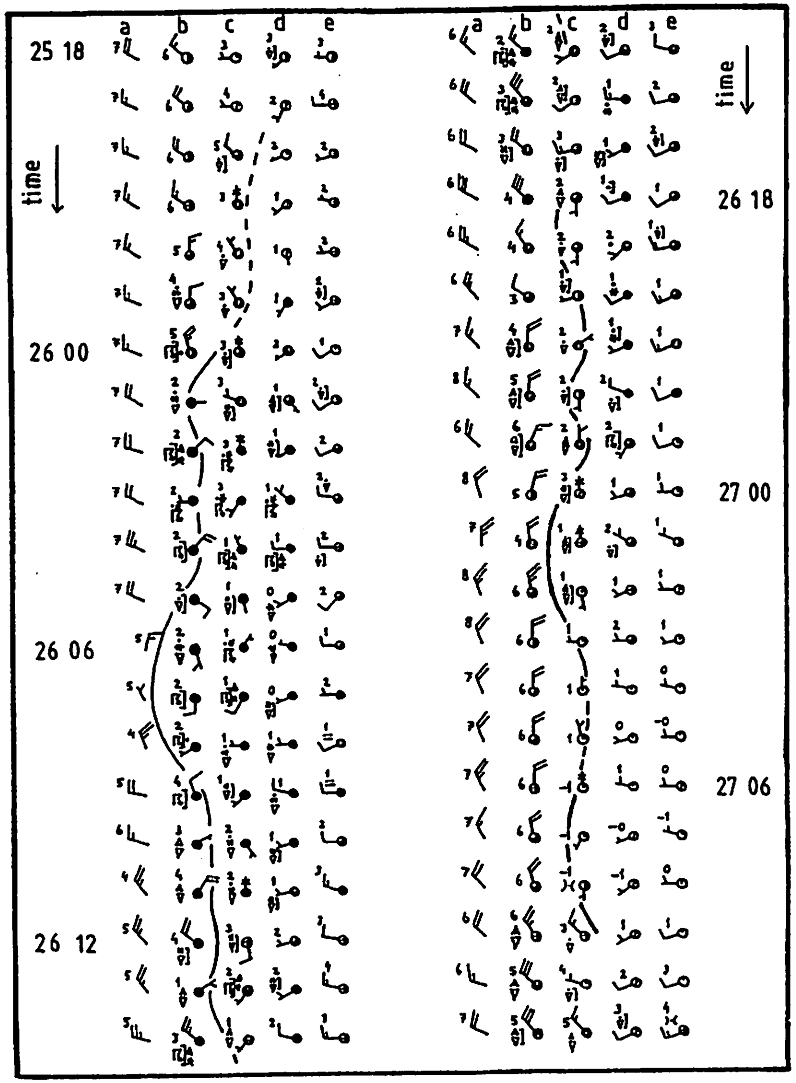
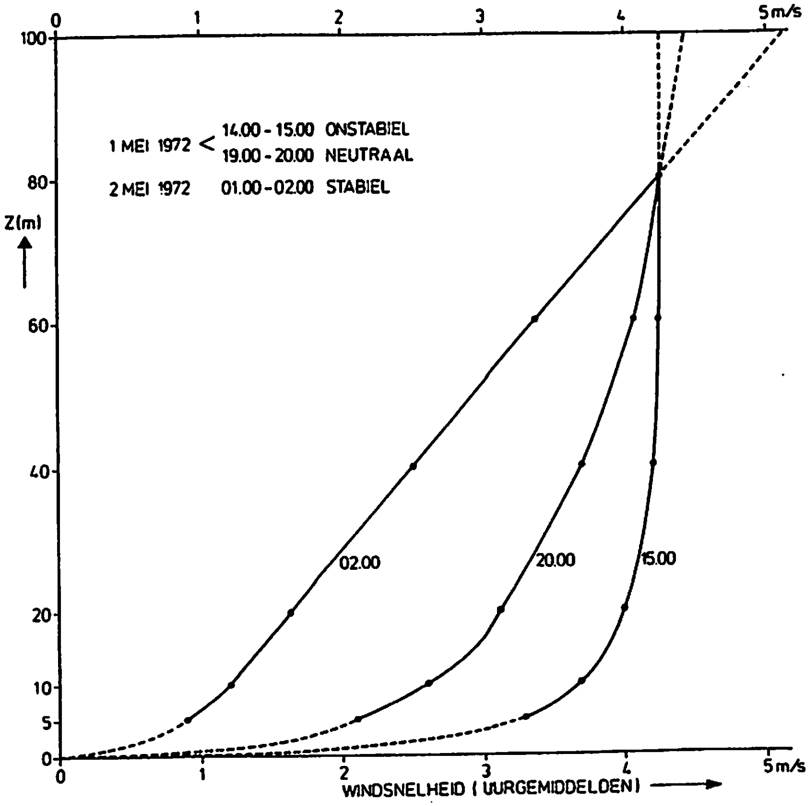


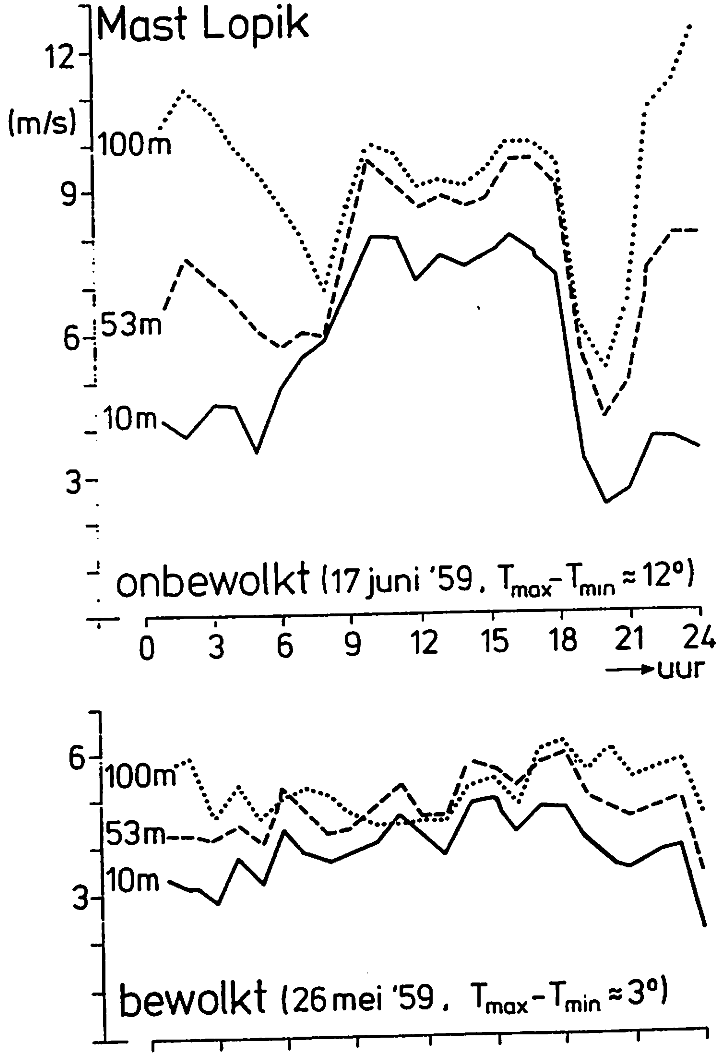
Fig. I-3: Time series of observed weather at 5 selected stations, 25-27 Nov. 1978. Position of the coastal front, based on hourly maps as fig. I-2, is sketched.
Stations :: a. Goeree (offshore), b. Hook of Holland (at the coast), c. Rotterdam airport (onshore), d. Gilze-Rijen (inland), e. Volkel (far inland).



Figuur 3.5 *Windsnelheidsprofielen te Vlaardingen in verschillende stabiliteitstoestanden van de oppervlaktelaag*

40

(Wieringa et al., 1983)



Figuur 3.6
Dagelijkse gang van de windsnelheid op enige niveaus in de oude TV-mast te Lopik

(Wieringa et al., 1983)

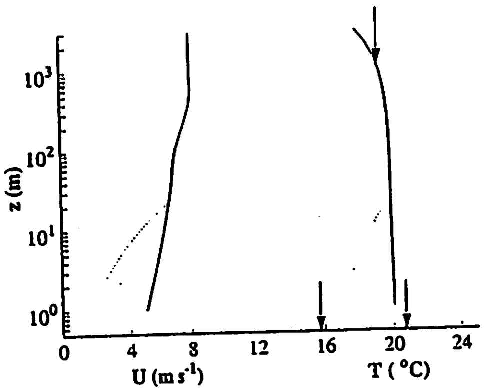


Figure 8: Modelprofielen van windsnelheid en temperatuur aan de kust (ononderbroken lijnen) en 1 km landinwaarts (onderbroken lijnen) op 11 augustus 1994, 21^{h}.

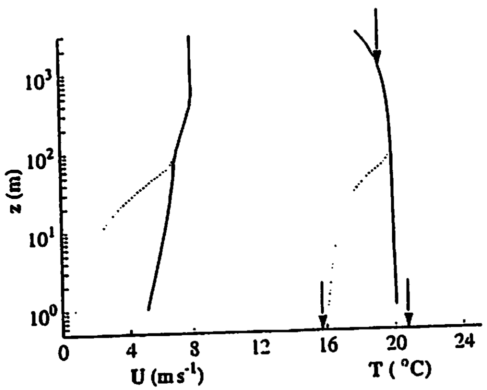


Figure 9: Modelprofielen van windsnelheid en temperatuur aan de kust (ononderbroken lijnen) en 42 km landinwaarts vóór de overgang naar het IJsselmeer (onderbroken lijnen) op 11 augustus 1994, 21^{h}.

(Verkaik, 1999)

Suggestion for future developments

- optimization of MOS forecasts to $U \approx U_{rated}$ (e.g. 10 m/s)
- forecasting (risk/duration) of periods with prolonged calm ($U < U_{ci}$) or gale ($U > U_{co}$) conditions; timing of U decreasing below U_{ci} and U increasing above U_{co} resp.
- development of direct MOS/DMO wind output at several (hub) heights
  possible approach: use of 'dry' high resolution (1 km mesh) boundary layer model (nowcasting only, HH +1 till HH +6) nested in mesoscale model
- development of MOS wind forecasts for the site itself based on >2 years of 'in situ' wind speed observations at hub height
- verification $U_f \leftrightarrow U_m$ or $P_f \leftrightarrow P_m$ (f = forecast, m = measured at the wind power site) in order to correct systematic errors in (model) forecast or derivation method or power curve

Literature

Coelingh, J.P., A.J.M. van Wijk and A.A.M. Holtslag, 1998: Analysis of wind speed observations on the North Sea coast, J. Wind Engin. Industr. Aerodyn. 73, p 125-144.

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Tijm, A.B.C., 1999: Sea-breeze studies, Ph.D. Thesis, University of Utrecht, The Netherlands.

Van den Berg, W.D., 1987: Coastal frontogenesis in the Netherlands, observations and modeling, Ph.D. Thesis, University of Utrecht, The Netherlands.

Verheij, F.J. and L. v.d. Snoek, 1989, Handboek Energie-opbrengsten van windturbines (in Dutch), MT-TNO, Apeldoorn, The Netherlands.

Verkaik, J., 1999: 1-D Model voor interne grenslagen voor water en land, preliminary paper (in Dutch), KNMI, De Bilt, The Netherlands; will be included in scientific report: V.N. Kudryavtsev, V.K. Makin, A.M.G. Klein Tank and J.W. Verkaik, 2000: A model of wind transformation over water-land surfaces, KNMI, De Bilt, The Netherlands.

Wieringa, J., 1992: Updating the Davenport roughness classification, J. Wind Engin. Industr. Aerodyn. 41 p 357-368.

Wieringa, J. and P.J. Rijkoort, 1983: Windklimaat van Nederland (in Dutch), Staatsuitgeverij, Den Haag, The Netherlands.

Figure captions

Fig. 1: Wind 'energy' forecast based on model output.

Upper panels UKMO forecast (high resolution at 10m), lower panels ECMWF forecast.
Wind direction: northeasterly.
Wind speed 10m (left): isolines {4,5,6} kts as indication of U_{ci}, isolines {10,15} as indication of moderate winds, isolines of 20 kts (solid) as indication of strong winds.
Geostrophic wind 1000 hPa (right): isoline of 20 kts as indication of low level U_{ci}, isolines of {30,40} kts (solid) as indication of low level strong winds.

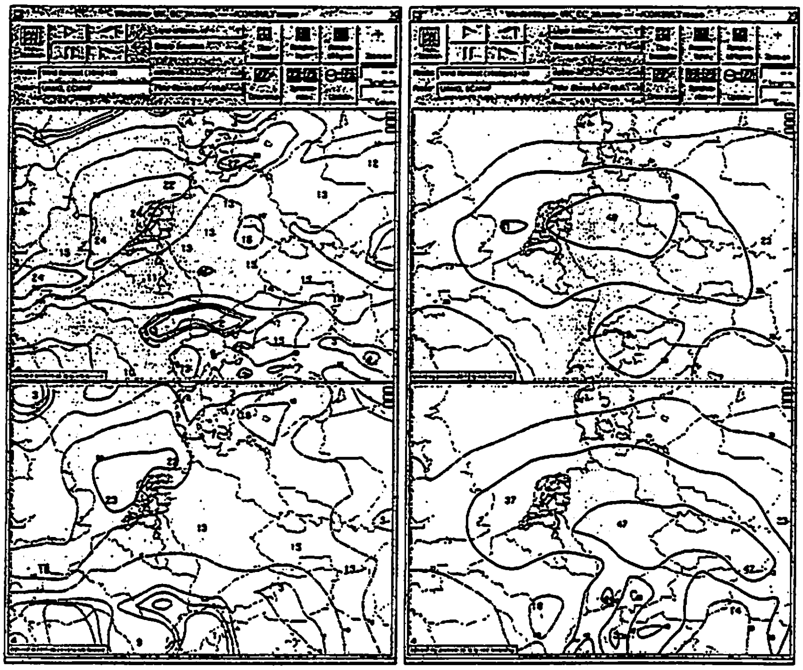
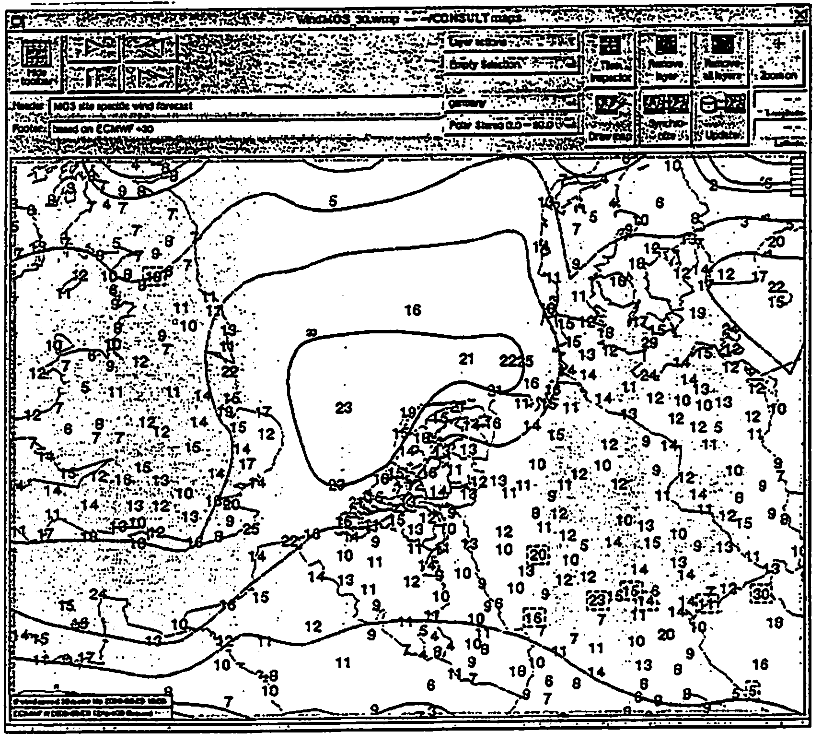


Fig.2: MOS wind forecast.

MOS forecasted wind speed (kts) at 10m at WMO stations compared with ECMWF 10m wind field. Isolines: see fig. 1.



WindMOS_30.wmp — ~/CONSULT maps

Header: MOS site specific wind forecast

Footer: based on ECMWF +30

germany

Polar Stereo 0.0 – 90.0

Fig. 3: Ensemble wind forecast for location Den Helder

Wind speed in m/s.
Operational forecast: ECMWF T_L319 (60km).
Control forecast and 50 Ensemble forecasts: ECMWF T_L159 (120 km).

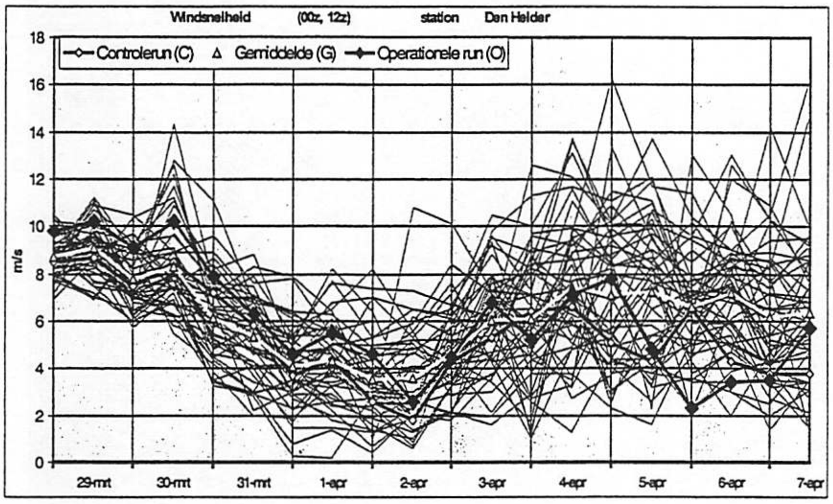
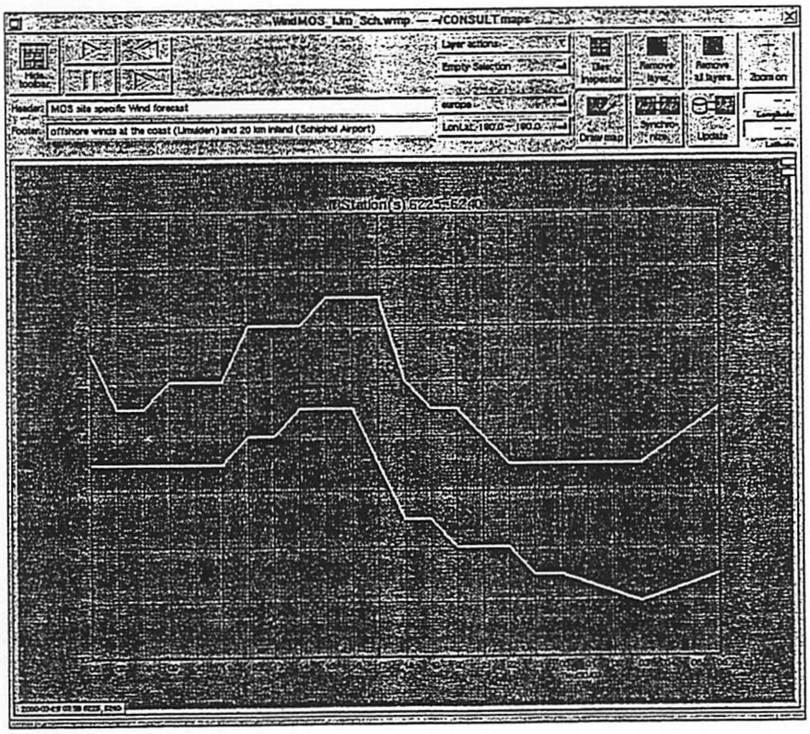


Fig. 4: MOS wind forecasts

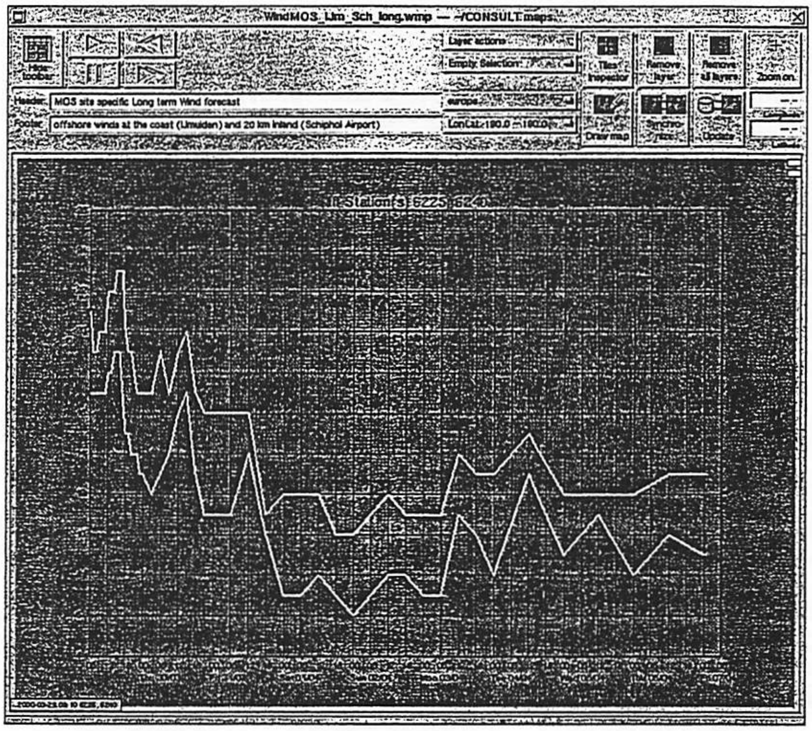
4a. Wind speed in kts.
24h-forecast for IJmuiden (1 km offshore) and Schiphol airport (20 km onshore).


WindMOS_IJm_Sch.wmp — ~/CONSULT maps

Header: MOS site specific Wind forecast

Footer: offshore winds at the coast (IJmuiden) and 20 km inland (Schiphol Airport)

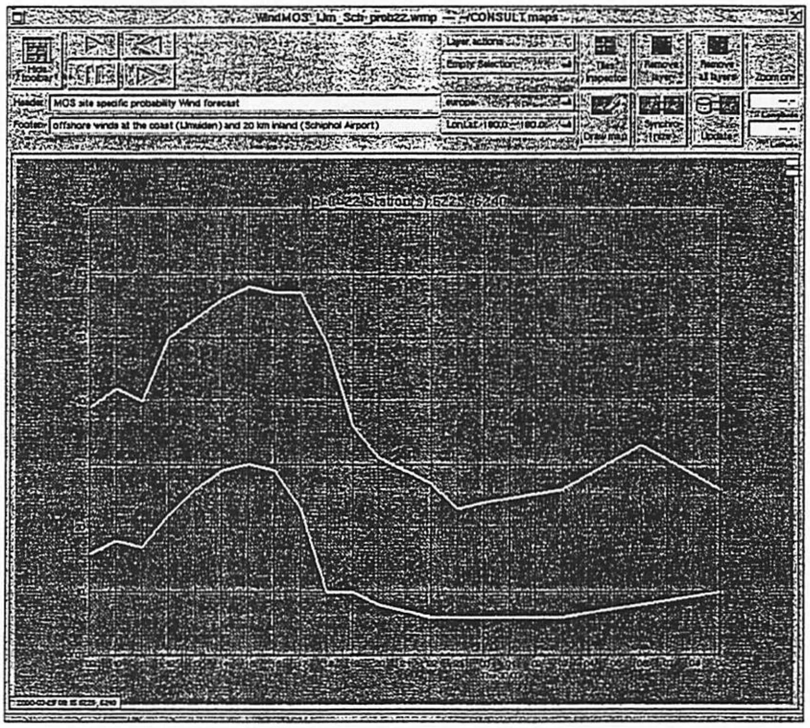
4c. Wind speed in kts.
Long term forecast for IJmuiden (1 km offshore) and Schiphol airport (20 km onshore).



Header: MOS site specific Long term Wind forecast

Footer: offshore winds at the coast (IJmuiden) and 20 km inland (Schiphol Airport)

4b. Probability forecast, P_ff>22 kts.
24h-forecast for IJmuiden (1 km offshore) and Schiphol airport (20 km onshore).



Header: MOS site specific probability Wind forecast

Footer: offshore winds at the coast (IJmuiden) and 20 km inland (Schiphol Airport)

Table 1: verification results of MOS wind forecasts.

Period: March 2000, 1-28
Element: wind at 12z and 00z (in kts)
Forecast Periods (FP) based on ECMWF 12z run.

	FP	+24	+36	+48	+60	+72	+84	+96	108	120	132	144	gem 24-72	gem 96-144
station	type of error													
K13 Alpa (100 km offshore)	ME	0	1	0	2	0	1	-1	1	0	2	0	0.6	0.4
	AE	*1*	2	2	3	3	3	4	4	5	5	5	2.2	4.6
	RMSE	2	3	2	4	3	4	6	5	6	6	6	2.8	5.8
Noordwijk (6 km offshore)	ME	0	0	-1	0	1	0	-1	0	-1	0	0	-0.2	-0.4
	AE	3	2	3	2	3	3	4	3	4	4	5	2.6	4.0
	RMSE	3	2	4	3	4	3	5	4	5	5	5	3.2	4.8
IJmuiden (1 km offshore)	ME	0	0	0	0	0	0	0	0	0	0	0	*0.0*	*0.0*
	AE	2	2	3	3	3	3	4	4	5	5	5	2.6	4.6
	RMSE	3	3	4	3	4	5	5	5	6	6	6	3.4	5.6
Valkenburg (2 km inland)	ME	1	0	1	-1	0	0	-1	-1	-1	0	0	0.2	-0.6
	AE	3	2	3	3	3	4	4	4	5	5	5	2.8	4.6
	RMSE	3	2	4	3	4	4	5	5	6	6	6	3.2	5.6
Soesterberg (50 km inland)	ME	1	-1	1	0	0	0	-1	-1	0	0	0	0.2	-0.4
	AE	2	2	2	2	2	3	3	3	3	4	4	*2.0*	*3.4*
	RMSE	3	2	3	2	2	3	4	3	4	4	4	*2.4*	*3.8*

Wind Energy Forecasting

Blueprint for a Pilot Tool

A.J. Brand

T. Hegberg
I.G. Kamphuis
E.R. van Selow

and others

ECN - Wind Energy
ECN - Energy Efficiency

P.O. Box 1
1755 ZG Petten
Netherlands

ECN

Overview

Scope

Test cases

Methodology

Conclusion

Scope (1)

Renewable energy forecasting

- Wind Energy Dpt
- Solar Energy Dpt
- Energy Efficiency Dpt
- Policy Studies Dpt

Central objectives

- To identify
  - Potential users
  - Specifications
  - Methods demonstrated
  - Predictability
- To design a wind energy forecasting method

Scope (2)

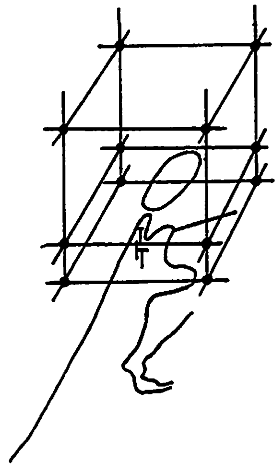
Main deliverables

- Report
- Prototype

Characteristics

- Funding:
  ECN - Basic Research (ENGINE Programme)
- Duration:
  01-I-2000 thru 31-XII-2000
- Capacity:
  ≈ 1600 hours
- Budget:
  ≈ kEURO 145

Test cases (1)



Test cases (2)

Production

- Wind farm, 16 x 80 kW, line
- On-shore, sea climate
- Relevant quantities:
  - Power production, hourly samples
  - Energy production, dayly cumulative

Test cases (3)

Meteorological

- Meteo station
- On-shore, sea climate
- Relevant quantities:
  - Wind speed
  - Wind direction
  - Pressure
  - Temperature

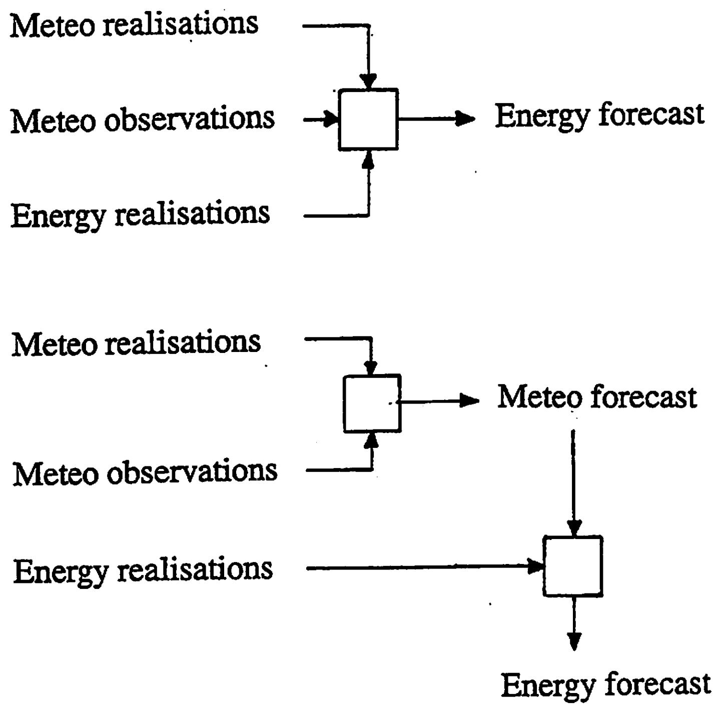
  Hourly, not average

Test cases (4)

Research questions (a.o.)

- Resolution:
  - Horizontal - 55 km, 22 km, 11 km, 5.5 km, ...?
  - Time increment versus time step?
- Realistic forecasting horizon - 48 h or 3 h?
- Approach - Physical, statistical, hybrid?
- Minimal requirement?

Methodology (1)


Meteo realisations

Meteo observations

Energy realisations

Energy forecast

Meteo realisations

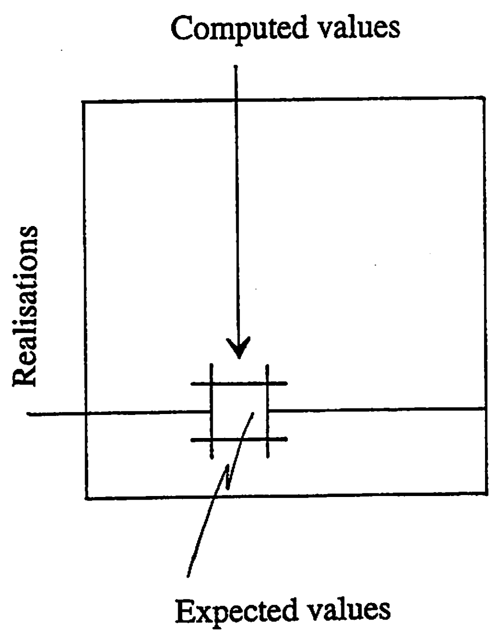
Meteo observations

Meteo forecast

Energy realisations

Energy forecast

Methodology (2)


Computed values

Realisations

Expected values

Methodology (3)

Input specifications

- Atmospheric model output
  - Raw
  - Post-processed
- Observations
  - Meteo variables
  - Energy production
- Any other

Methodology (4)

Output specifications

- Expected energy production
- Forecast in statistical terms, e.g.
  - Expected conditional average and st. deviation
  - Expected min and max given uncertainty level
- Disclaimer included

Methodology (5)

Box colour options

- Black: 100% statistical
- Grey: hybrid
- White: 100% physical

Box contents

- Top layer - White:
  - Meteorological sub-models
  - Auxiliary functions
- In between layer - Black:
  - Correlation methods
- Bottom layer - White:
  - Frequency distribution
  - Sectorwise power curve

Conclusion

- Validation and demonstration of wind energy forecasting prototype
- Design and development of wind energy forecasting method
- Study of need for renewable energy forecasting method

ECN

EPRI-DOE-NREL-CEC Wind Energy Forecasting Program

Chuck McGowin
EPRI, Palo Alto, CA

IEA Expert Meeting on Wind Forecasting
April 4-5, 2000, NWTC, Boulder, CO

EPRI-DOE-NREL-CEC Wind Energy Forecasting Program

- Program Objectives:
  - Develop and test wind energy forecasting systems at U.S. wind plants.
  - Evaluate systems for a range of site conditions, e.g. topography, wind resource, meteorology, wind turbine designs.
  - Transfer EU technology to the U.S.

EPRI-DOE-NREL-CEC Wind Energy Forecasting Program

- Program Scope:
  - Develop and test three systems in parallel (WSI, Risoe, and TWS)
  - Two projects underway:
    - 75 MW Southwest Mesa Wind Plant, McCamey, Texas
    - California Project: Four wind projects to be selected for testing.
  - Limited testing completed at Buffalo Ridge, MN

Texas Wind Energy Forecasting Project

- Southwest Mesa Wind Plant, McCamey, TX.
- 75 MW Nameplate
- 100 NEG-Micon 750 kW wind turbines
- Installed 1999
- Operator: FPL Energy
- Energy Customer:
  Central and South West Corporation

Texas Wind Energy Forecasting Project

Objective:

- Develop, operate, and evaluate and test a wind energy forecasting system at the 75 MW Southwest Mesa Wind Plant.

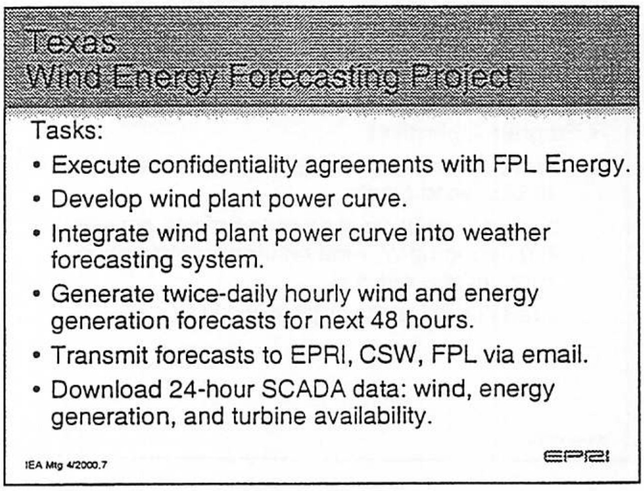
Scope:

- Two parallel systems to be developed and tested:
  - Weather Services International with assistance from Ron Nierenberg
  - Risoe National Laboratory.

Texas Wind Energy Forecasting Project

Scope (cont'd):

- Two-Phase Development:
  - Phase 1: Initial brief test.
  - Phase 2: One year test by WSI and Risoe.
- Funded by DOE and EPRI.

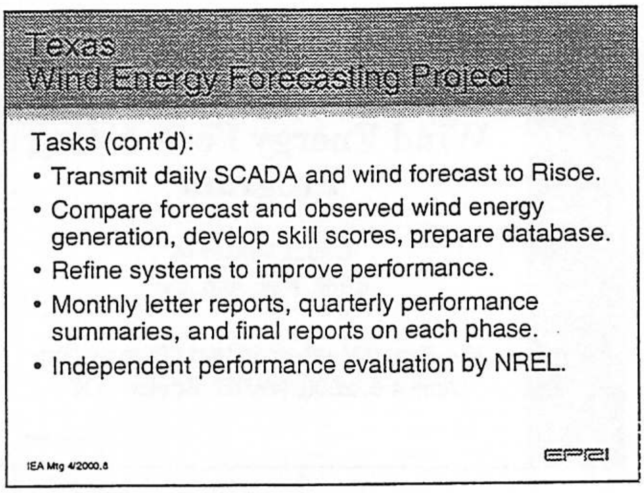


Texas Wind Energy Forecasting Project

Tasks:

- Execute confidentiality agreements with FPL Energy.
- Develop wind plant power curve.
- Integrate wind plant power curve into weather forecasting system.
- Generate twice-daily hourly wind and energy generation forecasts for next 48 hours.
- Transmit forecasts to EPRI, CSW, FPL via email.
- Download 24-hour SCADA data: wind, energy generation, and turbine availability.

IEA Mtg 4/2000.7 EPRI

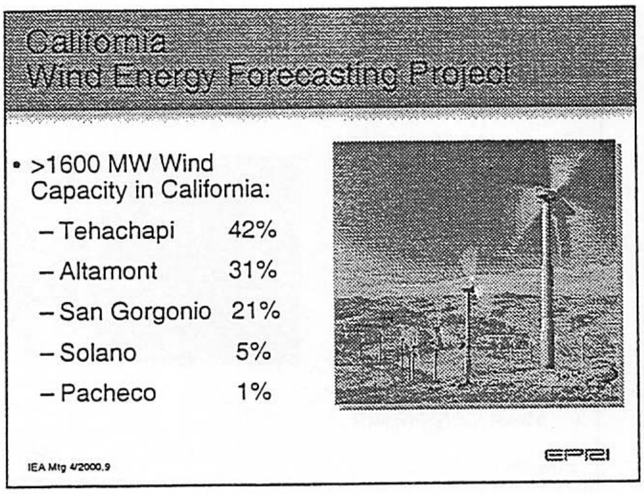


Texas Wind Energy Forecasting Project

Tasks (cont'd):

- Transmit daily SCADA and wind forecast to Risoe.
- Compare forecast and observed wind energy generation, develop skill scores, prepare database.
- Refine systems to improve performance.
- Monthly letter reports, quarterly performance summaries, and final reports on each phase.
- Independent performance evaluation by NREL.

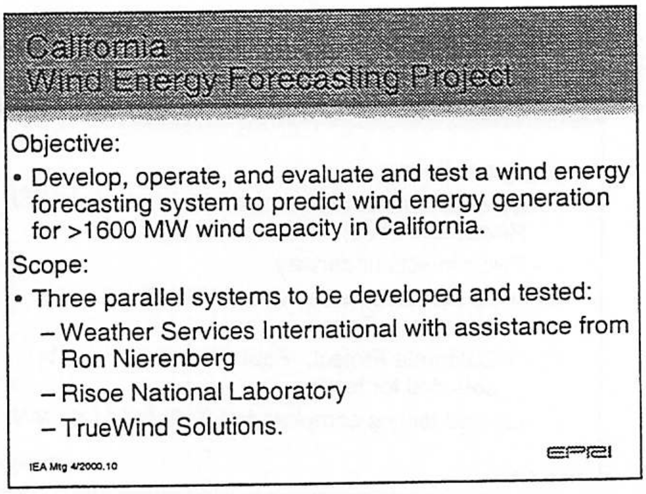
IEA Mtg 4/2000.8 EPRI



California Wind Energy Forecasting Project

- >1600 MW Wind Capacity in California:
  - Tehachapi 42%
  - Altamont 31%
  - San Gorgonio 21%
  - Solano 5%
  - Pacheco 1%

IEA Mtg 4/2000.9 EPRI



California Wind Energy Forecasting Project

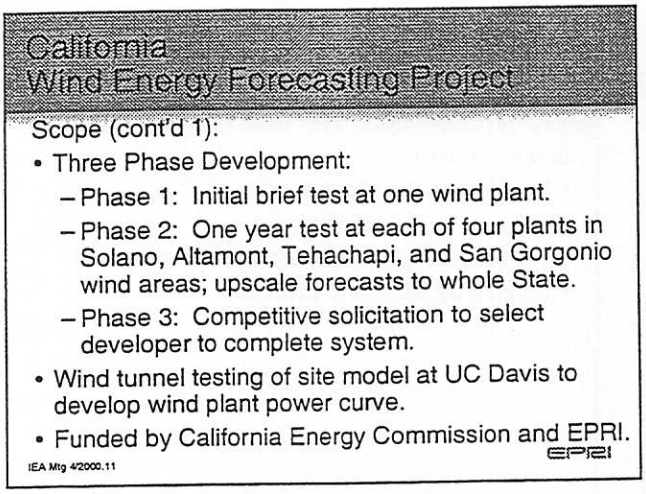
Objective:

- Develop, operate, and evaluate and test a wind energy forecasting system to predict wind energy generation for >1600 MW wind capacity in California.

Scope:

- Three parallel systems to be developed and tested:
  - Weather Services International with assistance from Ron Nierenberg
  - Risoe National Laboratory
  - TrueWind Solutions.

IEA Mtg 4/2000.10 EPRI

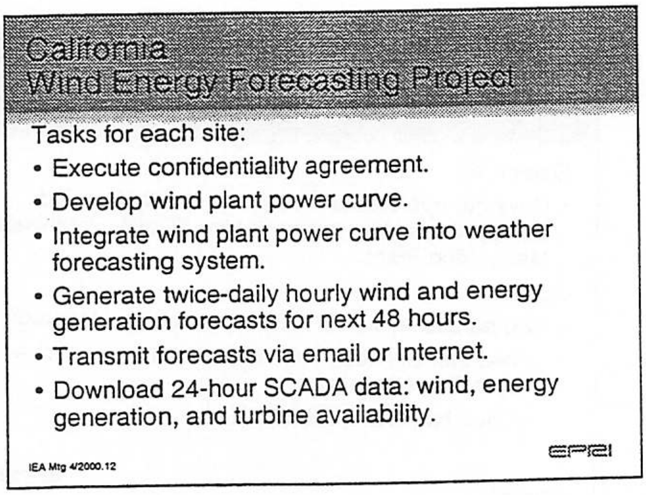


California Wind Energy Forecasting Project

Scope (cont'd 1):

- Three Phase Development:
  - Phase 1: Initial brief test at one wind plant.
  - Phase 2: One year test at each of four plants in Solano, Altamont, Tehachapi, and San Gorgonio wind areas; upscale forecasts to whole State.
  - Phase 3: Competitive solicitation to select developer to complete system.
- Wind tunnel testing of site model at UC Davis to develop wind plant power curve.
- Funded by California Energy Commission and EPRI.

IEA Mtg 4/2000.11 EPRI



California Wind Energy Forecasting Project

Tasks for each site:

- Execute confidentiality agreement.
- Develop wind plant power curve.
- Integrate wind plant power curve into weather forecasting system.
- Generate twice-daily hourly wind and energy generation forecasts for next 48 hours.
- Transmit forecasts via email or Internet.
- Download 24-hour SCADA data: wind, energy generation, and turbine availability.

IEA Mtg 4/2000.12 EPRI

California
Wind Energy Forecasting Project

Tasks for each site (cont'd):

- Transmit daily SCADA data to Risoe and TWS, wind forecast data to Risoe.
- Compare forecast and observed wind energy generation, develop skill scores, prepare database.
- Refine systems to improve performance.
- Monthly letter reports, quarterly performance summaries, and final reports on each phase.
- Independent performance evaluation by NREL.

IEA Mtg 4/2000.13

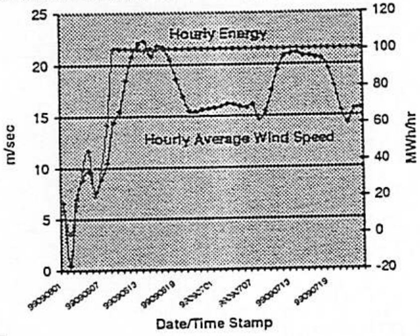
Buffalo Ridge
Wind Energy Forecasting Project

Additional Testing at Buffalo Ridge:

- Develop wind plant power curves for 25 MW LG&E and 107 MW Enron Lake Benton 1 wind plants (WECTEC).
- Generate four-times daily hourly wind and energy generation forecasts for next 48 hours (WSI).
- Transmit forecasts to EPRI and WECTEC by email.
- Compare forecast and observed data, calculate skill statistics.
- Three month test; continue if owners provide $.

IEA Mtg 4/2000.14

Wind Energy Forecast
Lake Benton 1, Sept. 6-7, 1999



IEA Mtg 4/2000.15

EPRI-DOE-NREL-CEC
Wind Energy Forecasting Program

- Status and Next Steps:
  - Texas Project:
    - Temporarily on hold pending resolution of funding
    - Expect to add True Wind Solutions to project team.
  - California Project:
    - Funding approved by CEC
    - Three of four host sites have been identified in Tehachapi and San Gorgonio areas
    - Will add sites in Altamont and Solano County later.

IEA Mtg 4/2000.16

SHORT TERM FORECASTING: APPLICATION OF A WIND SPEED FORECASTING METHODOLOGY FOR WIND ENERGY APPLICATIONS IN THE MIDWEST

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Martinez, California 94553
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Abstract

Wind energy forecasts provide estimates of the hourly energy generation by a wind energy facility at future time periods. This work describes the application of a wind energy forecasting methodology developed by Riso National Laboratories in the Midwestern U.S. Staff at Riso developed a model relating wind energy generation to topography, surface roughness, and turbine layout and to the predicted wind speed and wind direction at a nearby reference point. The wind predictions at time intervals out to 48 hours in the future are generated using data from numerical weather prediction models typically used for general weather forecasting. The Riso model is applied using data from two sites in Northwestern Iowa. Numerical weather prediction data for the test period are obtained from the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. Forecasts of wind speed at 6-hour intervals out to 48 hours in advance are generated twice daily for these two sites for a two-year period (1994-96). The model predictions were generally good, showing that 50 meter wind speeds could be predicted with a fair degree of accuracy using numerical weather prediction model data. The U.S. results are consistent with results of other applications of the model in Northern Europe and the Mediterranean Region.

Introduction

There is continuing interest in developing automated processes to forecast hourly estimates of wind energy production from wind energy facilities. NREL staff (Mulligan, 1995) authored a study demonstrating that wind speed forecasting and the ability to predict the output of renewable energy facilities would have real economic benefit to utilities. Some Department of Energy (DOE) research in wind speed forecasting occurred in the late 1970s and early 1980s when the MOD wind turbine research was underway. The initial wind forecasting studies funded by DOE and performed by Battelle and others used classical approaches. Standard objective forecasting techniques such as Model Output Statistics (MOS) and semi-objective forecasting techniques were applied in an attempt to see if wind, both speed and direction, could be accurately predicted in areas of known wind speed resources. More recent work on wind forecasting in the U.S was done by McCarthy (1997), Oregon State University (1999), EPRI (1999) and Meso, Inc. (2000).

Research on wind speed forecasting and, correspondingly, the forecast of electric energy output from a wind energy facility, is actively pursued in Europe. Staff at the Institute of Mathematical Modeling (IMM) at the Technical University of Denmark and ELSAM, a Danish Utility company, completed a three-year study on wind power prediction and dispatch of wind energy facilitates within ELSAM's service territory (Madsen, 1995). The model is a statistical one that provides predictions of total wind generated electricity for the ELSAM area for 0.5 to 36 hours ahead in half-hourly time steps.

Riso National Laboratory staff developed a physical power prediction model for wind plants and tested this model for facilities in Denmark, Germany, Great Britain, and Crete. This development and testing is part of a recently completed European Union (EU) funded program titled "Implementing Short-Term Prediction at Utilities". This model is applied to the two locations in the Midwestern U.S.

Forecasting Model

In order to prepare a wind energy forecast at specific times in the future, one must have a forecast of the wind speed and wind direction. Riso National Laboratory staff opted to assemble a model to predict the energy output of a wind farm. A complete description of the model is found in Landsberg (1997). The integration of numerical weather prediction information with a diagnosis of local effects and the specific characteristics of the wind turbine are the key features of the approach. The basic components of the model include:

- Predictions of wind speed and wind direction.
- A description of the site (orography, roughness, obstacles).
- A description of the wind turbine (hub height, power curve, thrust curve).
- A description of the wind plant.

Predictions of wind speed and wind direction are obtained from a numerical weather prediction model. These predictions are modified using the geostrophic drag law and the logarithmic wind profile to produce an estimate of the surface wind speed and wind direction. This estimate is then used in the Wind Atlas Analysis and Application program (WasP) to generate a local wind value. A program is then applied to simulate the wakes and array effects in the wind park itself for each individual turbine. The power production in the wind park is based on the calculated array efficiency for each sector. In addition, there are some local corrections applied to the predicted wind speed and wind direction and to the estimated power production. Thus, some historical knowledge of the wind park wind resource and the power performance of the wind park must be known before the model is developed.

Numerical weather prediction models use current conditions and past trends to predict the future behavior of the atmosphere. The numerical weather prediction data for the Riso forecasting model are obtained from one of a variety of models routinely operated by the national weather forecasting services in various countries. For example, here in the United States, the numerical weather prediction data could be obtained from the National Center for Environmental Prediction (NCEP), the military services, many universities and consortiums, and private meteorological concerns. The frequency of applying any model and the model forecast time steps vary. Typically, numerical weather prediction model forecasts are available twice daily with forecasts prepared for a period 48 hours in advance in time steps of six or twelve hours. There are a variety of models to choose from, and dependent on the model, differing forecast intervals. For example, the Rapid Update Cycle (RUC) model forecasts are available every six hours (four times each day) at three-hour intervals out to twelve hours. The Aviation Model (AVN) forecasts are available every twelve hours (twice daily) at twelve-hour intervals out to seventy-two hours in advance. Model descriptions are available at NCEP's WWW site (http:\\www.ncep.noaa.gov).

For the application of the model in the U.S., data from the Nested Grid Model (NGM), operated by NCEP, are obtained from NCAR. These data include the following:

- Height above ground of the 1000, 950, 850, and 700 millibar (mb) pressure levels;
- U-component and V-component of the wind at 10 meters above ground level and 950 mb, 850 mb, and 700 mb.
- Temperature at 1000, 950, 900, 850, 800, 750, and 700 mb.
- Relative humidity at 1000, 950, 900, 850, 800, 750, and 700 mb.
- Sea level pressure.

The pressure levels, 1000, 950, 900, 850, 800, 750, and 700 mb, basically refer to atmospheric conditions measured at horizontal layers above the surface of the ground. The greater the value, the closer to the surface of the earth. For example, the 850 mb pressure level is nominally 1,500 meters above ground level and the 700 mb level is 3,000 meters above ground level. The NGM is one of the older numerical weather prediction models and it uses a fairly coarse grid spacing, which is depicted in Figure 1. At 40 degrees north latitude, the distance between grid points is 153 kilometers. The advent of more computationally powerful computers allows more recent weather prediction models to have much smaller grid spacing, on the order of 50 km or less.

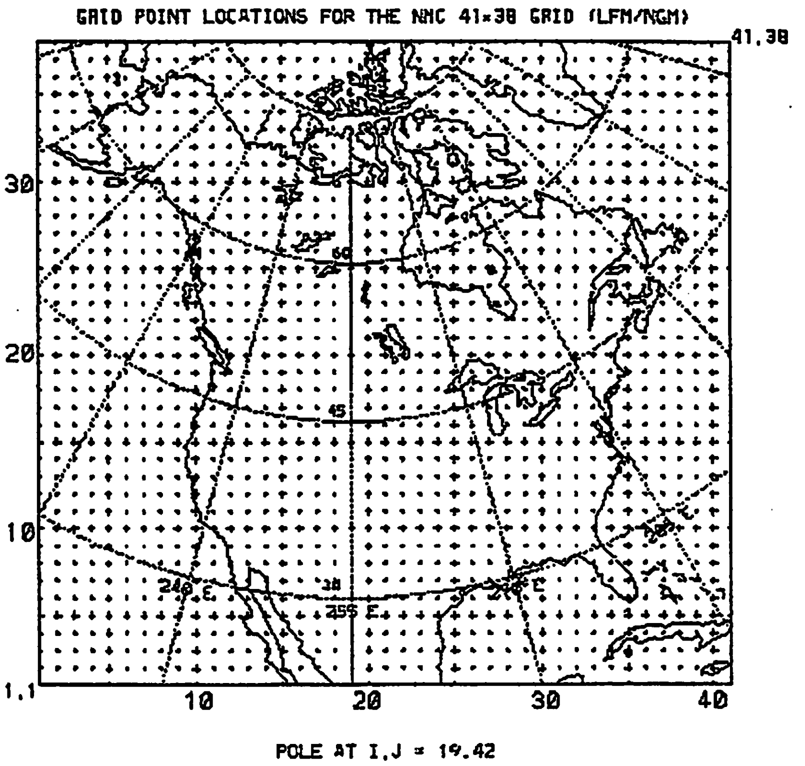

Figure 1 - Grid Point Locations for the NMC 41 By 38 Grid (NGM)

The period of record for the data set was 1/1/94 to 3/31/96. The data set was quite large and included 27 data fields at the initial forecast time and (twice per day at 0000 Greenwich Mean Time [GMT] and 1200 GMT) and 8 forecast periods (every 6 hours out to 48 hours in advance).

Midwestern U.S. Sites

The State of Iowa embarked on a program in the early 1990s to characterize the wind resource within the state. This program was highlighted by the installation of 50-meter tall meteorological towers at a dozen locations within the state and extensive wind flow modeling to define the wind resource at 50 meters above ground level. Two of these sites, one at Alta, Iowa and the second at Sibley, Iowa, are located in the northwest corner of the state. These two sites are located in the area identified as having the best wind resource and also the area where large wind energy projects are now installed. The Iowa Wind Energy Institute (IWEI), courtesy of the Iowa Energy Center (IEC), provided data for these two towers, for the period May 1994 - April 1998 for Alta and May 1994 - December 1996 for Sibley.

Model Application

The Riso Model is applied to predict the wind speeds at the meteorological site at Alta, Iowa and the meteorological site at Sibley, Iowa (Figure 2). From the numerical weather prediction data file, the 10 meter, 950 mb, 850 mb, and 700 mb wind speed data are extracted. These forecast data are made for NGM model gridpoints closest to the meteorological tower locations. The data from a matrix of four sites are extrapolated to the Alta site and the Sibley site. This forms the basis of the predicted wind speed. Therefore, for twice each day, a forecast wind speed and forecast wind direction are generated for each of four levels (10m, 950 mb, 850 mb, and 700 mb) for eight time periods at six-hour intervals out to 48 hours in advance.

For the two sites, Alta and Sibley, the forecasts are generated and compared to the actual wind speeds. Only a roughness file is employed in the modeling. Topographical implications are not included due to the generally uniform nature of the terrain surrounding the site. MOS corrections are applied to the data by comparing the observed and forecast wind speeds by wind direction and calculating scaling factors for each 30 degree bin or sector and also by time of day. The time-of-day classifications are used to take into account different stability conditions. These scaling factors, developed using the data from a six-month period in 1994 (July - December) are applied to the forecast values.

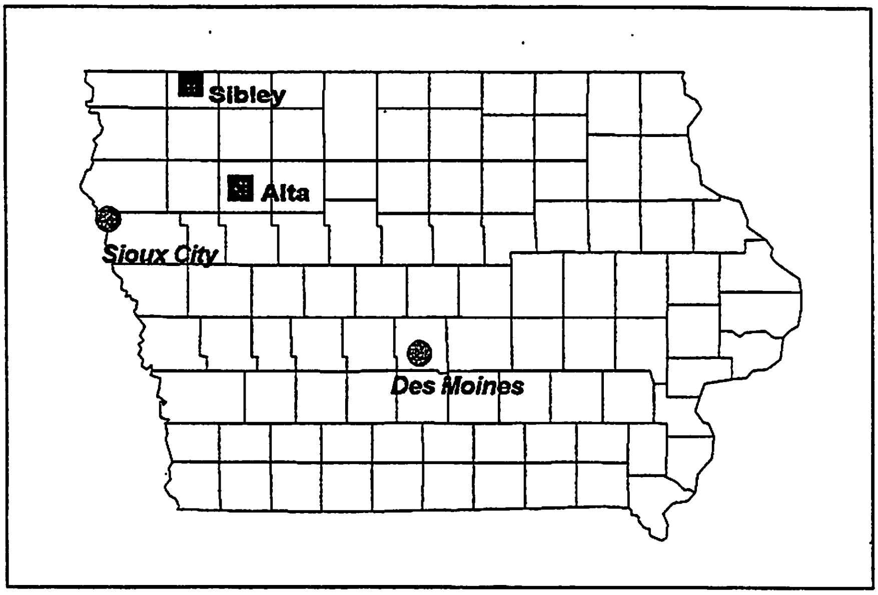

Figure 2 - Location of the Alta and Sibley Sites in Iowa

Model Results

The results are presented in Figure 3 and Figure 4 for all cases combined. Note that these scatter plots show a reasonable linear relationship between the actual 50 meter wind speed values at Alta and Sibley and the forecast values based on the data from the numerical weather prediction model. The forecasted wind speed values based on the numerical weather prediction model for the Alta site, even with the

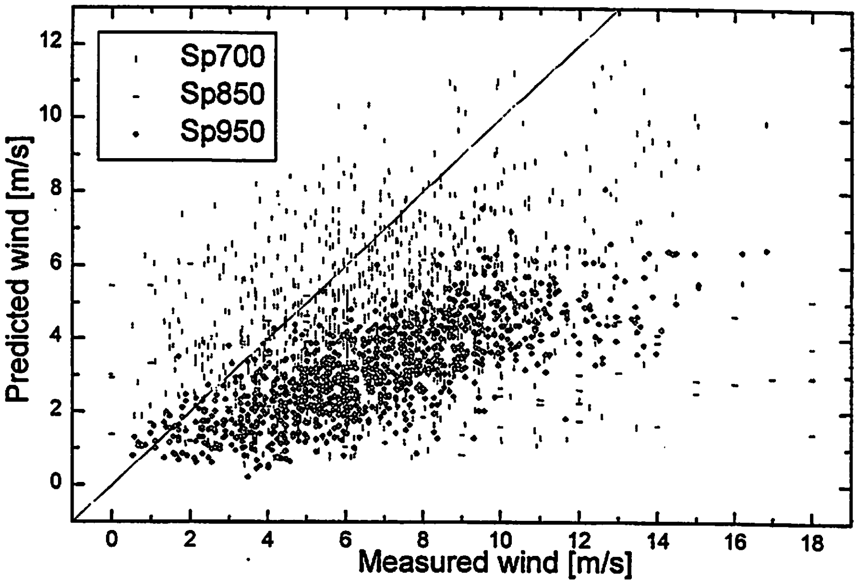

Figure 3. Predicted Versus Observed Wind Speed for Alta, Iowa. Predictions Based on NGM Forecast Data for the 950 mb, 850 mb, and 700 mb Levels.

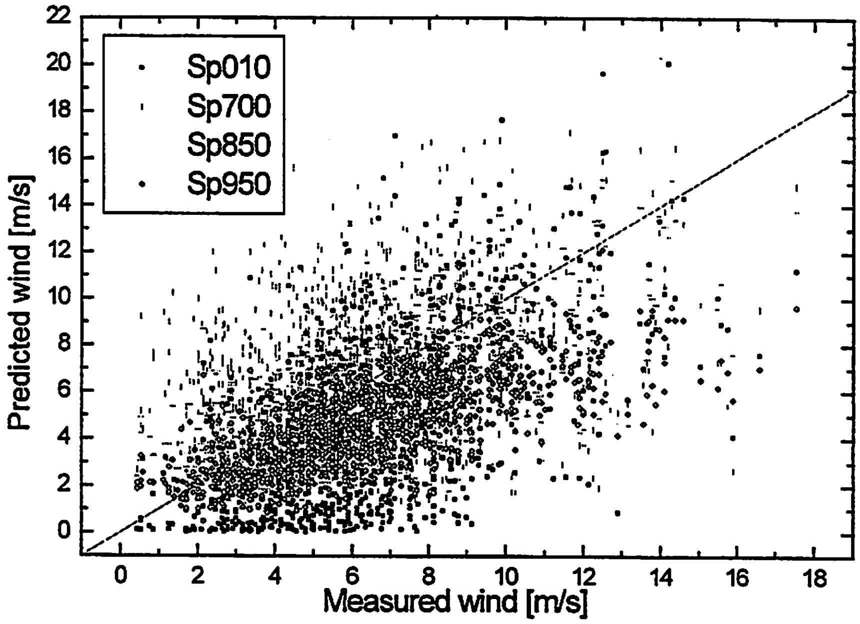

Figure 4 - Predicted Versus Observed Wind Speed for Sibley Iowa. Predictions Based on NGM Forecast Data for the 10m, 950 mb, 850 mb, and 700 mb Levels.

scaling factors applied, appear to consistently under predict the observed wind speed while the fit appears better for the Sibley site. The correlation coefficients between the predicted wind speeds, based on the data from the NGM Model (10m, 950 mb, 850 mb, and 700 mb levels) and the observed wind speeds are presented in Table 1 for the eight 6-hour forecast periods.

Table 1 - Correlation Coefficients Between Predicted and Observed Wind Speeds for 6-hour Forecast intervals at Alta and Sibley, Iowa.

Site	Forecast Interval	10 M Level	950Mb Level	850 Mb Level	700 Mb Level
Alta	06 Hours	0.41	0.57	0.72	0.39
	12 Hours	0.70	0.73	0.70	0.36
	18 hours	0.67	0.56	0.68	0.35
	24 hours	0.62	0.67	0.66	0.16
	30 hours	0.59	0.53	0.63	0.34
	36 hours	0.55	0.62	0.60	0.36
	42 Hours	0.54	0.47	0.58	0.33
	48 Hours	0.48	0.55	0.54	0.33
Sibley	06 Hours	0.73	0.55	0.67	0.33
	12 hours	0.66	0.64	0.60	0.25
	18 hours	0.66	0.50	0.62	0.29
	24 Hours	0.58	0.58	0.56	0.26
	30 Hours	0.60	0.47	0.58	0.30
	36 Hours	0.50	0.54	0.51	0.26
	42 Hours	0.52	0.41	0.52	0.29
	48 Hours	0.42	0.47	0.44	0.24

For the wind speeds at both Alta and Sibley, the predictions based on the 10 meter level the 950 mb level and the 850 mb level are all reasonably good. There is a general decrease over time, implying that the numerical weather prediction models are less accurate than farther away from the initial forecast hour. The predictions based on the 700 mb level are quite poor, no greater than 0.39, and do not show much difference over time. The 700 mb level is approximately 3,000 meters above ground level and it may be this distance above the surface that severely limits the usefulness of this level as a predictor.

Summary and Conclusions

A wind speed prediction model developed by Riso National Laboratory is applied to two sites in Iowa. The model uses data from numerical weather prediction models and applies local adjustments to create predictions of wind speed and wind direction at 6-hour time intervals, twice daily, out to 48 hours in advance. The wind speed prediction for the two meteorological sites in Iowa was reasonably successful and parallels other successful applications of the model in Europe and the Mediterranean Region. The use of more advanced numerical weather prediction models with smaller grid spacing may result in improved predictions in future applications.

Acknowledgements

This work was supported by the US DOE - EPRI Wind Turbine Verification Program. Gregor Geibel of Riso National Laboratory performed the data analysis and prepared Figure 3 and Figure 4.

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Barbour, P.L., S.N. Walker. Site Wind Forecasts From a Regional Weather Prediction Model. ASME Wind Energy Symposium/37th AIAA Aerospace Sciences Meeting, Reno, NV, January 1999.

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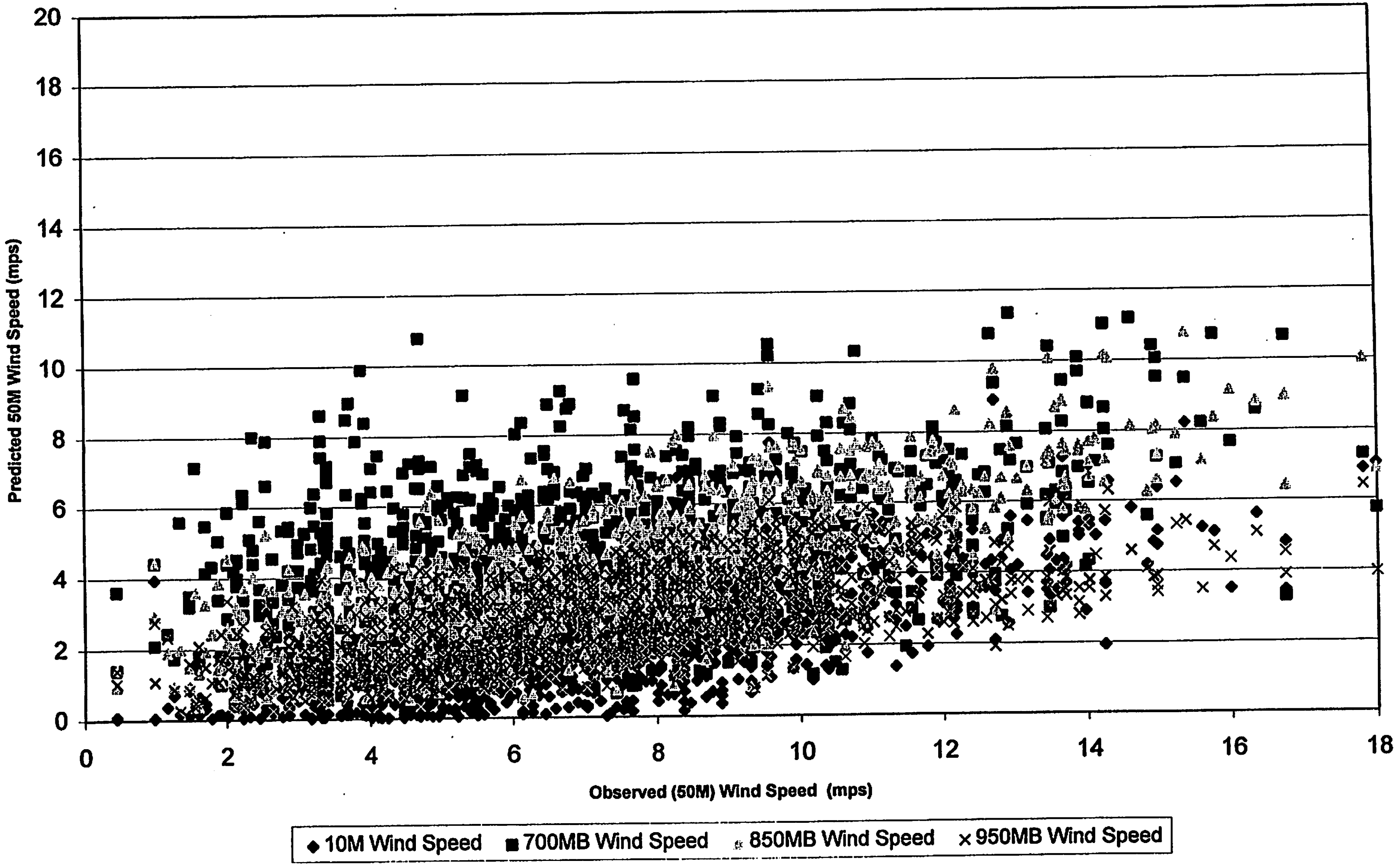
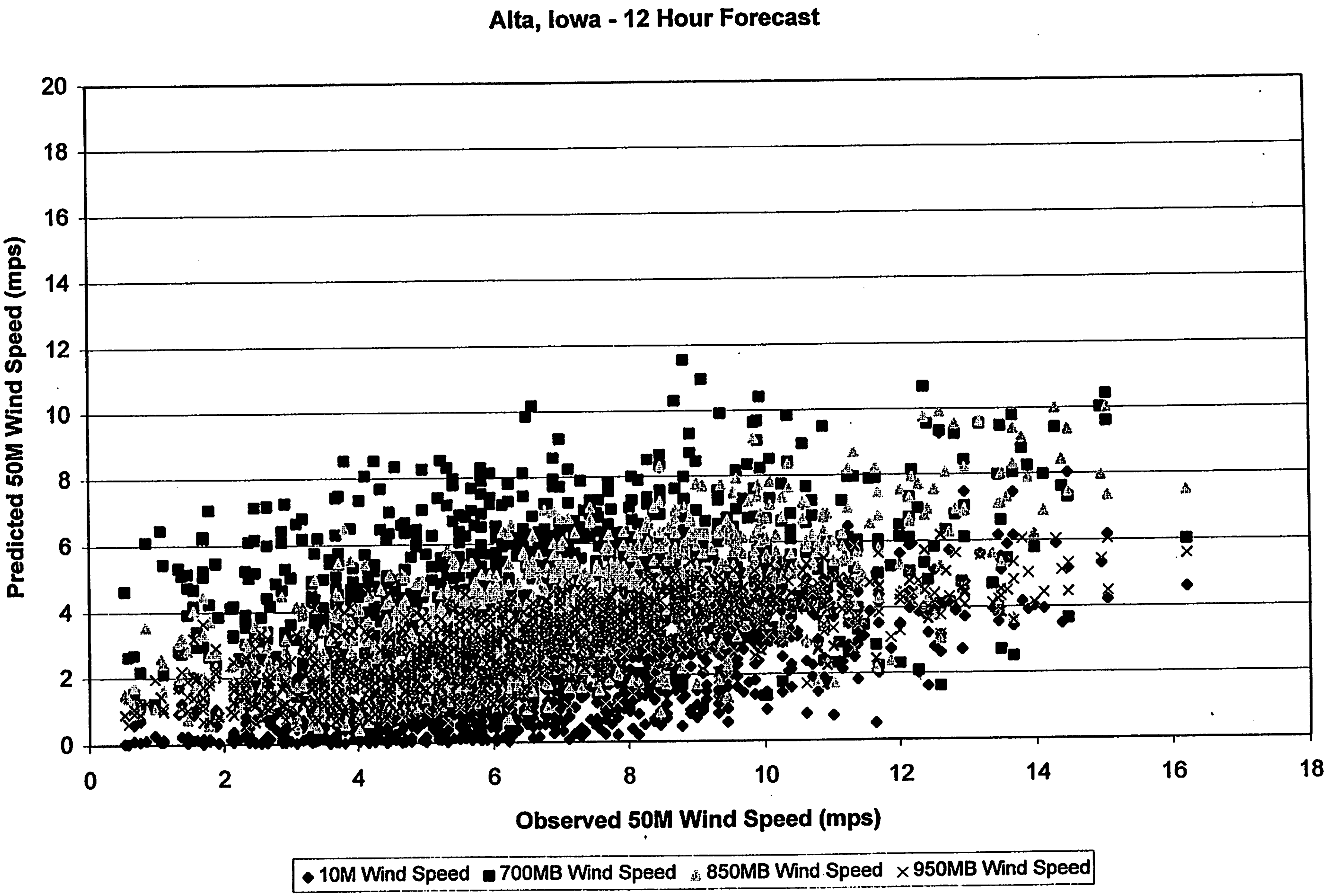
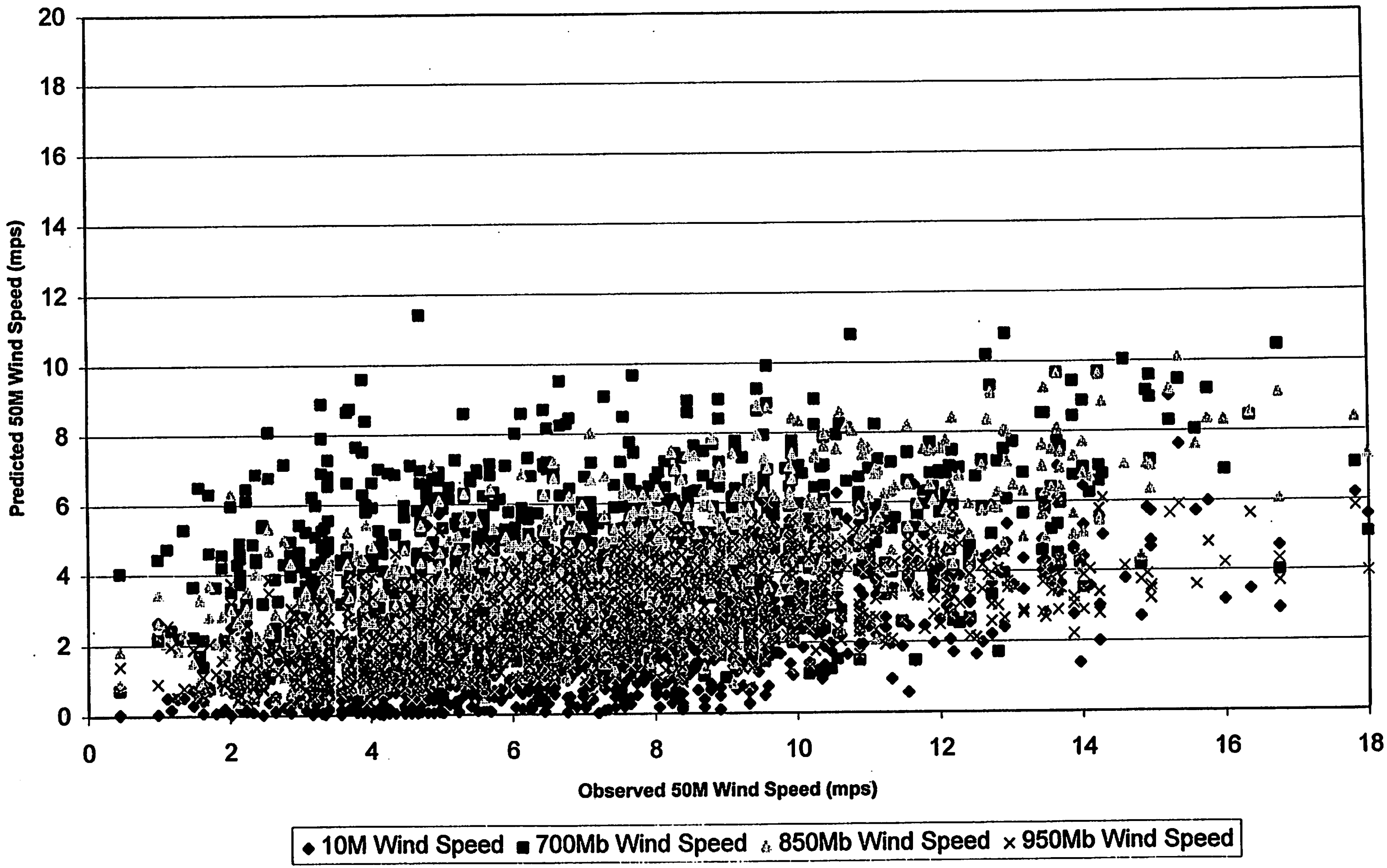
Madsen, H. (Ed.), Wind Power Prediction Tool in Central Dispatch Centers - Final Report. Commission of the European Communities (DG XII) under Contract No. JOU2-CT92-0083, 1995, 187pp

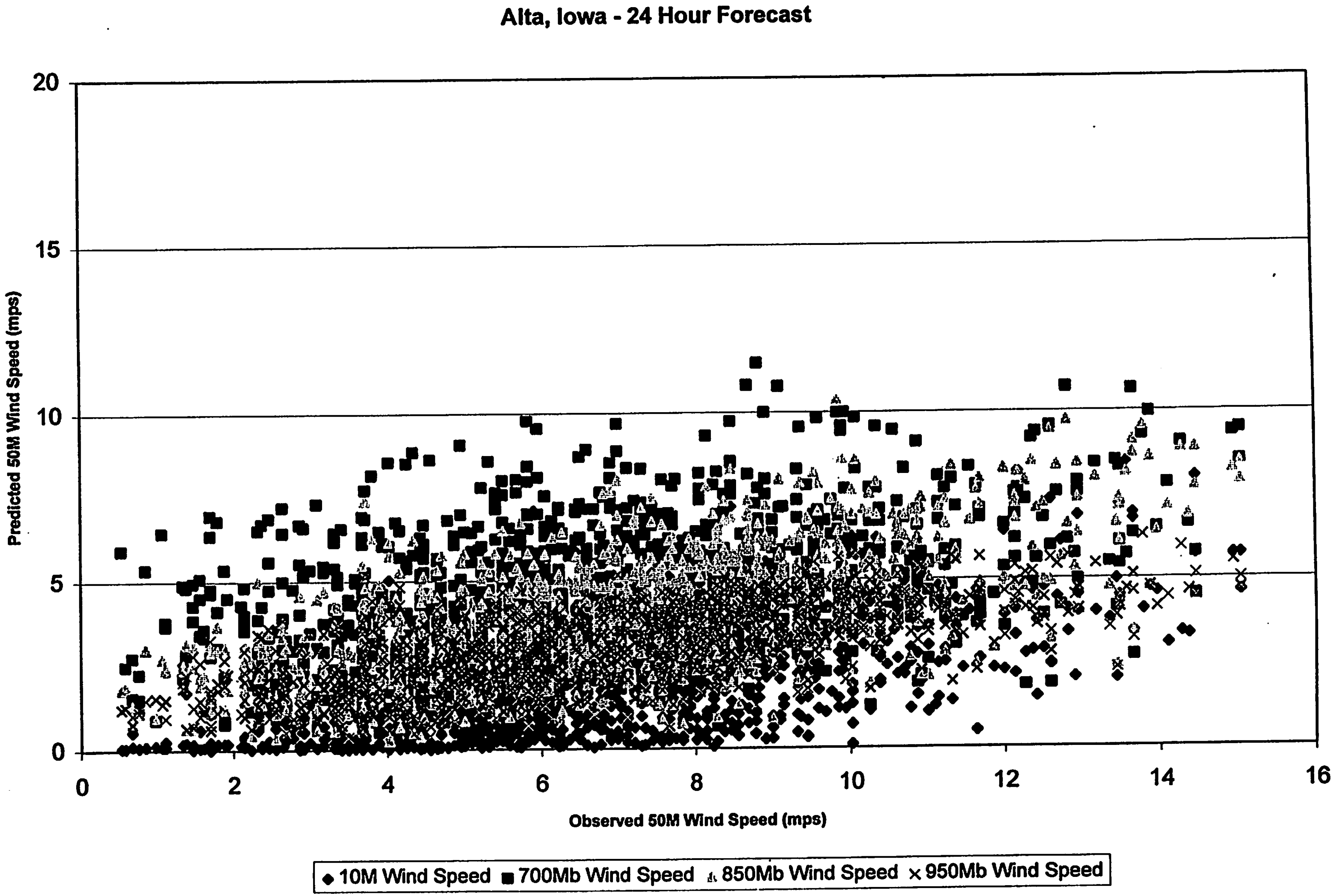
Alta, Iowa - 6 Hour Forecast




Alta, Iowa - 12 Hour Forecast
Predicted 50M Wind Speed (mps)
0
2
4
6
8
10
12
14
16
18
20
Observed 50M Wind Speed (mps)
0
2
4
6
8
10
12
14
16
18
◆ 10M Wind Speed
■ 700MB Wind Speed
▲ 850MB Wind Speed
× 950MB Wind Speed

Alta, Iowa - 18 Hour Forecast




Alta, Iowa - 24 Hour Forecast
Predicted 50M Wind Speed (mps)
0
5
10
15
20
Observed 50M Wind Speed (mps)
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12
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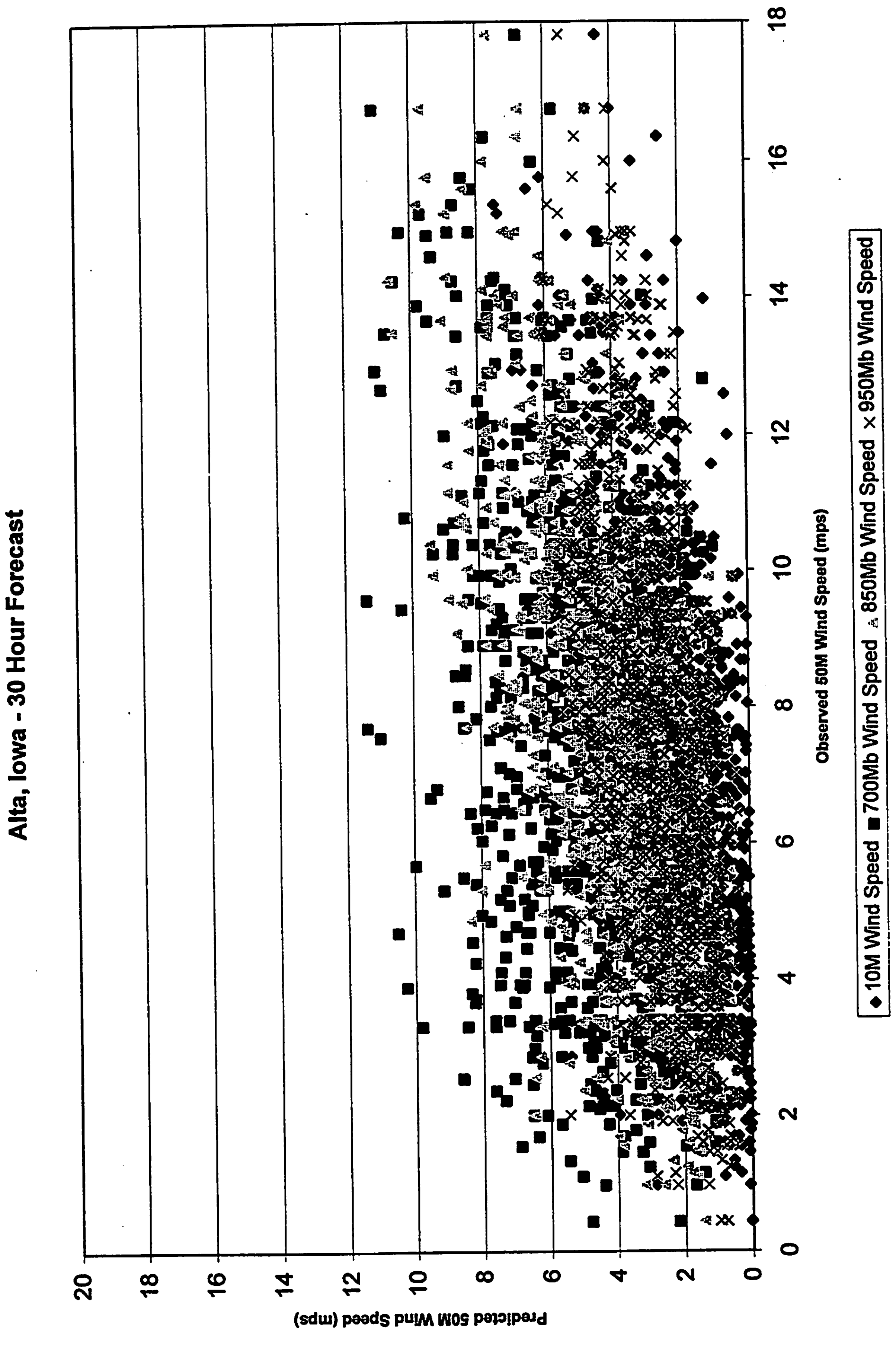
16
◆ 10M Wind Speed
■ 700Mb Wind Speed
▲ 850Mb Wind Speed
× 950Mb Wind Speed


Alta, Iowa - 30 Hour Forecast
Predicted 50M Wind Speed (mps)
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2
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6
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Observed 50M Wind Speed (mps)
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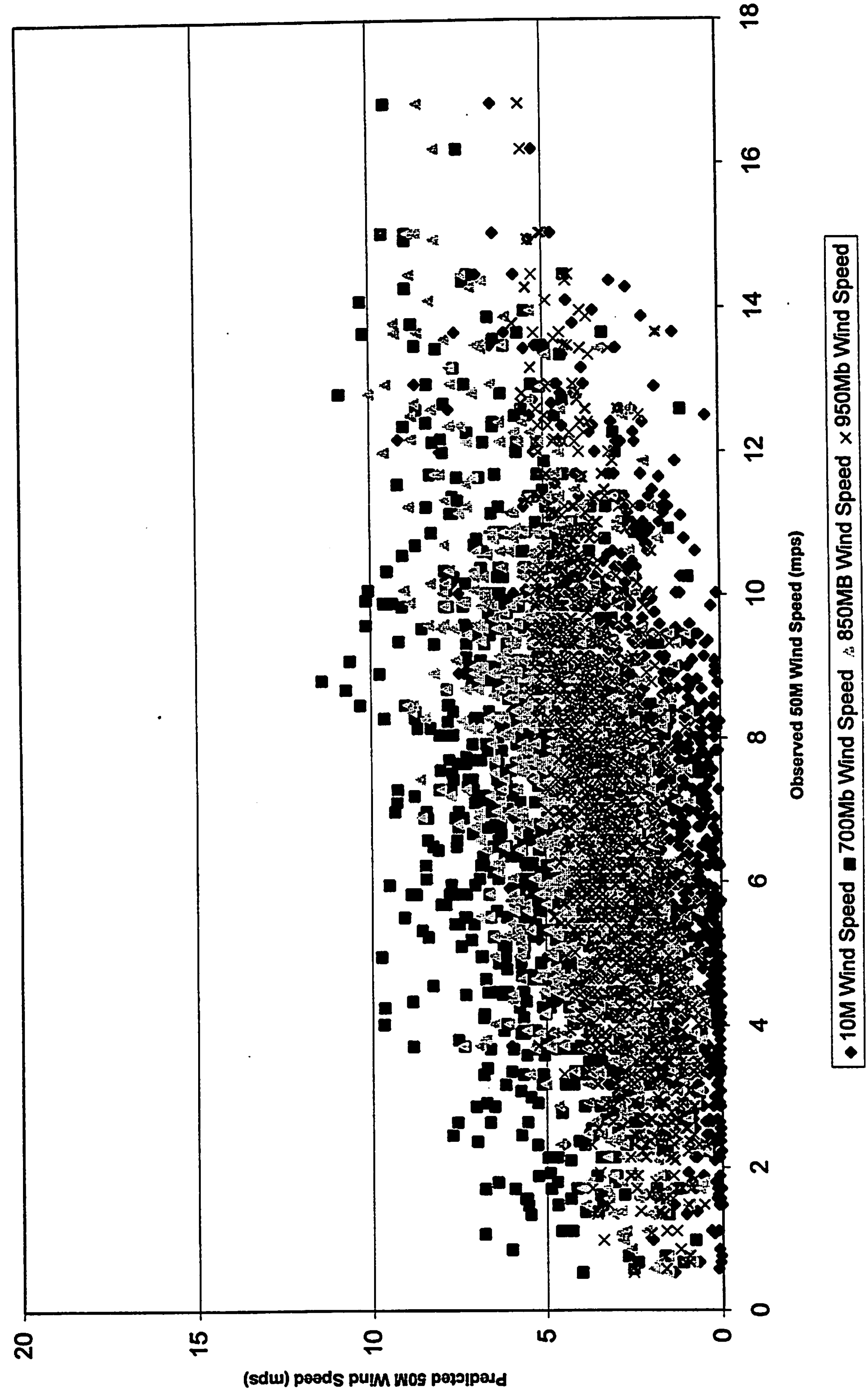
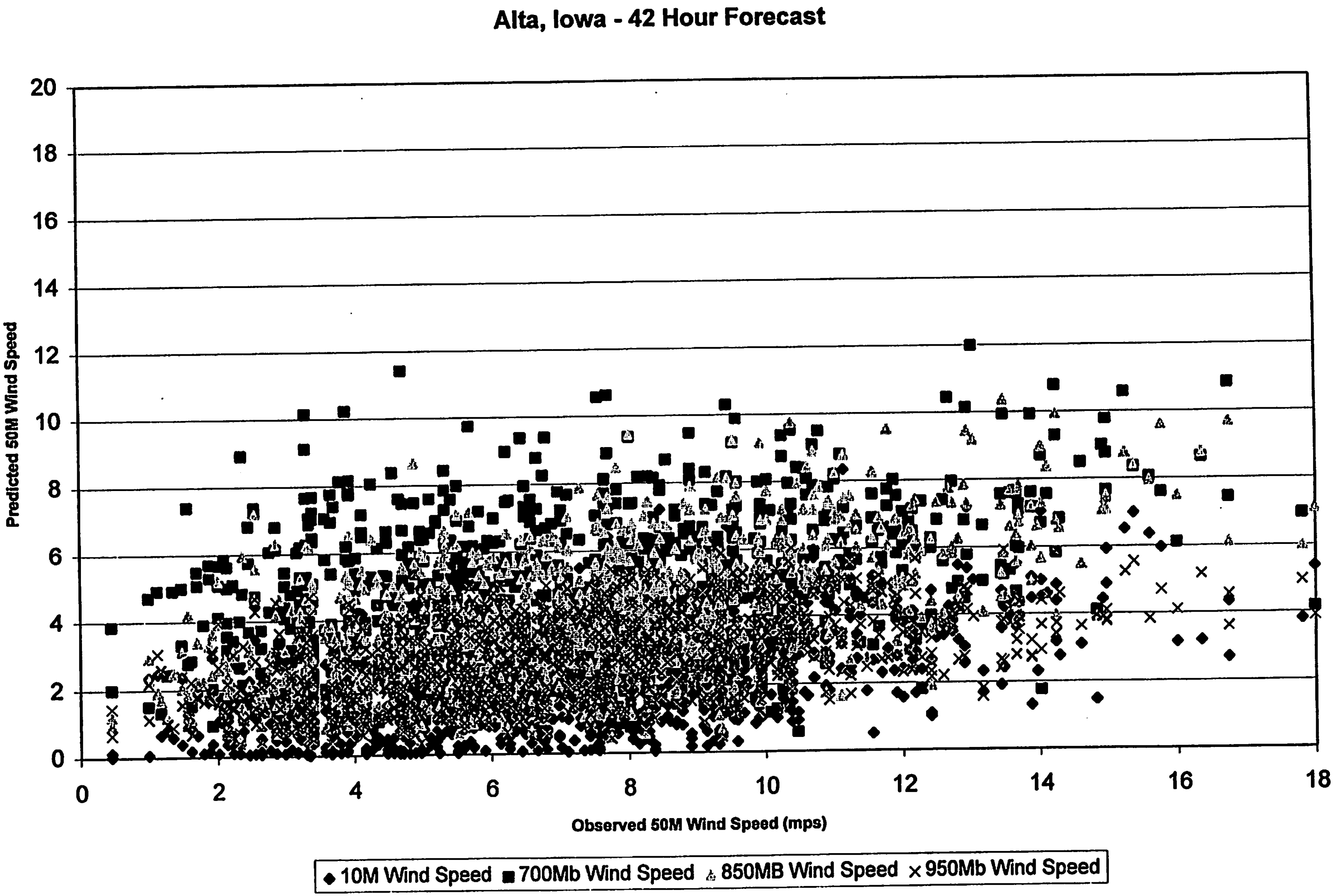
18
◆ 10M Wind Speed
■ 700Mb Wind Speed
▲ 850Mb Wind Speed
× 950Mb Wind Speed

Alta, Iowa - 36 Hour Forecast




Alta, Iowa - 42 Hour Forecast
Predicted 50M Wind Speed
0
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8
10
12
14
16
18
20
Observed 50M Wind Speed (mps)
0
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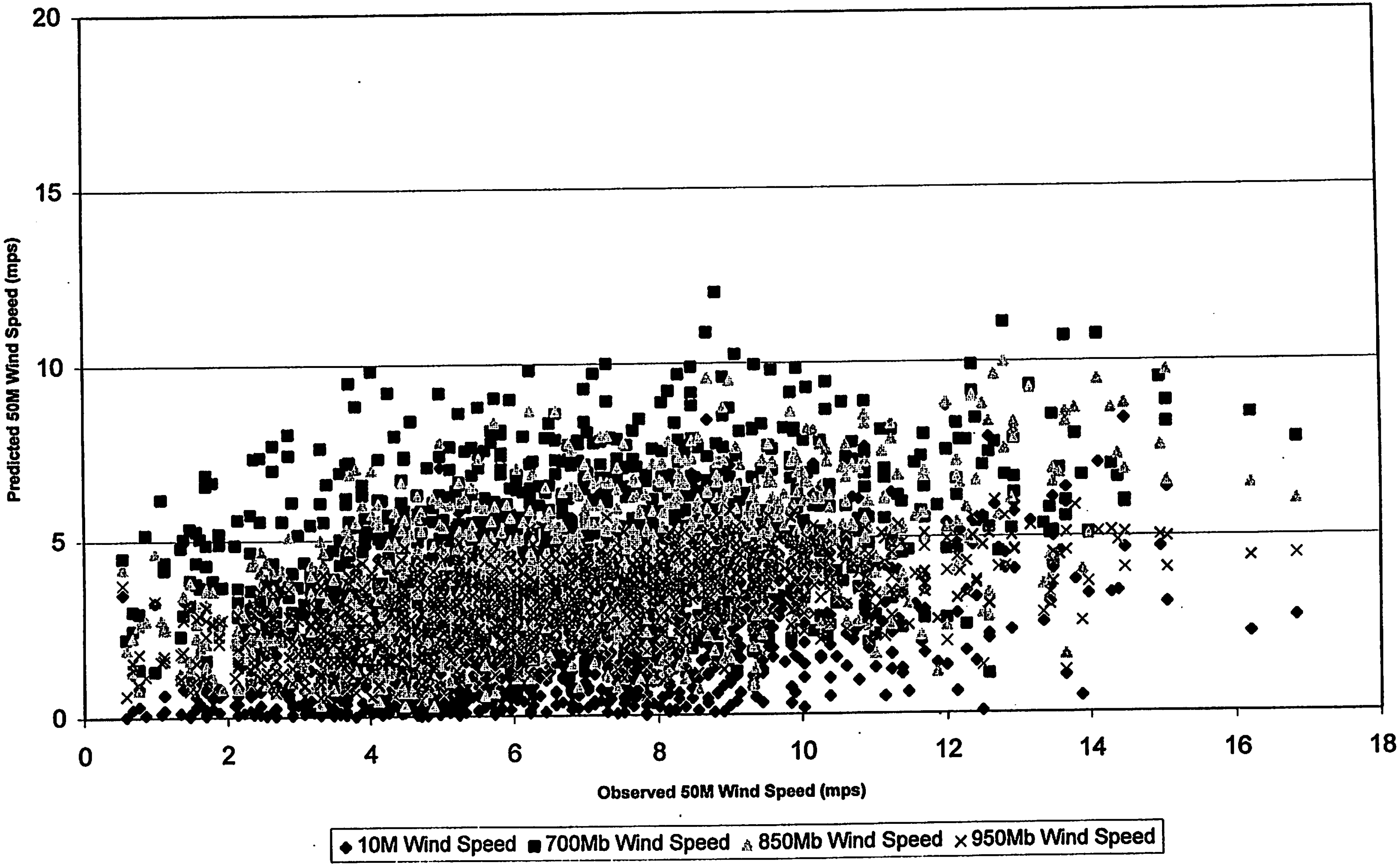
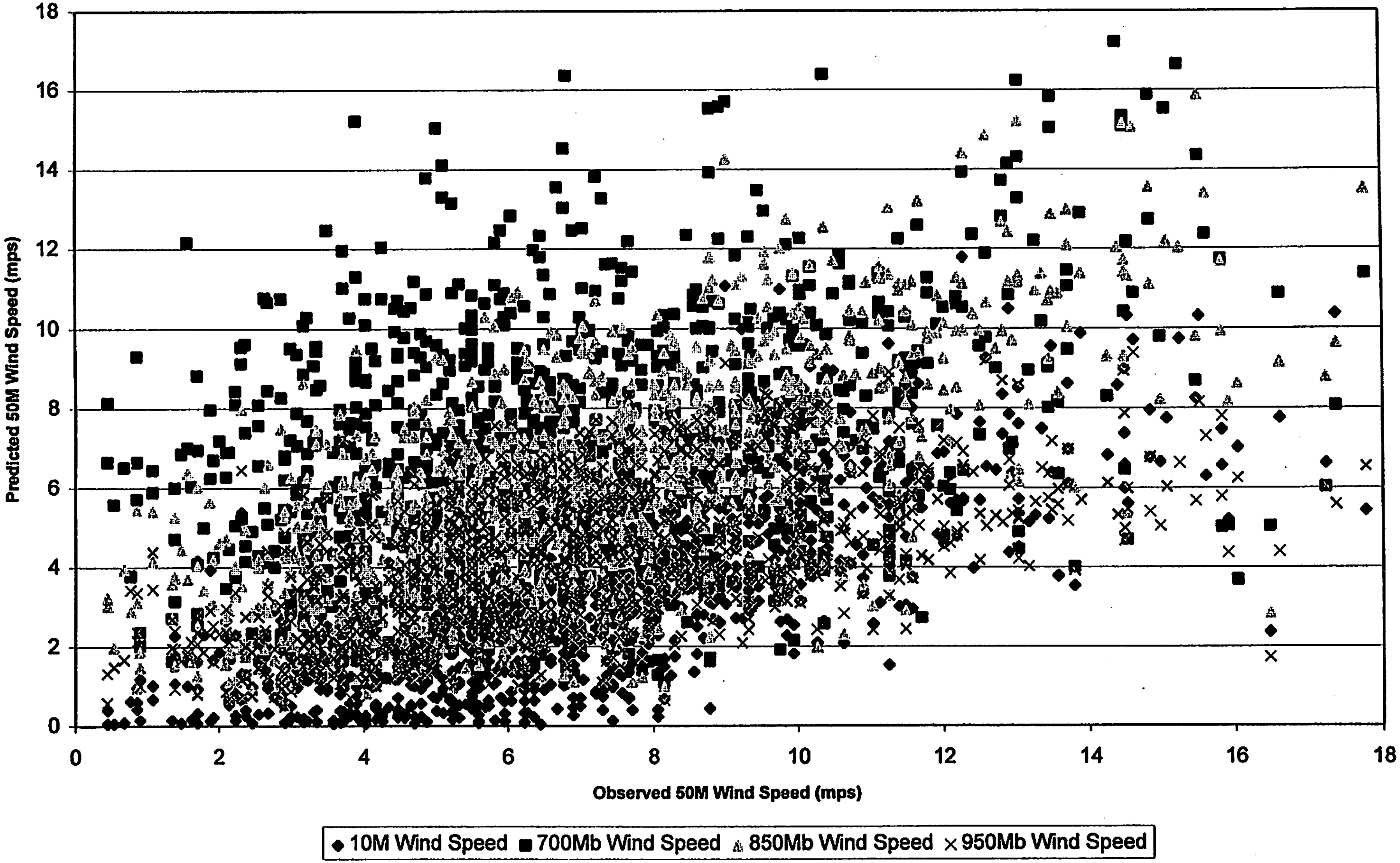
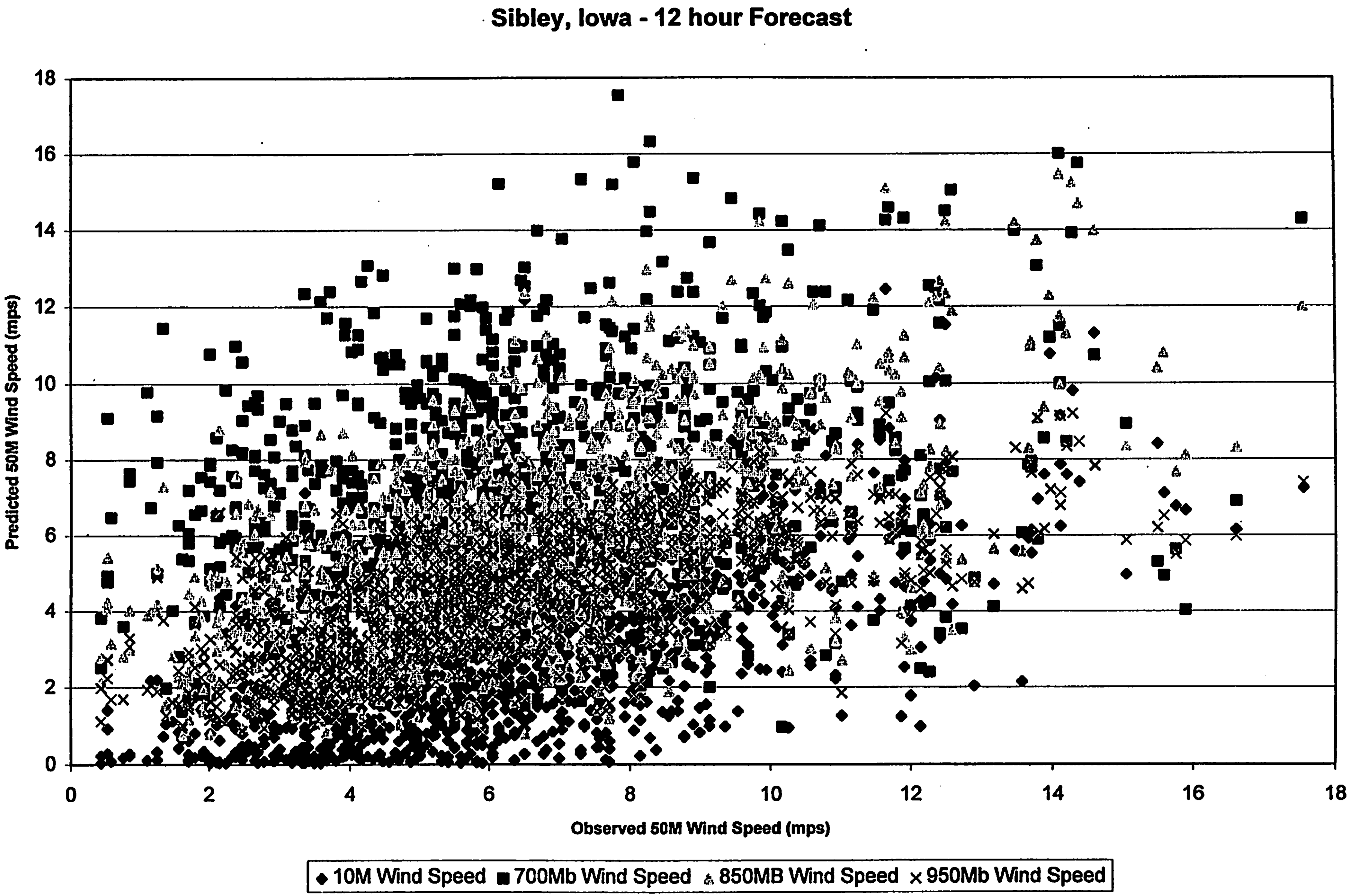
16
18
◆ 10M Wind Speed
■ 700Mb Wind Speed
△ 850MB Wind Speed
× 950Mb Wind Speed

Alta, Iowa - 48 Hour Forecast



Sibley, Iowa - 6 Hour Forecast




Sibley, Iowa - 12 hour Forecast
Predicted 50M Wind Speed (mps)
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Observed 50M Wind Speed (mps)
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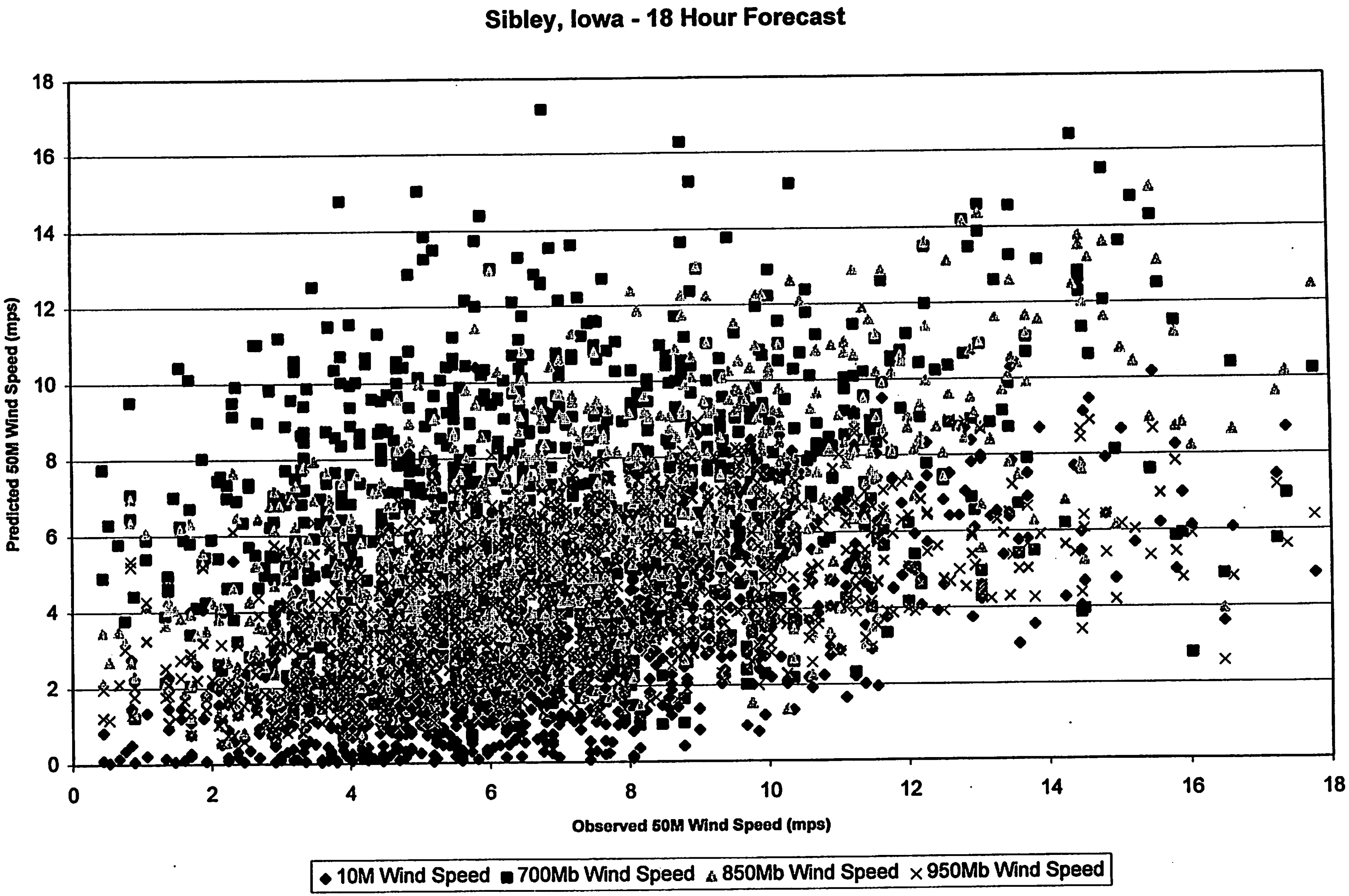
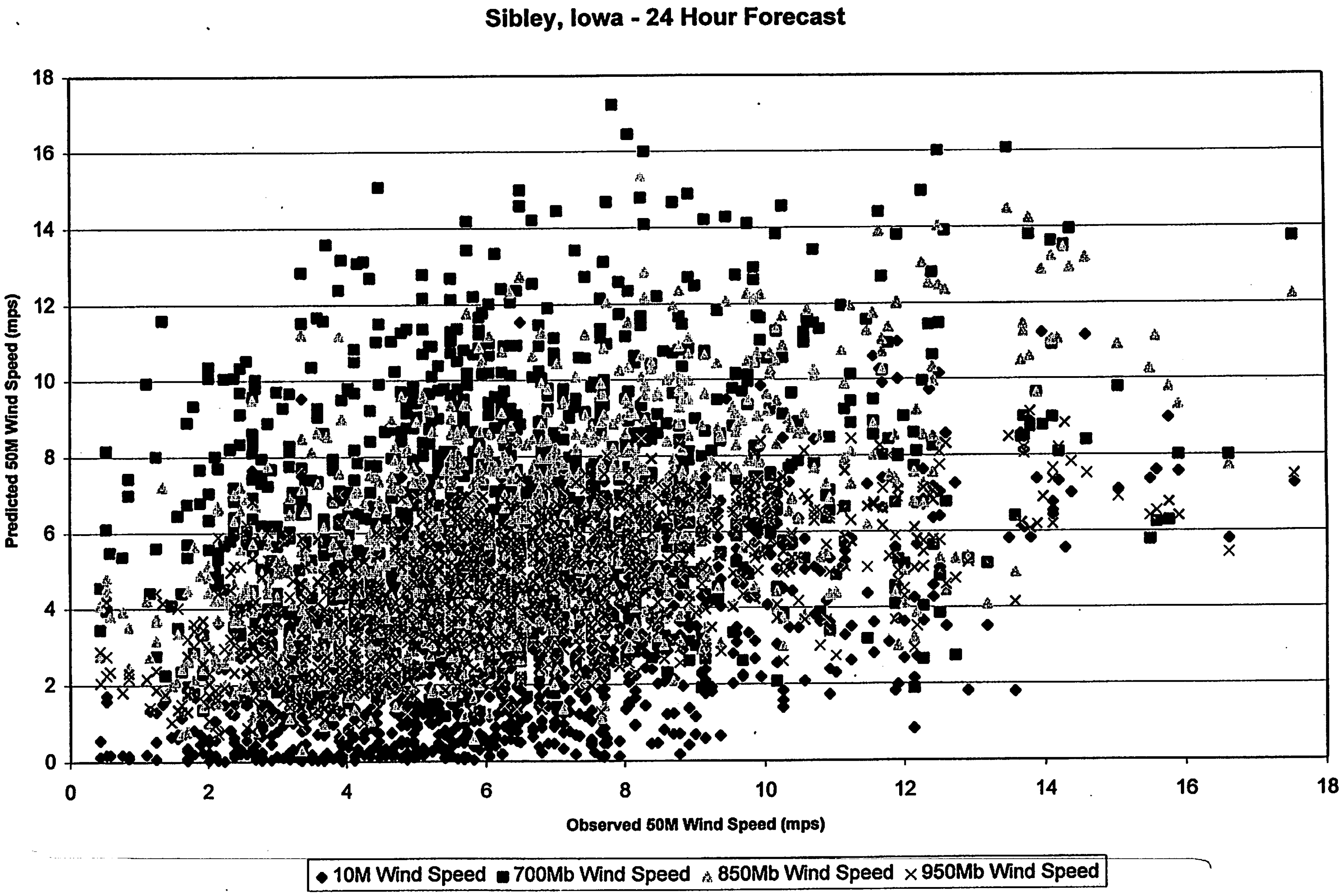
◆ 10M Wind Speed
■ 700Mb Wind Speed
▲ 850MB Wind Speed
× 950Mb Wind Speed



Sibley, Iowa - 18 Hour Forecast


Sibley, Iowa - 24 Hour Forecast
Predicted 50M Wind Speed (mps)
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Observed 50M Wind Speed (mps)
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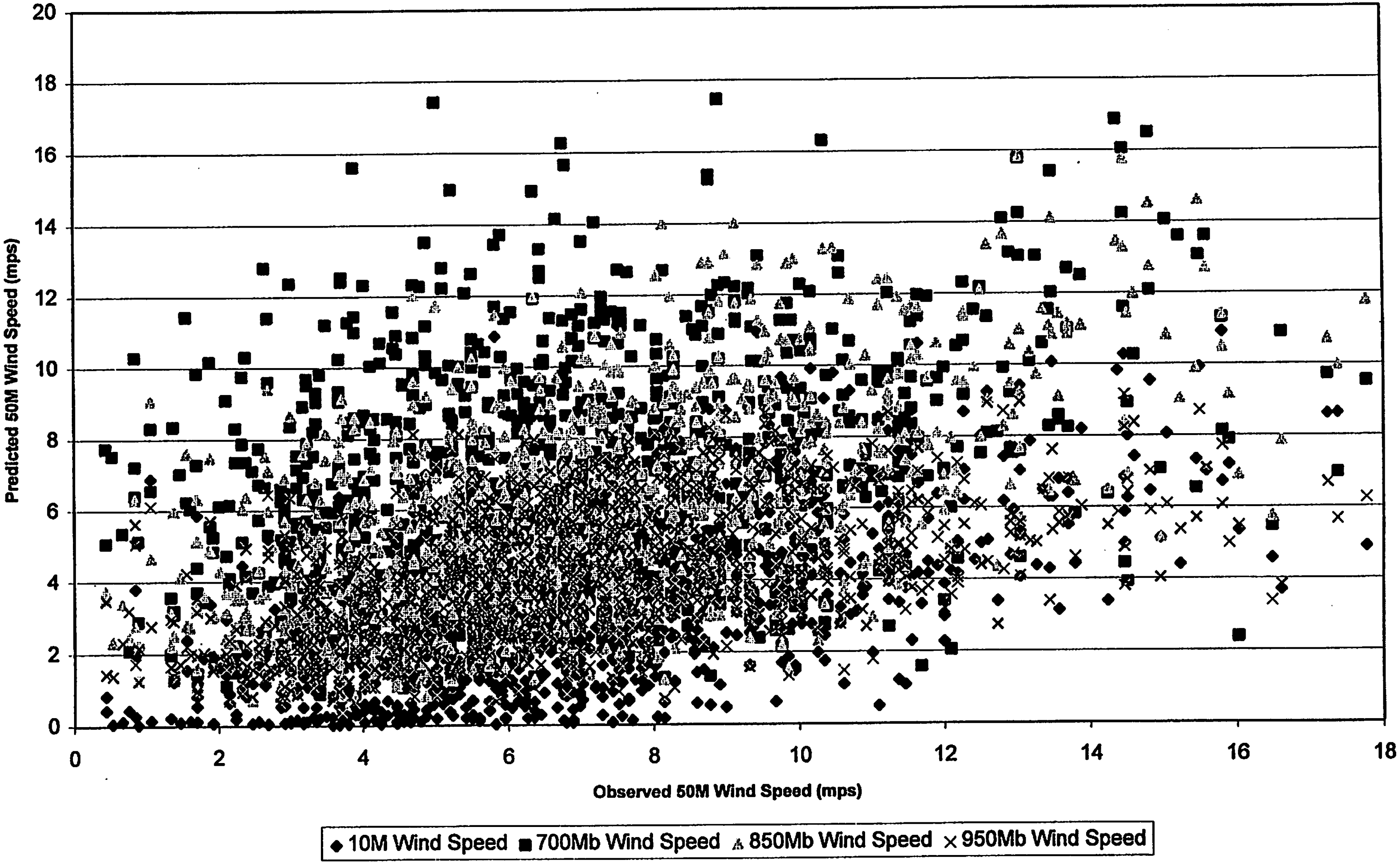
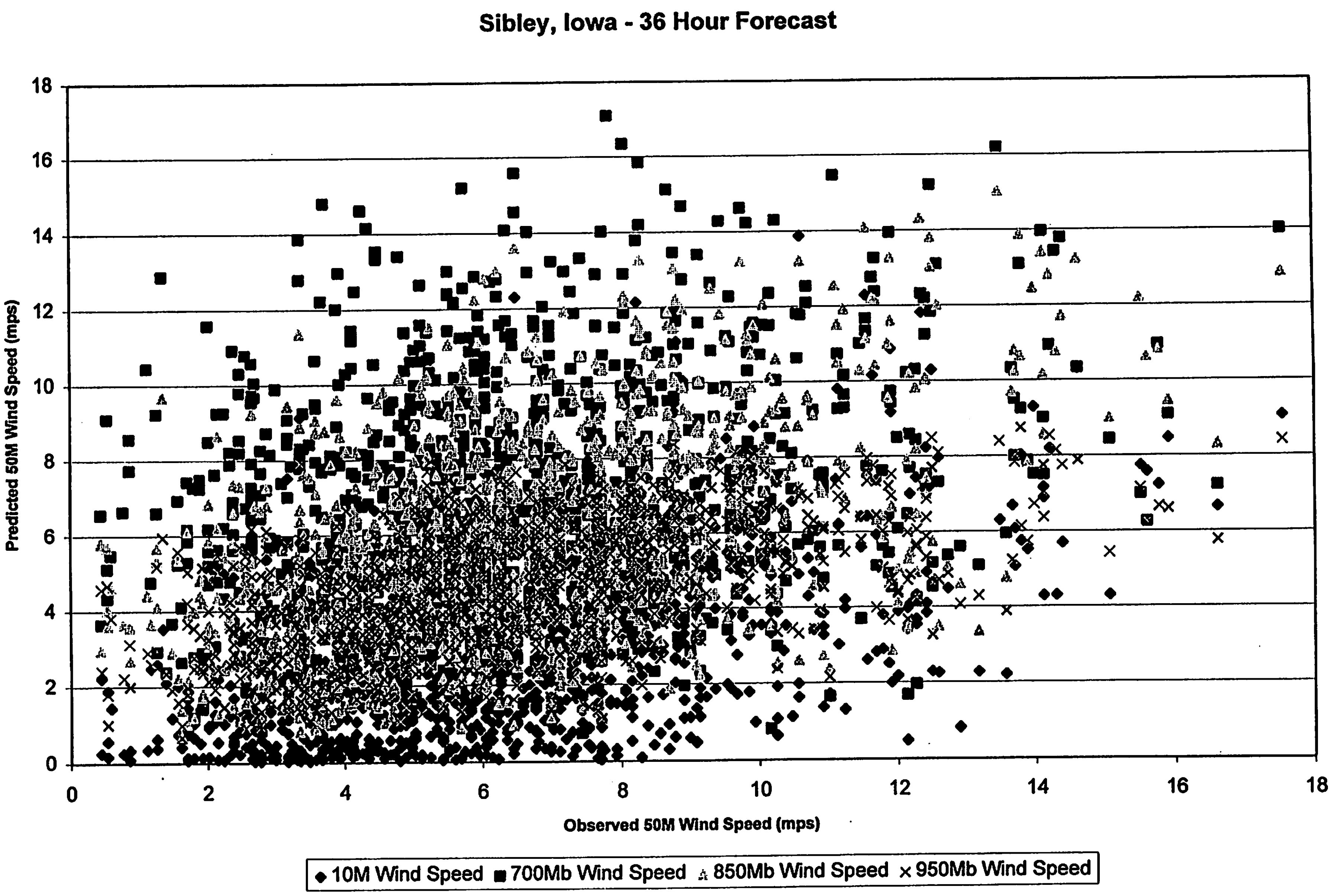
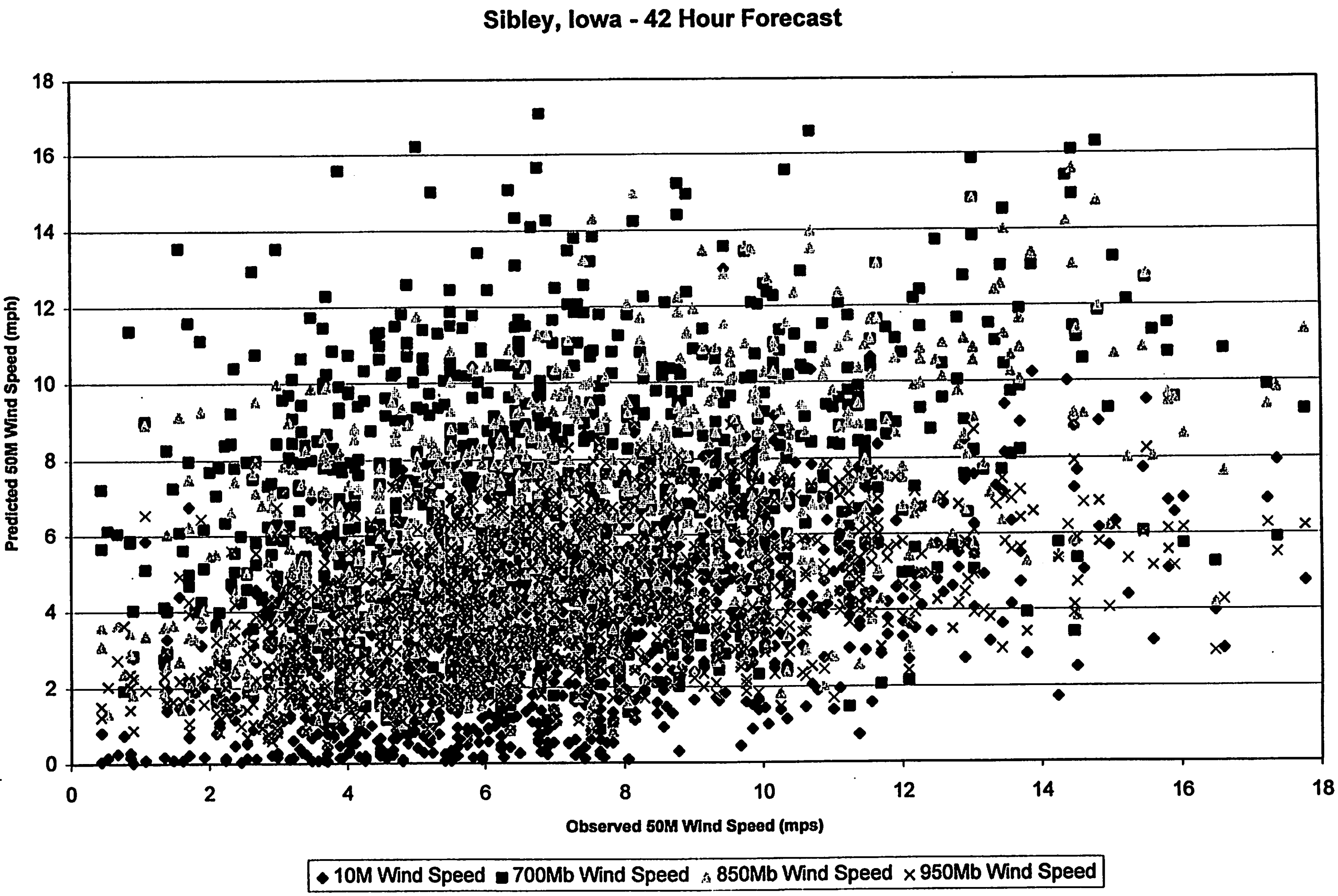
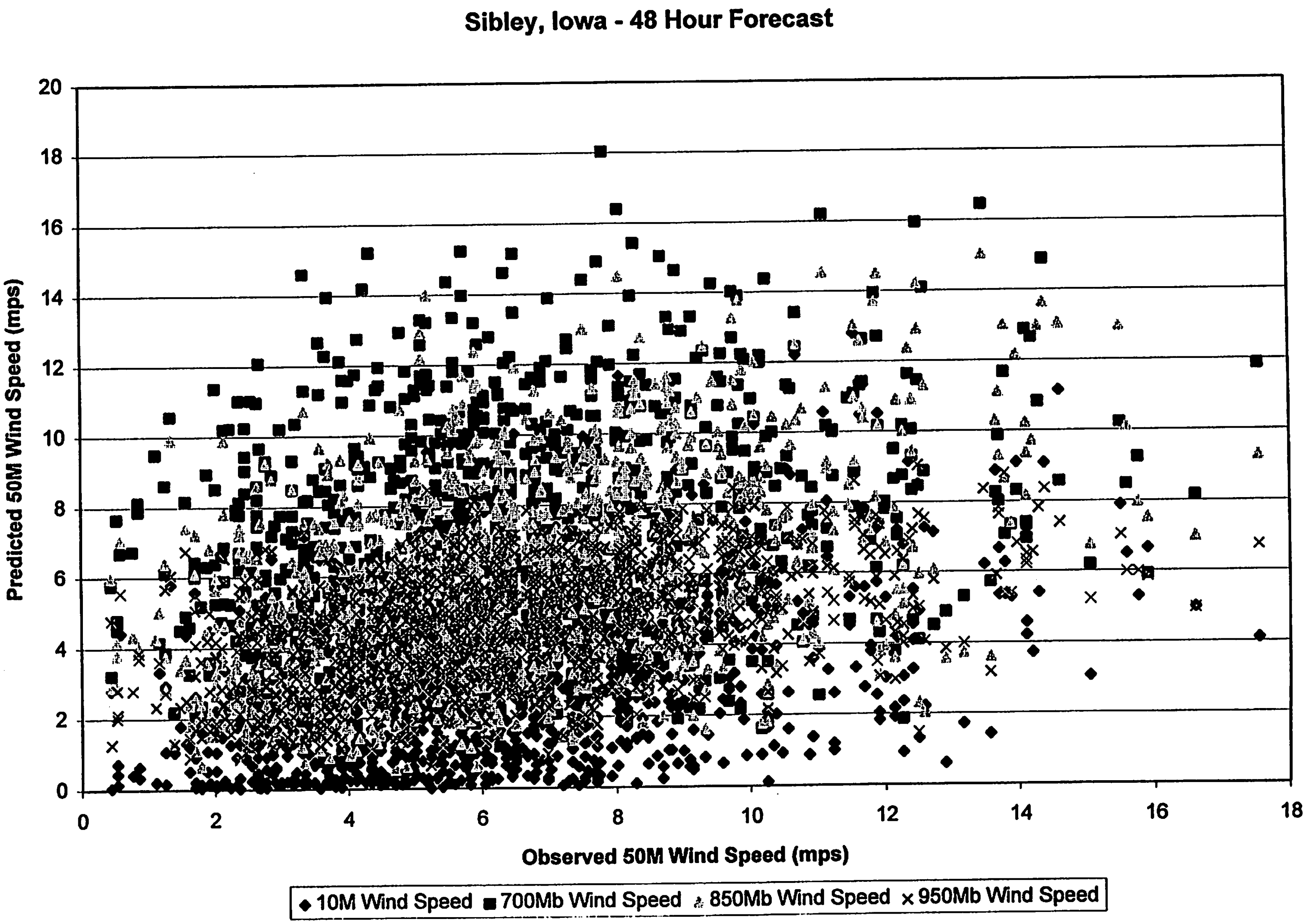
18
◆ 10M Wind Speed
■ 700Mb Wind Speed
△ 850Mb Wind Speed
× 950Mb Wind Speed

Sibley, Iowa - 30 Hour Forecast




Sibley, Iowa - 36 Hour Forecast
Predicted 50M Wind Speed (mps)
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
Observed 50M Wind Speed (mps)
◆ 10M Wind Speed
■ 700Mb Wind Speed
△ 850Mb Wind Speed
× 950Mb Wind Speed


Sibley, Iowa - 42 Hour Forecast
Predicted 50M Wind Speed (mph)
0
2
4
6
8
10
12
14
16
18
Observed 50M Wind Speed (mps)
0
2
4
6
8
10
12
14
16
18
◆ 10M Wind Speed
■ 700Mb Wind Speed
△ 850Mb Wind Speed
× 950Mb Wind Speed


Sibley, Iowa - 48 Hour Forecast
Predicted 50M Wind Speed (mps)
0
2
4
6
8
10
12
14
16
18
20
Observed 50M Wind Speed (mps)
0
2
4
6
8
10
12
14
16
18
◆ 10M Wind Speed
■ 700Mb Wind Speed
▲ 850Mb Wind Speed
× 950Mb Wind Speed

Short Term Forecasting: Application of a Wind Speed Forecasting Methodology For Wind Energy Applications in the Midwest

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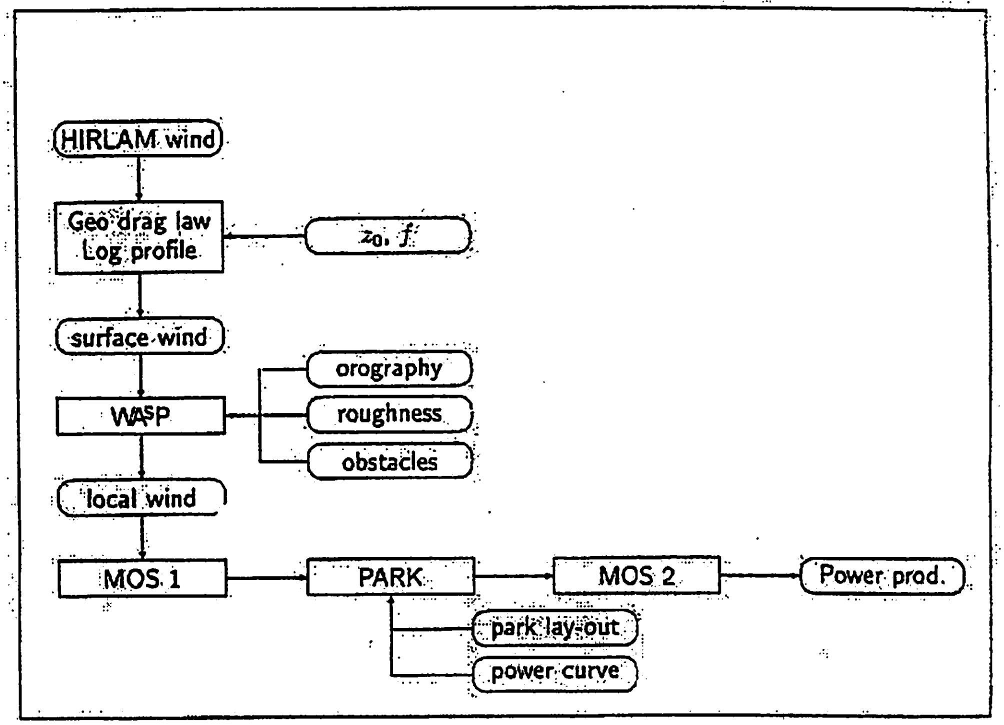
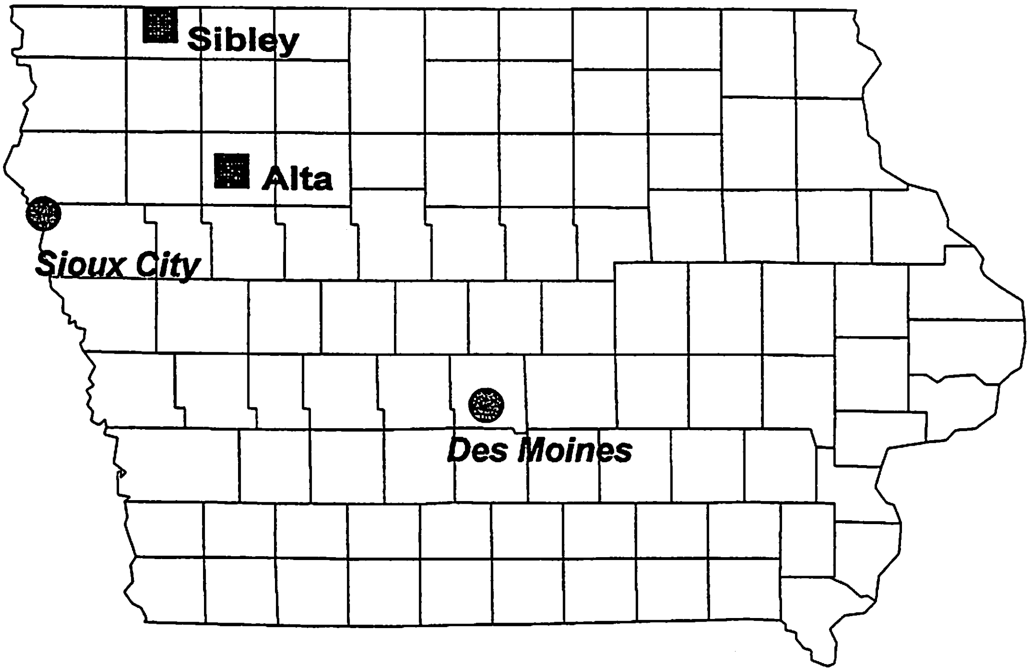
IEA Expert Meeting on Wind Forecasting Techniques
NWTC/NREL
April 4-5, 2000

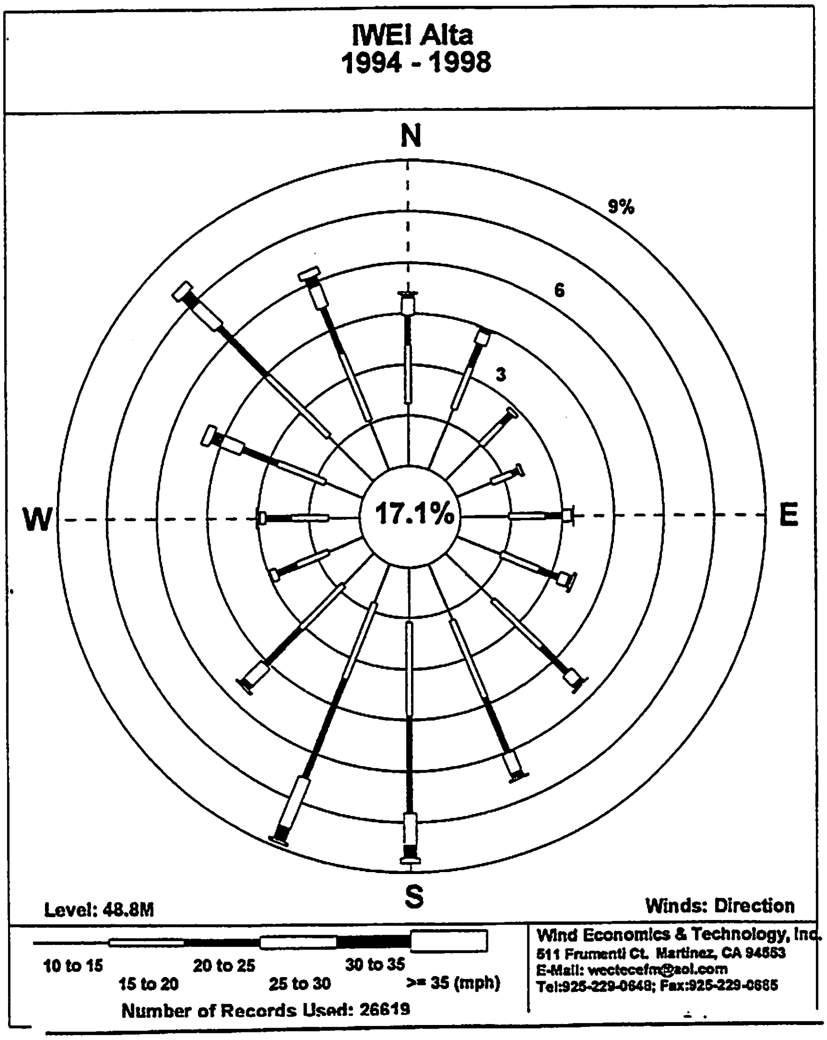
Overview

- EPRI/DOE Participation in the EU Study " Implementing Short-term Prediction at Utilities".
- Application of the Risoe Forecasting Model to Sites in the Great Plains.
- Wind Speed and Wind Direction Data Obtained From the Iowa Wind Energy Institute (IWEI) for a 4-Year Period (1994-98) for the Alta and Sibley Sites in NW Iowa.
- Wind Plant Data (1994 - 1996) Obtained From LG&E for the 25MW Buffalo Ridge Facility In SW Minnesota
- Numerical Weather Prediction Data Obtained from the National Center for Environmental Prediction (NCEP) for the Nested Grid Model (NGM).
- Risoe Model Predictions Created Twice-Daily at 6-Hour Forecast Intervals Out to 48 Hours.

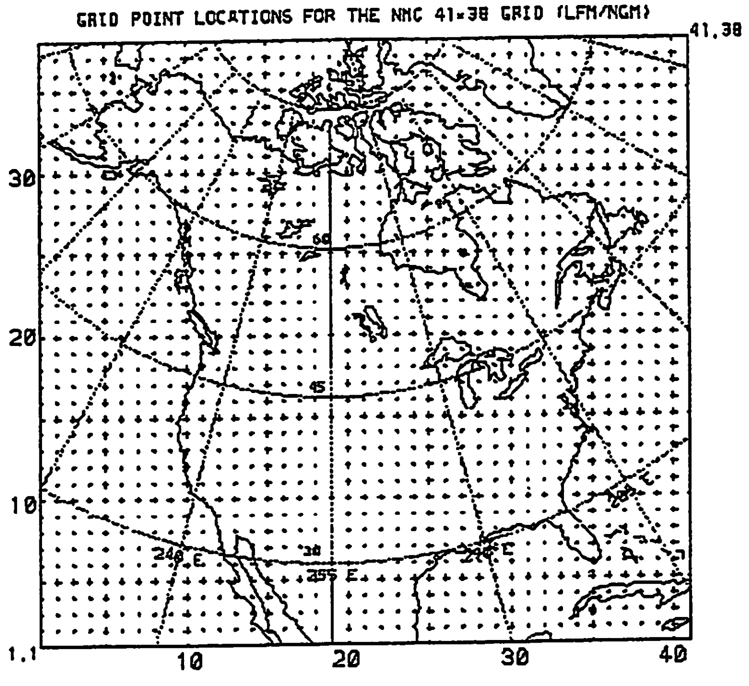


Risoe Forecasting Model Flowchart





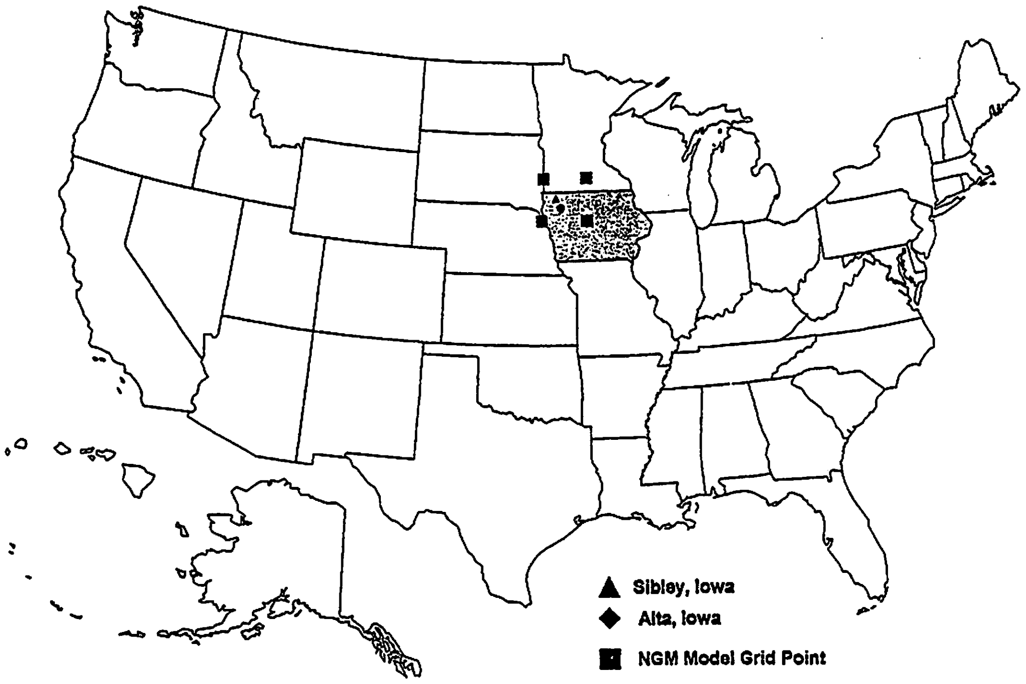
Nested Grid Model



POLE AT I,J = 19.42

Model Parameters

- 1000 mb, 950 mb, 850 mb, 700 mb Pressure Levels
- Heights, U-Component and V- Component of the Wind
- Temperature and Relative Humidity
- Sea Level Pressure



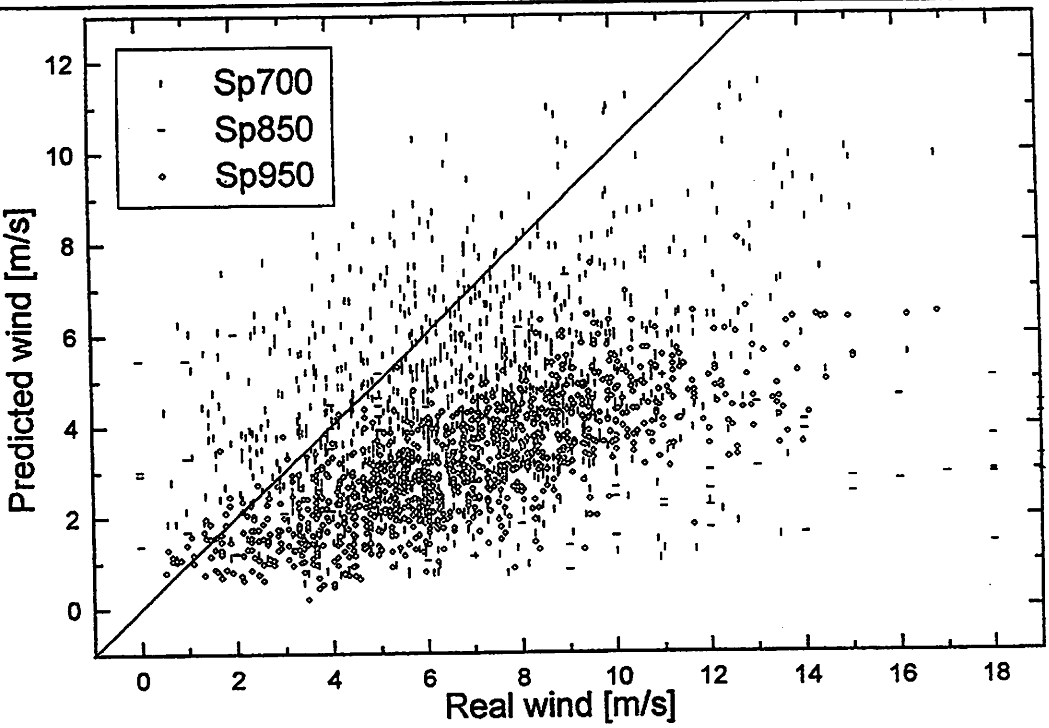


Figure 3. Predicted Versus Observed Wind Speed for Alta, Iowa. Predictions Based on NGM Forecast Data for the 950 mb, 850 mb, and 700 mb Levels

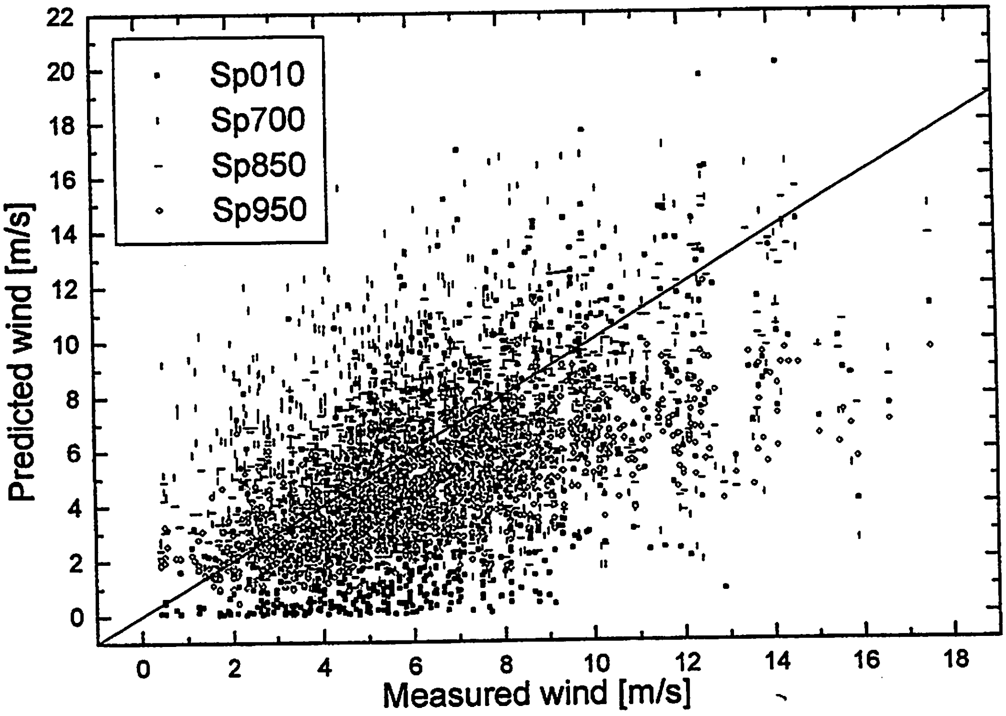


Figure 4 - Predicted Versus observed Wind Speed for Sibley, Iowa. Predictions Based on NGM Forecast Data for the 10m, 950 mb, 850 mb, and 700 mb Levels

Correlation Coefficients Between Predicted and Observed Wind Speeds for 6-hour Forecast intervals at Alta and Sibley, Iowa.

Site	Forecast	10 M	950Mb	850 Mb	700 Mb
Alta	06 Hours	0.41	0.57	0.72	0.39
	12 Hours	0.70	0.73	0.70	0.36
	18 hours	0.67	0.56	0.68	0.35
	24 hours	0.62	0.67	0.66	0.16
	30 hours	0.59	0.53	0.63	0.34
	36 hours	0.55	0.62	0.60	0.36
	42 Hours	0.54	0.47	0.58	0.33
	48 Hours	0.48	0.55	0.54	0.33
Sibley	06 Hours	0.73	0.55	0.67	0.33
	12 hours	0.66	0.64	0.60	0.25
	18 hours	0.66	0.50	0.62	0.29
	24 Hours	0.58	0.58	0.56	0.26
	30 Hours	0.60	0.47	0.58	0.30
	36 Hours	0.50	0.54	0.51	0.26
	42 Hours	0.52	0.41	0.52	0.29
	48 Hours	0.42	0.47	0.44	0.24

Conclusions

- The Wind Speed Predictions For Alta and Sibley, Iowa Appear Reasonable For All Eight Forecast Periods.
- Additional MOS Adjustment Is Needed For The Alta Site.
- The Data From the 10M, 950Mb, and 850Mb Pressure Levels Are The Best Predictors.
- The Predictions For The Buffalo Ridge Wind Plant Are Poor. The Cause Is Thought To Be Corrupted Summary Data From The Wind Plant Control System

Acknowledgements

- Iowa Wind Energy Center (IWEC) for providing the meteorological data for Alta and Sibley, Iowa.
- LG&E for providing the data for the Buffalo Ridge Wind Plant.
- Gregor Geibel, PhD student at Risoe National Laboratory, for the data analysis and creation of the scatter plots.
- EPRI and DOE for providing support under the Turbine Verification Program (TVP).

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Wind Forecasting Activities of the Oregon State University Wind Research Cooperative

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INTRODUCTION

The Wind Research Cooperative (WRC) was formed in 1991 in an effort to conduct research on topics of importance to government agencies, utilities and other organizations interested in promoting the development and use of wind energy in the Pacific Northwest. Oregon State University was chosen to host the WRC because of its long history of wind research in the region. The organization was structured with the philosophy that a regional research unit could address the direct interests of the PNW and provide a flexible and interactive framework from which to address technical issues and provide a better understanding of wind as an energy resource in the region. This was seen as an important feature in the region because of its complex topography, its unique geographic and meteorological characteristics and the regional nature of the energy resource supply.

From the inception of the WRC, one topic of considerable interest has been the topic of wind and energy forecasting. The WRC members have recognized the important role forecasting can play in overcoming the intermittent nature of the wind that is often cited as an obstacle to its wide acceptance. Adequate forecasts can also significantly improve the utilization and value of wind generated energy as well as help alleviate problems resulting from limited transmission capacity. One of the main objectives of the WRC over the past several years has been to work on developing and evaluating methods of producing wind forecasts. This paper is a brief and general overview of the past wind forecasting activities of the WRC and a discussion of some of the current work being conducted.

COMPLETED PROJECTS

Wind Forecasting Overview

In order to gain an understanding of the issues surrounding wind forecasting an overview of the topic was first conducted by the WRC (WRC 94-01). This involved several different aspects of wind energy forecasting including the results of interviews with different utilities, a summary of potential forecasting methods, a catalogue of meteorological data sources in the region and recommendations suggesting how to proceed with developing the tools needed to produce useful wind and energy forecasts.

The utility interviews were of particular importance and helped outline much of the subsequent work on the topic. Within most utilities in the PNW there are two groups that would benefit from wind forecasts; utility schedulers and dispatchers. The functions of these groups are quite different and, therefore, the types of forecasts they would require are also different. The main difference is the time frame over which the forecasts cover. Dispatchers are generally interested in short-term forecasts that would aid in their task of maintaining a supply of energy to accommodate current load requirements as well as ensuring a safe control margin in the event of a failure in the system. Schedulers on the other hand are interested primarily in forecasts covering a time range of about 1-5 days. This time frame is necessary if a scheduler is to include projections of wind facility output into the list of available resources for the next several days. The time frame of the forecast is significant because different approaches are required to obtain forecasts for different time frames.

Most of the continuing efforts of the WRC have been in the area of scheduling. While the dispatching side may be of considerable importance, it is believed to be more difficult to address in general terms. The short-term forecasts of use to dispatchers are considered to be very site specific and may require a considerable investment in instrumentation to monitor and predict changes over the short time intervals. It is believed that this topic is best addressed when a specific need arises.

Evaluation of Operational MOS Wind Forecasts.

With an idea in mind of the types of forecasts that would be needed, several possible approaches were then considered. Primary among these was the use of Model Output Statistics (MOS) forecasts (Glahn and Lowry 1972). The MOS approach has been the mainstay of objective forecasting methods and has provided useful and adequate site-specific forecast of many variables. In the MOS approach, predictions from one of a number of large-scale Numerical Weather Prediction (NWP) models are used, along with observations, to develop forecast regression equations. These regression equations are then applied to future cases. The strength of the MOS approach is that the procedure is objective, relatively simple, and the method accounts for many of the systematic biases present in any model. With a sufficient sampling period, the MOS approach can be used to produce accurate and effective objective forecasts.

To examine some of these issues and to determine the level of accuracy of current operational MOS wind forecasts, an evaluation was performed for several sites in the PNW. Other studies have evaluated the use of MOS forecasts for wind energy purposes, however, most of these summarized results for a group of stations. The objective of this study was to determine, on a site-specific basis, the level of accuracy that was currently possible operationally. Wind forecasts from eight sites were examined. These included six coastal sites as part of the Coastal Marine Automated Network (CMAN) and three inland National Weather Service (NWS) surface sites. MOS wind predictions, for both the 00 UTC and 12 UTC forecast cycles, were examined for two different time periods.

The results of the evaluations showed several interesting features. First, it became clear that care must be taken when evaluating results for different forecast cycles. The errors in MOS wind forecasts are largely dependent on the magnitude of the wind and will, therefore, vary depending on the diurnal variations of a site. This is illustrated in Figure 1. in which the Root Mean Square Error (RMSE) values are shown for both the 00 UTC and 12 UTC cycles at Newport Oregon. The phase difference is apparent and illustrates the need to either separate forecast cycles or to normalize values when examining errors for different forecast projection times. This is mentioned because in many previous evaluations, errors for both cycles were combined to show a lower level of error that increased slightly with forecast projection time. In this evaluation, the level of accuracy appeared to vary depending on the site and the mean wind speed and was in general agreement with other studies on the subject. In addition, some degree of model bias was observed at nearly every site and revealed a slight tendency toward under-prediction of the wind speed.

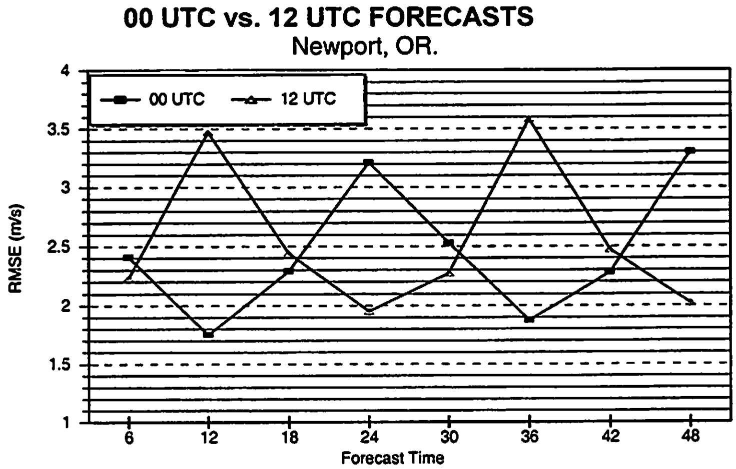


Figure 1: Root Mean Square Error of MOS wind forecasts for the 00 UTC and the 12 UTC forecast cycles at Newport, Oregon

While MOS forecasts have proven useful and the general level of error within reason, a number of inadequacies emerged during this study. Perhaps the biggest problem is an implementation problem. In order to define the regression equations, it is necessary to have a considerable calibration period over which model predictions can be compared to observations. Some estimates suggest that a period of between six months and two years should be used. This is important to ensure that a good representation is established for the most common meteorological conditions at a site. But this places a difficult burden on the method. Each time a significant change is made to a NWP model, the calibration process must be repeated. This is an extremely cumbersome and expensive process and ties up computing resources that could better serve other purposes. There are other problems with the MOS approach as well. Because regression equations are used, forecasts will always tend toward the mean relationship. While this may be good for examining long-term statistics, it may not bode well for certain situations. In particular, rare or extreme events may not be adequately predicted.

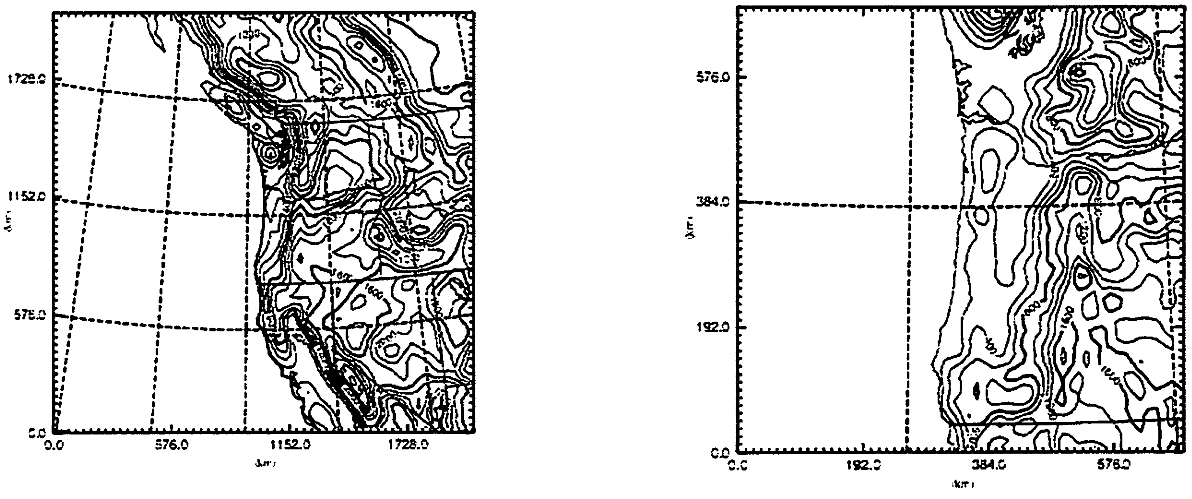
Use of a Regional Weather Prediction Model

Because of the inadequacies involved in the current MOS wind forecasts, other approaches were considered that might provide forecasts to utility schedulers. One approach of considerable interest is the use of regional weather prediction (mesoscale) models. These models differ from operational NWP models in several ways. First, by concentrating on a limited domain it is possible to use a much higher spatial resolution. The benefits of a higher resolution are that it is possible to more accurately resolve the terrain and other physical processes that have a significant influence on the observed weather. Operational use of these models is rapidly becoming a reality; due primarily to advances in computer speed and technology and to increased access to data. In order to evaluate the use of a regional model for potential use in wind energy forecasting, the WRC began the process of acquiring, installing and testing the use of a regional mesoscale model.

To examine the use of a regional model for these purposes, the Advanced Regional Prediction System (ARPS) was selected. ARPS was developed by the Center for the Analysis and Prediction of Storms (CAPS) at the University of Oklahoma. It is a three dimensional, non-hydrostatic, mesoscale model with nesting capabilities, and numeric and physical elements that enable it to adequately predict local and regional weather conditions (Xue et. Al, 1995). For most of the initial studies the model was run in a two-nest configuration with 36 km outer grid and a 12 km inner grid. Initial and time dependent boundary conditions for the outer grid were obtained ETA model run by the National Centers for Environmental Prediction (NCEP). The model was run in a one-way nesting configuration in which the boundary and initial conditions for the inner grid were obtained from the outer grid. A limited number of runs using a resolution of 4 km were also performed.

Wind forecasts produced by the model consisted primarily of simple grid-point values. These grid-point values were constructed by interpolating horizontally from model points to the location of a monitoring site. This was done as a simple means of assessing the models potential and identifying any benefits and problems that might be encountered. The results for several groups of case studies were summarized over several years each using a slightly different model configuration. In the most recent series of evaluations, a domain centered over the coast of Oregon was used (Figure 2). While this is not considered to be a prime location for future wind facility development, the region does contain a number of well-exposed monitoring sites with high winds. The wind in this region is also strongly influenced by the presence of topographic features and should provide an adequate test of the models capabilities. This area was also chosen in part to coordinate with other studies being conducted in the area.

Eleven case studies were used to perform a preliminary evaluation. These case studies included examples of both synoptically driven conditions and conditions in which large-scale variations in heating played a more important role. Forecasts of thirty-six hours were performed for each case study. Model predicted winds were compared to observed winds at several sites and showed a number of interesting features. First, the model appeared to have a negative bias compared to observed values. This was observed in both the scalar wind predictions and the predictions for the wind components and was fairly large in some cases. This is illustrated in Figure 3 showing the frequency distribution of the forecast error for Cape Arago. The highest frequency of errors lie below 0.0 with a general peak in the curve somewhere near -20% to -40% and suggests that, at least for the case studies examined, there was a tendency for the model to under-predict the magnitude of the wind.



36 km

12 km

Figure 2. Domain and terrain features used in the 36 km and 12 km versions of the ARPS mesoscale model forecasts for the PNW.

Comparisons of observed and predicted wind component values for Cape Arago are shown in Figure 4. Both the west-east (u) and south-north (v) wind are shown for the forecasts of all of the test cases. What is clear from this diagram is that the model has a much higher skill in predicting the v component than the u wind component. The correlation between the forecast and observed v component is 0.80 while it is only 0.51 for the u component. This is somewhat significant since the winds in this area generally blow from either the north or the south and the v component is usually much larger. The fact that the model shows this indicates that it is resolving the general influence created at the land-sea boundary. However, the tendency for under-prediction of the wind speed and the lack of skill in the u component suggest some possible problems. One possible explanation for both these observed characteristics is that the 12 km resolution of the model may be insufficient to adequately account for the factors that influence the winds along the coast. The use of a 12 km resolution may in effect be smoothing the local pressure gradients and terrain features resulting in slightly lower wind magnitudes.

Of the six sites examined in this study, most showed similar characteristics. However, the wind forecasts for one site showed a remarkably poor performance. In nearly every error value examined, poor results were obtained for Gold Beach on the southern Oregon Coast. While this might be due to data quality problems, it may also be the result of local influences at the site that are not captured by the use of a regional model. Such things as the presence of an upwind structure or a local terrain feature might cause such an error characteristic. This illustrates the necessity of using sites that have good exposure and points out one of the limitations of this type of approach.

In general, the grid-point projections examined here suggest that a regional model may provide useful and reasonably accurate forecasts for individual sites. Future model improvements and improvements in the techniques used to convert model winds into site predictions might improve wind forecasts further.

Model Output Adjustment

With the improved resolution of current regional mesoscale models, more of the important dynamic and physical processes can be resolved explicitly rather than through the use of parameterization schemes. As a result, such things as terrain influences, surface exchanges, and cloud and convective processes should be better represented leading to more accurate and complete predictions. However, even with the highest resolutions currently possible, model errors will still be present. These errors can be caused by a number of factors including local influences at a site and factors such as errors in the initial and boundary conditions. While little can be done about many of these, systematic biases can be characterized and, at least partially, accounted for.

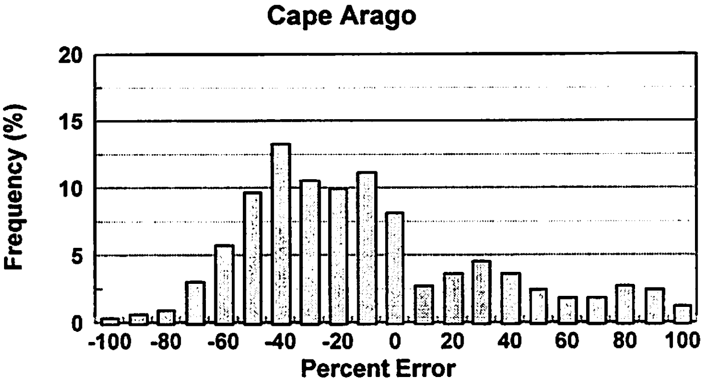


Figure 3. Frequency distribution of error (forecast – observed) for wind speed predictions at Cape Arago.

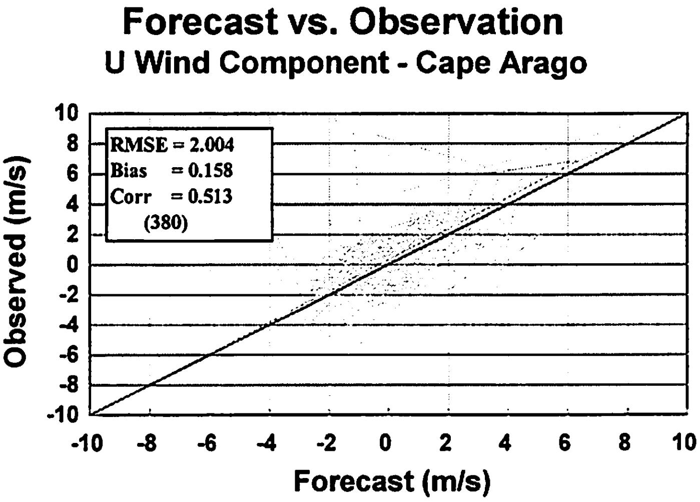
One of the ways this has traditionally been addressed is to use of the MOS approach. MOS forecasts essentially correct model forecasts based on observed biases over time. As mentioned in a previous section, however, a relatively long sampling time is required before reasonable results can be obtained. A large number of cases must be sampled before conditions of significance can be sampled and represented by the regression equations. This can be particularly troublesome when major changes are made to the model. Changes generally require re-calculation of the basic MOS relationships, a process that can be extremely time and resource intensive. In the case of regional models, changes are made quite often and it would be difficult to maintain an adequate consistency to MOS forecasts.

Because mesoscale models are capable of resolving more of the physical processes explicitly, it may be possible to partially circumvent this time requirement and use a simple alternative to the traditional MOS forecast approach. To test this, a modified grid-point adjustment method was developed and evaluated for use in producing wind forecasts. This method represents the simplest approach possible above direct grid-point predictions and is viewed as a first step in developing a more complete and detailed adjustment schemes. The basis of this approach lies in the belief that although most of the important physical and dynamical processes of the atmosphere can be represented by current models, systematic biases will still be present. The method begins with a simple grid-point prediction of the wind for a site obtained from an operational model. To account for the biases, a simple linear regression equation is computed each day using only a limited sampling period consisting of the near-recent history at a site. For the results presented here, a 10-day, 20-day and 30-day regression equations are tested. A new correction is computed and applied each day resulting in an adjustment method that accounts for the recent biases in a model.

This grid-point adjustment approach has a number of benefits as well as potential shortcomings. The biggest benefit is that the regression equations are simple to compute and require a limited amount of resources. They also represent the recent biases of an operational model. However, it is reasonable to expect that the model biases will vary depending on the type of weather conditions present. During steady, persistent conditions, the model biases should remain fairly constant. During transition periods, however, the model biases might show more variation. Therefore, we would expect to see better results during periods of persistent weather.

One of the biggest problems with this approach is the use of a short "calibration" period. By limiting this period drastically, we limit the number of conditions represented by the regression equations. Under certain situations, this method may not be used appropriately. If the new grid point prediction is outside the range of the predictions used in the calibration process, then the method is not appropriate and either the direct grid point prediction must be used, or the calibration period must be extended. For example, if our regression equations are developed using conditions under which the winds varied from 8.0 m/s to 12.0 m/s, then trying to apply this to a predicted wind speed of 2m/s will not work.

To evaluate this proposed method, forecast data from the NCEP ETA model were collected and stored as well as observations from several wind sites in the PNW. Although the ETA model is not strictly a regional mesoscale model, it does have a sufficient resolution to allow the merits of the proposed method to be evaluated. If results show promise, the approach can be used with a regional model at a later date. Some results for a period between January 1, 1999 and June 30, 1999 are shown here for several sites in the PNW including a wind site at Newport on the Oregon Coast and Sevenmile Hill in the Columbia River Gorge.



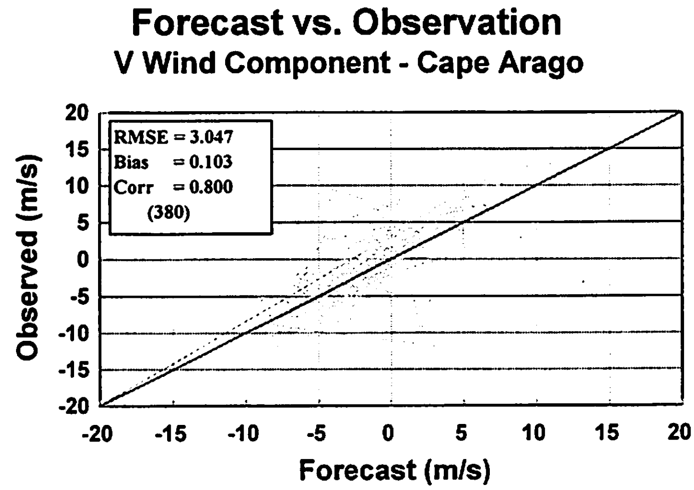


Figure 4a-b: Scatter plots showing the relationship between observed and model predicted wind components for eleven case studies at Cape Arago.

In Table 1, RMSE and mean bias values are shown for both Newport and Sevenmile Hill. These represent the errors associated with direct grid-point predictions from the ETA model for this portion of the study. It is fairly clear that the error values at Sevenmile Hill are quite large in comparison to those at Newport. This is primarily due to the bias at Sevenmile Hill that is on the order of –4.0 m/s to –5.0 m/s. The large bias a Sevenmile Hill is most likely due to the resolution of the ETA model. Sevenmile Hill sits on the top of a ridge overlooking the Columbia River Gorge. The strong winds at the site result from large-scale thermal differences and the channeling effects of the gorge. At the resolution of the ETA model the terrain and these channeling effects are most likely smoothed.

Table 1. RMSE and Bias values for ETA grid-point forecasts at two site in the PNW

	Newport			**Sevenmile Hill**		
Fcst hr	N	RMSE m/s	Bias m/s	N	RMSE m/s	Bias m/s
0	143	3.02	-1.16	151	5.84	-4.73
6	137	2.85	0.08	150	5.39	-4.02
12	136	2.74	0.27	150	6.40	-4.87
18	140	2.62	-0.65	151	7.08	-5.62
24	142	3.15	-0.84	150	5.93	-4.89
30	132	3.51	0.08	147	5.56	-4.05
36	136	3.22	0.28	150	6.52	-4.88

To test the use of the proposed model output adjustment method, simple linear adjustment was applied to the direct ETA grid-point predictions using ten, twenty and thirty day calibration periods. In this example, only wind speed was used as a predictor variable and only wind speed values were adjusted. This process of using a single variable to adjust itself is a special case of the general model output adjustment approach. The results are summarized in Table 2 showing the change in RMSE. The two sites showed substantially different results. At Sevenmile Hill, an improvement on the order of 40% was observed while at Newport, the adjustment produced a small increase in error. These results generally reflect the current bias in the model. The correction of the high systematic bias at Sevenmile Hill contributed to a substantial reduction in the error. Since the bias was small at Newport to begin with, the application of the simple, single variable adjustment had a slightly negative effect. Results for other sites used in this study showed similar characteristics. For sites with a significant bias, a substantial improvement can be obtained even using this simple approach.

Table 2. Change in RMSE values when a 10-day, 20-day and 30-day linear adjustment is applied to ETA grid-point forecast for various sites in the PNW

Site	30-Day	20-Day	10-Day
Buoy 46005	-14.2	-13.0	-13.5
Buoy 46050	-11.7	-8.8	-4.3
Cape Arago	1.7	2.0	5.4
Newport	0.5	3.8	7.5
Cape Blanco	-23.8	-22.9	-19.3
Goodnoe Hills	-39.1	-37.8	-32.8
Kennewick	-41.7	-44.7	-42.2
Sevenmile Hill	-43.6	-44.0	-40.2
Total	-21.5	-20.7	-17.4

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CURRENT WIND FORECAST PRODUCTS

Over the past year, an effort has been made to produce real-time wind forecasts using several of the methods evaluated by the WRC. Two methods are currently being used to generate wind forecasts for sites of interest in the Pacific Northwest.

1) Grid-point predictions: Forecasts are being produced using output from the daily ARPS model runs that consist of simple grid-point output values. The forecasts are being made using initial data from the 00 UTC ETA forecast cycle and cover a period of 36 hours. For these sites, temperature and pressure are included along with wind speed and direction.

2) Model Output Adjustment: Currently, output from the NCEP ETA model is used along with the simple model adjustment procedure discussed in a previous section.

Generating real-time products provides a number of challenges that are not faced when conducting research projects and this work has created an opportunity to address many of these issues. This effort also provides a framework on which future improvements can be based and a means by which feedback can be obtained.

PLANNED WND FORECASTING PROJECTS

With the potential benefits of using a regional mesoscale model well documented, continuing efforts will be applied in this area. These include further efforts to validate model output, to improve the modeling capabilities and to improve methods of utilizing the model output. The following is a brief list of planned projects.

1) Forecast Data Archival: Since June 1, 1999, the ARPS model has been run daily to produce forecasts for a coastal domain similar to the one shown in Figure 2. From these daily runs, two-dimensional fields of surface and near surface fields are being archived. In addition, interpolated profiles for 13 sites in western Oregon are being saved and archived. These data sets should provide an opportunity to examine the long-term relationships between the model predicted quantities and the site observed winds and will enable a number of studies to be conducted. This effort will continue through the foreseeable future.

2) Continue with Real-time Forecasting: The forecast products currently being produced will be continued and enhanced where necessary. One planned change is the addition of verification products that can help the viewer interpret results more accurately. Other changes planned include improvements to the format of the forecasts including the use of confidence or prediction intervals.

3) Model Output Adjustment: Work towards implementation of a more sophisticated model adjustment procedure will continue. The goal is to develop and test a method that includes multiple variable rather than the single variable version currently being used.

4) Implement Model Changes: The ARPS model has been installed on a new computer but has not been optimized to take advantage of multiple processor capabilities. Once this is done, a number of substantial changes will be made. A larger domain is planned along with the use of a 4 km inner grid over selected area. The new computer resources should allow wind forecasts to be generated for a greater number of sites in the Pacific Northwest.

5) Coordinate with Other Projects: Much of the forecasting work has benefited from interactions with other research units at Oregon State University, primarily the College of Oceanic and Atmospheric Sciences. This includes a coastal monitoring program, funded by the Office of Naval Research (ONR) that has provided most of the computing resources. As part of one of these projects, work with a separate mesoscale model has begun. The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), developed by the Naval Research Laboratory, has been installed and initial tests are underway. The objective of this is to have the system running in an operational mode by summer 2000 to provide forecasts and assimilation products for portions of the PNW coast.

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Barbour, P.L. and S.N. Walker, 1994: An Overview of Wind/Energy Forecasting. **WRC 94-01**, *Wind Research Cooperative*, 56 pp.

Glahn, H.R. and D.A. Lowry, 1972: The Use of Model Output Statistics (MOS) in Objective Weather Forecasting. *Journal of Applied Meteorology*, **11**, 1203-1211.

Xue, M., K. Droegemeier, V. Vong, A. Shapiro, and K. Brewster, 1995: ARPS Version 4.0 User's Guide. Center for the Analysis and Prediction of Storms, University of Oklahoma, 380pp.

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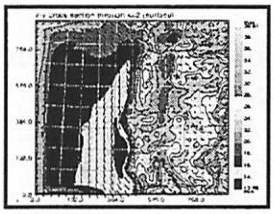
WIND FORECASTING ACTIVITIES

(www.me.engr.orst.edu/WRC)

PHILIP BARBOUR
RESEARCH ASSISTANT

STEL WALKER, Ph.D.
ASST. PROFESSOR



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- PACIFIC NORTHWEST POWER PLANNING COUNCIL
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WIND RESEARCH COOPERATIVE

- Formed in 1991
- Members Include Utilities, Government Agencies and Wind Developers
- To Address Research Topics of Importance to Wind Energy in the PNW
- 22 Research Projects Completed

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PREVIOUS PROJECTS

- An Overview of Wind Energy Forecasting *(WRC 94-01)*
- Individual Site Evaluation of Model Output Statistics (MOS) Wind Forecasts *(WRC 95-02)*
- Evaluation of an Integrated Network for use in Wind/Energy Forecasting *(WRC95-03)*
- The Use of Mesoscale Weather Prediction Models for Wind Energy and Utility Applications *(WRC 96-04)*
- A Preliminary Evaluation of the Use of a Mesoscale Model for Wind Energy Forecasting *(WRC 97-01)*
- Site Wind Forecasts from a Regional Weather Prediction Model *(WRC 98-01)*
- Site Wind Forecasts from an Operational Numerical Weather Prediction Model *(WRC 99-01)*

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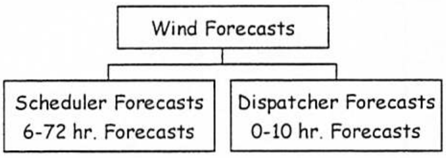
WIND FORECASTING



Wind Forecasts

Scheduler Forecasts
6-72 hr. Forecasts

Dispatcher Forecasts
0-10 hr. Forecasts

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DYNAMIC MODEL APPROACH

- Rely on Dynamic Models to Predict large-scale Atmospheric Features
- Determine Local Conditions Associated with these features.
  - Statistics (MOS)
  - Regional Mesoscale Models

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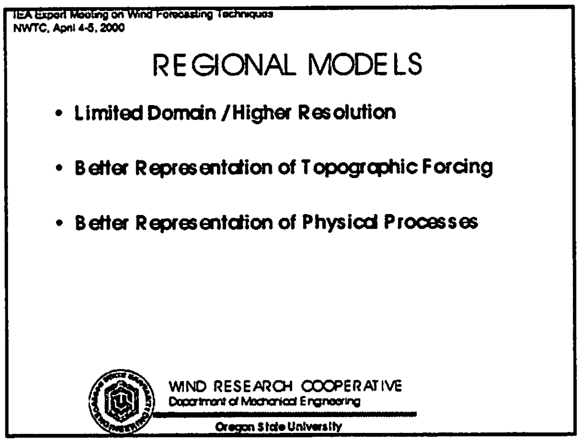

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REGIONAL MODELS

- Limited Domain / Higher Resolution
- Better Representation of Topographic Forcing
- Better Representation of Physical Processes

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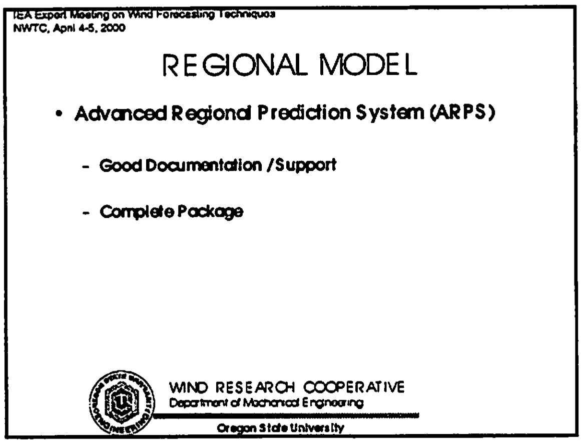

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REGIONAL MODEL

- Advanced Regional Prediction System (ARPS)
  - Good Documentation / Support
  - Complete Package

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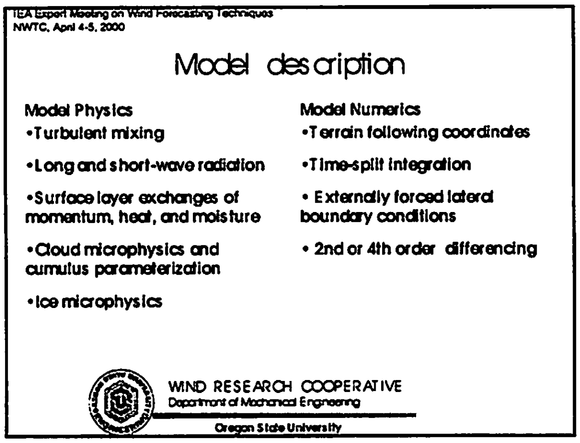

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Model description

Model Physics	Model Numerics
•Turbulent mixing	•Terrain following coordinates
•Long and short-wave radiation	•Time-split integration
•Surface layer exchanges of momentum, heat, and moisture	• Externally forced lateral boundary conditions
•Cloud microphysics and cumulus parameterization	• 2nd or 4th order differencing
•Ice microphysics	

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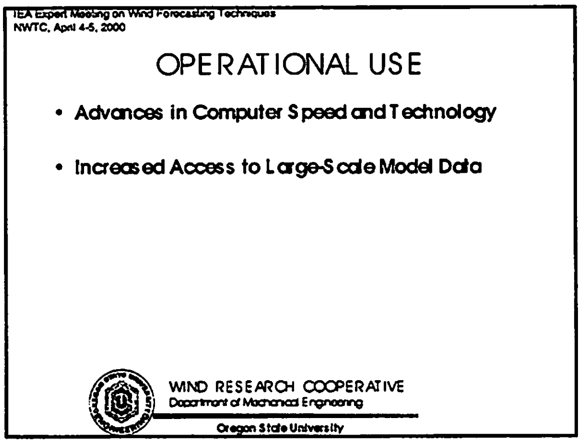

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OPERATIONAL USE

- Advances in Computer Speed and Technology
- Increased Access to Large-Scale Model Data

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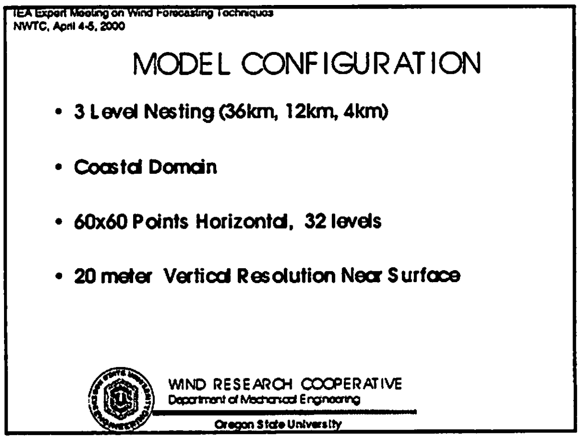

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MODEL CONFIGURATION

- 3 Level Nesting (36km, 12km, 4km)
- Coastal Domain
- 60x60 Points Horizontal, 32 levels
- 20 meter Vertical Resolution Near Surface

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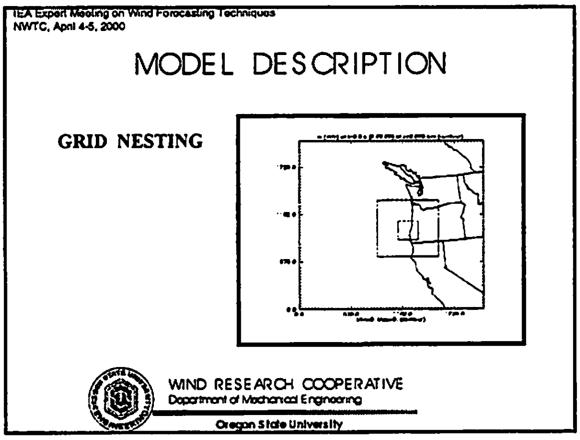

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MODEL DESCRIPTION

GRID NESTING

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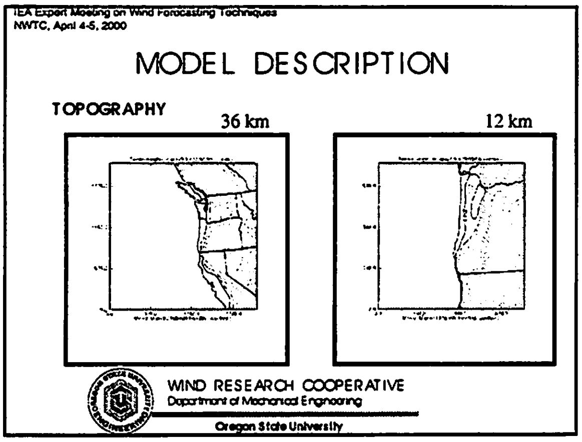

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MODEL DESCRIPTION

TOPOGRAPHY

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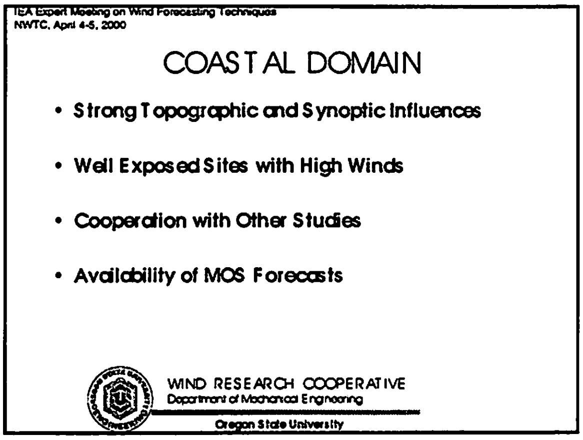

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COASTAL DOMAIN

- Strong Topographic and Synoptic Influences
- Well Exposed Sites with High Winds
- Cooperation with Other Studies
- Availability of MOS Forecasts

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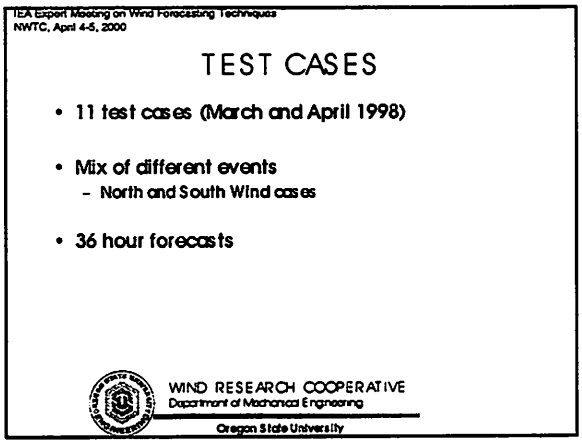

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TEST CASES

- 11 test cases (March and April 1998)
- Mix of different events
  - North and South Wind cases
- 36 hour forecasts

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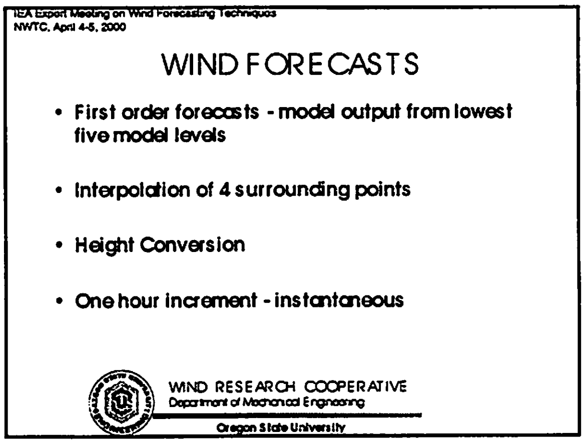

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WIND FORECASTS

- First order forecasts - model output from lowest five model levels
- Interpolation of 4 surrounding points
- Height Conversion
- One hour increment - instantaneous

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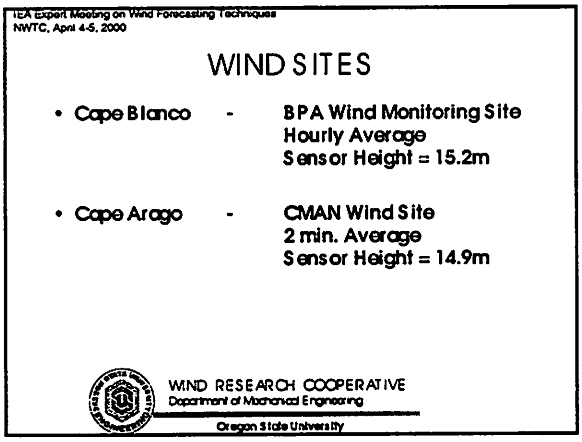

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WIND SITES

• Cape Blanco	-	BPA Wind Monitoring Site Hourly Average Sensor Height = 15.2m
• Cape Arago	-	CMAN Wind Site 2 min. Average Sensor Height = 14.9m

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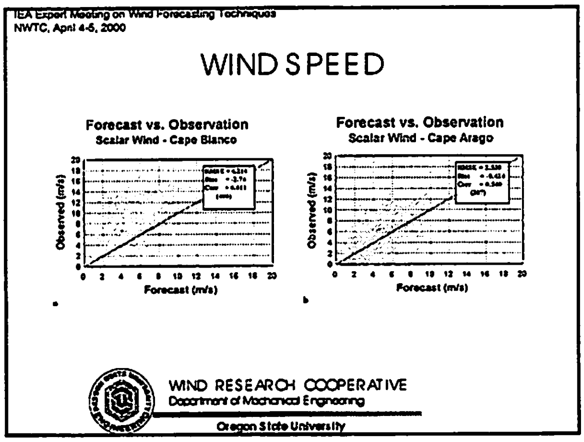

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WIND SPEED

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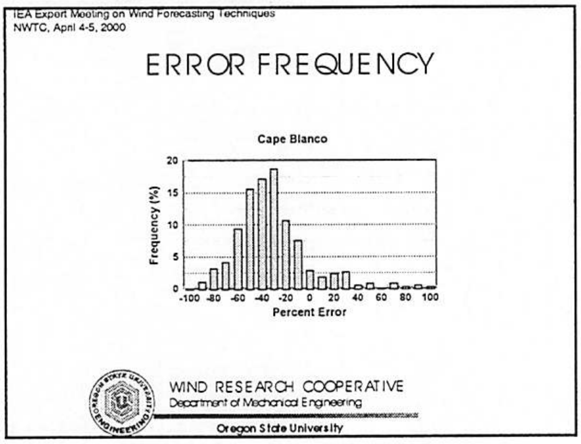

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ERROR FREQUENCY

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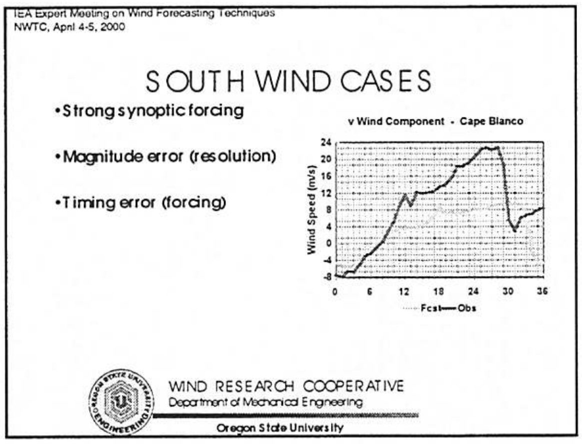

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SOUTH WIND CASES

- Strong synoptic forcing
- Magnitude error (resolution)
- Timing error (forcing)

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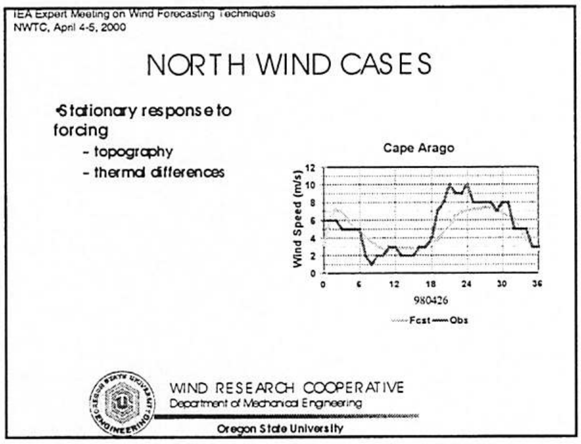

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NORTH WIND CASES

- Stationary response to forcing
  - topography
  - thermal differences

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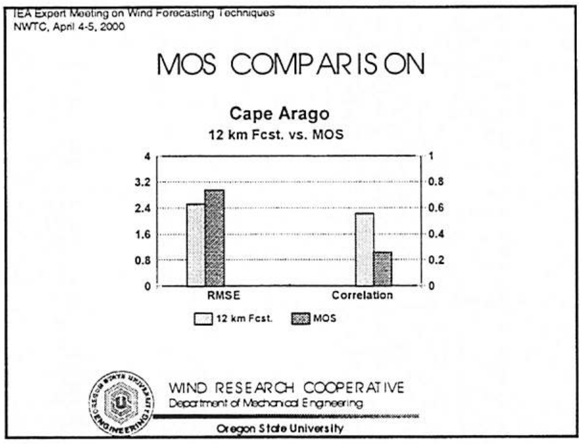

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MOS COMPARISON

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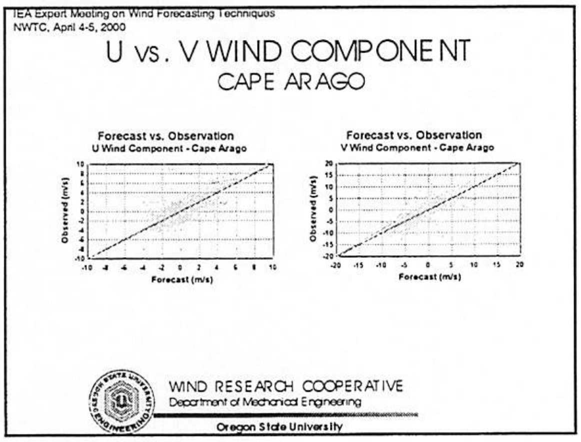

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U vs. V WIND COMPONENT
CAPE ARAGO

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Conclusions / Current Work

- Dynamic Model / Regional Model approach shows potential for forecasting.
- More Cases, statistical corrections needed
- Application to wind resource areas.

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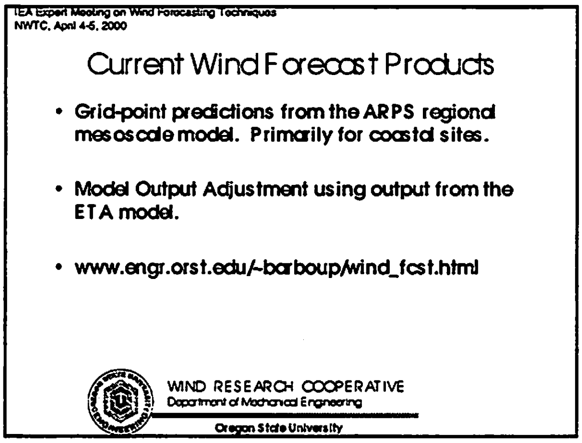

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Current Wind Forecast Products

- Grid-point predictions from the ARPS regional mesoscale model. Primarily for coastal sites.
- Model Output Adjustment using output from the ETA model.
- www.engr.orst.edu/~barboup/wind_fcst.html

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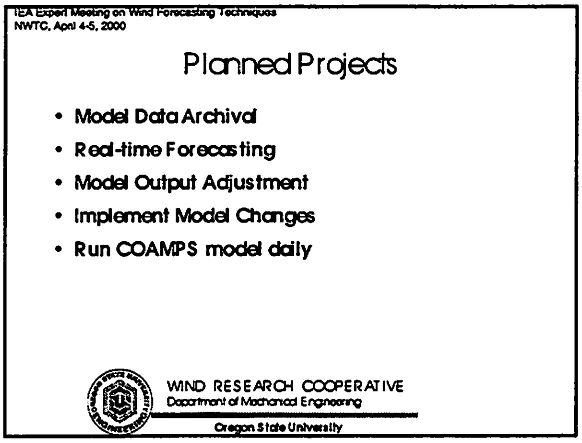

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Planned Projects

- Model Data Archival
- Real-time Forecasting
- Model Output Adjustment
- Implement Model Changes
- Run COAMPS model daily

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Short-term prediction towards the 21st century

SYNOPSIS A new chapter in the continued and exiting story of short-term prediction has begun! The paper will describe a new project funded by the Danish Ministry of Energy where all the Danish utilities (Elkraft, Elsam, Eltra, and SEAS) will participate. The goal of the project is to develop and implement on-line a prediction system combining the Risø and IMM models. This will ensure that the best forecasts are given on all prediction horizons form the short range (0-9 hours) to the long range (36-48 hours).

INTRODUCTION

Electrical utilities, wind farm owners, green certificate and power traders and everybody else with a commercial interest in wind energy must realise that – in a marked which expands 30% every year – the variability of the wind and thereby the power production must be dealt with as efficiently as possible.

There is no doubt that if one is a utility with more than 10% of the electrical power coming from wind energy the variability is a real problem; but recently also new players have come on the marked. This is because of the opening of the electrical market. These players include the wind farm operator who must give accurate estimates of the expected production in order to avoid severe penalties imposed by the power buyers.

One way of handling the variability is to predict the expected wind energy produced power well into the future, ie up to two days in advance. This is possible now (as first demonstrated in [1]) using numerical weather prediction (NWP) models.

This paper will describe a new model which is under development in a co-operation between Risø and IMM and all the Danish electrical utilities. The paper will also begin by briefly outlining what today is considered state-of-the-art.

STATE-OF-THE-ART

Presently there are two models to predict the power production from wind farms in operation at electrical utilities and these are both considered state-of-the-art:

1. The Risø model
2. The IMM model

The two models both use weather predictions from NWP models (here the Danish Meteorological Institute HIRLAM model) as input. The way this input is used is different for the two models:

The Risø model uses mainly physical relations to transform the predicted wind into predicted power: the geostrophic drag law, the logarithmic wind profile, WAsP corrections for local influences, PARK calculations for actual wind farm output. The results are corrected using a mathematical filter (a MOS filter). The model predicts for individual wind farms or groups of wind farms representing an area.

In *the IMM model* statistical methods are applied for predicting the expected wind power production in a larger area using online data covering only a subset of the total population of wind turbines in the area. The approach is to divide the area of interest into sub-areas each covered by a wind farm. Predictions of wind power with a horizon from half an hour up to 39 hours are then formed for the individual wind farms using local measurements of climatic variables as well as meteorological forecasts of wind speed and direction. The wind farm power predictions for each sub-area are subsequently up-scaled to cover all wind turbines in the sub-area before the predictions for sub-areas are summarized to form a prediction for the entire area.

THE PROJECT

The present paper describes a modeling system which will be developed in a project funded by the Energy Research Programme (EFP) under the Danish Ministry of the Environment and Energy. The title of the project is "Wind farm production predictor" and it has as its aim to develop a model which is a combination of the two models mentioned above and implement the system at all the Danish utilities.

The partners in the project are:

- Risø National Laboratory (coordinator)
- Institute of Mathematical Modeling at the Danish Technical University
- Elkraft, utility
- Elsam, utility
- Eltra, utility
- SEAS, utility

These partners give a good blend of research and industry.

The project started in April 1999 and will run for three years. The first version of the new model is expected to be ready in April 2000. The project involves 94 man months of work.

WHY A NEW PREDICTION SYSTEM?

The main goal is to merge the two state-of-the-art models (Risø's and IMM's), to obtain synergy between the physical and the statistical approach. This will give reliable forecasts on the short (0-9 hours) as well as the long term (24-48 hours).

Since the two "old" models were developed a lot has changed on the programming side as well, so the opportunity is taken to implement the newest programming methods: A Client/Server architecture build as Java Beans, connected to a SQL database interfaced via JDBC (see later for details).

A last advantage is that by developing a uniform model for all the Danish utilities, all efforts are focused on this model, which gives the best possible improvements and easier maintenance.

THE NEW SYSTEM

There are two aspects of the new system: the mathematical model and the system architecture. Both of these will be described in the following.

The model

This section describes how a prediction model covering the total wind power production in an area can be derived. The approach is to divide the area of interest into a number of sub-areas. Predictions of wind power with a lead time from half an hour up to 48 hours are then formed for the individual sub-areas using data of the local power production as well as weather forecasts for the sub-area. The power predictions for each sub-area are then summarized to form a prediction for the entire area.

In the model setup described in the following it is assumed that data will be available from three sources:

- Weather forecasts for some selected climatic variables – primarily wind speed and wind direction.
- On-line measurements of power production in a number of (reference) wind farms in the area. Each sub-area

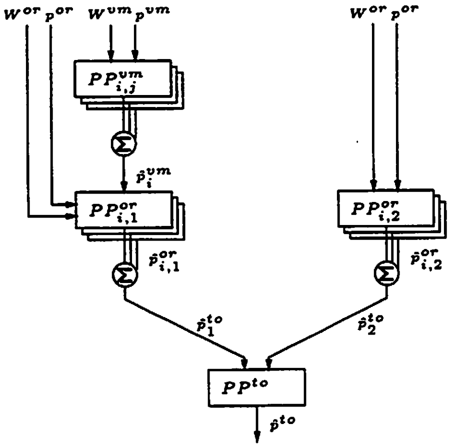

Figure 1: Model overview.

  must include at least one of the reference wind farms.

- Hourly sums of the power production for the entire population of wind turbines in each sub-area. These data will be available on a daily basis, i.e. they are not on-line measurements.

With data from these sources in hand a prediction model for the total wind power production in the area can be derived as illustrated in Figure 1. The model consists, as it is seen from the figure, of two model branches each providing a prediction of the total power production in the area but using different input data.

In the left hand model branch a dynamic wind farm prediction model ($PP^{vm}_{i,j}$) calculates predictions of the power production for the individual wind farms in a sub-area using local measurements of power production and weather forecasts. The wind farm prediction model can be written as

$$\begin{aligned}\hat{p}^{vm}_{t+k|t} &= a(k,\theta^{vm}_{t+k|t})\cdot F(p^{vm}_{t}) + \\ &\quad b(k,\theta^{vm}_{t+k|t})\cdot P^{vm}(W^{wm}_{t+k|t}) + \\ &\quad m(k,\theta^{vm}_{t+k|t}) \qquad (1)\end{aligned}$$

where $\hat{p}^{vm}_{t+k|t}$ is the predicted power production at time $t+k$ given at time t, p^{vm}_{t} is the observed power production at time t, $F()$ is a low-pass filter function, $W^{vm}_{t+k|t}$ are the local weather forecasts for the wind farm at time $t+k$ given at time t, $P()^{vm}$ is an estimated power curve function (see below) and finally $a()$, $b()$ and $m()$ are smooth functions of prediction horizon k and forecasted wind direction. The functions $a()$, $b()$ and $m()$ are unknown and has to be estimated (See [3]). The functions must depend on k as the uncertainty of the weather forecasts increases as the prediction horizon grows.

The predictions for the individual reference wind farms in the sub-area are summarized and subsequently up-scaled by $PP^{or}_{i,1}$ to cover all wind turbines in the sub-area. Here $PP^{or}_{i,1}$ describes the static relationship between the total power production in a sub-area and the predicted power production for the related reference wind farms as a function of local weather forecasts. The upscaling model is given as

$$\begin{aligned}\hat{p}^{or}_{t+k|t} &= b(k,w^{or}_{t+k|t},\theta^{or}_{t+k|t})\cdot\hat{p}^{vm}_{t+k|t} \\ &\quad +m(k,w^{or}_{t+k|t},\theta^{or}_{t+k|t}) \qquad (2)\end{aligned}$$

where $\hat{p}^{or}_{t+k|t}$ is the predicted power production for the sub-area at time $t+k$ given at time t and $b()$, $m()$ are smooth functions of prediction horizon and local forecasts for the sub-area of wind speed and wind direction.

The total power prediction for the left hand model branch is subsequently found by summarizing the power predictions for the individual sub-areas.

The right hand model branch does not, as opposed to the left hand side, rely on online observations. Instead the power predictions for the sub-areas are calculated using the sub-area prediction model $PP^{or}_{i,2}$, which describes the static relationship between the total power production in the sub-area and local weather forecasts. The sub-area prediction model is given as

$$\hat{p}^{or}_{t+k|t} = P^{or}(W^{or}_{t+k|t}) \qquad (3)$$

where $W^{or}_{t+k|t}$ are local weather forecasts for the sub-area at time $t+k$ given at time t and $P()^{or}$ is an estimated power curve function (see below). Once again the prediction of the total power production is found by summarizing the power predictions for the individual sub-areas.

The power curve for the wind farms and the sub-areas referred to above is given as

$$\begin{aligned}\hat{P}^{xx}(W^{xx}_{t+k|t}) &= m(k,w^{xx}_{t+k|t},\theta^{xx}_{t+k|t}) \\ &\quad +b(k,w^{xx}_{t+k|t},\theta^{xx}_{t+k|t}) \\ &\quad \cdot S^{xx}_{t+k|t} \qquad (4)\end{aligned}$$

where xx means either vm (wind farm) or or (sub-area), $S^{xx}_{t+k|t}$ is a local forecast of a stability measure (to be determined) and finally $b()$, $m()$ are smooth functions of prediction horizon as well as local forecasts of wind speed and wind direction.

Comparing the predictions from the two branches it is expected that the predictions calculated by the left hand branch will be superior for the shorter predictions horizons as they are anchored to "the real world" via the on-line power observations, whereas the opposite is expected to be true for the longer prediction horizons. The final power prediction for the total area is calculated by PP^{to} using the predictions from the two model branches as input. Using mean square error (MSE) as a measure this could be done simply by picking the best of the two predictions for the individual prediction horizons, or at bit more sophisticated by calculating the final prediction as the weighted average of the predictions from the two branches using MSE^{-1} as weighting.

The system architecture

Experience from the Danish utilities Elsam and Elkraft with the use of the existing prediction systems developed by Risø and IMM has shown that the prediction system needs to be highly flexible. Demands, such as the simultaneous use by several users, call for a Client/Server architecture, where all data assimilation and numerical calculations are performed by the server, and multiple clients can connect to the server for retrieving and viewing the predictions. Furthermore, to evaluate the performance of the models, it has to be possible to show historical predictions against the actual observations and the current status of wind farms connected to the system, e.g. in case of a wind turbine failure. Therefore the server will be responsible for maintaining a database of all relevant data collected by the system, which can be retrieved from the server and shown as e.g. tables or plots by the client.

Other features required by the Danish utilities include the possibility to add or remove wind farms to or from the system while the system is on-line, the possibility to include meteorological stations, to contain wind farms with different properties, e.g. farms where data is received hourly, and wind farms where data is only received once a day. Also, depending on the type of measurement at different wind farms, these could get different prediction models assigned. Furthermore, it should be possible to configure the system to use input from different numerical weather prediction models. The number and type of prediction models running in the system should be configurable, and each user should be able to configure personal client settings, e.g. which prediction model to use and if he wants to look at all the wind farms in the system or only a subset.

Based on all these requirements, the system will be implemented in an object oriented programming (OOP) language, which supports a Client/Server architecture and features a full set of graphical components for building GUIs (Graphical User Interfaces). The system (at least the clients, but preferably also the server) should run on various platforms.

Therefore, it has been decided to use the Java(tm) 2 platform from Sun Microsystems [2] for the implementation of the prediction system application. The graphical user interface will be based on the Swing package in the JDK(tm) 2 release from Sun, the Client/Server architecture will be implemented using RMI (Remote Method Invocation) and EJB (Enterprise Java Beans). An SQL (Structured Query Language) database, which supports the JDBC (Java Database Connectivity) interface, will be used for the data storage.

Figure 2 illustrates the Client/Server configuration, using Java technology that complies with open standards. This implies that the system becomes platform independent, and hence the server can run on a Unix workstation as well as on Windows NT workstations, while multiple clients running under different operating systems can connect to the server.

Figure 3 focuses on a lower level of detail in the system. It illustrates how different

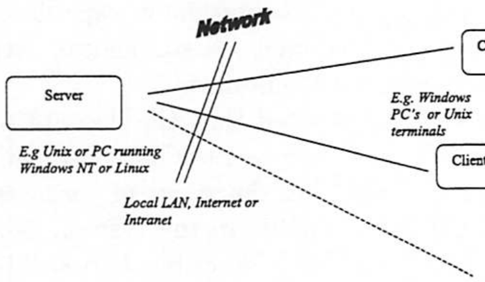

Figure 2: The Client/Server configuration using Java technology.

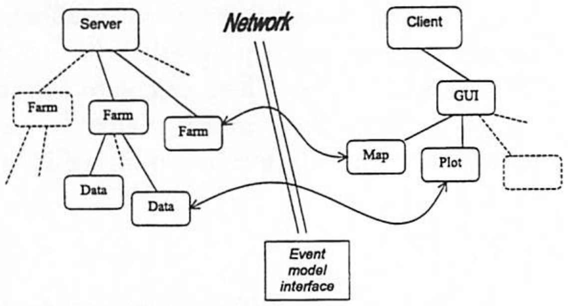

Figure 3: The linking of the different components in the system.

components in the system are linked. The server holds a reference to all modules on the server side of the application, e.g. all the farm modules, which are responsible for running the farm level mathematical models, and modules running mathematical models calculating the total power predictions. Each time the model is updated, this should be reflected in the GUI components in the client, e.g. a component showing the current state of a wind farm (production, wind direction, etc.), or a plot showing the total power predictions. This is accomplished by using an *event model* over the RMI interface. All client components, which are interested in notification when a component running on the server is updated, register themselves as *listeners* to this server component. The server component maintains a list of all interested listeners, and each time the server component is updated, it runs through the list calling all listeners to notify that an update or change has occurred.

Using this concept throughout makes it easy to build a highly dynamical system. The components in the server do not need to worry about the actual implementation of a large number of components in the client, and which components will need to be notified or not, since the client components decide themselves. Figure 4 shows a snapshot of a preliminary GUI, which serves as an illustration of how the actual GUI will be implemented.

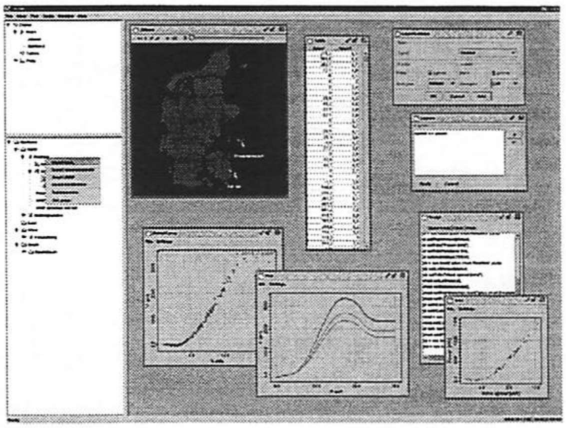

Figure 4: Snapshot of the GUI.

Figure 4 shows a screen shot of the graphical user interface (GUI) implemented in the Zephyr system. The GUI layout is project oriented, where a project is illustrated by a project tree. The system operates with two project definitions, and these two projects are illustrated by graphical tree components on the left hand side of the GUI. The lower left tree illustrates the project defining the system setup of a particular utility, and the tree in the upper left corner illustrates the project of a particular user.

The system setup of a particular utility is organized hierarchically. The basic objects in the system setup tree are regions, wind farms and tables of data, where data related to the regions and the wind farms are stored. The region objects defines the properties of a larger region, containing one or more wind farms. The properties of a region are eg the wind farms in the region, the model which is used to calculate total power predictions for the region and tables of measured and predicted total power production for the region. Similarly, the wind farm object contains properties of a wind farm, like the model for calculating the wind farm power predictions, and tables of data containing measured variables at the wind farm. Furthermore the wind farm object contains the state of the wind farm, ie if the farm is currently running or not and the current wind farm power production. The system setup is customisable via the system setup tree and node specific popup menus, allowing superusers to customise the system setup, ie wind farms can be added or removed, regions can be redefined, the models connected to the wind farms and the regions can be changed and so on. This changes are applied at runtime, and the system does not need to be restarted.

The user project tree holds the structure and definition of the windows which are shown in the right hand side of the GUI, each window is illustrated by a node in this tree. The user has the option of customising how the windows are organized to fit his or her's particular needs, by inserting, moving and deleting the position of the window nodes in the user project tree. Apart from the default windows defined by the system, like the wind farm window, windows showing plots of predictions and measurements, the user can create customized windows either using scripts or via dialog windows. When a new window is created, the user has to select the node in the tree where the new window will be placed as a sub-node. Each user is not limited to having only one project tree, the user project tree can be saved and loaded, allowing the users to operate with several trees, i.e. the user can define several user trees, where each tree is fitted to one particular operational situation.

The left hand side of the GUI screen shot shows some of the windows in the system. The windows shown are the map window, a table window, power curve scatter plots and power curves plots derived from models, the script window and the dialog windows used to create customized plots. The map window shows the area which the system is operation on. This map contains wind farm symbols, which illustrate the current running conditions at the wind farm, ie the wind farm status. Furthermore, the map window servers as as background for weather animations created from the weather predictions. The current implementation is capable of showing the predicted meteorological variables as contour animations.

It should be noted that the description of the system in this section has only been meant to illustrate the type of features, which will be available in the system. Several other features not described here will be implemented in the actual system, as well as what has been described here might change slightly, as the applications is still in the design phase. The modular design of the application, where e.g. wind farms with different characteristics can be plugged in to one or more total modules, which calculate the total power predictions, makes it easy to customise the application to different utilities.

SUMMARY

This paper has described a new system to predict the power output from wind farms. The system is being developed in a EFP-funded project which has Risø and IMM as the modeling team and all the Danish utilities as partners and users.

The mathematical model in the system is dual stringed, combining a model which uses predictions from a weather prediction model and on-line observations on the one side and weather predictions only on the other side. This is to give as accurate as possible predictions on both the short- and the long-term.

The system is designed as a Client/Server architecture, using the newest programming techniques which include: Java, Java Beans, RMI (Remote Method Invocation) and a SQL database supporting the JDBC interface. This design gives a very high degree of flexibility allowing the users to customise the system exactly to meet his or her requirements.

The final system will be ready in 2002, and the first version is expected on-line and operational in 2000.

ACKNOWLEDGEMENTS

The development of the prediction system is funded by the EFP-programme under the Danish Ministry of Energy and the Environment, contract number 1363/99-0017. Previous version of the models have been supported by the Danish EFP and European Union JOULE programmes.

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Short-term prediction of local wind conditions

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ABSTRACT: This paper will describe a prediction system which predicts the expected power output of a number of wind farms. The system is automatic and operates on-line. The paper will quantify the accuracy of the predictions and will also give examples of the performance for specific storm events. An actual implementation of the system will be described and the robustness demonstrated.

Keywords: Short-term prediction, wind farm power output, HIRLAM, WAsP, MOS

1 INTRODUCTION

In many areas of wind engineering predictions of the wind one to two days in advance have become important. These areas include wind energy where electrical utilities with a high wind energy penetration need this information in their scheduling. Transport of large structures as well as other high or low wind dependent engineering situations spring to mind as other possible applications.

A prediction model, called Prediktor, has been developed to this end and this paper will describe the model in some detail, but the main focus will be on the performance and operational aspects of the implemented model. The on-line implementation was carried out in an EU JOULE-funded project.

2 THE MODEL

This section will describe the model: the idea behind it and the equations used. Furthermore, an actual online implementation will be described.

2.1 *The model*

The method for predicting the output of a wind farm is outlined in Figure 1. The idea is to use physical models as 'far' as possible, this is done such that the large-scale flow is modeled by a NWP (Numerical Weather Prediction) model, here HIRLAM (Machenhauer 1988) of the Danish Meteorological Institute (DMI); the wind is transformed to the surface using the geostrophic drag law and the logarithmic profile. As we zoom in on the site more and more detail is required, this detail is provided by the Risø WA$^{\rm S}$P program (Mortensen et al 1993). WA$^{\rm S}$P takes local effects (lee from obstacles, effect of roughness and roughness changes and speed-up/down of hills/valleys) into account. To take the shadowing effects of turbines in a wind farm into account the PARK program (Sanderhoff 1993) of Risø is used. Finally, to take any effects not modeled by the physical model and general errors of the method into account two model output statistics (MOS) modules are used. The model is described and analysed in great detail in (Landberg 1999, Landberg & Watson 1994, Landberg 1998).

2.2 *The implementation*

To demonstrate that it is possible, not only to obtain accurate predictions of the wind farm production, but also to use these predictions in an on-line environment, the model was implemented at Risø. The implementation is outlined in Figure 2. The principle is that as soon as the over-all meteorological situation has been predicted by DMI's operational HIRLAM model the forecasts are transmitted via Internet e-mail to Risø. Here a UNIX computer, dedicated to the task, registers the arrival and executes the Risø prediction model, the calculation module then sends the predictions to the output module which generates pages containing the predictions in graphical as well as textual form written in HTML (Hyper Text Mark-up Language). These pages are uploaded to a Web-server accessible via any Web browser (as eg Netscape and Internet Explorer). The address is not public and the site has no links pointing to it, so only utilities with permission can view the predictions. If the information contained on the pages at some point will be con-

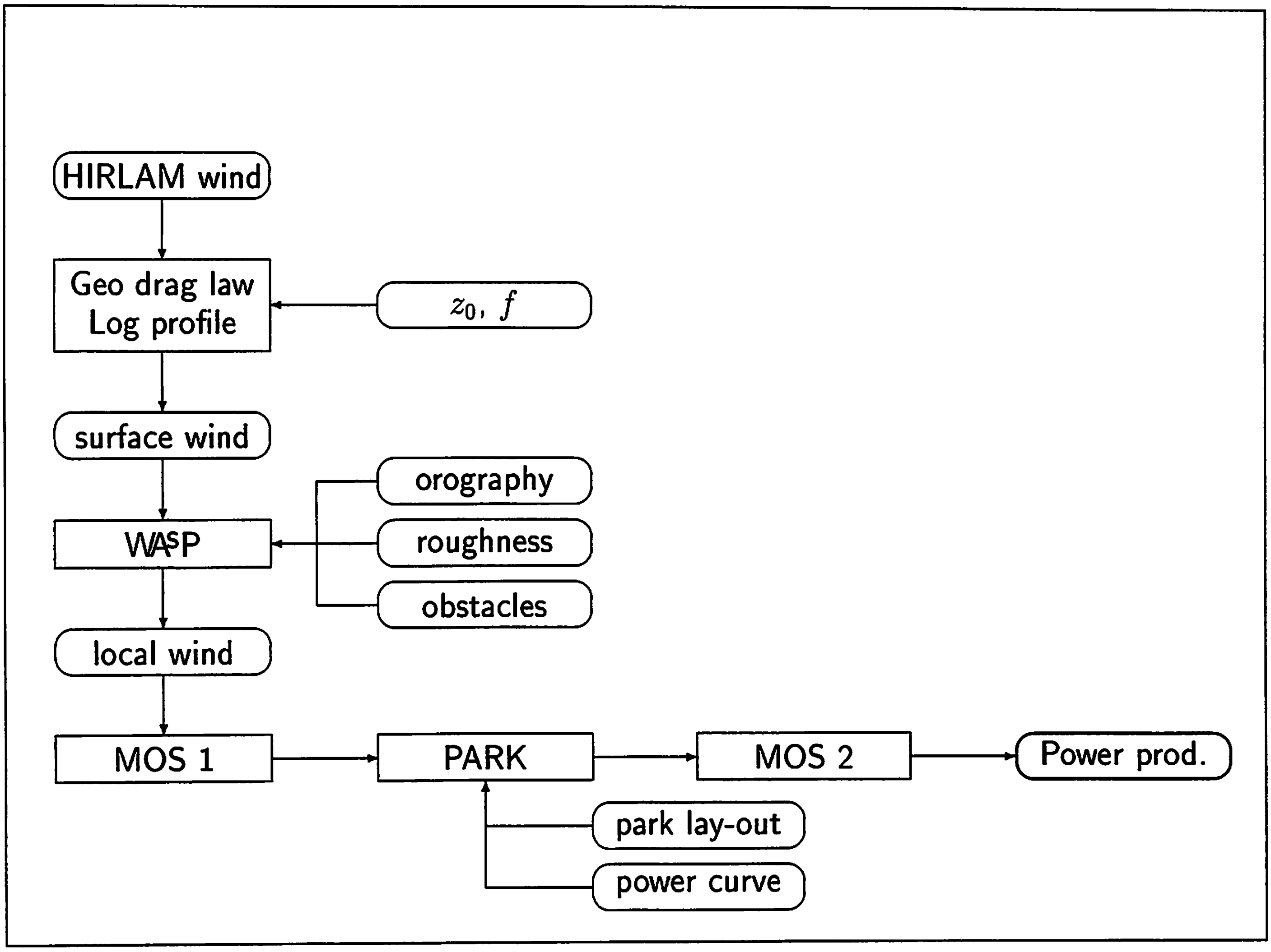

Figure 1: Flow chart describing the idea behind the model. The prediction from HIRLAM enters at the top and is transformed to the local wind moving down the figure, the production (including shadowing effects from the wind farm) is calculated moving along the bottom line. From (Landberg 1999).

sidered requiring a higher level of security, it is very simple to change the site to be password protected.

Predictions are made for the 47 wind farms shown in Figure 3 and the model is run twice a day generating predictions 36 hours ahead each time.

The model is implemented in such a way that a new wind farm can be added in a matter of a few minutes, HIRLAM predictions for the new site are typically available within 24 hours.

Each wind farm can also be changed to represent a region instead of just itself, this is done by scaling the power output with a factor, determined by the total installed capacity of the wind farms in the region.

The on-line predictions are available to the two Danish utilities, and since the focus of the Risø model is on the Elkraft area, the Elkraft utility is the one which has used the predictions in their daily planning and dispatch. This has been going on for seven months now (Feb 99).

3 RESULTS

In this section the quality of the model will be assessed in two ways: the standard way of comparing actual productions to predicted, but also by trying to see how successful the on-line implementation has been. At the end of the section another way of assessing the accuracy and usefulness will be described briefly.

3.1 *Accuracy*

The model has now run for two entire years and it is possible to draw some firm conclusions as to its performance. For independence of the evaluation, the model is evaluated on one year's worth of data taken from the Elkraft SCADA system. The wind farm observations are recorded every hour.

To get an estimate of the skill of the model the predictions are compared to those of the *persistence* model, which is a very simple model stating that

$$P(t+\ell) = P(t) \tag{1}$$

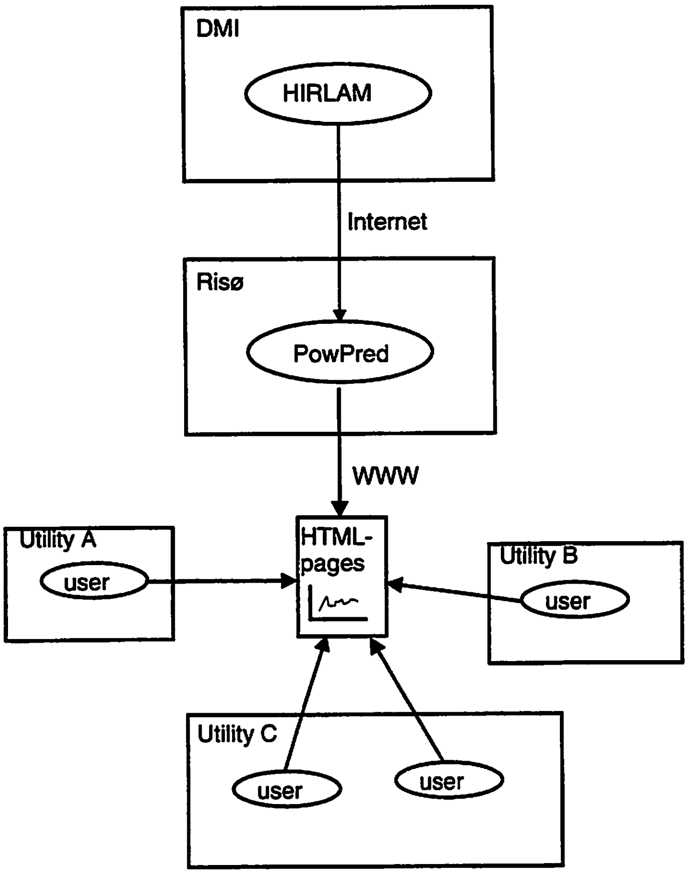

Figure 2: The on-line implementation. See text for details.

where $P(t)$ is the production at time t and ℓ is the look-ahead time. This model could popularly be called the 'what-you-see-is-what-you-get' (WYSIWYG) model! Despite its seeming simplicity, this model describes the flow in the atmosphere rather well, due to the characteristic time scales of weather systems; it is often experienced that the weather in the afternoon is the same as it was in the morning, so for some typical weather situations it is a rather difficult model to beat.

The results of the comparison between the two models for the Nøjsomhedsodde Wind Farm are shown in Figure 4 where the the mean error and the absolute mean error (=|predicted − observed|, a measure of the scatter, giving less weight to outliers than the standard deviation) of the prediction model are compared to those of the persistence model. The following can be seen:

- The prediction model outperforms the persistence model after six hours.
- The mean absolute error of the prediction model is around 15% of the installed capacity.
- The decay of the performance of the prediction model is very gentle, over the 36 hour time-span the error is only increased by less than 10%.
- The mean error of the persistence model is very small. This follows from the definition of the persistence model.

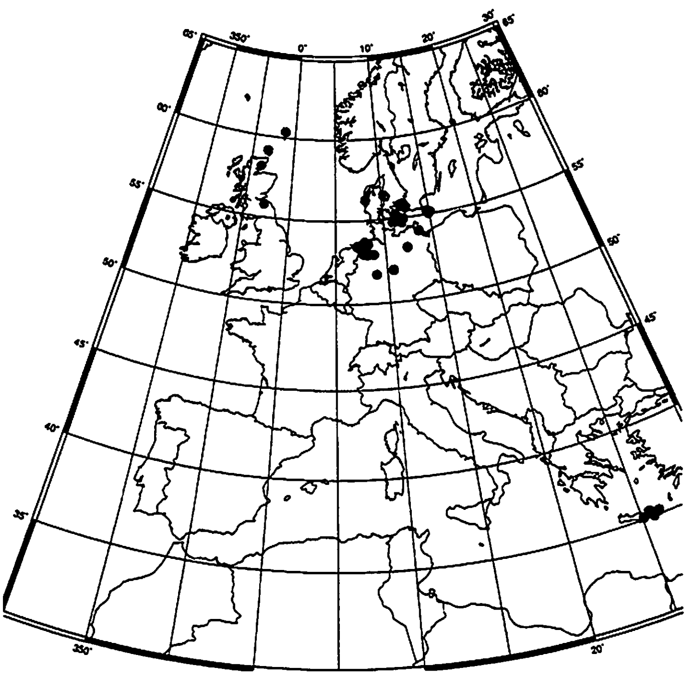

Figure 3: The location of the 47 wind farms. The wind farms are located in Denmark, United Kingdom, Greece and Germany.

These predictions are not the best and not the worst examples of the performance, a well-predicted wind farm has a scatter as low as 10% of the installed capacity and a not-so-well-predicted up to 20%.

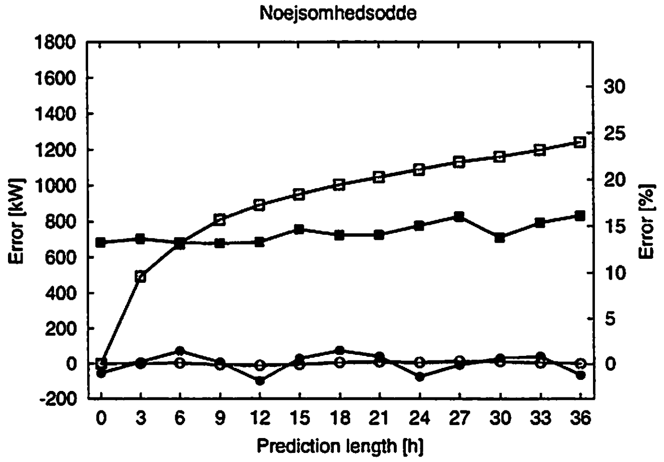

Figure 4: The mean error (circles) and the mean absolute error (squares) for the prediction of the power output of the Nøjsomhedsodde Wind Farm for the prediction model (filled symbols) and the persistence model (open symbols). The left-hand y-axis shows the absolute numbers (in kW) and the right-hand axis the numbers relative to the total installed capacity (in %). One year's worth of data has been used in the comparison. The farm is rated at 5.2 MW.

One very important feature which can not be seen from this figure is how well the model predicts storms.

Here the persistence model has no chance, since it assumes status present. In a previous study (Landberg & Joensen 1998) all storms in 1997 and 1998 in the period 1 Jan 97 to 1 Aug 98 were identified for the Avedøre Wind Farm and the performance of the prediction model was evaluated in qualitative terms. The result can be found in Table 1.

The definition of 'storm' is here taken to mean an event where the production rose from a very low value (ie close to 0 kW) to around 3 000 kW (approx. 80% of the total installed capacity) and then down again to a low value over a period of a few days. Using this selection criteria 7 storms were found in 1997 and 9 in the first seven months of 1998.

These 16 storms are depicted as "thumb-nail images" in Figures 5 and 6 and listed in Table 1.

Studying the data in detail reveals that of the seven storms in 97 two were predicted very well and one was predicted satisfactorily. In 98 five were predicted very well and three satisfactorily. This is very much in line with the results found for the wind speed at the Risø mast: in the first half of 1997 the HIRLAM model had problems, which then seem to have been fixed.

The results shown here differ slightly from the results in (Landberg & Joensen 1998), in that the cases where cut-out (ie the wind is so high that the turbine must stop in order to avoid structural damage) was originally predicted are now removed, since the model has been changed to reflect the fact that cut-out very seldomly is seen in the observations. It is critical to get this right, of course, since missing a cut-out situation will make an enormous difference for the dispatch, by either predicting 100% production (no cut-out) or 0% prediction (cut-out).

3.2 *Track record/reliability*

This section will focus on some operational aspects of the implementation.

The results from the HIRLAM model are typically available after 2 hours, the transit time between DMI and Risø is typically less than a minute and the prediction model runs in less than two minutes for the predictions to be calculated and another two minutes for the web-pages to be generated, the upload is instant. So, typically around two hours after the measurements have been taken at a large number of places around the Northern Hemisphere the predictions are available to the utility.

The system has run operationally for more than two years, with no break-downs. One planned shut-down took place, when the operating system was upgraded. The only problems have occurred when the DMI forecasts have been delayed for some reason. It is of course not possible to do anything about this from the utility side, so the times different from two hours are an indication of how often this occurs.

Figure 7 shows the distribution of the delay time, as can be seen, most of the time the delay is around two hours and after four hours 90% of the predictions have arrived. There are some outliers, and as mentioned earlier all of them are due to the fact that the HIRLAM predictions were delayed.

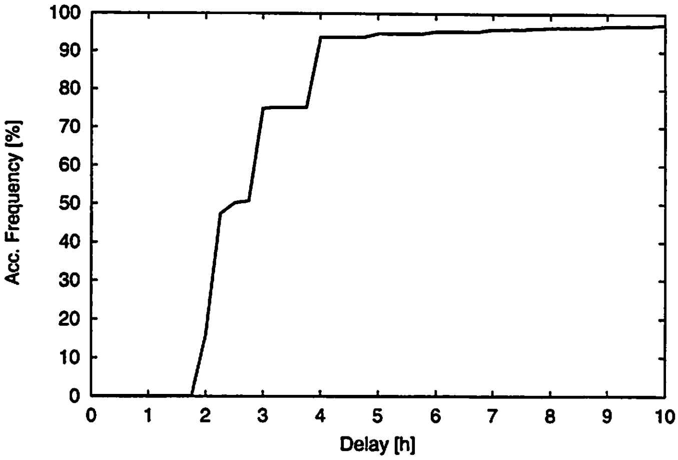

Figure 7: Accumulated distribution of the delay time of the predictions from the E (previously called DKV) version of the HIRLAM model.

3.3 *Savings in fossil fuel*

Another very important way of accessing the accuracy from a utility point of view is to see how much conventional fuel and thereby money is saved because of the predictions, other papers are dedicated to this, see (Watson et al 1994, Watson et al 1999). The main conclusion is that significant savings are indeed found, the higher the penetration the higher the savings. Typical results are that the use of predictions becomes significant at 25% penetration (note that many areas today have a penetration of more than 20%) and that the savings are more than 25% higher than just using persistence.

4 THE FUTURE

At present the model is used as-is in a JOULE project, predicting the power for 13 wind farms in Germany (location of the wind farms is shown in Figure 3).

For the very near future two model refinements are planned, the first one is a direct improvement of the existing model (described in the following) and the second is a completely new model, where the Risø model described here is combined with the IMM model (Nielsen & Madsen, 1999), this development will be carried out in a project funded by the Danish Energy Agency, with the goal of implementing this model at all the Danish electrical utilities.

Table 1: The storms identified in the period 1 Jan 97 to 1 Aug 98. In the column marked 'Quality' the predictions are graded according to the following: – bad, = OK, + good.

1997 Start	End	Quality	Notes	1998 Start	End	Quality	Notes
7/1	9/1	–	level missed	14/1	18/1	+	
12/1	15/1	–	start-up missed	26/1	29/1	+	
18/3	20/3	=	end missed	15/2	18/2	=	
21/4	24/4	–	missed completely	25/2	2/3	+	
10/5	12/5	–	missed completely	6/3	8/3	=	
17/11	22/11	+		10/3	13/3	–	level missed
25/12	27/12	+		19/3	20/3	=	
				15/6	19/6	+	
				14/7	16/7	+	

It is also hoped that other utilities will be interested, EPRI in the US has already shown interest.

4.1 *Using the 10 m wind as input*

Due to the decrease in grid size and the improvement of the boundary-layer parameterisation of HIRLAM, the level from which the wind has to be taken has changed from when the model was first developed and implemented (see (Joensen et al 1999) for further details). In the original model the wind found in model level 5 (approx. 550 m agl) should be used as the best approximation of the geostrophic wind, now, however, the wind from the lowest level has the smallest scatter when compared to the observed wind at the wind farm site. This means that since the original model had to transform the wind from a geostrophic wind via the geostrophic drag law to the surface the model must be changed, since this transformation has already been done by the HIRLAM model. Referring to Figure 1 the box labeled 'Geo. drag law, Log profile' must therefore be removed. Calculating the mean error and std. dev. of the original model and the model proposed here applied to the Risø mast, the same qualitative picture is found as in Figure 4, however, the predictions using the 10 m wind show a reduction in the standard deviation of typically 20% on the prediction of the wind speed.

5 CONCLUSION

This paper has described an automatic on-line prediction system, Prediktor, for wind farm production output. The model was described and analysed and the performance of it was shown to be good. The on-line implementation was also described and it was shown that the model had been operational for two years with very few interruptions. The predictions have been used by the Danish utility Elkraft for seven months. Lastly, new applications of the model were described.

For up-to-date information about Prediktor, please visit www.prediktor.dk.

ACKNOWLEDGEMENTS

The on-line implementation of the model has been funded by the Commission of the European Communities under the JOULE programme, contract JOR3–CT95–0008. The on-going project in Germany is also funded by the JOULE programme, contract JOR3–CT98–0272. The development of the original model was as funded by the EFP-programme under the Danish Ministry of Energy and the Environment, contract 1363/94–0005 and the JOULE programme, contract JOUR–0091–MB(C). G Giebel, Risø, is thanked for calculating the delay time of the HIRLAM predictions.

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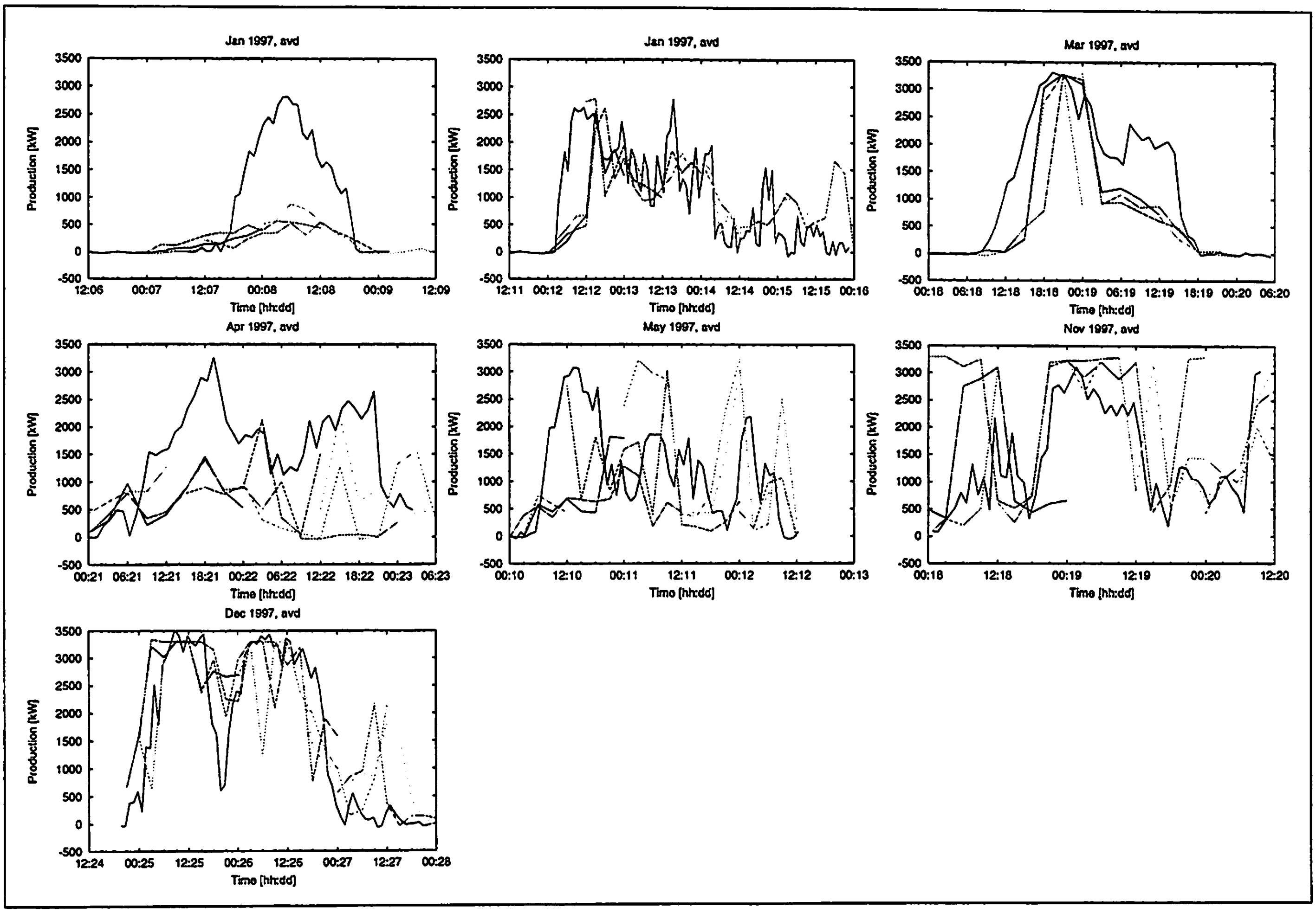

Figure 5: The storms in 1997 as registered at the Avedøre Wind Farm (capacity 3.6 MW). Solid line is the observed production, dashed lines are the predictions.

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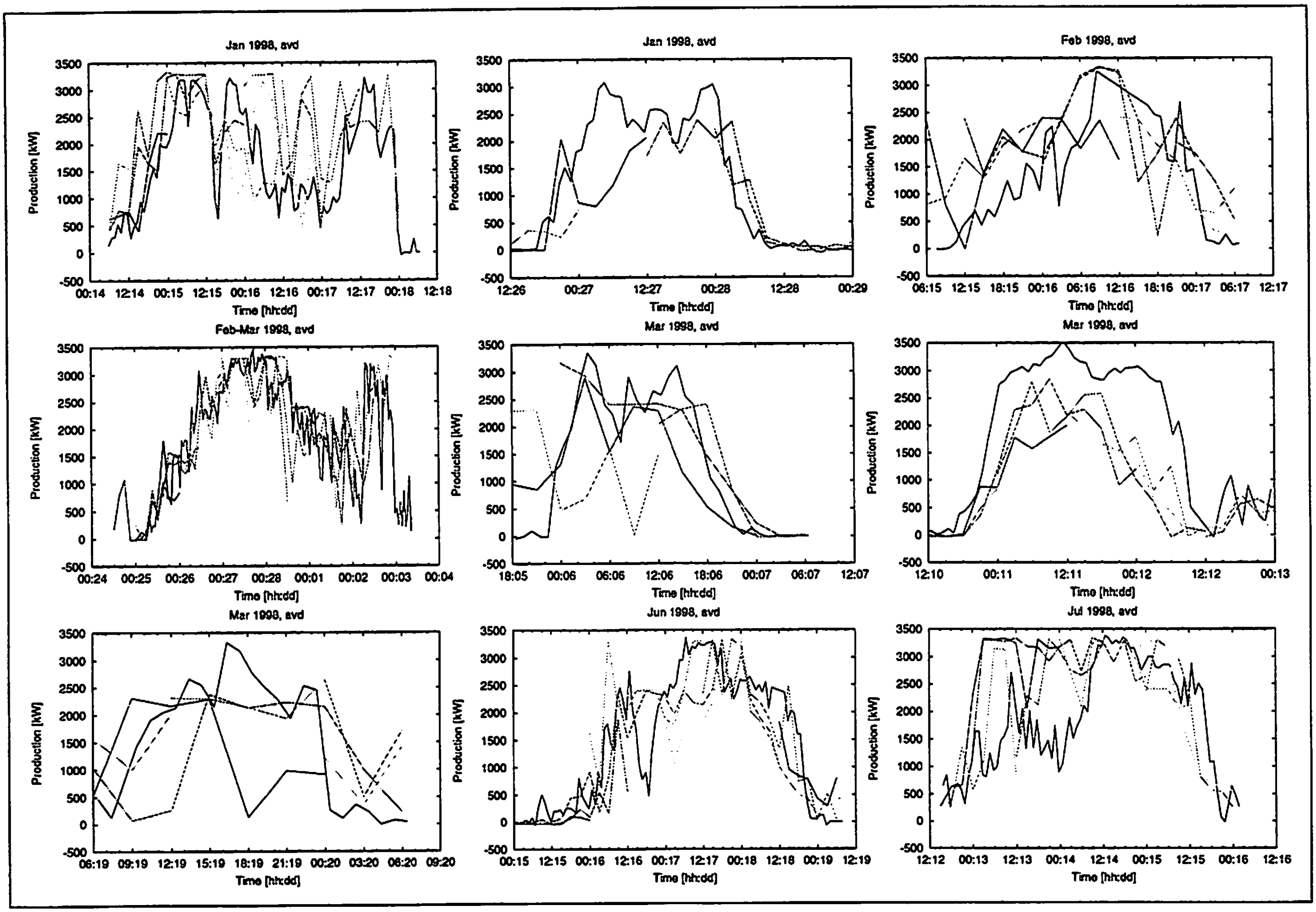

Figure 6: Storms in 1998 (until 1 Aug) as registered at the Avedøre Wind Farm (capacity 3.6 MW). Solid line is the observed production, dashed lines are the predictions.

WPPT, A TOOL FOR ON-LINE WIND POWER PREDICTION

Torben Skov Nielsen[*], Henrik Madsen[*], John Tøfting[†]

Abstract

This paper describes WPPT (Wind Power Prediction Tool), an application for assessing the future available wind power up to 36 hours ahead in time. WPPT has been installed in the Eltra/Elsam[1] central dispatch center since October 1997. The paper describes the prediction model used, the actual implementation of WPPT as well as the experience gained by the operators in the dispatch center.

1 INTRODUCTION

During these years the world experiences an increased interest in power production from renewable sources, and it must be expected, that power production from wind turbines will be of still increasing importance in the future. In the western part of Denmark the installed wind power capacity corresponds to 13% of the total installed capacity and it is foreseen that the amount of wind power will double within the next 10 years. Such a high level of wind energy penetration clearly calls for reliable methods for predicting the future wind power production not only for planning purposes (minimization of spinning reserves, maintenance schedules for fossil fuel power units etc.), but also the marked value of wind energy on Europe's future free energy markets will depend on the availability of such methods.

In WPPT statistical methods are applied for predicting the expected wind power production in a larger area using on-line data covering only a subset of the total population of wind turbines in the area. Our approach is to divide the area of interest into sub-areas each covered by a wind farm (a reference wind farm). Predictions of wind power with a horizon from $\frac{1}{2}$ up to 36 hours are then formed using local measurements of climatic variables as well as meteorological forecasts of wind speed and direction.

The wind farm power predictions for each sub-area are subsequently up-scaled to cover all wind turbines in the sub-area before the predictions for sub-areas are summarized to form a prediction for the entire area.

The WPPT application has been developed as a co-work between Elsam and the Department of Mathematical Modeling (IMM) at the Technical University of Denmark (DTU). The work was initiated in 1992 as a part of a project, *Wind Power Prediction Tool in Control Dispatch Centers*, sponsored by the European Commission. During this project a statistical model utilizing only measurements of wind power and wind speed was developed and together with a graphical user interface implemented at Elsam's control dispatch center at Skærbæk. WPPT version 1 went into operation in October 1994 and was subject to a three months trial period. The experience gained as well as further details regarding the models and user interface developed can be found in [1] and [2]. In short it became apparent that WPPT 1.0 was capable of providing the operators with useful

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[1] Eltra/Elsam is the power distribution/production utility responsible for the power supply in the Western part of Denmark.

predictions up to 8 to 12 hours ahead, but for larger prediction horizons further model development was needed.

In ([3], [4]) physical models describing the wind farm layout and the influence of the surroundings are used in combination with meteorological forecasts of wind speed and direction to make predictions of power production with a horizon of up to 36 hours but their approach had less performance on shorter horizons. In our project it was therefore a natural idea to improve the previous developed models in WPPT by using meteorological forecasts from the national weather service as input to the models.

The paper is organized as follows. Section 2 gives an introduction to the Eltra/Elsam power utility. Section 3 describes the data used in WPPT as well as the data collection system. The methods applied by Elsam when planning with the wind power are presented in Section 4. The estimation methods as well as the developed prediction models for the reference wind farms are described in Section 5 and Section 6, respectively. Section 7 discusses the implementation of WPPT and describes briefly some parts of the user interface. In Section 8 the experience gained by the operators in Elsam's control dispatch center are outlined.

2 FACTS REGARDING ELSAM

From January 1998 Elsam has been divided into two companies. The transmission network is now operated by a separate company, Eltra, which also is the system responsible for the area. Thus, the new Elsam can concentrate on trade, export, production of electricity, and the purchase of fuel. Eltra/Elsam operates in the western part of Denmark (the peninsula Jutland and the island Funen).

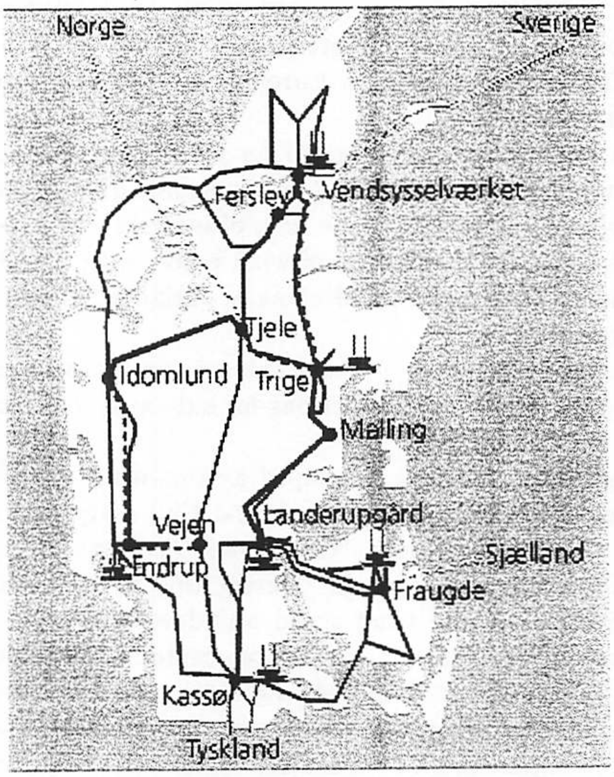


Figure 1: *Transmission network and power stations in the Eltra/Elsam supply area.*

Elsam produces electricity at six Jutland-Funen power stations. Elsam is organized in six divisions:

- *Operation Division:* Plans and operates the production at the six Jutland-Funen power stations which allocates the production capacity at the disposal of Elsam. Together with Eltra production from the local CHP-plants and wind power is handled.
- *Market Division:* Is active in the Northern European energy market. Purchases and sells electricity on long-term contracts and on the spot market.
- *R&D Division:* Is responsible for the technological development in the field of power production.
- *Finance Division:* Co-ordinates the practical financial activities between the individual power stations and responsible for financing investments in plant expansions and the construction of new plants.
- *Fuel Division:* Is responsible for the purchase, transport, handling and storage of fuels (primarily coal, natural gas, and biomass) and the utilization/depositing of the residual products from electricity production.
- *Administration Division.*

A quick overview of the size of the Eltra/Elsam activities as well as the relative importance of the wind power production can be summarized by the following key figures:

Key figures for 1997 (incl. Eltra):

- Electricity consumption: 20.5 TWh.
- Production: 24.8 TWh (primary power stations: 17.6 TWh, local CHP-units: 5.7 TWh, wind: 1.5 TWh).
- Export, net: 4.3 TWh.

Expected key figures for 1998 - Elsam only (approx.):

- Turnover (incl. district heating): 3.6 billion DKK (0.5 billion $).
- Sale of electricity in Denmark: 12,5 TWh.
- Sale of district heating: 35000 TJ.
- Export of electricity: 4 TWh.

Installed power in the Elsam/Eltra area (January 1, 1998):

- Primary power stations: 4625 MW.
- Wind power: 870 MW (incl. utility owned: 125 MW).
- Local CHP units (more than 250): 1300 MW.

The maximum load in 1997 was about 3700 MW.

2.1 Elsam and Wind Power

The era of wind power in Denmark started in 1975 when a carpenter connected his homemade windmill in the backyard to the public network without permission.

In the first years the development was driven by enthusiasm from a growing number of "grass-roots". In the 1980'ties the first industrial manufacturing of windmills started and it is now the fastest growing industry in Denmark.

In 1988 about 100 MW wind power was installed in the Elsam/Eltra-area growing to 870 MW now. This will grow to about 1500 MW in the year of 2005. Today we have only one off-shore park (5 MW) - in the future most of the new parks will be off-shore.

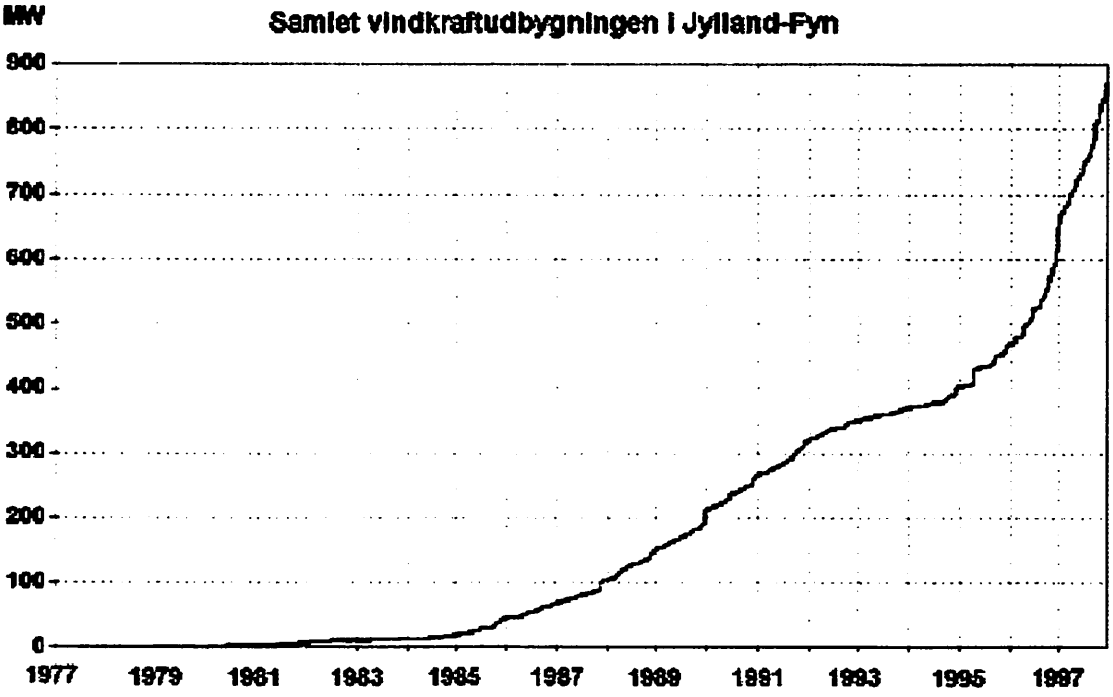


Figure 2: *Development in installed wind power capacity from 1977 to 1997.*

3 DATA AND DATA COLLECTION

For this project 14 wind parks was selected to represent all the wind power in the Eltra/Elsam supply area. The criteria for the selections were geographic distribution and the possibilities to get reasonable data.

From the parks we collect the following measurements:

- wind speed 1.
- wind speed 2 (reserve).
- wind direction.
- air temperature.
- production.

All values are sampled as 5 minute mean values.

The measurements mean values are calculated locally and transmitted to Elsam on the public X-25-network every 5 minutes. This is controlled by a SCADA system from ABB-Denmark at Eltra. This SCADA system is also handling other data as a front-end-system for the EMS/SCADA-system in the Elsam and Eltra Dispatch Centers. The data is converted to ASCII-files and transmitted to the VAX computer running the WPPT software.

Almost all measurements are obtained using new equipment for this project, and is not based on existing equipment in the parks. Our experience is, that such equipment is not stable enough for this purpose.

In any case measurement systems will always be equipment with errors, so WPPT is designed to be robust against errors in data and most important: it produces an error report, when bad measurements are detected. It is also important to have an organization that can handle errors on equipment fast and correctly.

The meteorological forecasts used as input to the models in WPPT are provided by the Danish Meteorological Institute (DMI) using their HIgh Resolution Limited Area Models (HIRLAM) system. The forecasts are updated every 6 hour and cover a horizon of 48 hours ahead with a 1 hour resolution (See [5] for details).

The observations and meteorological forecasts are subsampled, respectively interpolated, to form the 30 minute values used as input to the statistical model for forecasting.

4 Planning with Wind Power

For several years now, Elsam has planned with the power from windmills as production rather than a disturbance/uncertainty on the load. This implies that we, as for the power stations, have to make a "plan" for the wind power production.

In the long term planning (week/months) the production from wind is calculated simply by using the annual mean value of the production. This can in some cases be corrected with the statistical determined diurnal variation.

WPPT (Wind Power Prediction Tool) is used in the daily planning at Elsam and Eltra. Every day the production plan for tomorrow is prepared before noon. One of the inputs for the Economic Load Dispatch calculation is the 36 hours prediction of wind power production from WPPT. The operator in charge of the load dispatch compares the WPPT prediction with the weather forecasts on TV or other sources. The operator decides then the "plan" for wind power production (half-hourly). In general the WPPT system provides very reliable forecasts but reasons for overruling the WPPT-forecasts can be:

- Instability of the weather (high or low pressure domination).
- Consequences of bad predictions (risk of lack of productions capacity or the opposite).
- Obviously bad input data to WPPT (measurements, forecasts from the Danish Meteorological Institute).
- malfunction of WPPT.

When the predictions are bad, the operator on duty has to take care of the difference. He has different choices:

- small differences (< 100 MW) are managed by sending the power stations short
- order message to regulate (Elsam has no AGC (automatic generator control))

- large differences (> 100 MW) are managed by a recalculation of load dispatch and maybe selling/buying with foreign companies (today in Norway, Sweden and Germany)

A special problem in the Elsam-system is a very large amount of combined production of electricity and district heating. This means, that in periods with large heat production, there will be a certain amount of electricity production. In periods with low electricity load (nights and weekends) there is very little "space" for the wind power production. We have several hours during a year, where we have to sell electricity too cheap. We say, that we have an "overrun" of electricity. Being able to predict this situation is very valuable, because it means that a better price can be obtained for the surplus electricity.

To handle the overrun-situation, the operator has some possibilities:

- Sell to foreign companies.
- Change of district heating production to lower the electricity production.
- Use of heat storage.
- Reduce efficiency at power plants (e.g. disconnect high pressure units).
- stop of local CHP units.

The operator has a priority list with the possible operations on each plant to lower the electricity production.

5 Model Estimation

The approach taken in WPPT is to use statistical methods to determine the optimal weight between the on-line measurements and the meteorological forecasted variables in ARX (Auto-Regressive with eXogenous input) type models. Using this approach the power production from a wind farm is described by a stochastic process, which by nature is non-linear as well as time varying (and consequently non-stationary). Models describing this kind of stochastic processes can not be handled successfully using ordinary least squares estimation techniques. When modeling systems containing non-stationary or non-linear dynamics two extremes in the modeling approach can be outlined as follows: A model containing all the physical relations governing the system is drawn up. Such a model will be capable of describing the complex dynamics and should ideally have constant (and known) parameters. Alternatively a model approximating the complex dynamics by linearization around the current working point is applied. Such a model will only give a reasonable description of the system dynamics in a region around the current working point and the model parameters will be time varying as the working point changes over time. This paper describes how the latter approach can be applied using a recursive least squares method to estimate the model parameters instead of direct linearization of a physical model.

5.1 Recursive Least Square Estimation

The estimation method used is often referred to as recursive least squares estimation with exponential forgetting ([6]). This method requires, that the model is linear in the parameters, i.e. it can be formulated as

$$y_t = \phi_t^T \theta + e_t \tag{1}$$

where θ is the parameter vector, ϕ_t is a vector of regressors and e_t is a independent identically distributed (*i.i.d.*) noise sequence.

The least squares method is based on minimizing a criterion of the form

$$\begin{aligned} V(\theta) &= \frac{1}{N}\sum_{t=1}^{N}(y_t - \hat{y}_{t|t-1}(\theta))^2 \\ &= \frac{1}{N}\sum_{t=1}^{N}(\tilde{y}_{t|t-1}(\theta))^2 \end{aligned} \tag{2}$$

where N is the number of observations, y_t is the observation at time t and $\hat{y}_{t|t-1}(\theta)$ is the prediction of the observation at time t given observations up to time $t-1$.

For the recursive least squares method with exponential forgetting the criterion (2) is changed to a criterion of the form

$$\begin{aligned} V(\theta_t) &= \frac{1}{N}\sum_{s=1}^{t}\lambda^{t-s}(y_s - \hat{y}_s(\theta_t))^2 \\ &= \frac{1}{N}\sum_{s=1}^{t}\lambda^{t-s}(\tilde{y}_s(\theta_t))^2 \end{aligned} \tag{3}$$

where λ is a forgetting factor ($0 < \lambda \leq 1$). It is seen that the adaptivity is obtained by multiplying the older observations with an exponentially decreasing weight function.

The choice of the forgetting factor λ is determined by a trade-off between the needed ability to track time-varying parameters and the noise sensitivity of the estimate. A low value of λ results in a system with a good ability to track time-varying parameters but a higher sensitivity against noise in the data. A typical choice of λ is in the range $0.95 \leq \lambda \leq 0.999$. The number of effective observations is given as

$$N_{eff} = \frac{1}{1-\lambda} \tag{4}$$

For $\lambda = 1$ and $t = N$ it is noticed that the least squares estimate in (2) is obtained.

5.2 1-Step Predictions

Conventionally the 1-step prediction errors are used in the recursive least squares method, see e.g. [6]. Later on in this section it is shown how the method can be extended to provide k-step predictions.

The adaptive recursive least squares algorithm is given by the following steps at time t

1. Calculation of 1-step prediction error using the estimate of θ at time $t-1$:

$$\tilde{y}_{t|t-1} = y_t - \varphi_{1,t}^T\hat{\theta}_{t-1} \tag{5}$$

2. An update of the covariance matrix for the parameter estimates is obtained using:

$$P_t = \frac{1}{\lambda}\left(P_{t-1} - \frac{P_{t-1}\varphi_{1,t}\varphi_{1,t}^T P_{t-1}}{\lambda + \varphi_{1,t}^T P_{t-1}\varphi_{1,t}}\right) \tag{6}$$

   The matrix $P(t)$ constitutes, except from a factor σ_e^2, an estimate of the covariance matrix for the parameter estimates at time t.

3. Update of the parameter estimates:

$$\hat{\theta}_t = \hat{\theta}_{t-1} + P_t\varphi_{1,t}\tilde{y}_{t|t-1} \tag{7}$$

The initial estimates of the parameters may be chosen quite arbitrarily – often zero is used. The initial covariance matrix has to be chosen such that the variance of the initial estimates is large – often selected as a diagonal matrix with all elements on the diagonal set to 100 or 1000.

The 1-step prediction of y_{t+1} at time t is calculated as

$$\hat{y}_{t+1|t} = \varphi_{1,t+1}^T \hat{\theta}_t. \tag{8}$$

5.3 k-Step Predictions

If a prediction horizon larger than one is needed a choice between two alternative ways of updating the estimates must be made.

- The estimates $\hat{\theta}_{t-k}$ and the regressors $\varphi_{k,t}$ are used instead of $\hat{\theta}_{t-1}$ and $\varphi_{1,t}$ in the algorithm described above, or
- pseudo prediction errors are used in the update of estimates. The pseudo prediction error at time t is calculated as
$$\tilde{y}_{t|t-k}^{pseudo} = y_t - \varphi_{k,t}^T \hat{\theta}_{t-1}, \tag{9}$$
from this equation it is seen that the pseudo prediction error corresponds to variables known at time $t-k$ (i.e. $\varphi_{k,t}^T$) and the most recent estimates (i.e. $\hat{\theta}_{t-1}$).

In both cases the true k-step prediction is calculated as

$$\hat{y}_{t+k|t} = \varphi_{k,t+k}^T \hat{\theta}_t. \tag{10}$$

Using the true k-step prediction error in the update of the most recent estimates will result in highly inappropriate estimates. This is due to the fact that the prediction error will give a feed-back not corresponding to the estimates that are to be updated.

6 MODELS FOR FORECASTING WIND POWER

Previously it has been shown ([1],[2]) that a reasonable ARX model based solely on measured data for predicting the power production from a wind farm is given by

$$\begin{aligned} \sqrt{p_{t+k}} &= a_1\sqrt{p_t} + b_1\sqrt{w_t} + b_2 w_t + m_{t+k} + e_{t+k} \\ m_t &= m + c_1 \sin[\frac{2\pi t}{48}] + c_2 \cos[\frac{2\pi t}{48}] \end{aligned} \tag{11}$$

where p_t denotes the measured power production at time t, w_t is the measured wind speed at time t, e_{t+k} is an *i.i.d.* noise sequence and m_t is a function describing both a level and the diurnal variation in the power production. Model (11) will also be referred to as the *WPPT version 1 model.*

The square root transformation of power and wind speed is motivated by the skew density of power and wind speed. In [1] it is shown that the square root transformation leads to distributions of the prediction errors, which can be approximated by the Gaussian distribution. Note that the transfer function from $\sqrt{w_t}$ to $\sqrt{p_{t+k}}$ is formulated using a second order polynomial expression.

The model given by (11) has a good performance for a prediction horizon up to 12 hours ($k = 24$), but in [7] it is made clear that for longer prediction horizons meteorological forecasts of wind speed and direction must be taken into account. Section 6.1 and 6.2 describes two different approaches for including meteorological forecasts into model (11).

The results obtained is assessed by comparison to the well known persistence predictor

$$\hat{p}_{t+k|t} = p_t \tag{12}$$

which simply states, that what you see now is what you will get in the future.

Furthermore the results are compared with a new statistical reference proposed in ([7],[8]). The reference proposed in ([7],[8]) addresses the fact that the persistence predictor performs very badly compared to a predictor given as the simple mean value for prediction horizons larger than 12 to 18 hours.

The statistical reference is simply calculated as the optimal weight between the persistence and the mean value predictor. In both cases the estimated standard deviation for the prediction error (denoted S.E. from here on) is used as the measure of performance.

6.1 Polynomial Extension to WPPT Model

As a first approach the meteorological forecasts have been included in model (11) using the same polynomial expression as used for the observed wind speeds. This leads to a model of the form

$$\begin{aligned} \sqrt{p_{t+k}} &= a_1\sqrt{p_t} + b_1\sqrt{w_t} + b_2 w_t + \\ &\quad b_3\sqrt{w^{HIR}_{t+k|t}} + b_4 w^{HIR}_{t+k|t} + \\ &\quad m_{t+k} + e_{t+k} \\ m_t &= m + c_1 \sin\left[\frac{2\pi t}{48}\right] + c_2 \cos\left[\frac{2\pi t}{48}\right] \end{aligned} \tag{13}$$

where $w^{HIR}_{t+k|t}$ is the forecasted wind speed at time $t+k$ given at time t.

This approach results in a simple extension, but it is a bit problematic if any dependency of wind direction exists, as both b_3 and b_4 must depend on the wind direction.

Some of the parameter estimates in the full model are not significant and especially b_1 and b_2 are found to be of little significance for most values of k. To assess the potential improvements by tailoring the models to the different prediction horizons, a model without the $b_1\sqrt{w(t)}$ term was estimated. A small reduction in S.E. is found for all values of k indicating that it is advantageous to tailor the prediction models to the individual prediction horizons. The reason is probably that the reduction in the parameter set makes the adaptive model less sensitive to noise thereby improving the prediction performance. The observed prediction performance is illustrated in Figure 3 as "P_{pol}".

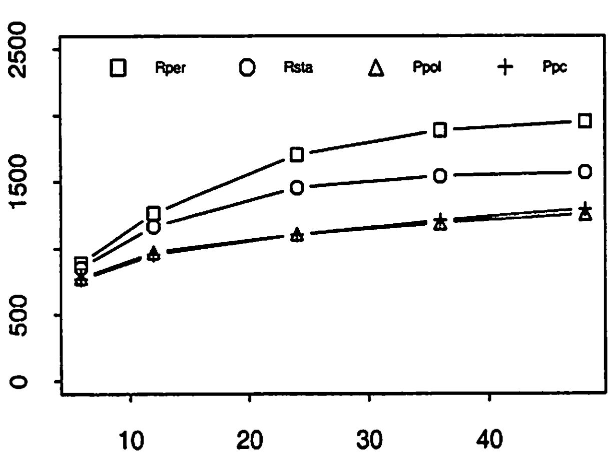


Figure 3: *S.E. [kW] versus prediction horizon [$\frac{1}{2}$hour] for the persistence reference (R_{per}), the statistical reference (R_{sta}), the WPPT version 1 model with polynomial extension (P_{pol}) as well as with power curve extension (P_{pc}).*

6.2 Power Curve Extension to WPPT Model

The model suggested in the previous section relied on a simple polynomial relationship between forecasted wind speed and power production. An alternative approach is to include the meteorological forecasts in model (11) through a power curve model.

$$\begin{aligned} G(w_t, \phi_t) &= \exp\left[-b \exp\left[-k(\phi_t)\, w_t\right]\right] \\ k(\phi_t) &= k_0 + \sum_{i=1}^{N_{tric}} \left[k_{i1} \sin\left[i\phi_t\right] + k_{i2} \cos\left[i\phi_t\right]\right] \end{aligned} \tag{14}$$

where ϕ_t is the wind direction at time t, and a Gompertz parameterization with a wind direction dependent power curve model is used.

Replacing the observed wind speed and direction in (14) by the forecasted wind speed and direction leads to the following power prediction model

$$\begin{aligned} \sqrt{p_{t+k}} &= a_1\sqrt{p_t} + b_1\sqrt{w_t} + b_2 w_t + \\ &\quad b_3\sqrt{G(w^{HIR}_{t+k|t}, \phi^{HIR}_{t+k|t})} + \\ &\quad m_{t+k} + e_{t+k} \\ m_t &= m + c_1 \sin\left[\frac{2\pi t}{48}\right] + c_2 \cos\left[\frac{2\pi t}{48}\right] \end{aligned} \tag{15}$$

where $\phi^{HIR}_{t+k|t}$ is the forecasted wind direction at time $t + k$ given at time t.

Contrary to model (13) such a model is already prepared for wind direction dependencies; but, as the power curve model has to be estimated separately, at the cost of a higher model complexity.

The observed performance for model (15) can be found in Figure 3 as "P_{pc}".

6.3 Summary

Comparing "P_{pol}" to "P_{pc}" in Figure 3 it is seen that for $k \leq 24$ model "P_{pc}" is slightly superior to model "P_{pol}" whereas the opposite is the case for $k > 24$. As the longer prediction horizons are of most importance and considering the added complexity in the "P_{pc}" model we have chosen to implement the "P_{pol}" model in WPPT version 2. This model is also referred to as the *WPPT version 2 model.* The reductions achieved in S.E. by introducing meteorological forecasts into model (11) are ranging from 13.7% for $k = 6$ to 35.6% for $k = 48$ when using the persistence predictor as a reference. When comparing with the statistical reference the similar reductions in S.E. range from 10.3% for $k = 6$ to 19.8% for $k = 48$.

An analysis of the weighting of the various input variables to the model shows, that for short prediction horizons (less than 4 hours) meteorological forecasts are of little value compared to online measurements of power production and local climate variables. For prediction horizons larger than 4 hours the meteorological forecasts become of increasing value as the prediction horizon increases.

7 IMPLEMENTATION

WPPT is implemented as two fairly independent parts, a numerical part and a presentation part, in the following denoted WPPT-N and WPPT-P respectively. Data exchange between the two subsystems is implemented via a set of files. A file based interface between WPPT-N and WPPT-P has been chosen for portability reasons as it is foreseen that WPPT will have to run on wide range of platforms. Currently WPPT have been successfully tested on HP Unix systems, VMS systems as well as a PC systems running Linux.

WPPT-N is meant to be running continuously whereas any number of WPPT-P processes can be running at a given time, i.e. WPPT is not restricted to be used by only one user at a time. In the following two sections WPPT-N and WPPT-P is presented in more detail.

7.1 The Numerical Part of WPPT (WPPT-N)

WPPT-N has been implemented in ANSI C and is designed to be straight forward to port to a new platform for which an ANSI C compiler is available.

WPPT-N can roughly be considered to consist of five major modules: data input (measurements and meteorological forecasts), data validation, model estimation and prediction, up-scaling module and finally performance logging and data output for WPPT-P. The measurements are given as 5 minute average values and the data validation is carried out on the 5 minute values before these are subsampled to the 30 minute values used by the models. The meteorological forecasts are given as hourly values which are interpolated to form 30 minute values before being used in the models. A brief description of the functionality within each module is given in the following.

- *Data input.* The data interface for exchanging measurements and meteorological forecasts between the local SCADA system and WPPT-N is established via a set of plain ASCII files. An ASCII file interface has been selected for two reasons:

  1. The interface is simple to establish on a wide range of systems.
  2. The input files provide a history for the measurements to the system. This is very helpful for fine tuning of the models as well as further model development.

  The input files are checked for consistency both with respect to timing as well as the number of values.

- *Data validation.* Experience have shown that despite large efforts on-line measurements are prone to failures (errors). It is therefore essential to have some sort automatic error classification of the measurements not only for protecting the models against the influence of erroneous measurements but also to ease the surveillance tasks for the operators (see Section 7.2).

  - Range check. The measurements are checked versus predetermined minimum and maximum values.
  - Stationarity check. The measurements are checked for stationarity, i.e. it is hung on a constant value. Measurements of wind speed and power are allowed to become stationary around 0 for longer periods of time but otherwise stationary measurements are discarded as erroneous.
  - Confidence check. Here the output models describing the relationship between related measurements, e.g. wind speed and power production, are compared with the actual measurements. If a measurement falls outside the confidence bands of a model it is classified as erroneous. This test is not implemented in the current version of WPPT but will become available in the next release.

  Only the measurements are subject to the data validation methods described above. It has been decided to leave the validation of the meteorological forecasts to the quality control of the national weather service. Hereafter the 5 minutes observation are averaged to form 30 minutes value.

- *Model estimation and prediction.* Each wind farm have a set of models covering the prediction horizon (30 minutes up to 36 hours) in steps of 30 minutes. Each model is a k-step prediction model for which estimation of model parameters and prediction of wind power is implemented as described in Section 5. The model implemented is the WPPT version 2 model – see Section 6. Every 30 minutes a new 36 hour forecast is calculated for the power production for each wind farm. During periods where model input is marked as erroneous the model estimation is inhibited in order to protect the model from the influence of bad data and the predictions for the actual park are marked as being unavailable.

- *Up-scaling.* Both power production measurements and forecasts for the selected wind farms are up-scaled and summarized so as to calculate an estimate for the power production in the entire Elsam supply area. For each wind farm a number of substitute wind farms have been defined and in case the values for a wind farm becomes marked as unavailable the wind farm in question is replaced by one of its predefined substitutes in the up-scaling.
- *Performance logging.* Every 30 minute the updated 36 hour forecasts for the reference wind farms as well as the total forecast for the entire Elsam supply area are logged and saved in individual files.
- *Data output for WPPT-P.* Finally the interface files between WPPT-N and WPPT-P are updated (5 minute values as well as 30 minute values).

It should be stressed that the models applied in WPPT-N are self calibrating, they so to speak learn from the observed data as time goes by, thereby rendering re-calibration superfluous. On the other hand this means that they have to run for some time, typically 7 - 14 days, before the forecasts can be considered to be reliable. To overcome this drawback in applying self calibrating models some additional features have been incorporated into WPPT-N:

- Accelerated learning enables WPPT-N to be started back in time and then use historical input files to calibrate the models before moving into real time operation.
- Saving of current model state ensures that the system will be able to restart quickly in case of power interrupts, system reboot or similar.

7.2 The Presentation Part of WPPT(WPPT-P)

WPPT-P is implemented in ANSI C++ and is based on the X11 and Motif graphical libraries. It has been tested under VMS, HP Unix and Linux and is expected to run on any platform for which X11, Motif and an ANSI C++ compliant compiler is available.

In the configuration used by Elsam WPPT-N is a rather large system taking 70 measurements and 14 meteorological forecasts as input. WPPT-P thus have to serve several purposes:

1. Display the 36 hour forecast of the total wind production in the Elsam supply area.
2. Provide an overview over the climatical conditions and the power production throughout the Eltra/Elsam supply area.
3. Provide an overview of the current status for the measurement equipment installed in the wind farms.
4. Display detailed information for each wind farm for diagnostic purposes, e.g. if an forecast seems to be unrealistic the detailed plot for the wind farms can be used to determine the reason for the bad forecast.

The need for providing both an overview as well as detailed information is reflected in the design of WPPT-P. The main window together with a number of plots directly accessible from the menu bar on the main window provides the operators with an overview of the system state whereas the system engineer have access to more detailed information through a set of sub-windows dedicated to the individual wind farms.

The following sections provides an overview of the functionality build into WPPT-P.

7.2.1 The Main Window

The main window consists of four elements - menu bar (top), map area (left), value field (right) and information field (bottom).

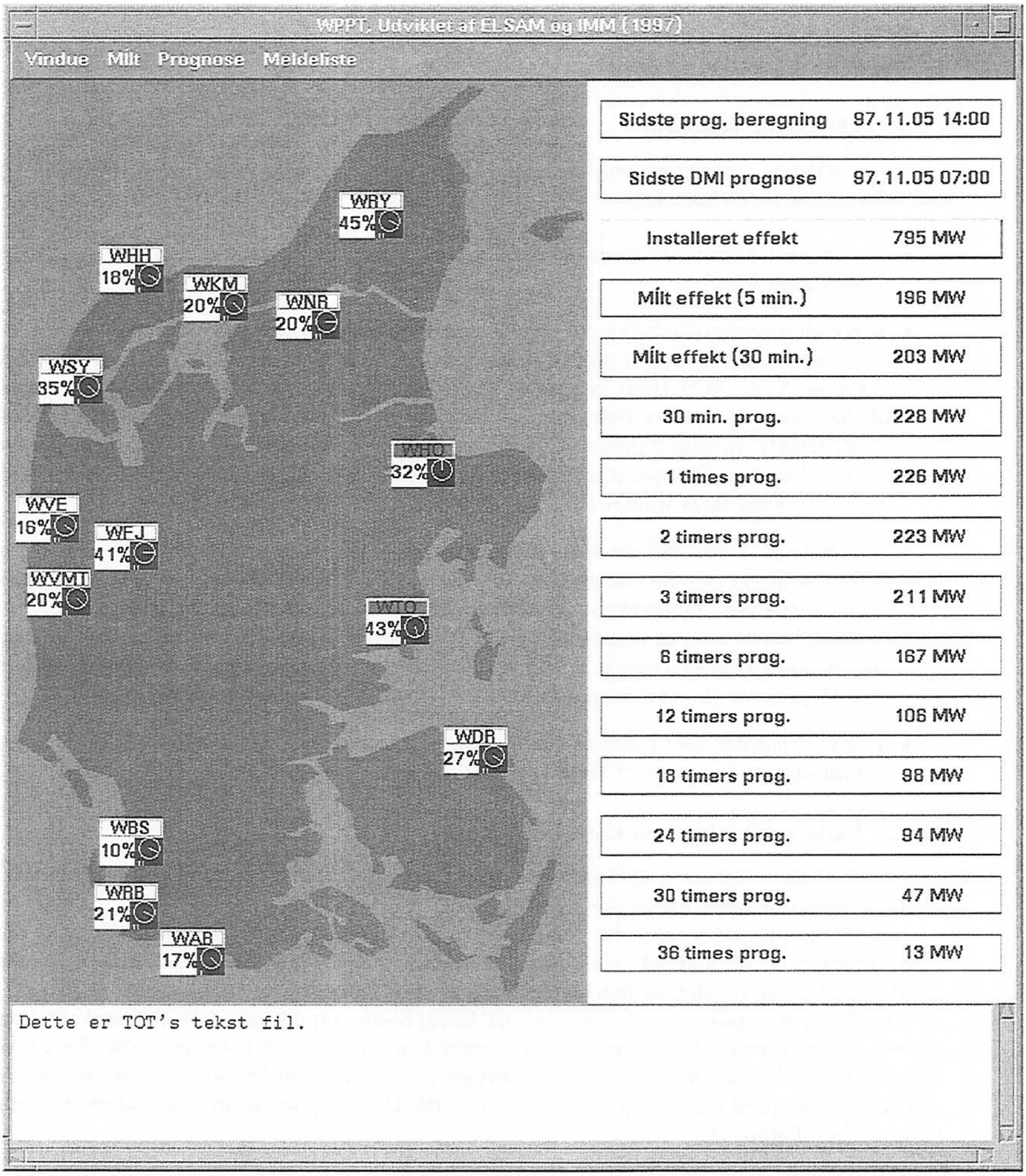
- *The menu bar* provides access to some system functionality as well as some overview plots (See Section 7.2.2).
- *The map area* contains a map of the Jutland/Funen area where the location of each reference wind farm is marked by a wind farm symbol. The symbol consists of a reference code for the wind farm (W*) (top), a number giving the farms current production as a percentage of the installed capacity (left) and a wind rose giving the current wind direction and wind speed (right). In case a measurement error have been detected in the wind farm the symbol turns red to alert the operator to the error. Furthermore clicking on a symbol with the mouse opens the wind farm window.
- *The value field* provides some key figures regarding the current system state. Field 1 and 2 from the top shows the calculation time for the current forecast respectively the reception time for the last meteorological forecast. Field 3 shows the total installed capacity in the Jutland/Funen area as registered by WPPT-N. Field 4 and 5 gives the current estimate of the total power production as a 5 minute and 30 minute average respectively and finally fields 6 to 15 presents the current power forecast for selected forecast horizons.
- *The information field* provides the system engineer with a bulletin board to give relevant information to the users of WPPT.

7.2.2 Plots available from the Main Window

A number of plots regarding the observations and the forecasts for the total power production are available from the menu bar in the main window.

In order to provide a mean for comparing the measurements from the 14 wind farms relative power production, wind speed, wind direction and air temperature for the 7 Northern most and 7 Southern most can be plotted together (See Figure 5 for an example).

The forecasted power production in the Eltra/Elsam supply area for the next 36 hours is presented together with the observed power production for the last 6 hours in a plot (See Figure 6). In order to provide an overview of the prediction performance for the total power production the observed power production is plotted together with historical predictions for selected prediction horizons (See Figure 7).



Sidste prog. beregning	97.11.05 14:00
Sidste DMI prognose	97.11.05 07:00
Installeret effekt	795 MW
Mílt effekt (5 min.)	196 MW
Mílt effekt (30 min.)	203 MW
30 min. prog.	228 MW
1 times prog.	226 MW
2 timers prog.	223 MW
3 timers prog.	211 MW
6 timers prog.	167 MW
12 timers prog.	106 MW
18 timers prog.	98 MW
24 timers prog.	94 MW
30 timers prog.	47 MW
36 times prog.	13 MW

Dette er TOT's tekst fil.

Figure 4: *Main window in WPPT-P.*

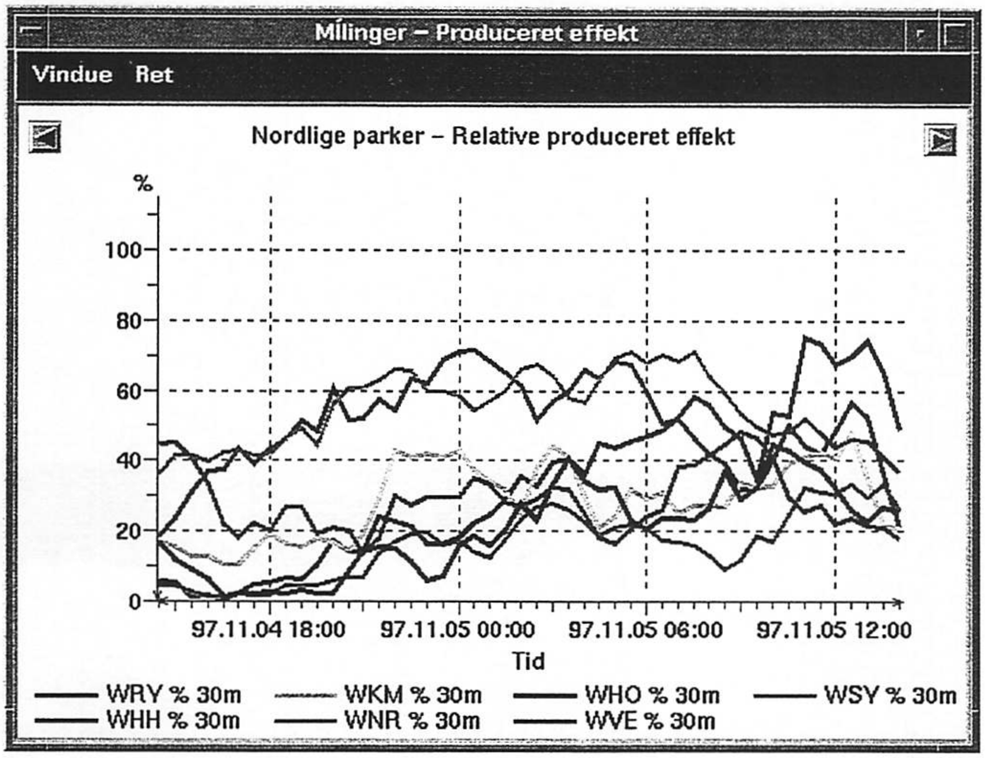


Figure 5: *The relative power production for the Northern wind farms. The plot covers the last 7 days.*

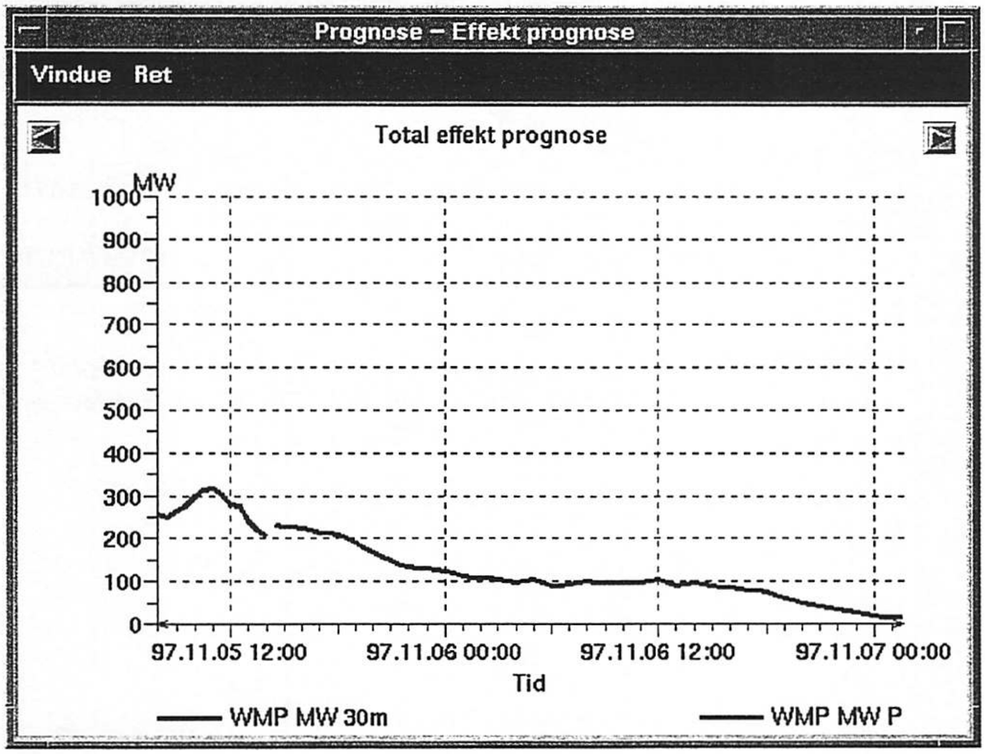


Figure 6: *Plot of the forecasted total power production for the next 36 hours together with the most recent observed values.*

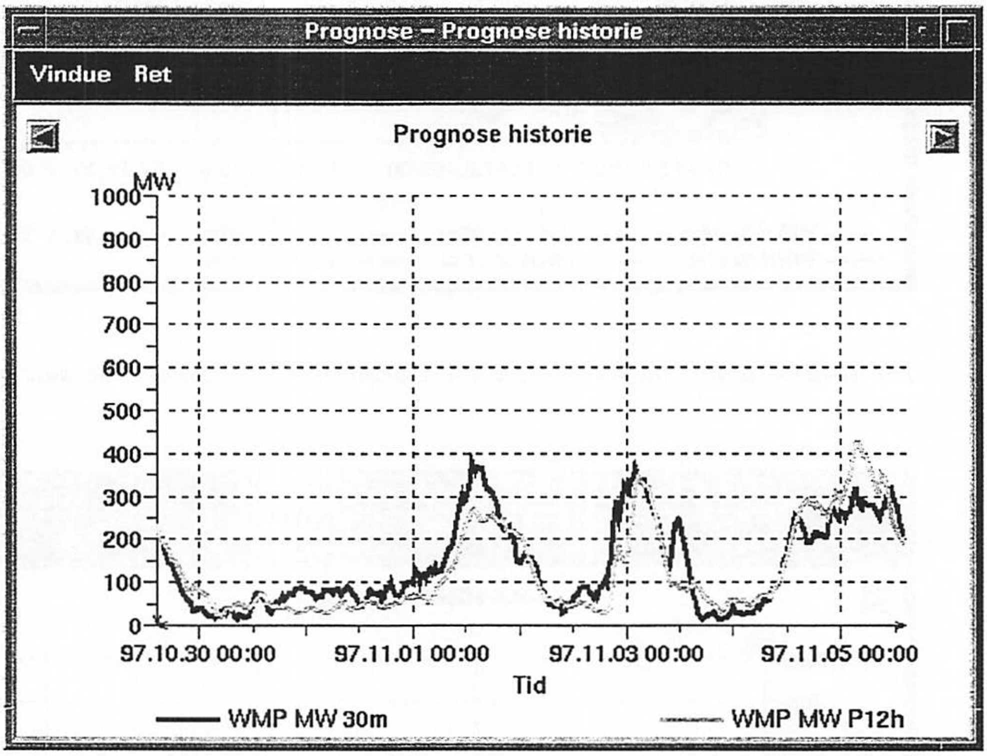
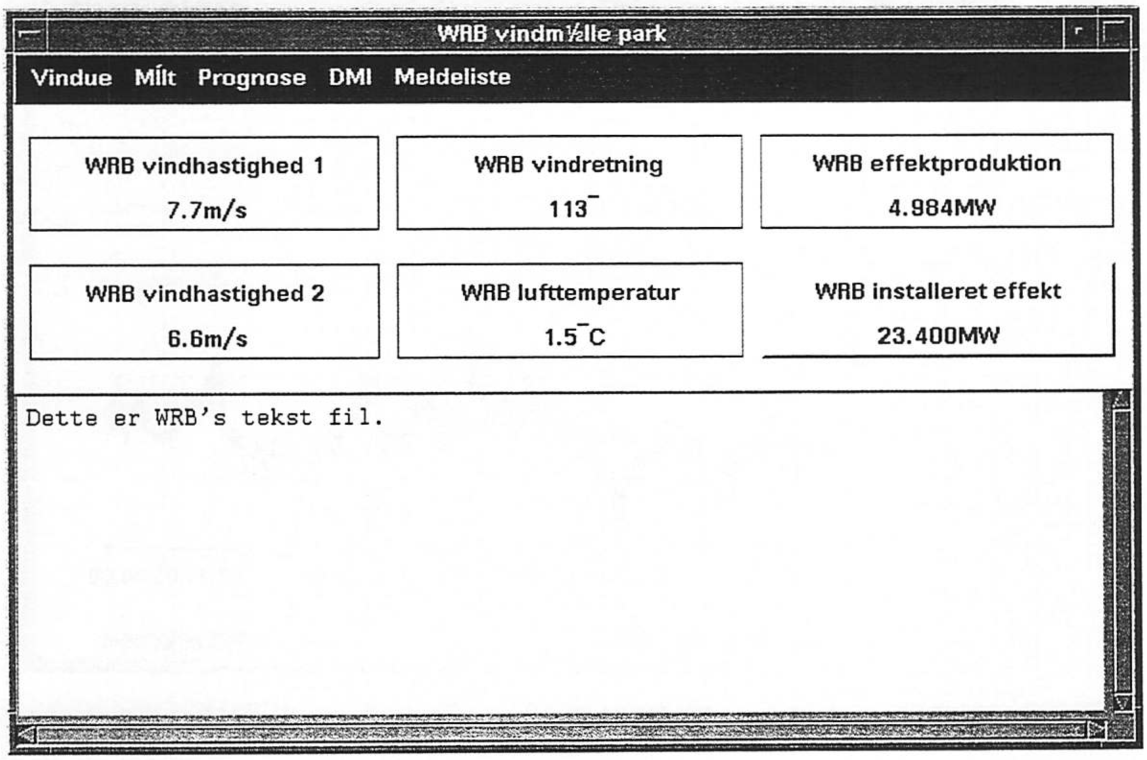


Figure 7: *Plot of the observed power production together with the historical 12 hour predictions. Also the 6 hour, 18 hour, 24 hour and 36 hour predictions can be selected for comparison.*

7.2.3 The Wind Farm Window



WRB vindhastighed 1
7.7m/s

WRB vindretning
113¯

WRB effektproduktion
4.984MW

WRB vindhastighed 2
6.6m/s

WRB lufttemperatur
1.5¯C

WRB installeret effekt
23.400MW

Dette er WRB's tekst fil.

Figure 8: *The wind farm window in WPPT-P.*

The wind farm windows consists of three parts: a menu bar (top), a measurement value field (middle) and an information field (bottom).

- *The menu bar* gives access to some system functionality as well as a large number of plots for the wind farms (See Section 7.2.4).
- *The measurement value field* displays the most resent 5 minute values for the wind farm measurements (two wind speeds, one wind direction, one air temperature and one power production). In the case that a measurement has been classified as faulty the measurement in question is marked by a red background colour. The last field shows the installed capacity for the wind farm as registered by WPPT-N.
- *The information field* provides the system engineer with a bulletin board where information concerning the wind farm can be given to the operators.

7.2.4 Plots Available from the Wind Farm Window

The wind farm window gives the user access to a number of plots which falls into 3 separate categories:

- *Plots of observations.* Plots of the 30 minute average values versus time are accessible directly via the menu bar for all of the five measurements (See Figure 9) but WPPT-P also enables the user to compose new plots where the various measurements can be plotted against each other.

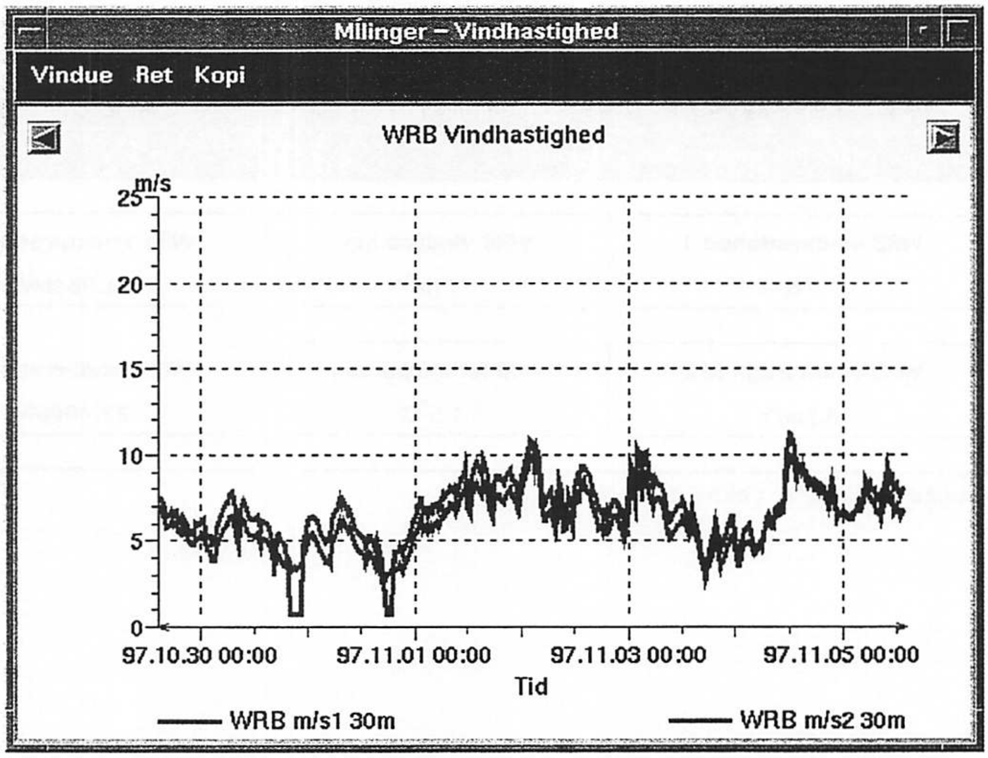


Figure 9: *Plot of the two wind speed measurements. Per default the plot covers the most recent 7 days.*

- *Plots derived from the power production forecasts.* Here the user has the possibility of plotting the forecasted power production for the wind farm (Figure 10), the historical forecasts for the wind farm as well as the uncertainty quantiles for the current forecast.
- *Plots derived from the meteorological forecasts.* Gives access to a plot of the most recent meteorological forecast of wind speed (Figure 11) as well as a plot of the historical performance for the meteorological forecasts.

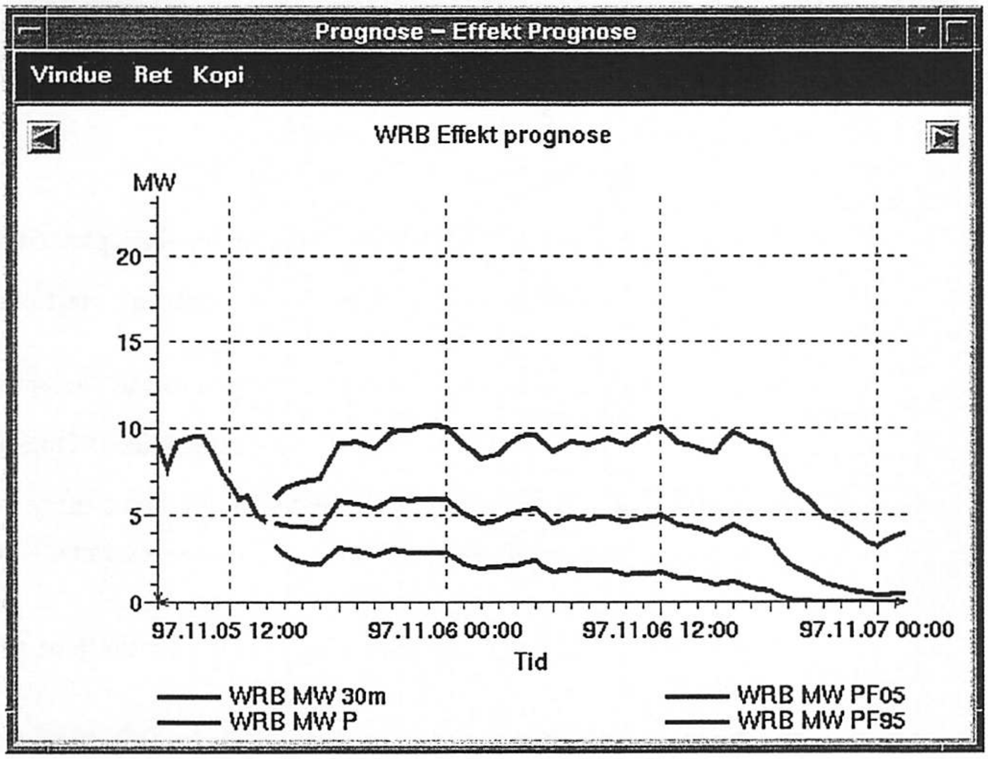


Figure 10: *Plot of the forecasted power production for the next 36 hours including the estimated uncertainty bands for the forecast together with the most recent observed values.*

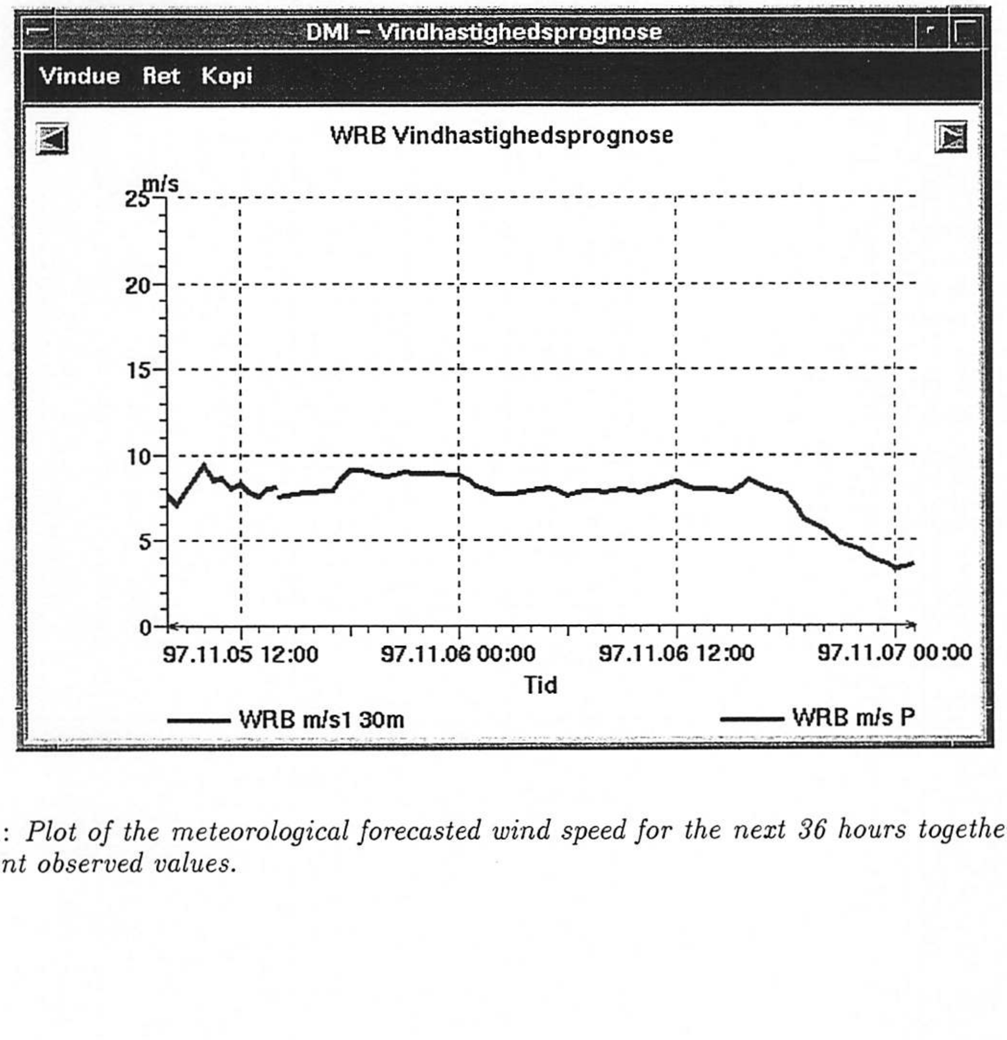


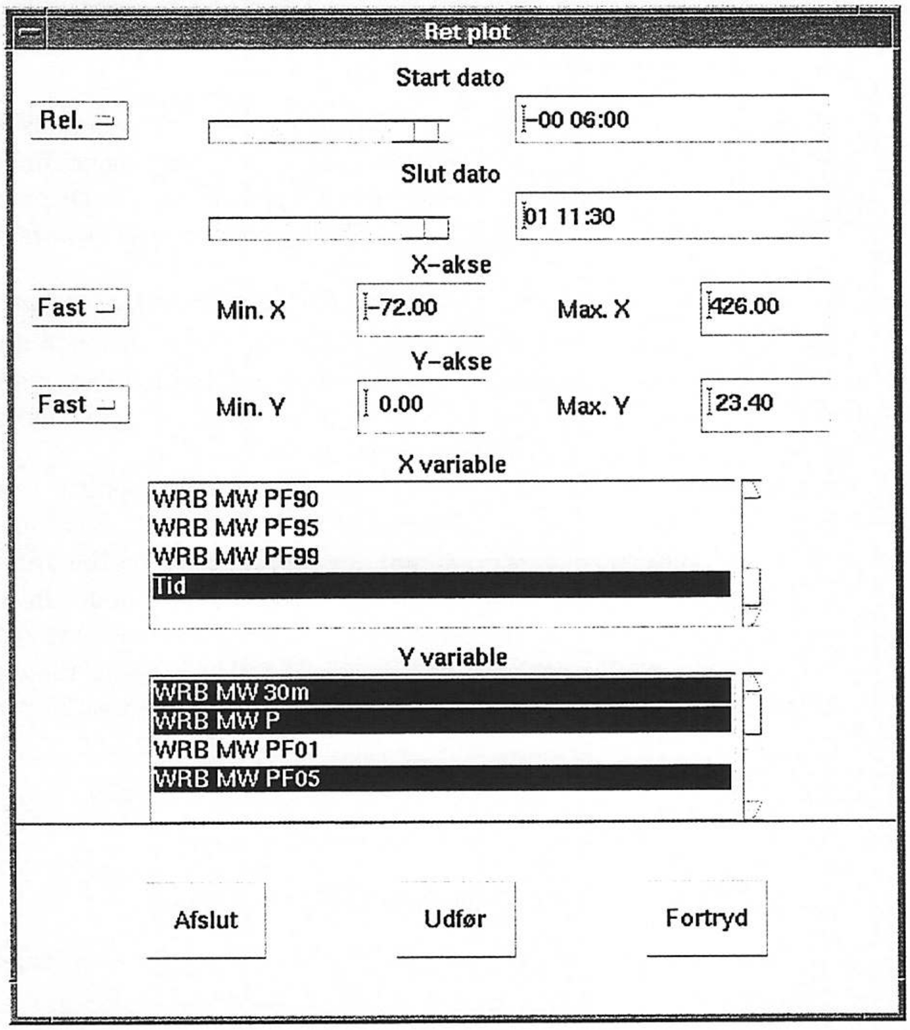
Figure 11: *Plot of the meteorological forecasted wind speed for the next 36 hours together with the most recent observed values.*

7.2.5 Options Available from a Plot Window

All plots can be printed if a postscript printer is available at the site. Furthermore each plot can be tailored by the user through a dialogue box. The dialogue box allows the user to change the time period considered, the scaling of the axis and the plot variables.

The following contains a brief description of the various options:

- *Time period.* Allows the user to select start and end date for the data plotted. Option modes:
  - **Fast**. The start/end date of the plot is fixed to a given date set via the scrollbar or the entry fields.
  - **Rel**. The start/end of the plot is set as an offset relative to the current time.
- *Axis scaling.* Allows the user to select the scaling of the x- and y-axis. Option modes:
  - **Fast**. The axis scaling is a fixed value set through the min/max entry fields.
  - **Rel**. The scaling is automatically selected according to the extreme values in the data set.
- *Plot variables.* Allows the user to select the variables to plot and the plot type (x-y plot or time series plot). Option modes:
  - **Ændre**. Change the plot variable.
  - **Tilføj**. Add a plot variable to the plot.
  - **Slet**. Remove a plot variable from the plot.



Ret plot

Start dato

Rel.

-00 06:00

Slut dato

01 11:30

X-akse

Fast

Min. X -72.00

Max. X 426.00

Y-akse

Fast

Min. Y 0.00

Max. Y 23.40

X variable

WRB MW PF90

WRB MW PF95

WRB MW PF99

Tid

Y variable

WRB MW 30m

WRB MW P

WRB MW PF01

WRB MW PF05

Figure 12: *The plot window dialogue box.*

8 EXPERIENCES AT ELSAM WITH WPPT

The need for good predictions of wind power production in the Eltra/Elsam area is evident.

In 1992-95 the first version of WPPT was developed. The predictions was based on statistical analysis on measurements from only 7 wind parks. The version was in operation in the Elsam Dispatch Center for some months, and the final conclusion was, that the predictions was inadequate for prediction horizons larger than 8 to 12 hours. The main reasons was:

- Bad reliability of measurement equipment.
- Too few wind parks included.
- Lack of meteorological forecasts.

A new project was started in 1996 with the aim to get better predictions by including more wind parks, better reliability of equipment and getting good meteorological forecasts.

A preliminary version of WPPT version 2 has been in operation at the Dispatch Centers of Eltra and Elsam since October 1997, and we now have a good tool for the operators for the planning of the production.

The goal is to predict the production within 50 MW up to 36 hours ahead. This seems to be possible most of the time, at least up to the 12-hour horizon, but it depends much on the type of weather at the time (stable or turbulent). The wind power production can in special cases change with up to 250 MW pr. hour. This can be predicted, but we have seen that prediction of the time point is difficult, so the difference can be large for some hours.

Anyway, the predictions are much better than an experienced operator can provide on basis of weather forecasts from any other known source (TV, Internet ...). The operators rely on the WPPT predictions and use them as basis for planning the production on the primary power stations and selling and buying electricity from day to day and from hour to hour. In periods with stable wind, the running reserve capacity on primary power stations are not changed due to the wind production. In an unstable wind situation it will be considered to raise it. Planned stop of primary power stations on the basis of the wind predictions is not used, because the prediction horizon is not long enough.

Bad predictions have been seen in some situations:

- Very fast developing depressions running fast over the area.
- Very high wind situations (storm) when windmills are stopped.
- Very local weather changes (thunderstorms) give problems to the up-scaling.
- Bad measurements that are not automatically detected.
- Delayed or missing forecasts from DMI (due to computer problems at DMI or Elsam or problems on the Internet).
- Bad forecast data from DMI (DMI has now increased their quality control).

These weather situations have been rare and are therefore not a big problem. The technical problems with the measurement equipment have already been reduced to a minimum.

The final version of WPPT is planned to go into operation in August 1998. Due to more measurements and hence a better modeling, we expect to get even better predictions by then. Because of the new free market for electricity in Northern Europe in the future, it is becoming more and more important to have good predictions of the wind power production.

ACKNOWLEDGEMENTS

This work was partially founded by the European Commission under JOULE II and JOULE III which is hereby gratefully acknowledged.

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ONLINE MONITORING AND SHORT TERM PREDICTION OF 2400 MW WIND CAPACITY IN AN UTILITY SUPPLY AREA

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Abstract: Based on long-term wind and power measurements made on wind turbine generator systems (WTGS) in the framework of the „250 MW Wind" programme, a simulation model will be presented, which ensures the calculation of the total wind power simultaneously fed-in to any supply area. The statistical analysis of the wind power time series improves the knowledge of the time behaviour of wind power supply. This allows the online recording of the total wind power fed into supply areas by extrapolation from power levels measured online at selected wind farms as well as the short term prediction based on the online-model and the weather forecast of the meteorological institutes.

Introduction: The ongoing use of wind energy in relevant scales in a liberalised energy market depends especially on the precise knowledge of the conditions of production for the integration in utility grids. This is complicated by the dependency of the produced wind power on the actual weather conditions, especially with regard to wind speed and different environmental conditions of individual sites.

Due to the fact that the installed capacity of WTGS reached the minimum load of several regional grids a procedure is necessary, which determines precise and detailed the actual and expected wind power and which further provides this information to the system demand control centre.

The precise prediction of the wind power will increase the market value considerably. The improved integration of wind power into the generation system will lead to a new assessment and a higher level of the capacity effect.

The development and verification of this method depends on three steps:

- the exact statistic analysis of time series of the fed in wind power of the concerned supply areas
- the online monitoring of the wind power feed-in
- the precise determination of the expected wind power output

Previous investigations: In order to investigate more closely the wind power feed-in within wide ranging supply areas, ISET was commissioned by a large utility company to provide the evaluation and statistical analysis of a representative time series for the total supply area. The analysis is based on measurement data of the „250 MW Wind" programme. The reliability of these results, and their stability in regard to the selected measurement sites were verified by means of a separate investigation. The calculated time series was examined with respect to the power duration and the power gradients between hourly values for an initial study.

Extrapolation Model: The further validity of the time series, derived from measured power data, depends on the development of the spatial distribution of WTGs in the supply area, and the further development of WTG technology coming into use. Due to the rapid changes of plant structure the ongoing adaptation of ISET's remote data acquisition network is not economically possible. Therefore ISET has developed a model which generates data of simultaneously wind power fed-in of all WTGs in arbitrary defined supply areas by evaluation of power signals from only a small number of representative sites. To achieve this, measured wind and power data at selected locations, will be transferred to all WTGs operating in a closer surrounding. In this way, a virtual power signal for every WTG operating in the supply area will be calculated, and united to a time series.

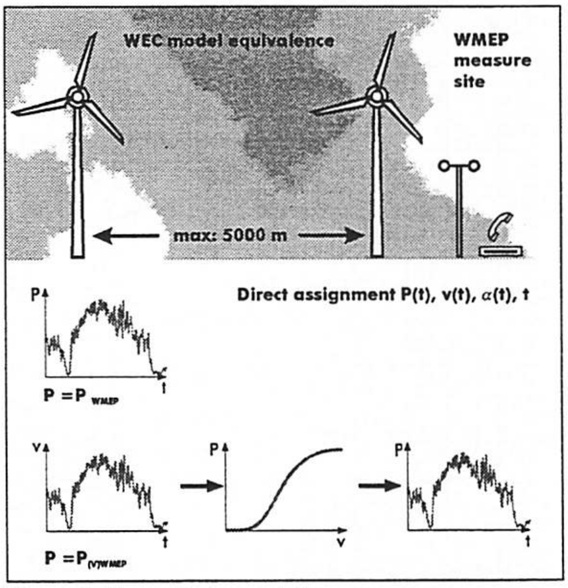

Figure 1: Extrapolation model case 1

The development and verification of this model is based on the long-term experience of the „250 MW Wind"-programme and its extensive stock of measurement data and evaluations. Two cases are especially distinguished for the estimation of the power signals of individual WTGs:

If a WTG is located in immediate vicinity to a WTG of the same type equipped with an ISET data acquisition system, then the measured power output is assigned directly (see figure 1).

If a direct assignment of the power signal is not possible, the signals of the three closest wind measurements will be evaluated. These wind signals will be transformed to a disturbance-free height and, through spatially weighted, vector addition, extrapolated to the WTG site. This wind speed will be transformed again under consideration of the roughness parameter of the site and at the hub height of the wind turbine (see figure 2).

The electrical power given by the WTG will then be evaluated through performance characteristics or certified power curves. Through the precise knowledge of the operational behaviour of the WTG types included in the „250 MW Wind“ programme, site specific and seasonal characteristics can be particularly taken into account.

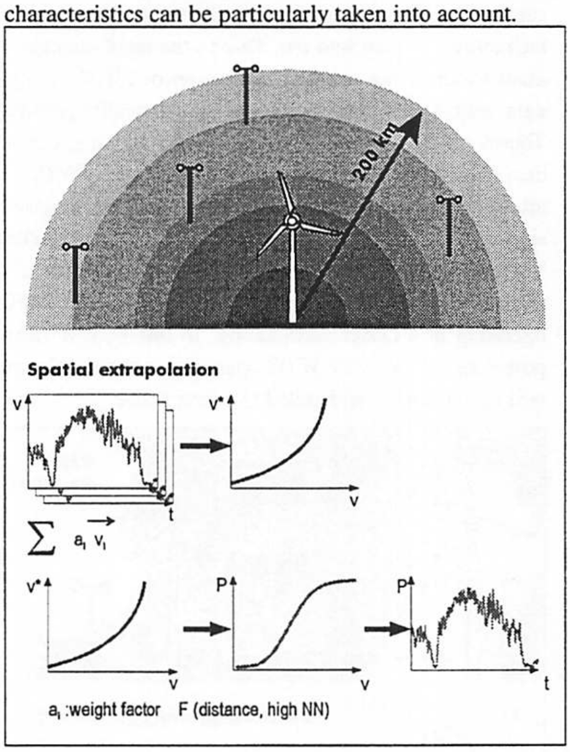

Figure 2: Extrapolation model case 2

Additionally, the performance characteristics are utilised from all WTG types measured in the „250 MW Wind“ programme. Through this action, the following distinctions can be made:

- Site category: To classify the site conditions, the locations are divided into the categories coast, North German plain and highlands.
- Season: To form distinctions between seasons, the curves are divided into four seasonal classes

Besides precise knowledge of the WTG operational behaviour (performance characteristics), the mediation of environmental influences on the WTG site are of great importance for the calculation models. Because of this, the roughness parameters are determined for all ISET measurement stations. All other WTG sites are classified appropriately.

The verification of the preliminary model is made by comparison of time series of measured power output and figures of the monthly energy production reports from over 1,500 WTGs as well. Figure 3 shows a measured time series (substation Marne-West) in comparison to another time series (SEPCaMo) calculated with the evaluation model through spatial extrapolation.

This example is based on 88 WTGs, measured at the transformer station Marne-West with turbines rated from 300 up to 1500 kW, and a total power of 46,2 MW. For the examination period of one month the average deviation (RMSE) of the model time series amounts to merely 8,2% of the total rated power.

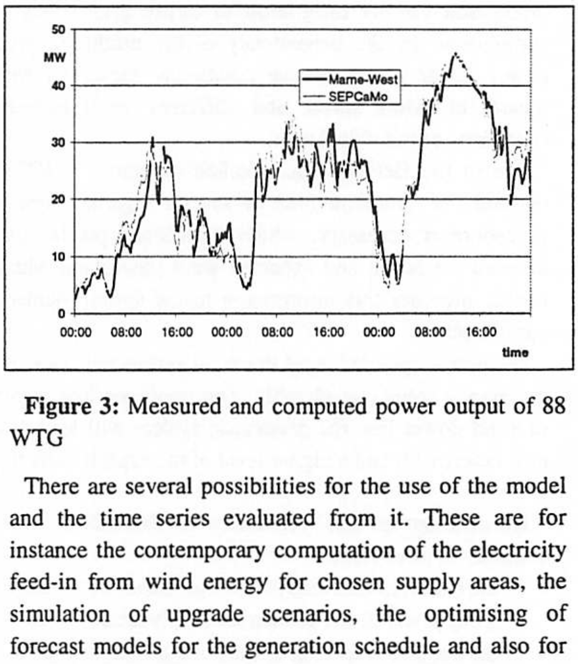

Figure 3: Measured and computed power output of 88 WTG

There are several possibilities for the use of the model and the time series evaluated from it. These are for instance the contemporary computation of the electricity feed-in from wind energy for chosen supply areas, the simulation of upgrade scenarios, the optimising of forecast models for the generation schedule and also for model calculation of online monitoring of wind feed-in, based on selected reference measurements.

Online acquisition and projection: Apart from meteorological data, important parameters for the generation schedules of large utility companies are, for example, the relevant expected load, the availability of the power station, the balance of electricity exchange with other utility companies, and also the consideration of necessary power reserves.

The online acquisition of the power contribution of all WTGs operated in a supply area, can be seen as the most precise procedure to obtain basis data for load prediction. However, the equipment of all WTGs with measurement systems can hardly be realised.

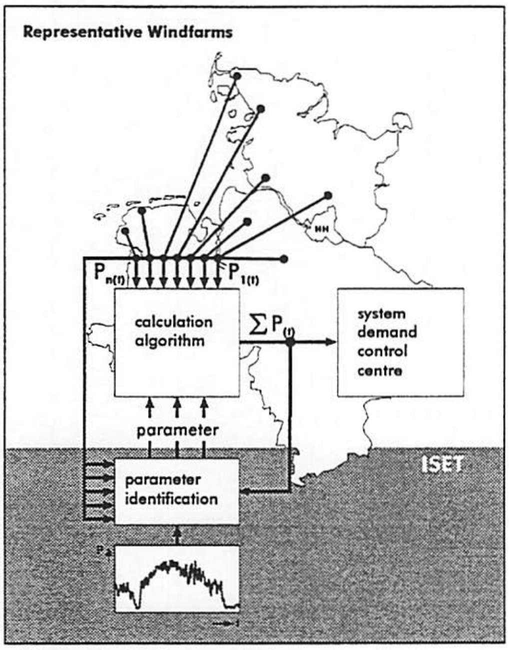

Figure 4: Online-acquisition and projection

Because the extrapolation model requires a high calculating time to compute the simultaneously wind power feed-in data, it is not suitable for the purpose of instant (online) calculation. Online monitoring requires a further evaluation model, which allows the transmission of measured time periods of the power output of representative wind farms to the total feed-in from WTGs of a larger supply area.

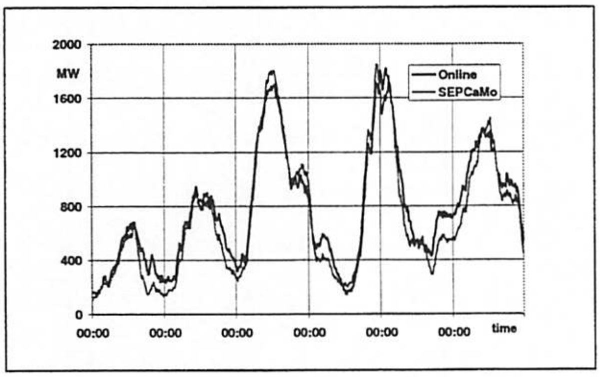

Figure 5: Time series of 2300 MW wind capacity

The actual wind power feed-in to supply areas will be determined by extensive equation systems and parameters, which also take the spatial distribution of WTGs into consideration. The measurement data of the chosen wind farms will thereby be transmitted by leasedlines to the control centre (see figure 4). The online evaluated time series for the load dispatcher are retrospectively compared with extrapolation of wind and power data and, by means of parameter optimising, continually conformed and improved. This regular testing and conforming of parameters obtains a high level of precision for the described procedure. Figure. 5 depicts a sum curve computed by the online monitoring model in comparison to the sum curve computed by the extrapolation model. The example is based on 4,400 WTG with a total nominal power of 2,400 MW.

Short term prediction: Besides precise knowledge of the statistical behaviour of wind power feed-in, the prediction of short-term to medium-term power expected for the generation schedule and load management of utility companies is of increasing importance. Different estimations and procedures already exist for the prediction of wind power. These models for wind power forecasts are based on the ability of neural networks to approximate non-linear associations and to intercede in the case of vague, incomplete or inconsistent data.

Investigations made by ISET have demonstrated the basic possibilities of predicting the total power of dispersed WTG systems using artificial neural networks.

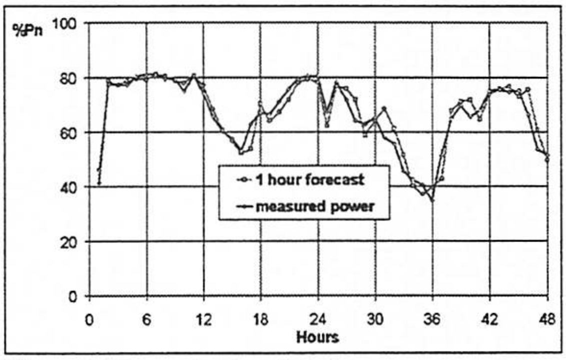

Figure 6: Measured and predicted sum curve

Figure 6. depicts an example of a wind power prediction, carried out by means of artificial neural networks, for one hour average values. The prediction period was chosen to one hour in advance.

Using the prediction of the geostrophic wind speed and other meteorological data like temperature and air pressure provided by the "Deutscher Wetterdienst (DWD)", the wind conditions at any desired location can be determined. With these data, the wind power of the (online measured) wind farms can be computed and used as input parameters for the online model. Therefore the online model allows a prediction of the total wind power feed-in of large utility supply areas, based only on a few locations with predicted wind speed.

Based on these models, the short-term prediction from 1 to 48 hours is another important step towards improved integration of wind energy into the system demand control and generation schedule of utility companies with a high share of wind energy.

As the presented model for the online monitoring of large wind capacity can be adapted to various supply systems, it is of special importance for various electricity utilities in order to improve the grid integration of their wind capacities. Further improvements can be reached by using the WTG control facilities within the system demand control centres.

IEA expert meeting
4th and 5th of April
The National Wind Technology Center of the National Renewable Energy Laboratory
Boulder, Colorado, USA

HIRLAM AND WIND POWER FORECASTS IN FINLAND

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ABSTRACT

The possibilities to use wind speed forecasts to predict 1-2 day wind power production in Finland is discussed briefly. The Finnish Meteorological Institute operates two versions of the HIRLAM (High Resolution Limited Area Model) weather forecast model. When looking at +24h and +48h forecasts it may be noted that on average they correlate quite well with observed wind speeds, but for individual cases the correlation has to be improved. Decreasing the size of the HIRLAM grids makes the orography and surface roughness more uniform within the grid.

HIRLAM forecasts can be used as input data for further local wind analyses and predictions of wind power production. Such a method is not yet in use at the FMI.

Interest to achieve wind power forecasts for from 1 day up to 5-7 days is increasing as the size of the wind power plants is growing especially now when we are operating in open electricity markets. However, at present in Finland there is no ongoing projects trying to achieve these wishes, or even to study the possibilities to produce accurate weather forecast for wind power purposes.

This preliminary paper is produced for the IEA expert meeting in Boulder 4th and 5th April 2000, and is more a summary for further discussion than presentation of any new results.

TABLE OF CONTENTS

1 INTRODUCTION

The nature of wind includes short term fluctuations, which vary from one climatological region to another and depends on weather situation. In Finland, and rest of Scandinavia, the climate is characterized by big seasonal variations and strong low pressure activity with anticyclones mowing eastward or northeastward direction from the North Atlantic producing e.g. large variations in wind speed and direction. This makes the weather forecasts more difficult in these regions compared to regions with more stable weather systems.

At present there are 29 wind power sites, totally 63 turbines giving 38 MW as nominated power and a production which is only 0.05 % of total consumption of electric power. Thus it has not been of great importance to combine the weather forecasts to wind power production. However, as the number and size of wind power plants is growing the short term (1- 3 days or even 1 week) forecasting of power production will become more important. The short term trading on electric power is typically based on 24 hour expected production, but for the whole power production (mixture of power plants) it would be important to know the wind power production over couple of next days in forehand. Thus reliable wind and wind power forecasts could have real economic benefits.

Production of wind power is mainly related to on-site hub height wind speed, or cubic of wind speed, which increases the requirements for accuracy of forecasted wind speed compared to typical needs within everyday meteorological weather forecasts. In Finland also variations in air temperature (or density) and icing has to be taken into account when making short time forecasts, or longer time predictions, for wind power production.

For a national weather service it would be natural to build the forecasting method for on-site wind speed and wind power production upon the operational weather forecasting model and then add some other models to make the forecast local.

2 HIRLAM

The Finnish Meteorological Institute (FMI) has used the HIRLAM (High Resolution Limited Area Model) for weather predictions since early 1990. HIRLAM data has also been used for wind energy statistics for areas with few or less representative wind measurements e,g. for the EU/JOULE project “Wind Resources in the Baltic sea”, under the contract number JOU2-CT93-0325.

As shown by Tammelin and Hyvönen in 1996 [8] the early version of the FMI HIRLAM clearly underestimated the wind speed at sea areas (Table 1).

Table 1. Measured annual mean wind speed (m/s) compared to contemporary predicted (HIRLAM +6h) wind speed at some offshore synoptic stations for the period 1990-1992. The prediction was calculated elevations 10 m, 35 m and 150 m a.s.l. [8]. The three first stations are from the Gulf of Finland and the others from the Bothnian Bay (see e.g. [7]).

	. m a.g.l/a.s.l	measured	H10	H35	H150
Bogskär (149)	31/31	8.6	6.8	7.9	9.7
Russarö (162)	15/28	6.4	5.8	6.5	8.8
Isosaari (173)	17/21	6.7	3.7	5.9	8.3
Valassaaret (225)	18/22	6.8	3.6	5.5	8.4
Hailuoto (246)	29/37	6.8	3.3	5.0	9.6
Kemi I (245)	15/25	7.4	5.4	6.3	8.3

HIRLAM predicts mean wind conditions for grids. The orography and topography are seldom very homogenous within one grid, and within the surrounding grids. Due to the nature of Finnish landscape the roughness parameter and also the stability and height of the boundary layer will vary strongly within the grids, especially on the coastal regions and at the arctic fjelds. Thus instead of predicted surface winds the HIRLAM upper winds (e.g. 150-250 m a.g.l) can be made more local by using local vertical wind profiles for each wind direction and case of stability as shown e.g. in references [2], [3], [8].

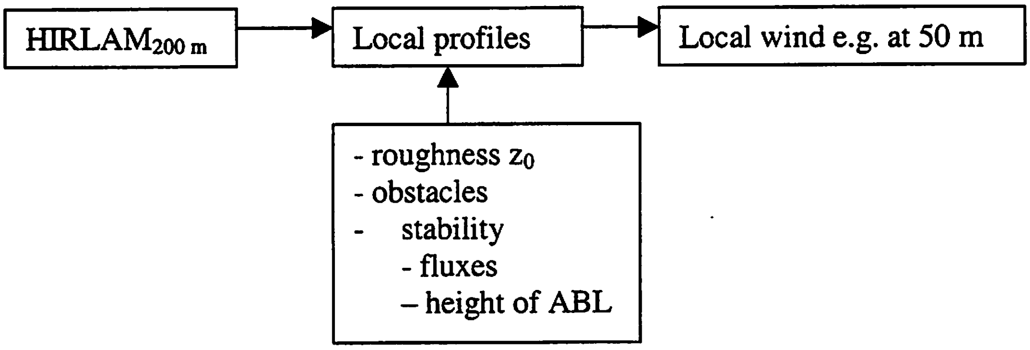


Figure 1. Principle of using HIRLAM data and local wind profiles to predict wind speed at a certain wind power site. [8].

Since the era for which the results shown in *Table 1* were taken, the HIRLAM model has been improved quite much. The present operational short range numerical weather forecast model at the Finnish Meteorological Institute is based on the HIRLAM version 2.5 [1]. Actually the FMI is operating two versions of the HIRLAM-model with different horizontal area and resolution. The main HIRLAM (ATL) with a gridscale of 0.4 degree, covers Europe and Northern Atlantic. Another version (EUR) produces forecasts for Northern Europe with horizontal resolution of 0.2 degrees, which translates to approximately 22 km. Both of them have 31 vertical levels and an identical number of grid points, i.e. 194x140. The newest version of HIRLAM for Northern Europe with

0.2 degrees resolution is called here ENO. The handling of the orography, surface layer and ABL is different to the earlier version. ENO-HIRLAM has been operative since November 1999, and the first preliminary comparison shows that significant improvement has again been achieved by the new version (*Figure 3*).

In principle the boundary layer (ABL) parametrization is based on the Monin-Obukhov theory of similarity. Surface fluxes of heat, momentum and water vapour are computed using drag coefficients that are functions of stability and the roughness length. Over open sea the roughness length depends on wind speed, and over land and ice the roughness is constant in time. Surface layer profiles of wind speed, temperature and humidity are computed diagnostically using data from the lowest model level and boundary layer parameters including the surface characteristics. In grid squares containing both land and sea, the characteristics of the dominating surface are used [12]. This fact is important for the interpretion of model data especially over coastal areas and archipelago, narrow seas and big lakes.

As show by P. Tiisler [12],[13], the high resolution model EUR is clearly better in short time prediction at less homogenous coastal areas, while e.g. at open sea where the surface is uniform over large areas the models ATL and EUR are equal.

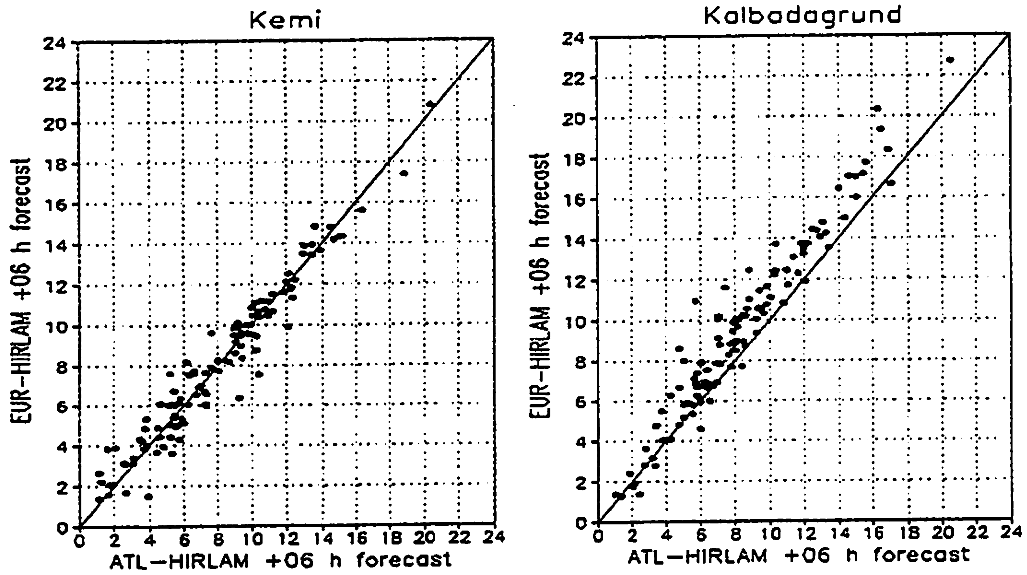


Figure 2. Comparison of predicted (+6h) wind speed in October 1998 at Kemi I (Bay of Bothnia) and at Kabådagrund (Gulf of Finland) synoptic stations, by using two different present HIRLAM versions [12], [13].

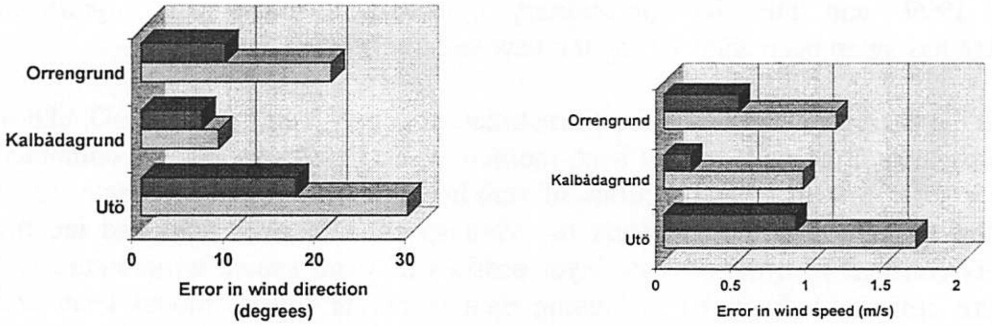


Figure 3. Systematic errors in wind direction (in degrees, left) and wind speed (m/s, right) when the +6h prediction is made by two HIRLAM versions, ENO-HIRLAM and EUR-HIRLAM [14].

At present the FMI produces HIRLAM weather predictions 4 times per day up to +54 hours. Predictions for longer periods, up to +10 days, are based on the products from the European Center (ECMWF) taken once per day.

3 VERIFICATION OF HIRLAM +24 h AND +48 h FORECASTS

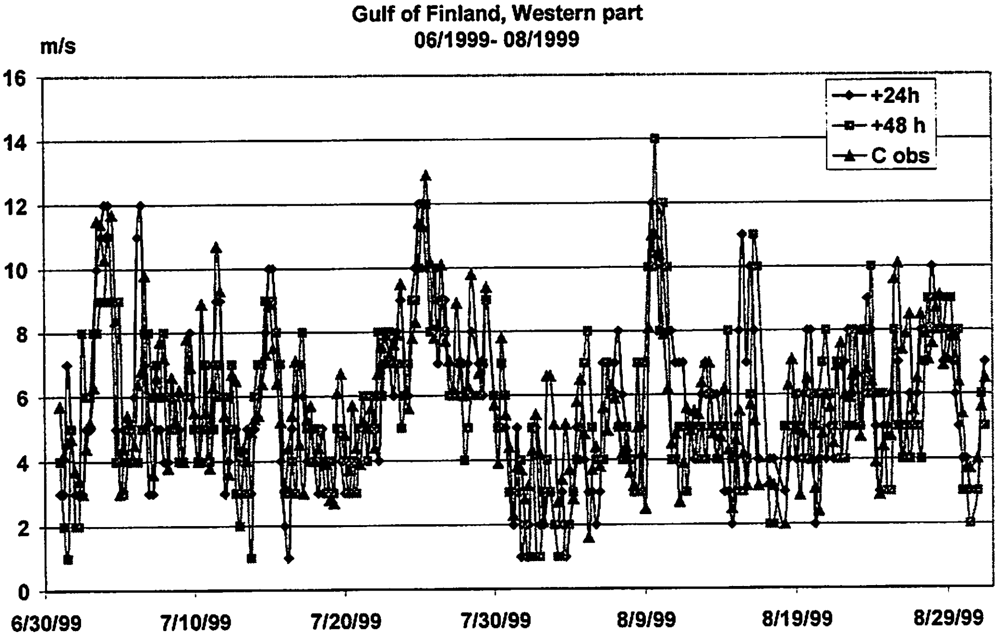
To verify the representativeness of wind parameters produced by HIRLAM one way is to compare it to observed wind. Meteorological measurements of wind speed and direction at synoptic stations typically represent wind conditions only at that site, especially in complex terrain (e.g. [6],[7],[15]), while HIRLAM surface winds represent larger areas including often variation in topography and orography.

3.1 Coast and offshore

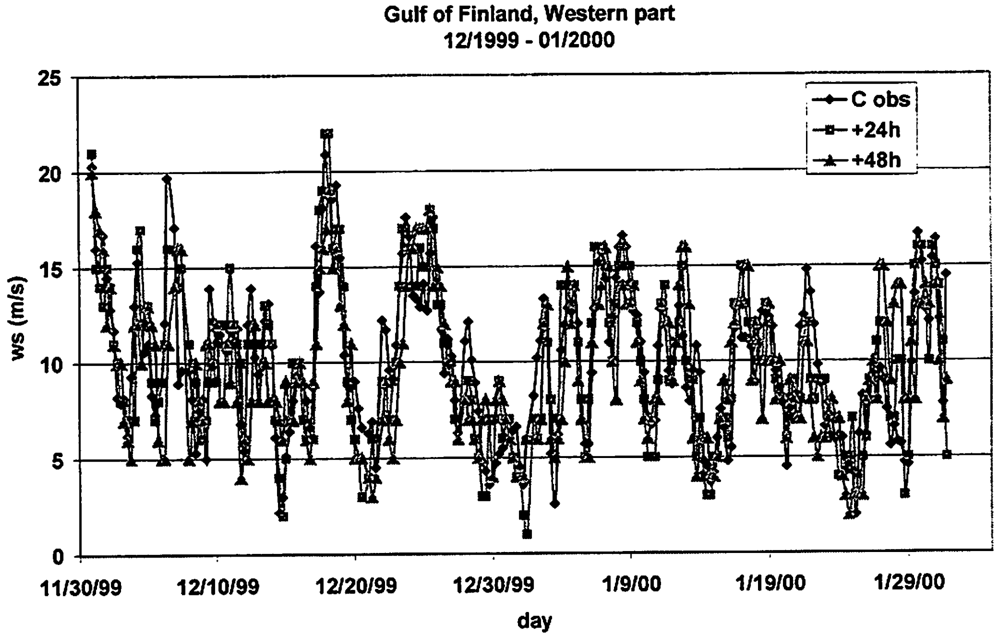
For this presentation we have looked at the western part of the Gulf of Finland.

As seen in *Figure 4* the fluctuation in wind speed is quite strong both in winter and summer. HIRLAM forecasts follow relatively well the observations and the trends in wind speed. However, having a look at individual forecasts versus observed wind speed scattering is quite big, while the correlation is much better during winter period with high wind speeds than during summer (*Figure 5*).

The correlation between the forecasted and observed wind speed will be even better if 24 hour averages are used instead of 10 minute averages.

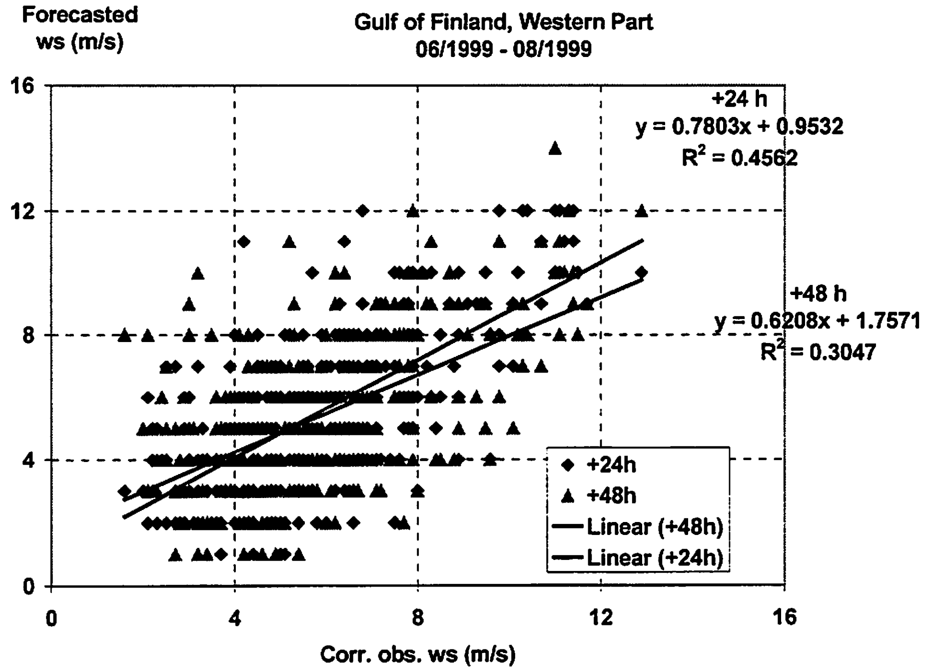


a)

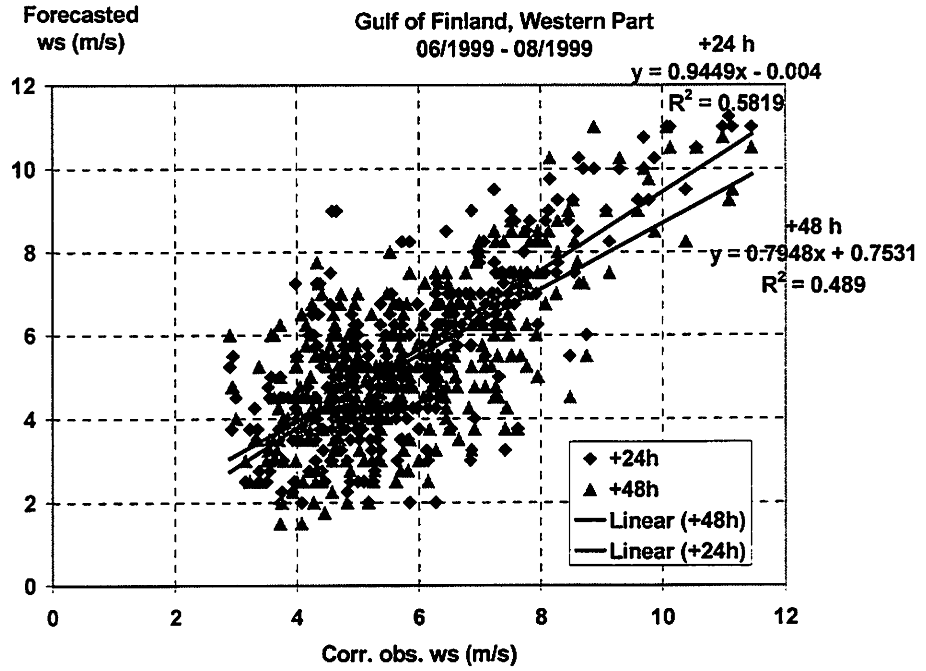


b)

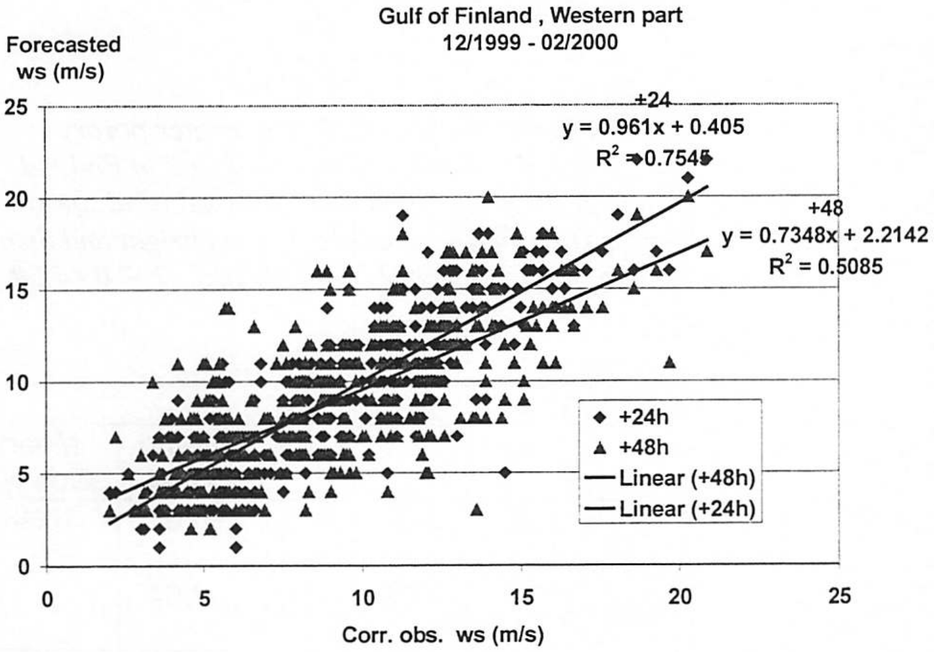
Figure 4. HIRLAM predictions (+24 h and +48 h) versus observed areal 10 minute wind speed (m/s) for every 6 hours in the western part of the Gulf of Finland a) during June-July and b) December-January.


Forecasted
ws (m/s)
Gulf of Finland, Western Part
06/1999 - 08/1999
+24 h
y = 0.7803x + 0.9532
R² = 0.4562
+48 h
y = 0.6208x + 1.7571
R² = 0.3047
16
12
8
4
0
0
4
8
12
16
Corr. obs. ws (m/s)
+24h
+48h
Linear (+48h)
Linear (+24h)

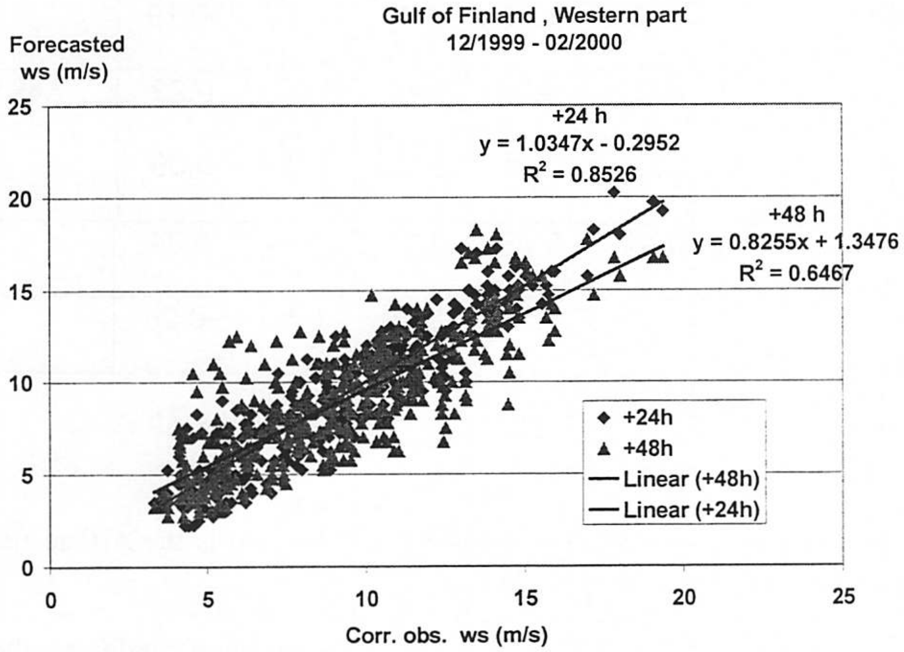
a)


Forecasted
ws (m/s)
Gulf of Finland, Western Part
06/1999 - 08/1999
+24 h
y = 0.9449x - 0.004
R² = 0.5819
+48 h
y = 0.7948x + 0.7531
R² = 0.489
12
10
8
6
4
2
0
0
2
4
6
8
10
12
Corr. obs. ws (m/s)
+24h
+48h
Linear (+48h)
Linear (+24h)

b)



c)



d)

Figure 5. The correlation between the 24 hour moving averages of predicted (+24h and +48h) and observed wind speed in the western part of the Gulf of Finland. The observed wind speed at the synoptic stations is corrected by taking into account the effect of nearby obstacles. Figures a) and c) correspond to 10 minute average winds and figures b) and d) to floating 24 hour avaerages.

It may also be noted, that the accuracy of forecasted wind speed is best for relatively high wind speeds (fresh wind speeds: 7-13 m/s) as shown in table 2.

Table 2. Calculated monthly mean wind speed (m/s) compared to contemporary predicted (HIRLAM +24h, +48h) wind speed in the Western part of Gulf of Finland some offshore synoptic stations for the period 1999-2000. The observed wind speed values from several weather stations is corrected, calculated to 10 m height and then avergaed. Wind speed classe used here: 0: 0-3.9 m/s; 1: 4.0 - 6.9 m/s; 2: 7.0 - 12.9 m/s; 3 : 13.0 - 25 m/s

		wsclass					
month	Data	0	1	2	3	Grand Total	Mean Obs ws
12	Average of (forecast+24-obs)	1.83	0.36	-0.02	-0.52	-0.01	10.48
	Average of (forecast+48-obs)	2.83	0.75	-0.84	-1.75	-0.64	
1	Average of (forecast +24-obs)	0.53	0.24	0.00	-0.97	-0.07	9.54
	Average of (forecast+48-obs)	1.03	1.30	-0.28	-2.55	-0.19	
2	Average of (forecast+24-obs)	-0.06	-0.25	0.44	1.40	0.22	7.89
	Average of (forecast+48-obs)	1.25	0.04	0.00	-0.96	0.06	
Total Average of (forecast+24 - obs)		0.41	0.05	0.11	-0.31	0.04	
Total Average of (forecast+48 – obs)		1.50	0.62	-0.40	-1.86	-0.26	

3.2 Arctic fjelds

The other important region for wind power production in Finland is the Artctic fjelds located on the northern side of the Polar Circle.

The caps of arctic fjelds in Northern Finland typically represent wind conditions above the ABL, while these regions are governed by the frequency of surface inversions reaching on average up to some 500 m a.s.l [9],[10]. At these regions HIRLAM is quite sensitive e.g. to the given boundary description: average height of ground level and surface roughness. For the present version the average height of ground has made more realistic, so that the effect of hill caps will not be overestimated.

At these sites the situation concerning wind speed forecasts is quite similar to that observed at coastal areas in Southern Finland: on average the HIRLAM observations (= +6 h forecasts) correlate well with observed winds at the caps of the hills and the annual wind distribution produced by the two methods are very alike. But in individual cases the correlation becomes very poor

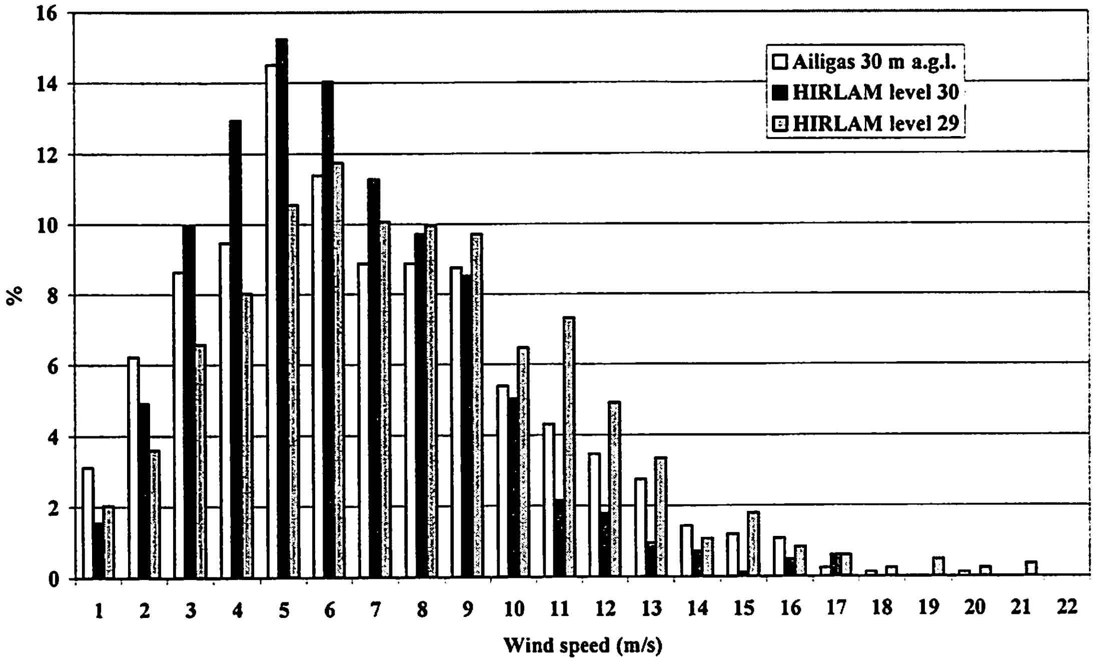


Figure 6. Annual distribution (%) of wind speed at the Ailigas fjeld, when the wind speed is taken from measurements and two HIRLAM levels (no 29 and 30).

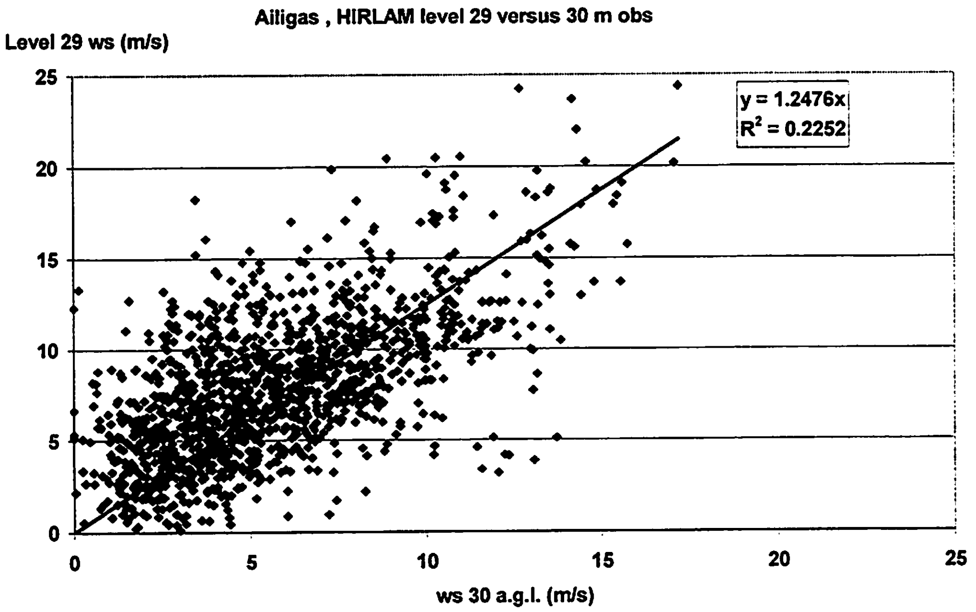


Figure 7. Correlation between HIRLAM observation (=+ 6 h forecast) and measured wind speed at Ailigas fjeld in Northern Finland.

4 REQUIRED LENGTH AND ACCURACY FOR WIND FORECASTS

To our knowledge there are no definitions, not at least in Finland, what the accuracy of prediction of wind speed or power production should be for different time intervals concerning wind power production. However, looking at the power curves of wind turbines (or power plants) it is obvious that at some area of the wind speed distribution the accuracy have to be better than for some others (see .

At relative low wind speeds, strongly ascending part of the power curve between 5-10 m/s, an error of ±1 m/s in wind speed gives an error of about 50 % in wind power production, while at nominal power the error in wind speed could be much larger without an error in predicted wind power. Then again at wind speeds close to 25 m/s (cut off) high accuracy in wind speed predictions is required.

There is a need to define some requirements for accuracy of prediction of wind /power production, perhaps even as a function of the size of the power plant, taking into account perhaps also the local grid and other restrictions and expectations.

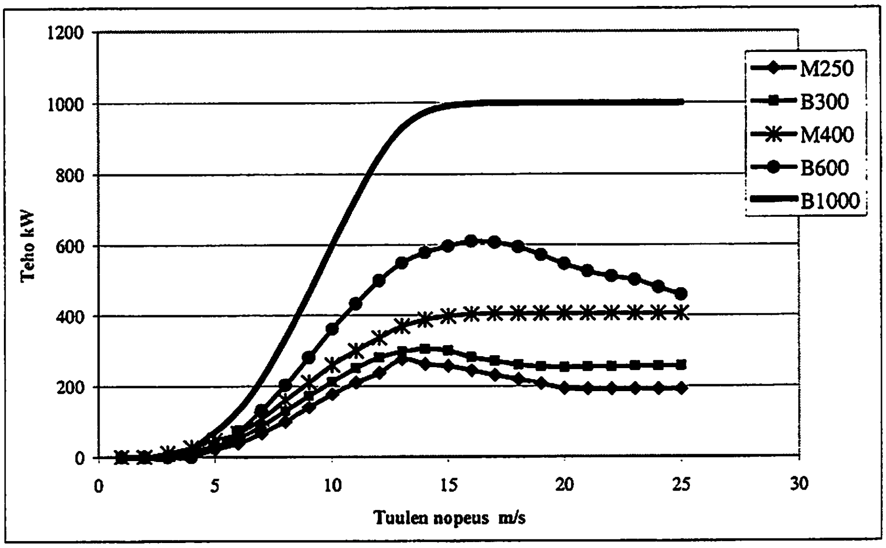


Figure 8. Typical power curves for some wind turbines in classes 0.2-1.0 MW.

5 ICING

Icing of blades will reduce significantly the power production of a wind turbine, and it may cause environmental danger. To be able to take the icing effect on production into account the duration of icing, amount of ice on the blades and lift and drag coefficients for iced blades have to be known. Due the possible danger it might be, that the wind power plant has to be stopped until the blades are surely ice free again, and thus also the duration of ice on the blades ought to be known [11].

Frequent severe in-cloud icing occur e.g. at Scandinavian mountains, Scotland, hilly regions in southern Germany, the Alps, Apennines in Italy, mountainous regions in southern France etc. [11].

6 FUTURE WORK

Wind power production, in spite of the historical development, is expected to increase strongly also in Finland within the coming years. Up to now wind power plants have been very small, but up to 200-300 MW offshore plants are under planning. But even now short term variation and uncertainty in 1-5 days power production by wind power plants has became an obstruct to enlarge the number of wind turbines for some power companies. As the number of wind power plants and proportion of electricity produced by these plants will increase the interest in forecasts of 1-5 days wind power production locally and country wide will grow.

To improve the on site wind forecasts, and predictions of power production, local wind profiles have to/can be used together with HIRLAM products. To do this local wind profiles have to be known for different stability situations in the ABL, and also the effect of nearby obstacles, changes in orography and surface roughness affecting the wind flow have to be taken into account. To have this part done, there is still much work to be performed due to our very complex terrain at the potential sites for large wind power plants.

In Finland, but also in many other regions in Europe, the daily variation in wind power production does not depend only on wind speed and wind conditions, but also on temperature (air density) and especially icing of blades, as shown in the recent EU/WECO project. Temperature forecasts are accurate enough to cover this part of the parameters, but icing remains a problem which has not been solved yet.

In principle our forecasting procedure for 24-54 hours could be as follows: Areal wind speed and direction, temperature and icing parameters are produced by HIRLAM weather forecasting model, on-site wind conditions for hub-height is calculated taking into account local surface roughness + obstacles + wind shear (e.g. WASP) and especially in hilly terrain perhaps some 3D-code produced in our EU-MOWIE[1] project [4], icing and icing effect on power production is calculated according to the method

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[1] See: http://www.fmi.fi/TUT/MET/energia/mowie.html

produced by the WECO project [11]. For forecasts shorter than 6 hours perhaps persistence or some other method would be better.

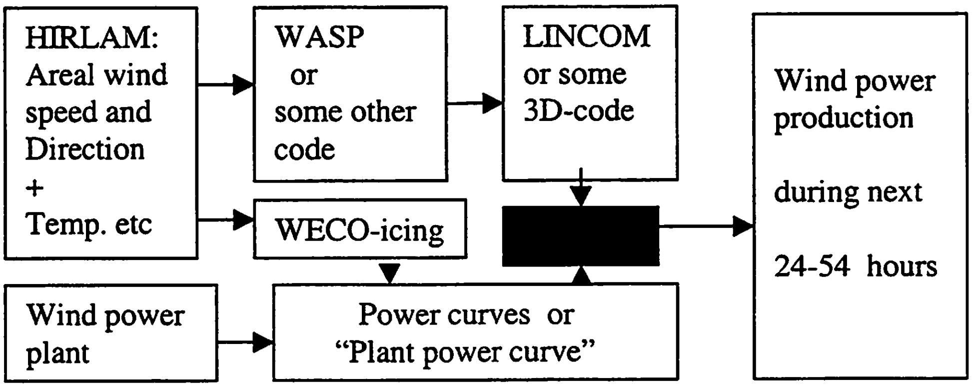

Figure 9. Schematic illustration of prospective procedure to produce short range forecasts of wind power productions in Finland. At present the FMI has good experience in codes and methods needed in all separate boxes.

Anyway, according to contacts with some utilities concerning this IEA meeting, it is obvious that there is interest and need to create a short range forecast system for wind power plants in Finland. This could be done within a national project, but the work could be more effective if it were performed within an international cooperative project.

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IEA Expert Meeting

Wind Forecasting Techniques

NREL National Renewable Laboratory
Golden , Colorado, USA
4./5. April 2000

WIND ENERGY DEVELOPMENTS IN IRELAND

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Irish EnergyCentre - Renewable Energy Information Office

WIND ENERGY DEVELOPMENTS IN IRELAND

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Abstract

The report gives a general outlook on the wind energy developments in Ireland. The focus is on wind forecasting. The relevant aspects in energy policy, which concern the wind energy development and system penetration aspects of wind energy are discussed. The importance of the political background is found in the conclusions of studies that have been carried out and identified the need for wind forecasting with regard to current and future developments. Two approaches of wind forecasting are presented, which are in planning and are the issue of the discussion in this meeting.

Introduction - General Outlook of Wind Energy in Ireland

Wind Energy Development (2000-2010) -Trends in electricity demand and supply

The last twenty years have seen significant growth in demand for electricity. Between 1990 and 1998 demand grew by 48%. Significant growth is anticipated to 2010, an increase of 65% compared with 1998. Table 1 traces this growth.

Table 1: Growth in electricity demand by sector 1980 - 2010 Terawatt Hours (TWh)

Year	Industry	Residential	Transport	Agriculture	Tertiary	Total
1980	3.30	3.59	0.00	0.00	1.79	8.69
1985	3.67	3.97	0.01	0.00	2.20	9.85
1990	4.62	4.14	0.02	0.43	2.80	11.99
1995	5.86	4.95	0.02	0.50	3.59	14.93
1998	7.09	5.64	0.02	0.58	4.43	17.77
2000	*7.92*	*6.28*	*0.02*	*0.65*	*4.94*	*19.81*
2005	*9.77*	*7.74*	*0.02*	*0.80*	*6.10*	*24.44*
2010	*11.67*	*9.27*	*0.02*	*0.95*	*7.30*	*29.22*

Most of this electricity is produced by ESB at thermal generating stations. Recent years have seen the emergence of independent power producers (IPPs) who use the electricity they produce on site or sell it to ESB. The electricity produced by these generators comes from renewable sources or cogeneration plants. The number of IPPs in the market place is expected to grow with the liberalisation of the electricity market (Feb. 2000).

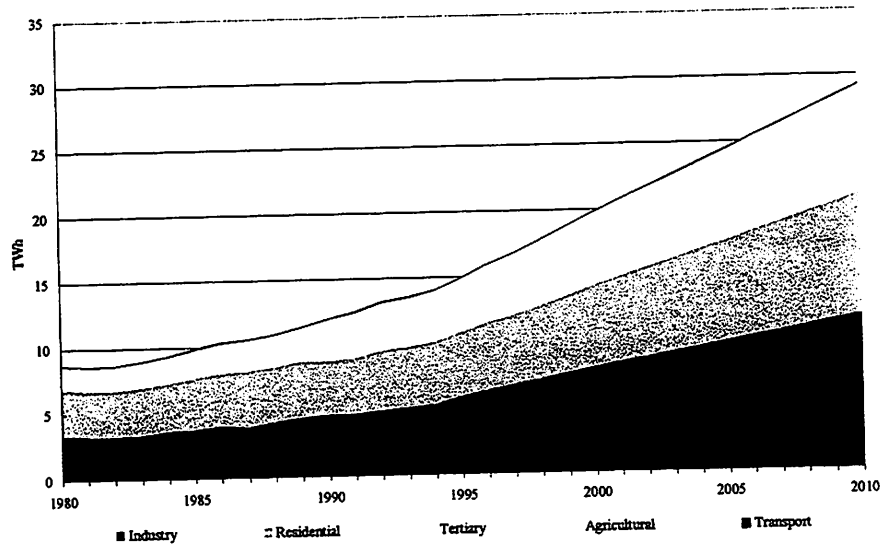


Figure 1: Growth in electricity demand by sector 1980-2010

In the same context the changes in fuel mix over this period is interesting. Two aspects are particularly noteworthy, namely (Figure 3):

- the steady, continuous coal input to the Moneypoint plant has varied very little over the period;
- the dramatic projected increase in the contribution of gas to the electrical supply mix, a widespread phenomenon in liberalised markets with access to natural gas. In 1998 gas accounted for 30% - it is projected by 2010 to account for 56% of the fuel mix for electricity generation.

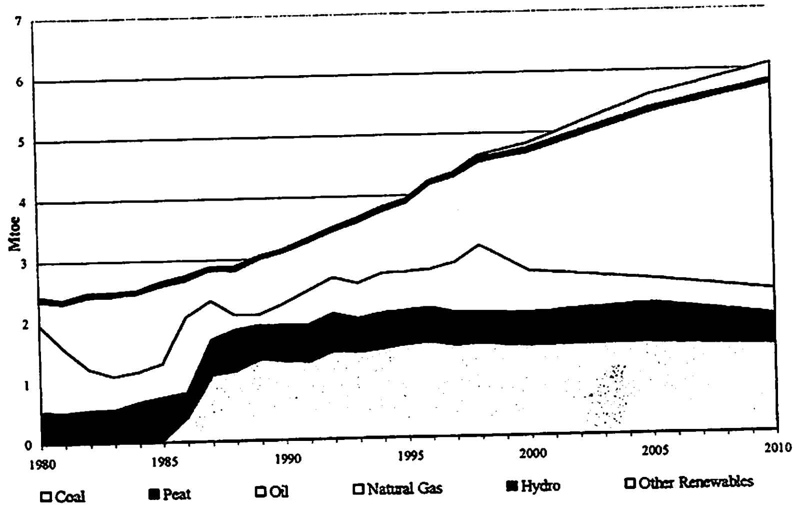


Figure 3: Fuel input for electricity production in Mtoe (1980-2010)

It is projected that indigenous energy sources other than natural gas will grow to 14% of the fuel mix, due to the coming on stream of Europeat and the continued renewable energy programme.

The Alternative Energy Requirement (AER) Programme

Under the AER competitive bidding scheme, **winning bidders who pass technical and commercial evaluation and who submit the lowest prices for the sale of electricity are entitled to:**

- A **15-year power purchase agreement** whereby the ESB buys the electricity output of the winning facility at the bid price.
- The **additional cost** of electricity procured under the AER schemes **is spread across all electricity consumers.**
- The prices **paid by the ESB** are increased annually in line with the **Consumer Price Index.**
- Apply for a **capital grant under the ERDF** Economic Infrastructure Operational **Programme 1994-1999.**

Category	AER I - target MWe	AER II - target MWe	AER III - target MWe	AER IV - target MWe	Total All AER competitions
Biomass/waste	*15*	*30*	*07*	*00*	*52*
CHP	*20*	*00*	*00*	*35*	*55*
Hydro	*10*	*00*	*03*	*00*	*13*
Wave	*00*	*00*	*05*	*00*	*5*
Wind	*30*	*00*	*90*	*00*	*120*
Total	*75*	*30*	*105*	*35*	*245*

Table 2: Targets set in AER competitions

Current status

By March 2000 a total of 67.5 MW of Wind Power has been installed. An additional 80 MW is anticipated by the end of 2000. This will bring the total AER capacity to 147 MW. The main reason for the shortfall with respect to the targets is the lack of cohesion between planning policy and energy policy.

Competitive systems versus fixed prices for the sale of electricity to the national grid from renewables

All EU Member States have recourse to instruments for stimulating renewable energy. Denmark, Germany and Spain, for example, have achieved considerable growth in the penetration of renewable energy based technologies through fixed price schemes. The additional capacity installed in 1998 is compared with total installed capacity in table 3. Ireland (AER programme) and the UK, on the other hand, deploy schemes, which focus on improving the price-performance ratio through a competitive process for the procurement of electricity generated from renewable sources. This is also illustrated in table 9.1 which shows that the cost of wind farm produced electricity from fixed price schemes is higher than in Ireland.

Country	Installed in 1998 / MW	Total installed / MW	Average price (? /kWh)
Germany	794	2,875	0.086
Denmark	300	1,448	0.079
Spain	195	707	0.068
UK	14	325	0.044
Ireland	10	63	0.035

Source: Working Paper of the European Commission: Electricity from renewable sources and the internal electricity market; New Energy Magazine (BWE); DPE, DTI (UK).

Table 3: Increases in wind energy penetration and average costs

Proposals for the future

A Renewable Energy Strategy Group has been established which includes representatives of planning authorities, the ESB, the Irish Energy Centre/Renewable Energy Information Office and relevant Government Departments, to recommend measures to redress the many constraints in the deployment of renewable energy. The Strategy Group reports to the Minister. The initial focus is wind energy. An integrated resource planning approach is being applied to the wind energy resource, electricity network and land use. The objective is to produce an action plan to ensure target delivery set in the green paper on sustainable energy and the Kyoto protocols.

WE-Contribution	**2000**	**2005**
Installed Capacity	67.5MW	601MW
Electricity Generated	453 GWh 1.0%	2001GWh 7.4%

Table 4: Targets for Wind power/energy

Identified Wind Energy Impact on the network

The impact, which wind energy electricity plants have on the network differs from other electricity plants largely because of the intermitted nature of the resource. As the level of wind energy on the system as a whole increase, this affects the importance of these issues, as does the geographic distribution of the wind farms. These issues include:

- *Operational Factors*

  power system characteristics, dispatch costs, measurement, **wind forecasting**, control, power quality, operational reserve, margin, maximum infeed
- *Effects on Dispersed Siting*

  Existing wind farms are all sited along the West Coast. Therefore a study has been carried out that suggest wind farms to be located also in the South and South Eastern Coast, where wind yields are quite satisfactory.
- *Long-term economic trends*
- *Capacity Credit*
- *Energy Credit*
- *Economics*
- *Interconnections operational between Northern Ireland and Scotland*

System Penetration Aspects of Wind Energy

In order to maintain a stable system and system frequency, the generation on a system must always meet the instantaneous demand of the system as electricity cannot be stored readily. With an increase level of wind penetration on any system, the output of other generators will need to change not only as a result of load variations, but also as a result of wind power changes.

Liberalisation of the Electricity Market in February 2000

The design of the market liberalisation framework gives priority to low carbon or renewable power generation. To date the liberalisation is organised as follows:

- 28% of the electricity is on the open market
- large electricity users can choose their suppliers (> 4GWh/year)
- all who wish to use "green electricity" can choose their supplier

To conclude, the key aspects in the liberalisation of the electricity market and the targets set in the Green Paper of Sustainable Energy point towards more detailed wind forecasting, dispersion siting and wind resource assessment for onshore and offshore wind farms. This applies especially to electricity suppliers.

A Note on Off-Shore Electricity Generation Potential

It is the policy of the Minister for the Marine and Natural Resources to encourage the maximum beneficial use of national off-shore resources, including the harnessing of enormous resources of wind and wave power for electricity generation. The Department of Public Enterprise, along with the Department of Economic Development, Northern Ireland, has commissioned a study, funded through the European Union Interreg Programme, in relation to the prospects for the development of off-shore windfarms. The results of this study will be published by the end of 2000 and will facilitate technical issues for developers interested in assessing the off-shore options. Hence, off-shore wind farms are not yet under consideration with respect to the wind forecasting.

Viewpoints for Penetration of Wind energy

Two parties with conflicting views are currently investigating the potential of wind energy generated electricity: the Irish Wind Energy Association (IWEA) and the

Electricity Supply Board (ESB). The IWEA is promoting energy from wind and assumes a high potential and tries to proof its applicability. ESB is more conservative and concerned about the actual operational effects on the quality of their supply system. That is, ESB's study (Ref. ESBI and ETSU, Total renewable Energy Resources in Ireland, 1997) on resource estimations and ongoing research on control advices for secure operation stated that especially wind forecasting is crucial to meet the target set to only 7%. IWEA's study (Ref. Wind Energy Penetration on the Irish Power System, Report by IWEA, 2000) assumes a possible penetration of wind energy into the electricity network of 10% immediately and 25% in the long term.

Wind Forecasting

The need for wind power forecasting was identified by the Irish Wind Energy Association (IWEA) and ESB and is increasing with the liberalisation of the electricity market.

In the MORE-CARE proposal the Electricity Supply Board (ESB- National Grid) stated that penetration of renewable energy sources in isolated and weakly interconnected power systems can be increased in a secure and reliable way, if advanced control tools are available to the operators of these systems. The main features of these control tools comprise advanced software modules for load and wind power forecasting, unit commitment and economic dispatch of the conventional and renewable units and on-line security assessment capabilities integrated in a friendly Man-Machine environment.

UCC's Sustainable Energy Group on the other hand is linked to the Renewable Energy Information Office (REIO) and will assist and contribute in the investigations of the identified need for wind forecasting. The Group has started discussion with various wind farm operators for online/real time wind data. Additionally the Group is collecting wind data at different sites in North and West Cork in conjunction with a wind farm planner. The availability of real-time data will ensure the testing for the planned wind forecast tool.

Plans and involved Institutions - Project Proposals

There are currently two major project proposals dealing with wind power forecast:

MORE CARE - under the EU 5th Framework ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT PART B: ENERGY - ESB

MORE ADVANCED CONTROL ADVICE FOR SECURE OPERATION OF ISOLATED POWER SYSTEMS WITH INCREASED RENEWABLE ENERGY PENETRATION AND STORAGE

ERI-ECOSITE - under the HEA Programme for Research in Third level Institutions 2000-2003 -University College Cork, Sustainable Energy Group

WIND ENERGY HYDROGEN BASED-ENERGY STORAGE PILOT SYSTEM INCLUDING WIND FORECAST MODELLING

Scenarios under discussion

The two scenarios under discussion are mainly dependent on the atmospheric physics implemented in the prediction of local wind fields. These are

Linear Interpolation

A Boundary-Layer model (WAsP), which solves the two-dimensional continuity equation to produce mass-conservative wind fields for a variety of meteorological conditions (which are parameterised dependent on the local conditions, terrain, vegetation, and orography).

Dynamical prediction

A Meso-scale model (MM5, GESIMA), which solves the so called "non-hydrostatic equations", i.e. conservation of momentum, heat and mass, and are highly non-linear. The models solve these equations numerically.

Approaches under discussion

UCC-REIO-MET EIREANN-approach

- HIRLAM geostrophic wind fields (23km horizontal resolution)
- Surface transformation via geostrophic drag law (aerodynamic roughness z_0 and Coriolis parameter f)
- WasP for adjustment of surface wind to local conditions (orography, roughness, obstacles)
- Model Output Statistics (MOS) via a (e.g.) Kalman filter to take effects into account that are not explained by the physical model (error analysis)
- Power prediction from wind via PARK

- Model Output Statistics (MOS) via a (e.g.) Kalman filter to smooth wind speed and adjust to power curves of wind turbines
- Turbine Power Output

This approach is based on the WasP model and has been developed by RISOE Denmark and is in operation since February 1999. It is currently under discussion by the Sustainable Energy Group UCC in collaboration with REIO and Met Eireann. See flow chart in Apendix 1.

UCC-MET EIREANN-ESB-approach

- HIRLAM geostrophic wind fields (23km horizontal resolution)
- Data Preprocessing with Interpolation (Cressman-type analysis and overlapping via bi-parabolic interpolation) and Adjustment (boundary blending and feedback)
- Mesoscale Model (MM5, GESIMA) for surface winds (non-hydrostatic model with surface parameterisation)
- Power prediction from wind via *Windfarm*
- Model Output Statistics (MOS) via a (e.g.) Kalman filter to smooth wind speed and adjust to power curves of wind turbines
- Turbine Power Output

This approach is under consideration and investigation by the Sustainable Energy group in collaboration with Met Eireann, GKSS (for supply of GESIMA) and ESB. See flow chart in Apendix 2.

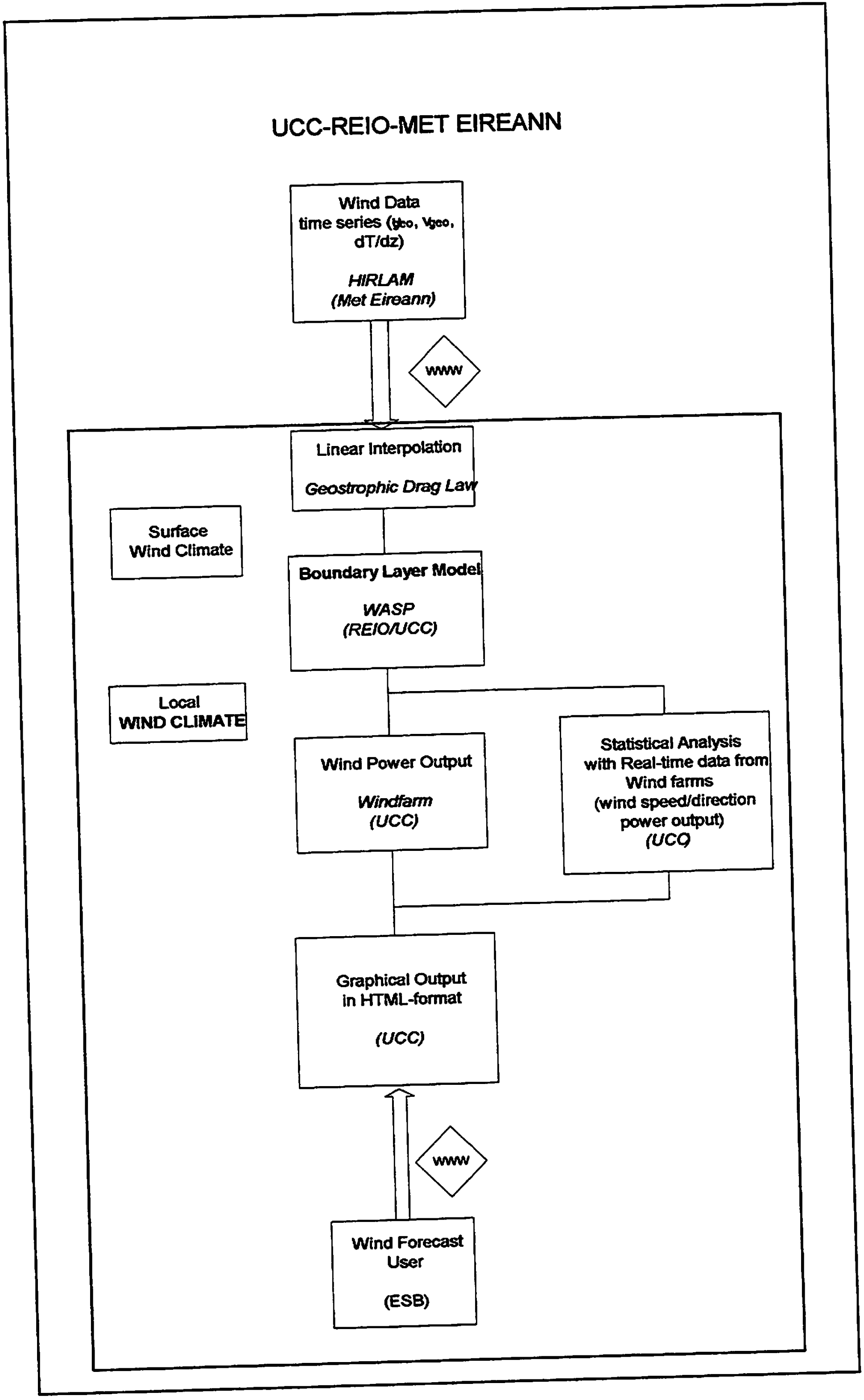
Conclusion

1. The Irish Government firmly committed to medium term of 500MW additional on-shore wind by 2005.
2. The need for wind energy forecasting was identified by the Irish Wind Energy Association (IWEA) and the Electricity Supply Board (ESB). This is due to:
   - the small island grid
   - increase in targets for wind energy
   - the market liberalisation
3. Two studies on wind forecasting are underway:
   - MORE-CARE by ESB National Grid
   - HEA-Programme for Research in Third level Institutions 2000-2003 by Sustainable Energy Group UCC

4. Two approaches for wind forecasting online tools are under discussion and investigation: a module based on linear interpolation and a module based on dynamical prediction.

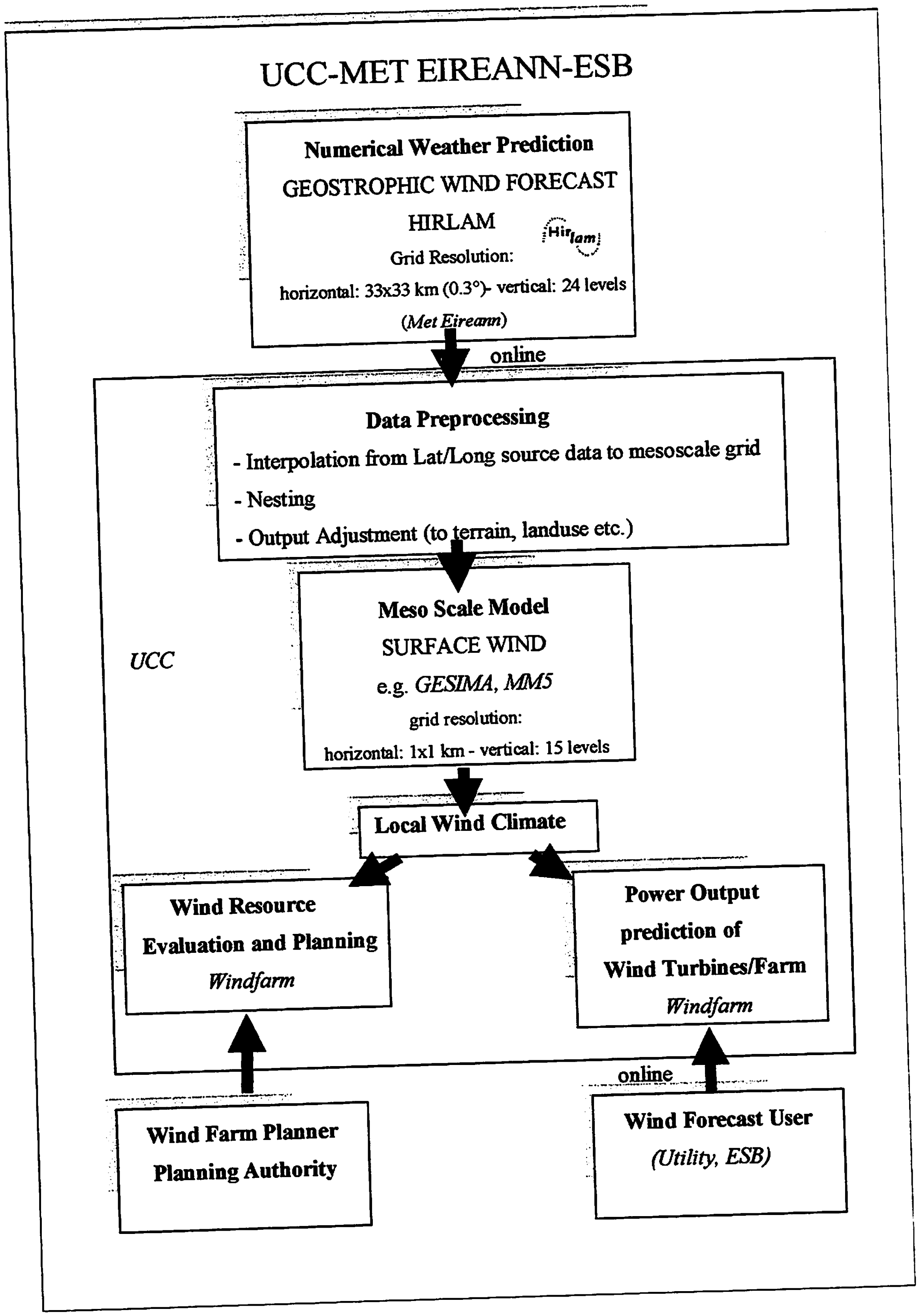
Apendix 1:

Figure 3: Model-complex 1 "UCC-REIO-MET EIREANN-approach"



Apendix 2

Figure 4: Model-complex 2 "UCC-MET EIREANN-ESB-approach"



Presentation of project proposal

Developing and testing of forecasting techniques for Norway

Asgeir Sorteberg, Norwegian Meteorological institute

Lars Tallhaug, Kjeller Vindteknikk AS

Prepared for

Expert meeting on "Wind Forecasting Techniques"

NREL Golden Colorado

April 4th and 5th 2000

Developing and testing of forecasting techniques for Norway

Introduction

The total primary energy consumption in Norway was in 1997 285 TWh. 114 (40%) of that was electricity consumption. Hydro is the dominating power source with a production in 1997 of 110.5 TWh. The remaining electricity (3.5 TWh) was imported from Sweden and Denmark. The hydro power production has a large inter annual variation due to variations in precipitation. In 1999 Norway was a net exporter.

The Joker in Norwegian energy policy is, however, the domestic use of the oil and gas recourses. Norway is the second largest oil exporter in the world, and also a significant exporter of natural gas. The policy for domestic utilisation of the fossil fuels and taxation of greenhouse gas emissions will probably influence the electricity pool prices and thereby the economics of wind power projects.

Utilisation of the remaining hydro power potential is controversial due to environmental effects. This in combination with the greenhouse debate forces the authorities too look for alternatives. A goal is therefor set up to have 3 TWh annually from wind by year 2010. Policy instruments is also put into operation to be able to each the goal. Investment subsidy of up to 25%, tax reduction of 7% and annual operational subsidy of 0.043 NOK/kWh (0.5 cents/kWh). This reduces the cost of energy from wind in Norway from about 0.30 NOK/kWh (3.8 cents) to under 0.20 NOK/kWh (2.5 cents). The cost is then approximately equal to the cost of new hydro power plants.

The marked price is (Mars 27. 2000) 0.11 NOK/kWh (1.4 cents) and it is possible to by contracts for 5 years in the order of 0.15 NOK/kWh (1.9 cents). Anyway the developers puts their hope in the continuos growing demand and the decreasing prices for wind turbines.

The installed wind capacity in Norway is 13 MW (April 2000). This number is expected to grow significantly in the years to come. Several developers has applied for permit for a total of 428 MW. In addition 43 MW is already granted for.

One of the first free markets for electricity – Norway

Norway was the first country in the world to liberalise the trade of electricity. The regional non-profit monopolies were fully deregulated. The goal of regional self-sufficiency was replaced with marked economics. The Energy act was operative from 1991.

The trade of electricity is now organised by the institution Nordpool. They organise in practice two different markets, Elspot and Eltermin.

Elspot is the Nordic contract market where electric power is traded on a daily basis for delivery the following day, with full obligation to pay. Bids for purchases and sales respectively are placed for every hour during the day. Every contract includes one load in MWh/h, one price (NOK/MWh) and a duration of one hour. A price is set for all 24 hours of the day. The prices are fixed on the basis of all participants' collected purchase and sale requests.

In addition to this spotmarket there is a regulating power marked to ensure the physical balance between production and consumption. If a wind farm owner has sold 100 MW each our the next day and the wind force becomes weaker than expected, he (she) is forced to buy the remaining power on the regulating power marked. The regulating power marked is a tool for the grid operators to be able to handle all unpredictable differences between real and planned exchange in the delivery phase on short notice.

Active bidders on the regulating power marked must be able to regulate their delivery and usage within a space of 15 minutes. This means that only producers bid actively without the buyers responding to the price. The bidders can both offer to cut production and add production, both to a certain price.

The second addition is that the country is divided into areas depending on transmission capacities. The system operators has a tool called capacity fee that can be used to adapt the flow of power to the transmission limits. If the are problems with transmission capacity from an area with excess of power the system operator adds a capacity fee until the production reduces down below the transmission limits.

Eltermin is a financial market for price hedging and risk management when buying or selling electrical power. It means that a seller can sell electricity ha does not have to a certain price. The seller must then by his electricity from Elspot. The risk is then moved from the buyer to the seller.

Direct long term contracts between buyer and seller is also an option. They can be both physical and fiscal.

The turnover (percent of total production) in the spot market is increasing and reached last year 36%.

The wind regime in Norway

The wind resources in Norway is so far not to intensively examined. This is both due to the low level of wind farm development, the complexity of the terrain and the length of the coastline (latitude 58 to 72). The focus so far has been on the long coastline. The measurements from the weather stations have been easier to interpret than the less exposed inland stations, and icing is regarded to be less problematic at elevations less than 500 m.

Around 60 sites have been monitored with 30 to 50 m tilt up masts. A well-exposed coastal site without local acceleration can be expected to have an annual mean wind speed of around 8 m/s at 50 m height. Favourable hilltops can achieve annual mean wind speeds exceeding 10 m/s. The variations due to both local and large scale effects are large.

Most of the winds at promising sites are synoptic winds. There are a few areas with thermal driven meso-scale winds. In the southern part a slight sea breeze can be found, and in the outlet of fjords in the northern part of the country valley winds can be experienced in the winter.

Due to the mountainous terrain gravity waves on the lee side of mountains is found in simulations.

Motivation for forecasting

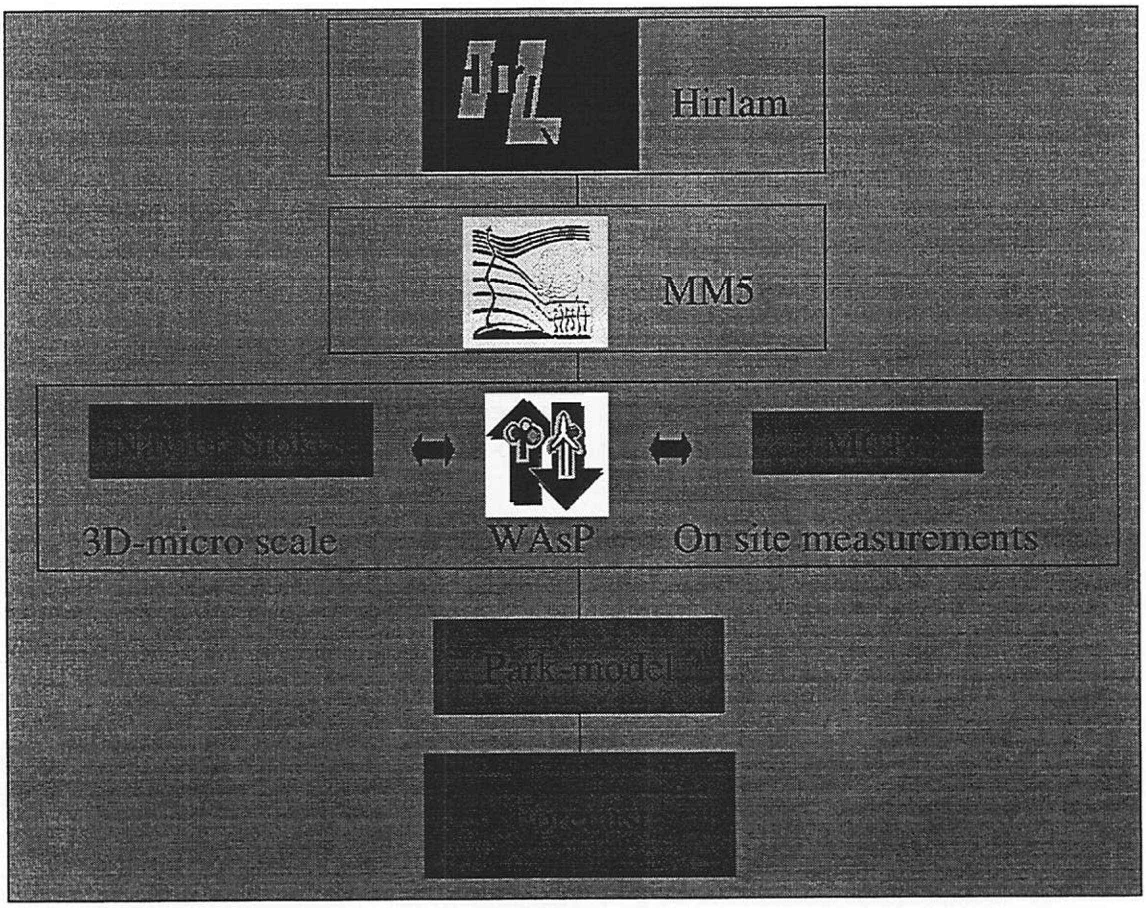
Due to the fact that there is no thermal power plants in the Norwegian system so far, and the hydro power plant are easy to control on short term basis, there is no need for forecasting for a physical operation of the system.

On the other hand the population in the windy areas of Norway are mostly sparsely populated. It means that the grid in these areas has limited capacity. It means that the operation of the grid will benefit knowledge of the wind production the next days.

In addition a wind farm owner trying to sell his energy on the free marked will hopefully increase the value of his power through knowledge of his future production.

Proposed project for developing forecasting techniques for Norway

Kjeller Vindteknikk (KVT), Institute for Energy Technology (IFE) and the Norwegian Meteorological Institute (DNMI) together possesses a broad expertise in wind measurements and forecasting on different scales. The KVT and IFE's knowledge of wind flow over complex terrain on a fine scale (100 m) and DNMI's expertise in numerical weather prediction on a synoptic and meso scale is proposed merged into a forecasting system giving the wind farm owners the opportunity to get a estimate of the energy production within the next 24 to 48 hours



The suite of numerical models is covering the synoptic to local scale wind variations with a final estimation the energy production, and consists of:

- HIRLAM (High Resolution Limited Area Model) , which is a hydrostatic numerical weather prediction model developed within a European framework over the last 15 years and is run operationally in 7 European countries. In Norway the model is run with 50 and 10 km resolution giving 48 hour forecasts twice every day.

- MM5 (Mesoscale Model 5) developed at NCAR (National Centre for Atmospheric Research). The model is based on the same dynamical equations as HIRLAM, but is a non-hydrostatic model, which makes it suitable for a running with a finer horizontal resolution than the HIRLAM model.

- WASP, which is used for more detailed wind simulations in smaller geographical areas to catch the small scale variations in the wind. It will also be considered to use other Navier-Stokes type models to simulate the small scale variations since WASP may have limited use in complex terrain.

- Park models (PARK and WIND FARMER) with detailed wake-models to incorporate the distortion of the wind flow due to the wind park itself and giving a estimate of the energy production.

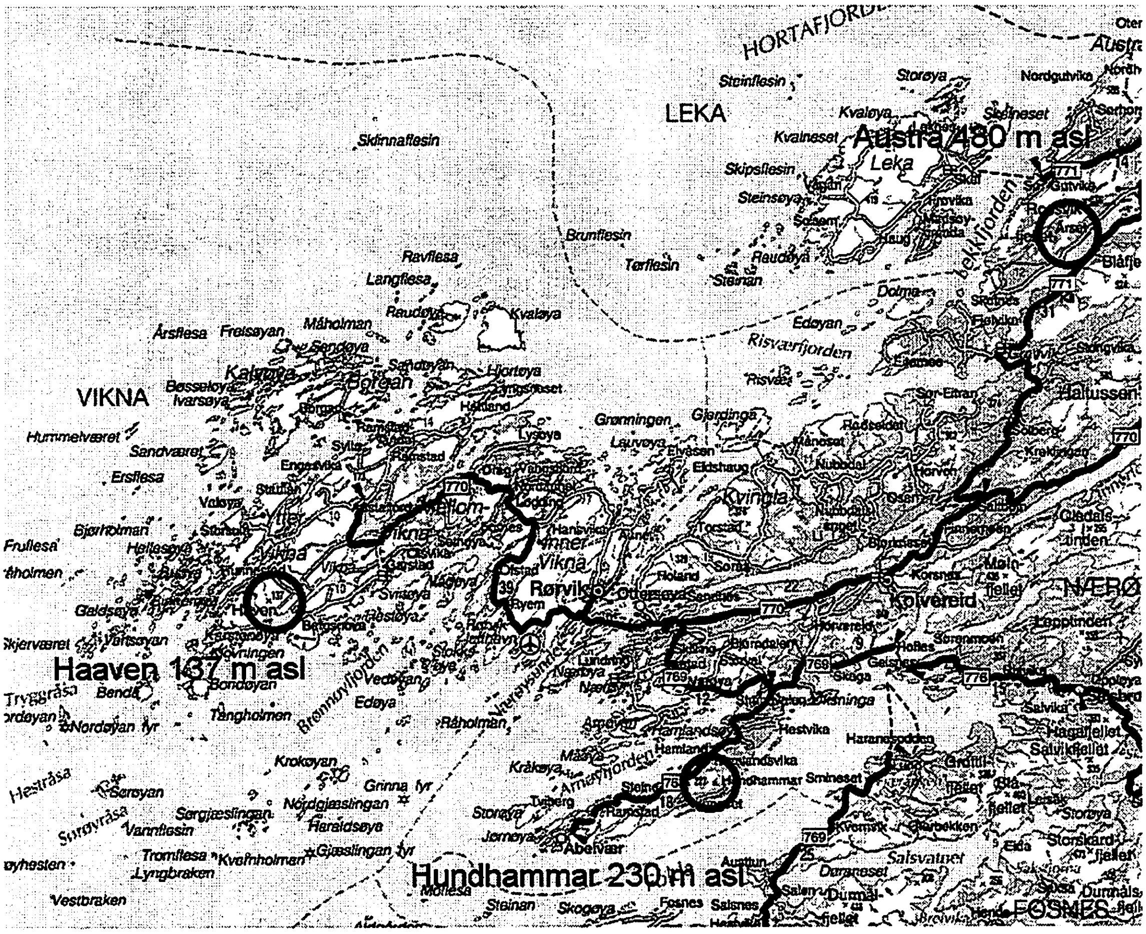
In addition to the suite of integrated numerical models covering synoptic to fine scale wind variations, the KVT's expertise in wind measurements over complex terrain and the synoptic observation network of DNMI will be used both to do long term validation of the near surface wind forecast from the current operational weather prediction models and to evaluate the effect of nesting MM5 with the HIRLAM system using IFE and KVT's observational database which include an extensive measurement campaign with several 50 m masts within a smaller area during a 2 month period. An important aim of this tasks is to evaluate the need for a non-hydrostatic model as an intermediate step in complex terrain to nest down from today's operational hydrostatic model to the very fine resolution models used to simulate local wind patterns in wind parks. Some preliminary results are shown in Figure 1 where HIRLAM with 10 km resolution, MM5 with 1 km resolution (2 cases with different vertical resolution) and speedup factors based on idealized runs with MM5 where relationships between geostrophic wind and surface winds are tried identified, are compared with wind measurements in 50 m.

Another part of the project will be to make a statistical correction procedure to correct the model results based local topographical information and possible biases in the model that is related to other meteorological parameters (wind direction, stability etc.)

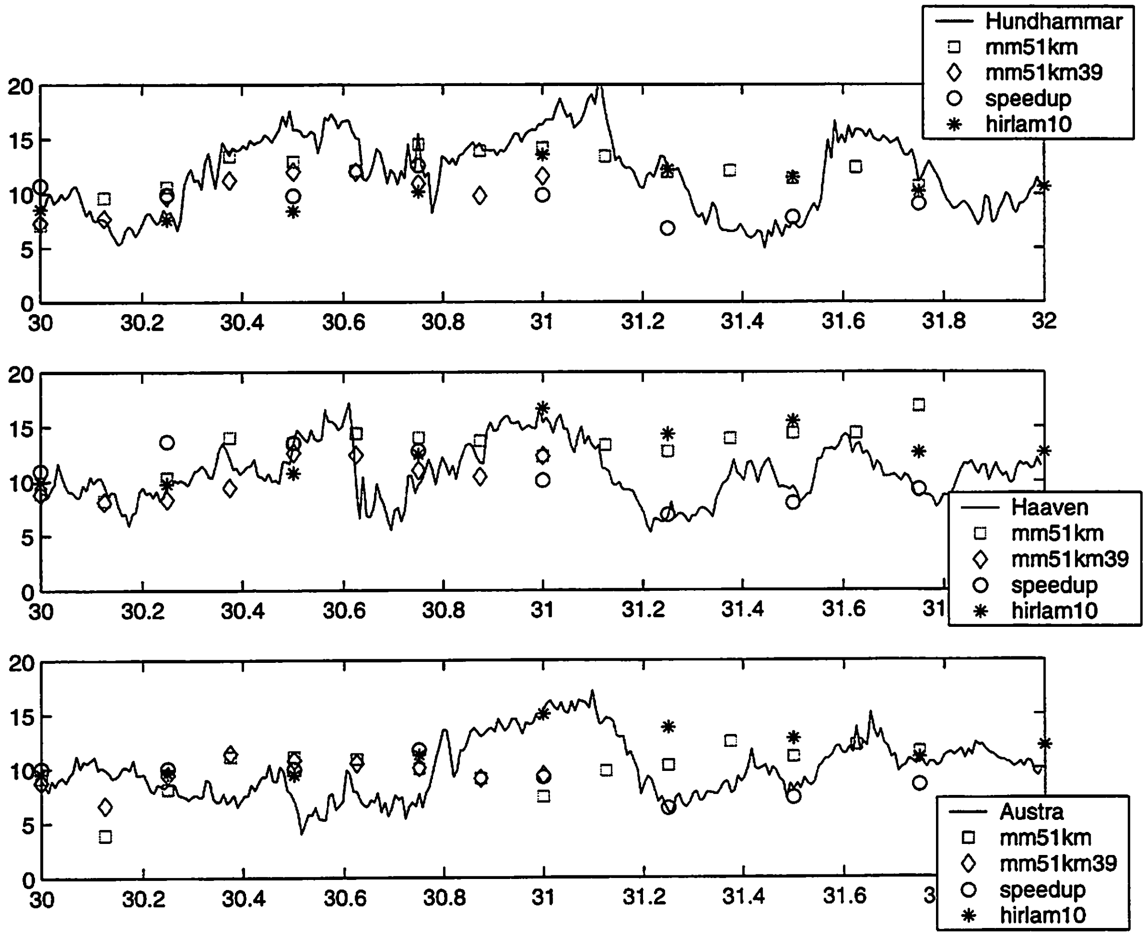
As part of the model studies several different turbulence parameterisations and different vertical and horizontal resolutions will be tested for the non-hydrostatic model. And both forecast skill and computing time requirements will be investigated in order to keep the computing time of the model system within realistic limits for developing of an operational service. Studies have shown that persistence or statistical forecasts based on local wind measurements often is better than models during the first 4-6 hours of the forecasting periods. The effects of assimilating in local wind measurements to improve the models short time forecast will be investigated.

When the ability of the different forecasts model to reproduce the local wind pattern is investigated relationships between the local wind (speed and direction) and the effect of the wind turbines will be addressed through the use of different wind park models.

The final aims of the project is to evaluate the necessity and usefulness of different models over complex terrain and develop a wind and energy forecasting system that can be run operationally on a supercomputer to give a 48 hour forecast of the expected energy production, with the choice to assimilate local wind observations and use local statistical relationship if available.



The map illustrates the location of the measurement stations. The distance between Haaven and Hundhammar is approximately 30 km.



The solid lines is measurements.

Figure 1: 48 hour forecasts of wind speed in 50m from HIRLAM with 10 km resolution, MM5 with 1 km resolution (2 cases with 31 and 39 layers) and speedup factors based on idealized runs with MM5 where relationships between geostrophic wind and near surface winds are tried identified, are compared with wind measurements in 50 m for 3 costal sites.

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Institute for Energy Technology

DNMI

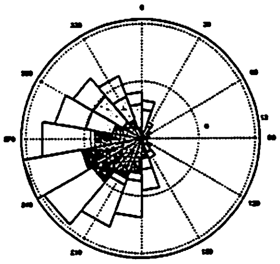
Do we need to cover all scales in order to improve the wind forecast ?

- **Understand the scale and mechanisms of the wind variations**
  - **Large scale winds compared to synop obs.**
  - **Idealized model runs**

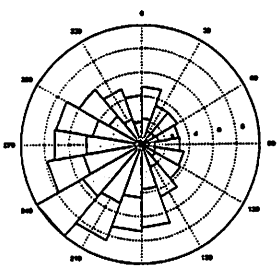
Relationship between large scale stability, and coastal windspeed

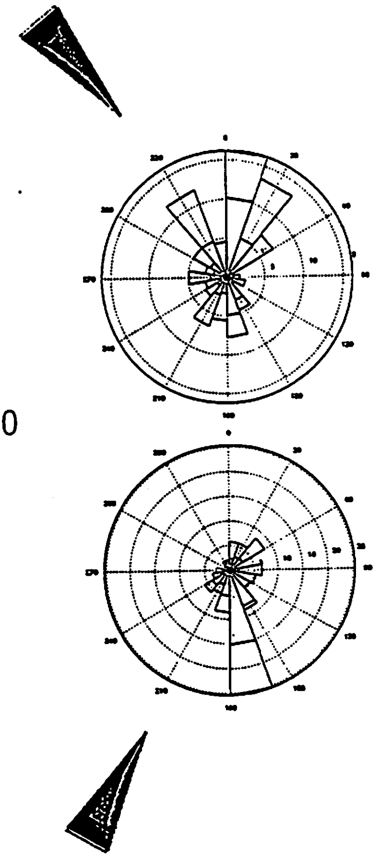
$$\boxed{\hat{h} = \frac{Nh}{U}}$$

$\hat{h} < 0.8$



$\hat{h} > 2$





$\hat{h} > 2.0$

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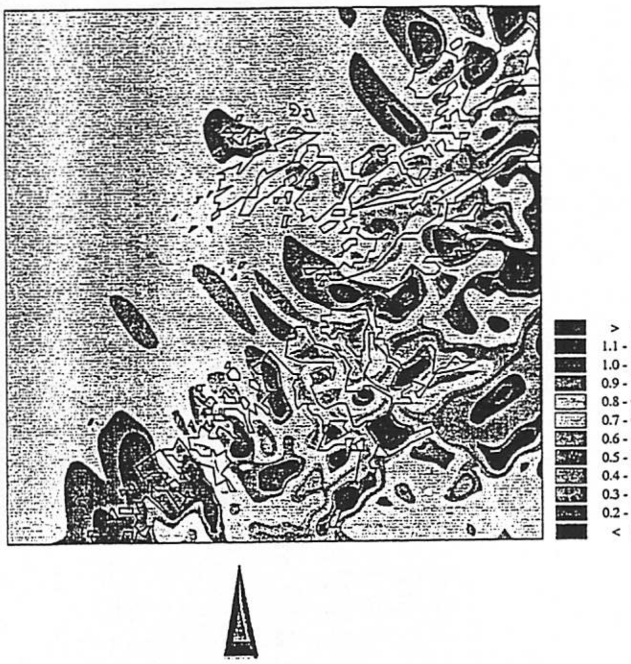
Speed up factors

$$\boxed{\frac{U_{loc}}{U_{g,pre}} = f}$$



$U_g = 15$ m/s
$\hat{h} = 0.6$

The quality of the operational models

- Long term verification of HIRLAM at costal sites
- Validation against campaign measurements

Do we improve the forecast quality by introducing MM5 ?

- Investigating the role of turbulence parameterization and model resolution
- Assimilation of local wind data
- Validation against campaign measurements

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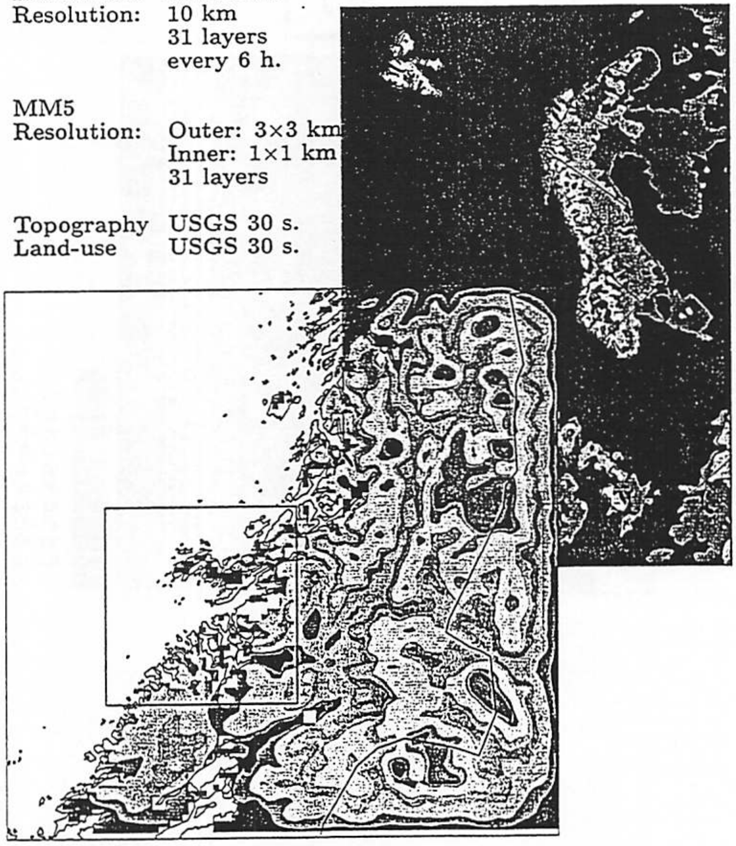
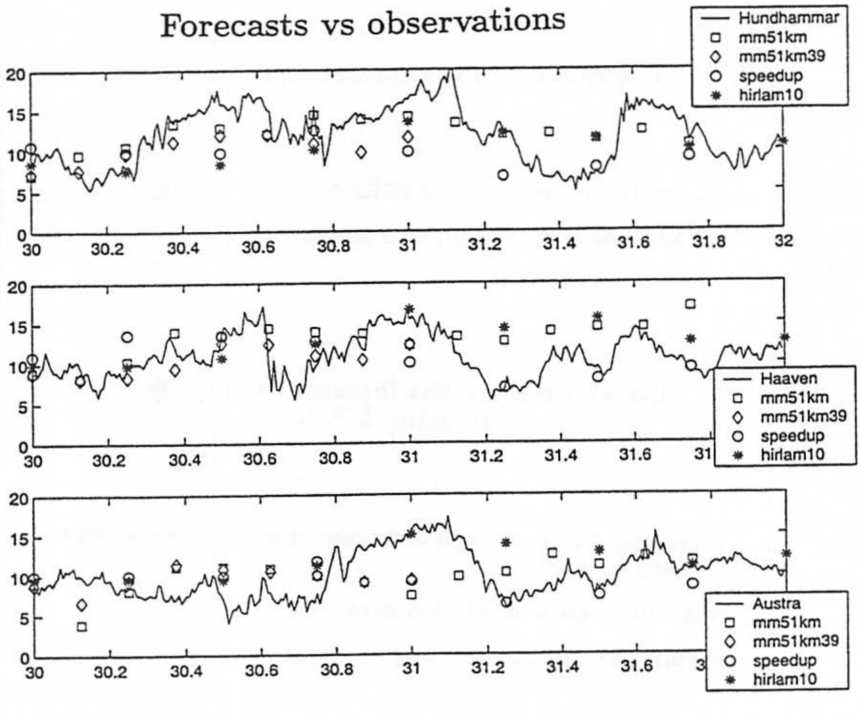
Preliminary test runs

Initial data	HIRLAM
Resolution:	10 km 31 layers every 6 h.
MM5	
Resolution:	Outer: 3×3 km Inner: 1×1 km 31 layers
Topography	USGS 30 s.
Land-use	USGS 30 s.





Forecasts vs observations

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Use of statistical corrections

- Statistical methods to correct the synoptic models based on large scale features (type of meteorological situation)
- Development of statistic methods to correct the model forecasts based on information about local topographic information and local meteorological parameters

Estimating energy production based on wind forecast

- Comparison against effect measurements

Final result of the project

- An evaluation of the necessity and usefullness of different numerical models over conmplex terrain
- Develop a wind and energy forcasting system that can be run operationally with the choice of assimilating local wind observations and use local statistical relationships if available

WIND FORECASTS: DEVELOPMENT AND APPLICATION OF A MESOSCALE MODEL

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Albany, NY 12203

Introduction

As the penetration of wind energy into electricity grids has grown, so has the importance of being able to reliably predict the output of wind power plants. The time horizon of interest to electric utilities and wind energy generators is typically one to two days, the period in which plant dispatch scheduling and spot-market purchases and sales are made [1]. Three main benefits are to be gained by making accurate wind energy forecasts available:

- Those responsible for scheduling and dispatching generating and transmission resources can better estimate how much wind energy will be available at any time, which can in turn lower the costs of meeting reliability and load requirements.
- Wind plant owners and operators can maximize the value of the energy they produce, for example, by contracting to sell excess wind power to others when available, or by purchasing in advance on the spot market to cover shortfalls in contractual obligations.
- Increased confidence in the accuracy of wind forecasts can help persuade utility companies and other power suppliers and purchasers to increase their use of wind energy and raise wind capacity payments.

This paper describes the development and initial application of a new wind forecasting system tailored for wind energy applications.

Status of Wind Forecasting

Although weather forecasting is a well-established science, techniques of wind forecasting for wind energy applications are quite new. Weather prediction, by and large, has not focused on producing accurate and geographically detailed wind forecasts. Numerical weather prediction models, such as those run by the US National Weather Service, typically operate on a very coarse grid scale such as 40 km, and the wind forecasts they produce cannot account for variations in terrain, surface roughness, surface albedo, and other important effects that occur over smaller distances.

With the growth of wind energy in Europe in the early 1990s, attention has been focused on the need for more reliable wind forecasts. The main research effort to date has been the EU-JOULE project, funded by the Danish Ministry of Energy and led by Risø National Laboratory of Denmark. Initial results from this project suggest that standard weather forecasts, coupled with a localized terrain model (WA^{s}P), can improve the accuracy of forecasted wind plant output under conditions experienced at sites in northern Europe. With the EU-JOULE technique, the percent reduction in the RMS error of predicted wind plant output, compared to a persistence model, appears to be in the range of 25 to 50 percent for 36-hour forecasts [2,3].

However, the EU-JOULE approach relies on a highly simplified wind flow model, WA^{s}P, to "zoom in" to the wind site from the coarse grid of the regional weather model. Jackson-Hunt models like WA^{s}P, along with mass-consistent models such as NOABL and *Wind*Map, do not capture many of the physical processes that can greatly influence winds near the ground, including sea and lake breezes driven by land-water temperature differences, thermal mountain winds, low-level nighttime jets, and other common phenomena. Moreover, such effects, which are especially important in complex terrain and weather regimes, cannot be fully represented in the regional weather models because of their coarse grid.

The Development and Validation of *Fore*Wind

The aforementioned drawbacks are entirely avoided by using the *Fore*Wind model. *Fore*Wind is a multi-scale numerical weather model that has been custom-designed to produce accurate near-surface wind forecasts on a fine grid. It represents almost all physical processes of importance to determining near-surface winds, including: (1) blocking and channeling effects of mountain ranges and passes; (2) the effects of variations in surface roughness and atmospheric stability on horizontal winds and vertical wind shear; and (3) local circulations forced by differential heating due to variations in surface properties (such as sea-land boundaries, vegetation density, soil texture, and slope of the land surface).

*Fore*Wind is based on the Mesoscale Atmospheric Simulation System (MASS), a state-of-the-art mesoscale weather model developed by MESO, Inc. MASS is used by several government agencies (including NASA's Kennedy Space Center, which uses it to enhance short-term weather forecasts for space launches) and for the real-time production of commercial weather information products [4,5,6].

*Fore*Wind was created by extracting a subset of the equations and modules contained in MASS. The adaptation employed simplifying assumptions described by Mass and Dempsey [7]. The two most important assumptions are: (1) The pressure at the top of the model domain is specified as an external boundary condition; and (2) the surface pressure is calculated hydrostatically from the domain-top pressure and model-determined temperature profile. These assumptions eliminate gravity and sound waves from the solution and permit the use of a much longer time step, making it practical to run the model on a very fine grid.

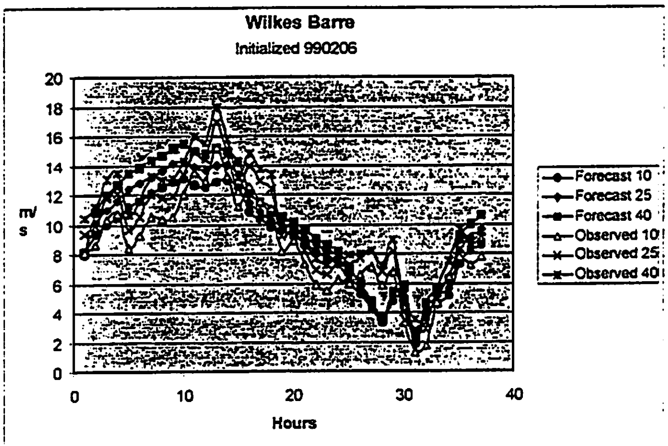


Figure 1. Sample comparison of forecast winds at three heights using Forewind and observed winds

*Fore*Wind is an operational real-time weather model. A run begins by importing an initial set of conditions (pressure, temperature, winds) from a regional weather model and interpolating those conditions throughout the model domain. *Fore*Wind then integrates forward in time using all prognostic terms to produce a wind forecast for up to 48 hours. During the simulation the boundary conditions are updated periodically.

Substantial effort has been invested in obtaining high-resolution (1 km) terrain and surface characteristics databases. These databases include land cover (94 categories), terrain elevation, soil type (12 categories), climatological vegetation amount (biweekly values), and water surface temperature.

The model is undergoing an evolutionary development. It is currently being run and evaluated at a 5 km resolution, which will soon be followed by runs at a 1 km scale. Each development step entails comprehensive validation using several surface wind monitoring stations and correcting for observed weaknesses and biases. Validation is performed daily for 15 sites located in the northeastern U.S. for hourly wind speed and direction at multiple heights (up to 50 m) above the surface (see Figure 1). Forecasts are compared with those of other models, including MASS (44 and 11 km), MM5 (45 and 15 km), NWS Eta, NGM MOS, and persistence. While early in its development, *Fore*Wind consistently outperforms these other models.

The *e*Wind™ Forecasting Service

The *Fore*Wind model, although critically important, is only one component of the *e*Wind forecasting service. The normal operation of *e*Wind is illustrated in Figure 2. Using input from a regional weather model, *Fore*Wind produces wind speed and direction forecasts up to 48 hours in advance at hourly or half-hourly intervals. The forecasts are then fed into an adaptive statistics model that corrects for recent biases in the predictions. For example, if in the preceding weeks the forecasts have generally been higher than the observed winds at the site, the model adjusts the current forecast downward to eliminate the bias. The statistical model also adjusts the near-term forecast to match current measurements and trends. This assures the best possible forecast performance over the entire forecast period.

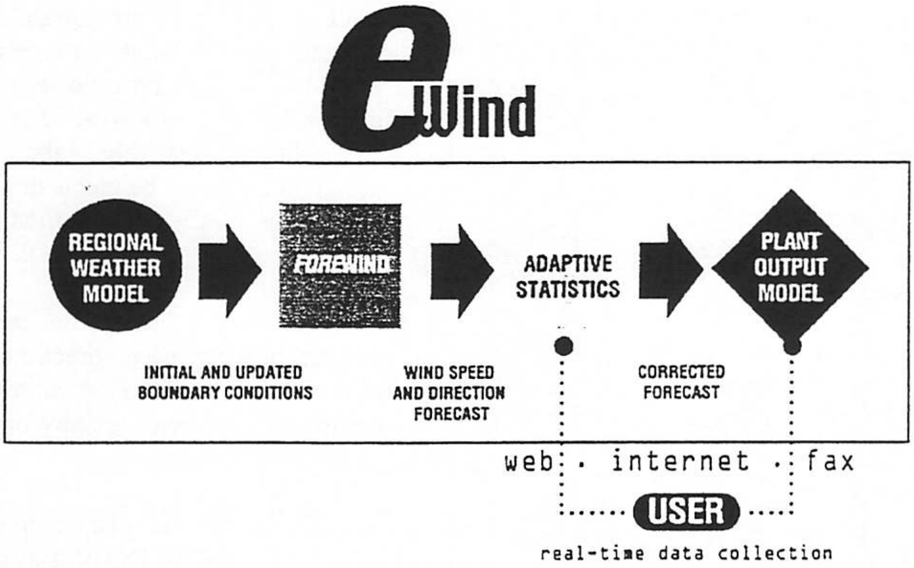


Figure 2. Schematic of the *e*Wind service. The adaptive statistical correction to the wind forecast is continually updated through real-time wind and plant output data collected from the forecast site.

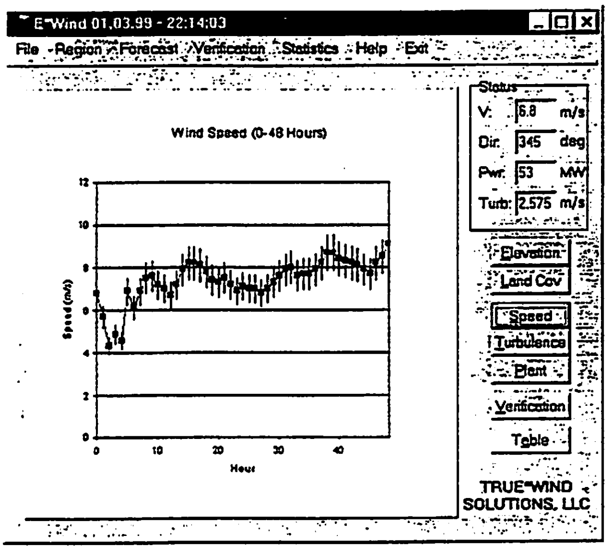
If wind plant output forecasts are desired by the user, the wind speed and direction forecasts are then fed into a plant output model. Depending on the complexity of the situation, the plant output model may be either a purely statistical model (based on the record of wind plant output versus wind speed and direction) or a physical model that accounts for wind turbine performance, wake losses, and other factors, or a combination of the two.

The wind speed, direction, and plant output forecasts are delivered automatically to the user via the Web, FTP, or fax. The *Fore*Wind forecasts are updated every 3, 6, or 12 hours, in accordance with the available data and weather regime. The adaptive corrections may be updated as often as every hour to ensure that the most timely and accurate information is available to the user at all times.

In addition to providing forecasts to the user, the forecast service also collects wind and plant output data (if desired) from the user at frequent intervals. These data are fed automatically into the adaptive statistics model, resulting in a continuous feedback between forecasts and measurement.

The *e*Wind Interface

The *e*Wind interface program (v. 0.1) is designed to download wind forecasts and other data automatically. Figure 3 displays the main program window. The easy-to-use interface allows the user to view all relevant forecast data with a click of the mouse. This view shows a 48-hour wind speed forecast. This is an unadjusted forecast – no statistical corrections have been applied. The error bars indicate the likely range of deviation from the forecast. The error range is not calculated merely as a percent of the central value, but reflects the current and projected weather regime. For example, an approaching storm may result in very large potential errors because of uncertainty in the time of arrival of the storm at the plant site. During relatively calm weather, the uncertainty will naturally be much smaller. The user may specify the confidence interval (67%, 95%, etc.).

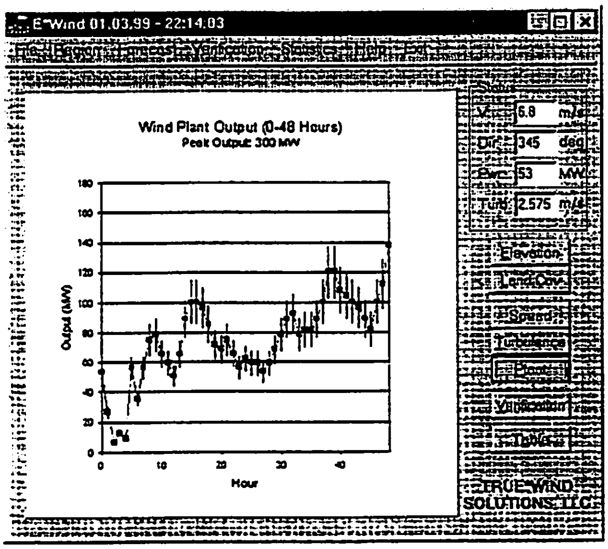


Status
V: 6.8 m/s
Dir: 345 deg
Pwr: 53 MW
Turb: 2.575 m/s

Figure 3. Main window of the *e*Wind interface showing a 48-hour wind speed forecast.

The main window also displays the current status at the plant (current wind speed, direction, plant output, turbulence). The data displayed represent averages over 5-minutes, 30-minutes, or any other averaging period desired by the user.

Figure 4 displays the wind plant output forecast for the same period. Here we have assumed a 300-MW (peak) wind plant. Once again, error bars indicate the likely range of deviation – information that may be of critical value to utility plant dispatchers and energy and transmission traders seeking to optimize their strategies. The data may also be viewed in tabular format by pressing the Table button.



Status
V: 6.8 m/s
Dir: 345 deg
Pwr: 53 MW
Turb: 2.575 m/s

Figure 4. A 48-hour wind plant output forecast. Also shown is the current plant status.

In addition to viewing the forecasts, users may at any time choose to examine the recent record of performance (verification). Figure 5 shows the comparison time series from the preceding 48 hours (i.e. starting at the current time T minus two days). Once again, it should be noted that the forecast data have not been adjusted for recent biases in the model. It is evident that the forecast tracked the wind trend quite closely in this period. The greater variability of measured winds is due to the relatively coarse grid (5 km) used for these runs. In a real application, the grid will be much finer (1 km or less) and the model will therefore be able to capture more accurately the effects of turbulence and other localized phenomena.

Another important parameter that can be forecast is turbulence. Periods of high turbulence can pose significant risks for wind turbines and can reduce wind turbine output. The *e*Wind service routinely forecasts turbulence and can also generate turbulence maps for the wind plant area.

The Benefits of Wind Forecasting

The availability of timely, useful, and accurate wind forecasts significantly increases the value of wind energy to wind plant owners, utility companies, and their customers.

Forecast errors increase electricity system fuel and operating costs in two ways. An *overestimate* of available wind energy forces the utility to resort to high-cost peaking plants to cover the unexpected shortfall, rather than making use of less costly, "slow-start" plants such as a coal or nuclear facility that require advance commitment. An *underestimate* of available wind energy, on the other hand, results in the utility committing too much "slow-start" capacity, thereby forcing it to dump excess power on the spot market because it cannot easily or quickly turn off the surplus units.

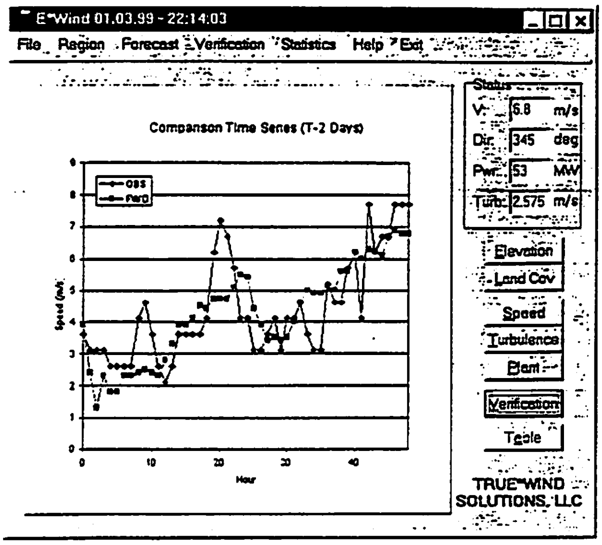


Figure 5. Comparison of forecasted and actual winds over a 48-hour period. The relatively coarse grid size (5 km) of this forecast accounts in part for the lesser variability in forecasted compared to measured winds.

That reliable wind energy forecasts would have real economic benefits was demonstrated in a recent study of the two largest California utility companies [8]. The authors used a production cost model (Elfin) to analyze the effects of short-term wind forecast errors on the utilization of generating resources (Fig. 5). The study indicates that reducing the average margin of error in 1-2 day wind forecasts by 15% would raise the effective value of wind energy by 1-3%.

This estimate does not consider the benefits of reliable wind forecasts for transmission pricing and scheduling, which are likely to be as large as the system energy and capacity benefits.

Conclusions

Wind forecasting is becoming increasingly important to the wind industry. Studies have shown that improvements in forecasting accuracy can lead to real increases in the value of wind energy and real savings for wind energy consumers. Forecasting improvements can also help to dispel the perception of wind plant generation unpredictability and to manage the inherent intermittency of wind-based generation.

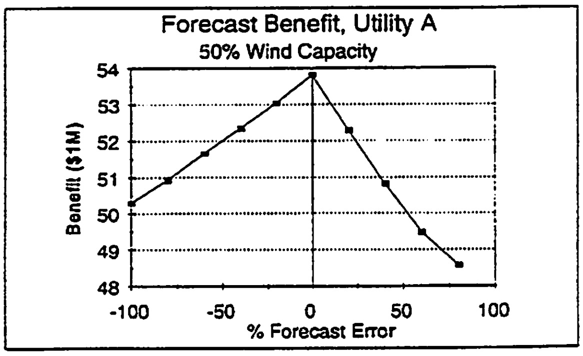


Figure 5. Estimate of the impact of wind forecast errors on utility system fuel and operating costs [8]. The benefit (left-hand scale) is the value of displaced fuel and operating costs due to wind generation at 50 percent wind capacity factor (assuming 1000 MW of total wind capacity).

Although forecasting for wind energy applications is relatively new, the science of weather forecasting is well-established. TrueWind Solutions has adapted a state-of-the-art weather model for the task of making accurate, near-surface wind forecasts on a fine spatial grid. This new model, *Fore*Wind, is already in real-time operation. The initial results appear highly promising, exceeding the performance of existing forecast models. Validation efforts will soon be expanded to operating wind plants across the U.S.

*Fore*Wind is just one component of a new wind forecasting service called *e*Wind, which is being marketed by TrueWind Solutions, LLC. The *e*Wind service provides all of the information desired by users without the need for up-front investments in equipment, software, and training. We believe this combination of state-of-the-art statistical and weather models and a full-service package best meets the needs of the wind industry.

Acknowledgements

This work is supported in part by a contract with the New York State Energy Research and Development Authority (Contract No. 4902-ERTER-ER-99) and by a subcontract with the National Renewable Energy Laboratory (Subcontract No. TAT-5-15208). TrueWind Solutions, LLC is a joint venture of AWS Scientific, Inc., Brower & Company, Inc., and MESO, Inc.

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Wind Forecasts: Development and Application of a Mesoscale Model

Bruce Bailey
AWS Scientific, Inc.

Michael Brower
Brower & Company, Inc.

John Zack
MESO, Inc.

TrueWind Solutions

Benefits of Accurate Wind Forecasts

- Energy companies can optimize scheduling & dispatching of generating resources
- Allows plant owners & energy marketers to optimize power trading strategies
- Increase wind capacity payments
- Accelerate acceptance of wind energy by improving predictability

TrueWind Solutions

Responding to Industry Growth

- Wind is making significant penetrations into the electric grid
- Wind must be integrated into scheduling and dispatch decisions
- Wind's intermittency and perceived unpredictability are key concerns

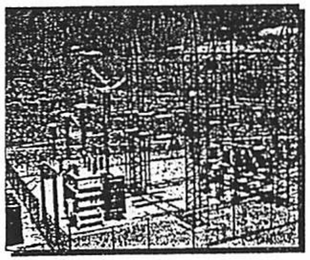
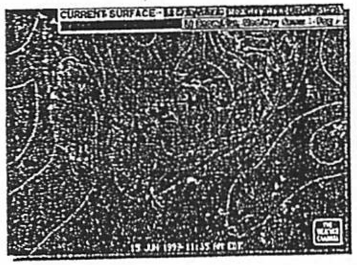


Photo courtesy of NREL

TrueWind Solutions

Status of Wind Forecasting

- Growing emphasis on mesoscale events and severe weather
- Improved accuracy & spatial resolution
- Little attention to detailed windflow prediction
- European experience
  - EU-JOULE Project led by Risø
    - Couples large-scale forecasts with WAsP



TrueWind Solutions

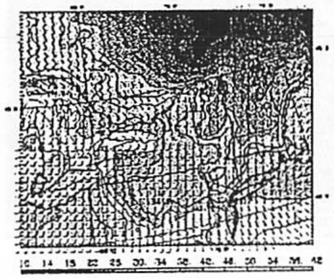
Weaknesses of Existing Models

- Rely heavily on coarse grid forecasts (15-40 km)
- Use simplified assumptions
- Don't capture important local processes
  - sea/lake breezes
  - low-level jets
  - thermal mountain winds
  - flow separations

TrueWind Solutions

MASS - What is it?

- Multi-scale physics-based atmospheric numerical model
- 11-km and 44-km resolutions
- Parameterized sub-grid scale physics
- Fundamental equations
  - conservation of mass, momentum & energy
    - equation of state



TrueWind Solutions

Development of *Fore*Wind

- New mesoscale wind forecasting model
- Based on the powerful Mesoscale Atmospheric Simulation System (MASS)
- Modifications improve speed at a very fine grid
- Supported by the New York State Energy Research and Development Authority and DOE/NREL

TrueWind Solutions

MASS Parameterization Schemes

- Planetary Boundary Layer
  - simulates TBL eddies
  - interacts with surface physics
- Moist Convection
- Precipitation Processes (water microphysics)
- Radiation (short and long wave)

TrueWind Solutions

MASS History

- Developed in early 80's at NASA Langley
- Advanced by MESO for DOD and NASA in the late 80's
- Migrated to computer workstations around 1990
- Further developed in 90's for USDA, DOC, DOD, NASA and NSF
- State-of-the-art model now used for research and forecast applications

TrueWind Solutions

MASS: Link to *Fore*Wind

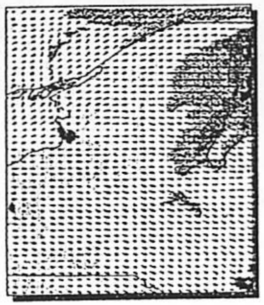
- Simulate local wind patterns forced by differential surface properties at 1 to 5-km
  - terrain
  - land/water distribution
  - vegetation & soil differences
- Ignore effects of moist convection and precipitation processes
- Execute simulations quickly on DEC Alpha workstation

TrueWind Solutions

---

*Fore*Wind Development

- Strip out unneeded MASS processes
- Create 5-km and 1-km surface databases
- Run 5-km model, validate and correct weaknesses
- Run and validate 1-km model; correct weaknesses
- Generate and test Model Output Statistics (MOS) equations for systematic biases
- Develop wind plant module



TrueWind Solutions

Terrain & Surface Characteristic Databases

- Land cover (94 categories)
- Terrain elevation
- Soil type (12 categories)
- Climatological Vegetation Amount (biweekly values)
- Water surface temperature

TrueWind Solutions

*Fore*Wind Validation

- Performed daily for 15 sites
- Hourly speed and direction values
- Predictions compared to other models
  - MASS (44 and 11 km)
  - MM5 (45 and 15 km)
  - NWS Eta
  - NGM MOS
  - Persistence
- *Fore*Wind consistently outperforms other models

Unadjusted Forecast

TrueWind Solutions

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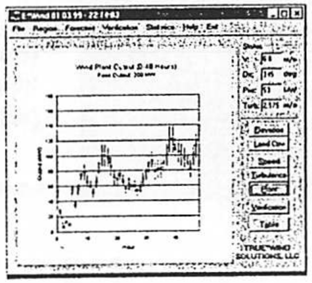
eWind Forecast Service Development

- Based on utility surveys
- 1-hr or 30-min forecasts out to 48 hours
- Boundary conditions updated every 3+ hours
- Model adapts to real-time feedback from windplant



TrueWind Solutions

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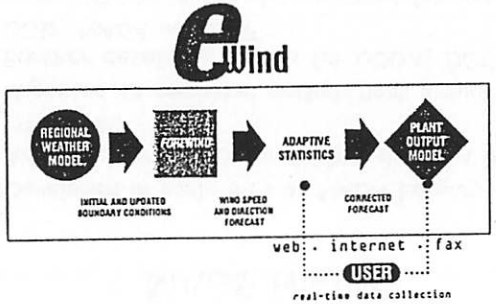
eWind Forecast Service



TrueWind Solutions

Conclusions

- Wind forecasting becoming vital to the wind industry
- Reliable forecasts have real economic benefits
- *Fore*Wind is an advanced model targeted for wind energy forecasting
- Undergoing trials by utilities and windplant operators
- Validations to be conducted throughout the world

Photo courtesy of NREL

TrueWind Solutions

WIND FORECASTING ACTIVITIES CIEMAT-DER

Ignacio Martí
CIEMAT-DER
Topical Expert Meeting on
Wind Forecasting Techniques

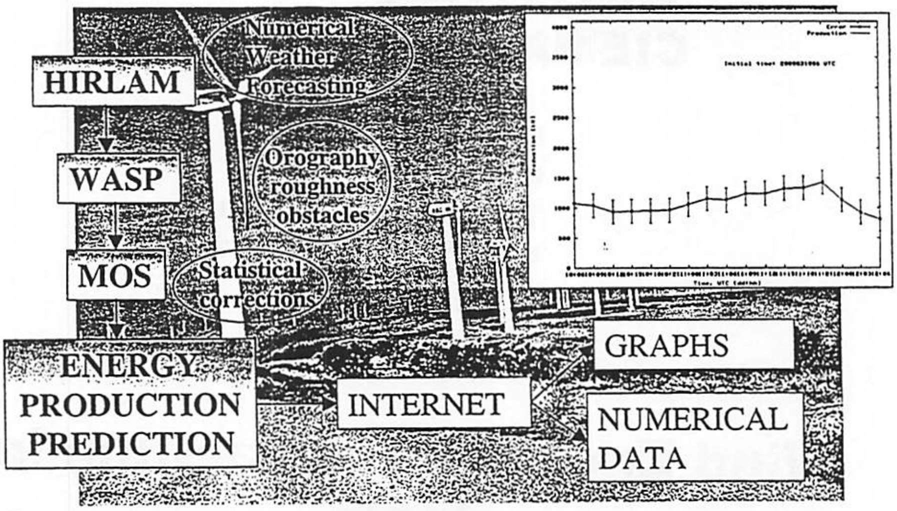
Wind Energy &Forecasting in Spain

- 2000 wind MW are connected to the grid. In some years there will be 8000 MW from wind parks.
- Prediction models will help:
  - To improve the efficiency of the energy system.
  - To increase the installed capacity in areas with weak grid conditions.
  - To reach the 8000 MW target.

ACTUAL PROJECTS ON WIND FORECASTING

- Development of a wind prediction model for two wind farms in Spain in complex terrain. CIEMAT-RISO
- Development of a wind prediction model for an isolated system at CIEMAT test station. CIEMAT-RISO

La Muela II & III WIND PREDICTION PROJECTS



HIRLAM

WASP

MOS

ENERGY PRODUCTION PREDICTION

Numerical Weather Forecasting

Orography roughness obstacles

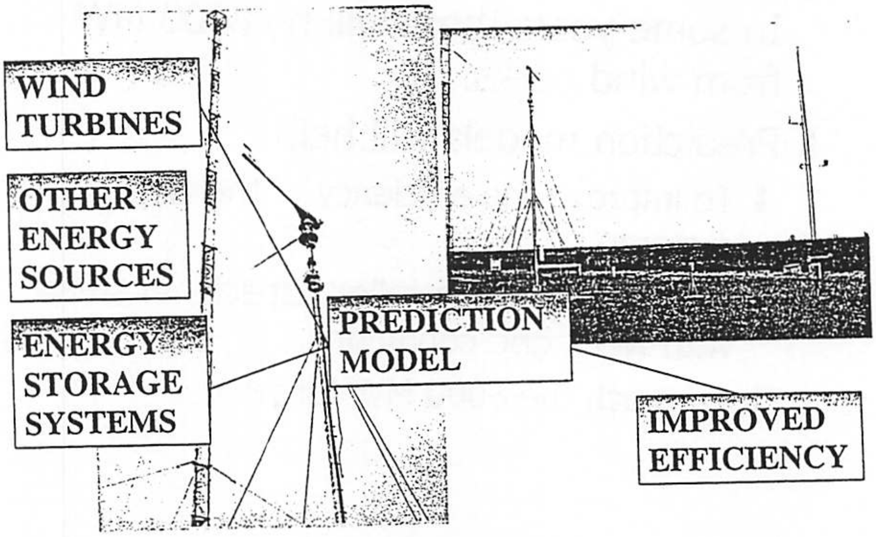
Statistical corrections

INTERNET

GRAPHS

NUMERICAL DATA

CEDER Test Station PREDICTION PROJECT



WIND TURBINES

OTHER ENERGY SOURCES

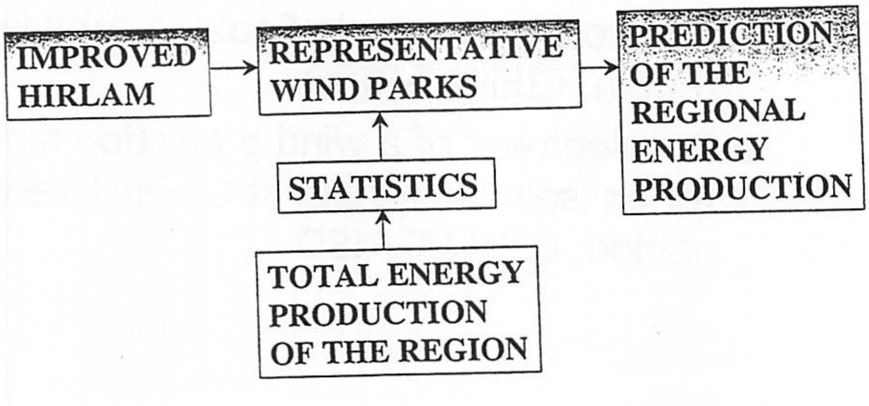
ENERGY STORAGE SYSTEMS

PREDICTION MODEL

IMPROVED EFFICIENCY

FUTURE PROJECTS

- WIND PREDICTION MODEL FOR REGIONAL SCALE



IMPROVED HIRLAM

REPRESENTATIVE WIND PARKS

PREDICTION OF THE REGIONAL ENERGY PRODUCTION

STATISTICS

TOTAL ENERGY PRODUCTION OF THE REGION

21st February 2000
Lennart Söder

Some comments concerning wind speed forecast research

My name is Lennart Söder and I am currently a professor at Royal Institute of Technology in Stockholm. I have a PhD where the title of the thesis is *Benefit assessment of wind power in hydro-thermal power systems.* Since the thesis was presented in 1988, I have continued to study the integration of wind power in power systems. In 1994 I published a report with the name *Integration study of small amounts of wind power in the power system.* In this report I studied the problems of decreased efficiency in the power system depending on continous wind power variations, both forecasted and unforecasted. In this work I started to analyze the consequencies of wind speed forecasts.

First some comments of how to operate a power system including wind power. The short term operation (daily operation) is performed in the following way:

1. Forecast important features such as load, wind power production and power price.
2. Plan how to operate the units in your system for the following hours, based on these forecasts. Since the forecasts are uncertain, reserves have to be kept in the system. In some deregulated systems (e.g. the Swedish one) bids are put for the reserve requirements. The estimated total uncertainty (load + wind + possible outages) defines the total requirement of reserves. If the uncertainty is high this increases the probability that the reserve bids will be used.
3. Operate the system approximately according to the plan. Since the forecasts are not perfect the plan can not normally be followed exactly, so the reserves have to be used.
4. Go back to point 1 and update the forecasts and the plans.

In this way the operation in continously replanned and new forecasts must be continously available.

What are now the consequences for needed wind speed forecasts. I will here adress some items that I think are important:

Total wind power uncertainty

From the power system point of view it is the variation of *total* wind power that is of interest. Assume e.g. that wind power is spread out in a whole region. Then there might be a correlation between the forecast uncertainties, in such a way that in some parts of the region the real wind becomes *higher* than expected, and in some parts it becomes *lower.* This of course means that forecast of *total* power is better (in percent) than the forecast for the power from each single units. It should be interesting to see how this limited correlation is dependent on e.g. distance. The larger the area, the lower the positive correlation.

Based on the assumption of *persistance forecasts* an estimation can be made. This is shown in the figures below.

The figures show that the correlation between the forecast errors increases with increased forecast length. This implies that in the short term run the forecast errors are

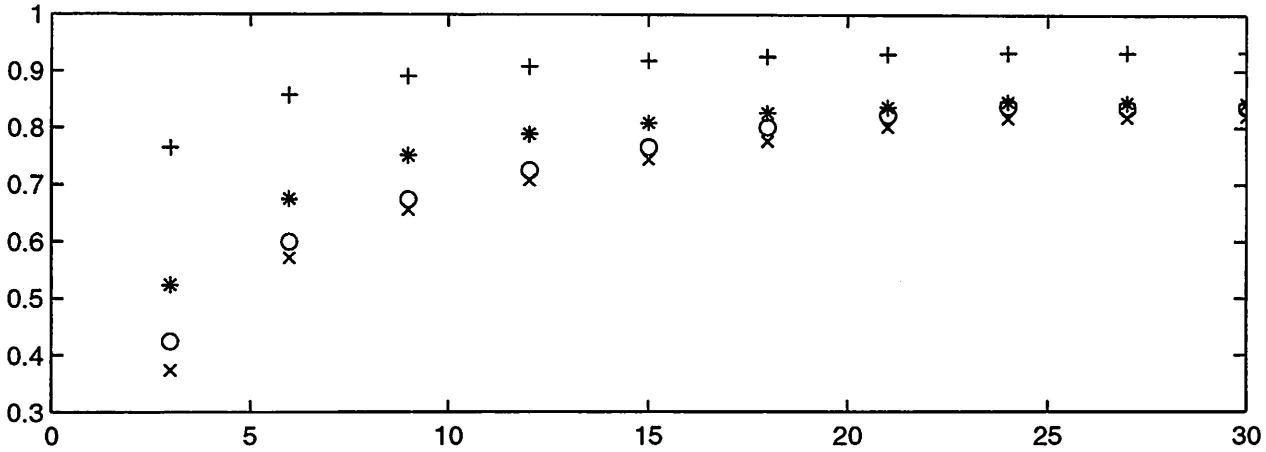


Figure 1: Correlations as a function of forecast length between sites with internal distances 15–26 km

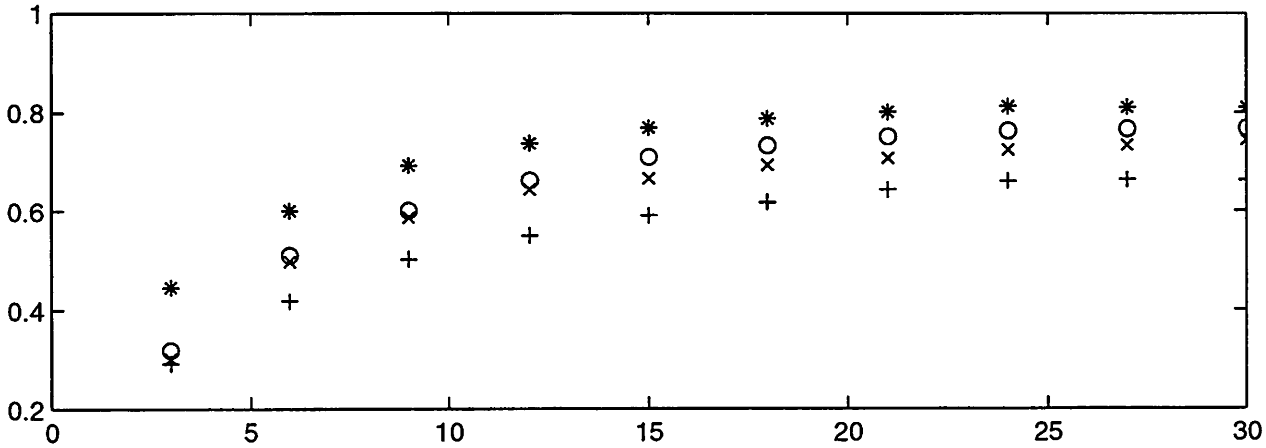


Figure 2: Correlationsas a function of forecast length between sites with internal distances 26–89 km

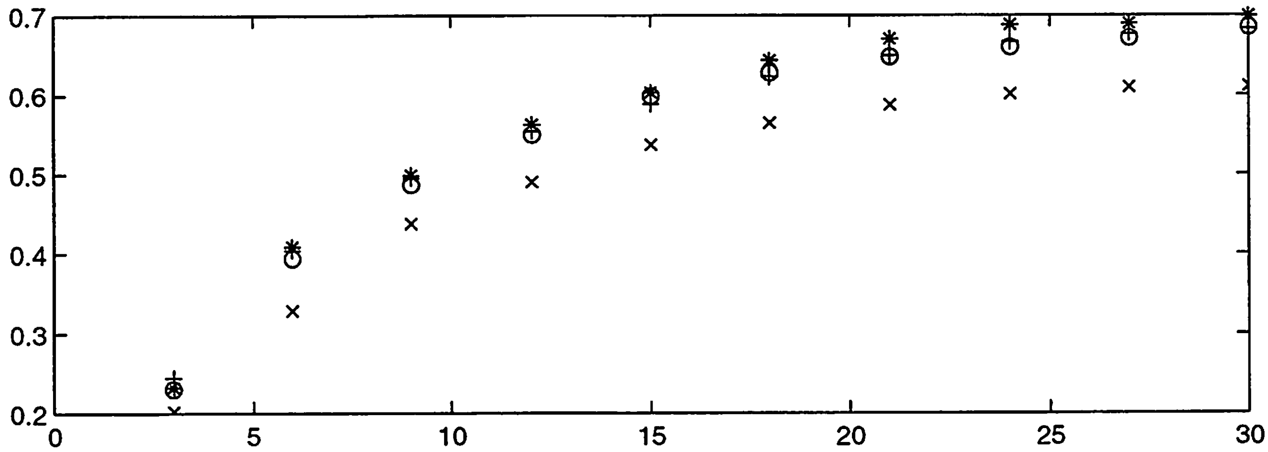


Figure 3: Correlations as a function of forecast lengthbetween sites with internal distances 101–102 km

more independent. For longer forecasts the correlation increases which mean that what is happening on different sites in the region is more the same for the different sites in the region. High correlation means that the forecast errors at the different sites are in the same direction, e.g. too low forecasts at all sites.

It must though be noted that the figures shown here are based on *persistance forecasts*, which of course is a too rough method in reality. But I think that the same structure is valid also for real forecasts. I also think that this type of curves gives some kind of understanding of what the forecast errors depend on. If forecast errors on different sites in a region are highly correlated, then it is the trend in the wind that is not correctly forecasted. If the forecast errors, on the other hand, are uncorrelated, then it is the stochastic nature of the wind that is difficult to forecast.

Wind-load correlation

From the power system point of view it is the total variations that are of some interest. Today the load uncertainty dominates since wind power in most systems is only a marginal source. But with increasing utilization of wind power these uncertainties become more and more important. This means that it is important to study e.g.:

- Probability of unforecasted decrease of wind power at the same time as the load forecast is too low.
- Probability of the opposite, i.e., increased wind at the same time as increased load. This means that the net result is not so bad.
- The total idea is to study the correlation between forecasts of load and total wind power production.
- It is also important to contact the power system operators (ISO or TSO) in order to get an estimation of when it is more important to make good forecasts, e.g., in the morning, or in the summer or ...?

Successive forecasts

One important feature is that new forecasts are needed continously in the power system operation planning. Assume, e.g., that new forecasts are available each hour and that at hour=0 a forecast is made for the wind power production (and load) at hour 5. This forecast will in reality be updated 4 times until the hour occurs. The question is now how these successive forecasts for hour 5 are correlated. Will all forecasts estimate too high production or are the forecasts uncorrelated?

In the figure an exmple is shown where successive persistance forecasts have been evaluated. The figure shows that for long forecasts, the forecast does not change so much when the we approach the hour. But for short forecasts (3-4 hours) the forecast can change rather much from hour to hour. The figure shows the case for one example of *persistance forecasts*. The question is how it is for real forecasts? If the correlation is very low, that means that the forecasts for a specific hour varies rather much. This means of course that it is more difficult to plan the power system for that hour!

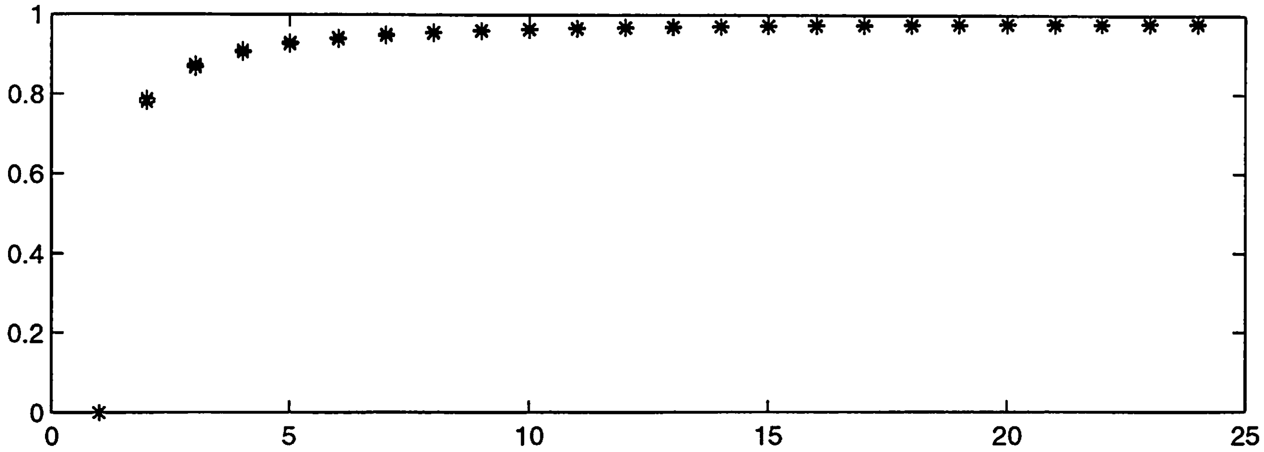


Figure 4: Correlation as a function of forecast length between errors of successive forecasts

Final comments

Except for the three items mentioned above, I think that there are some things that have to be mentioned:

- About the definition: When, e.g., the accuracy of a "3-hour forecast" is mentioned, I think it is essential that one should mean that the power system operator has this forcast 3 hours in advance of the real hour. Sometimes I have seen the definition that the data are collected 3 hours in advance. Then the calculation of the forecast takes 1 hour, which means that it in reality is a 2-hour forecast. I think it is important to define what you mean.
- I have seen example of forecasts with a rather high standard deviation, but with a systematic error, i.e., the mean forecast error is not equal to zero. When you compensated for the systematic error, there was a significant reduction of the standard deviation. In reality, there will of course be a compensation for systematic errors, if they are known. Conclusion: When forecast uncertainties are presented, assume no systematic error.

If anyone has any questions about this, do not hesitate to contact:

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Wind Prediction: Profits and Penalties

Hans Cleijne

KEMA, The Netherlands

KEMA and wind energy

KEMA

- Certification, Testing & Consultantancy
- Staff: 1200

Windenergy consultancy

- Project development
- Offshore wind energy: system studies, component development
- Value of wind energy in liberalized electricity market
- Monitoring Renewable Energy in the Netherlands

The present situation

From centralised system to liberalised electricity market

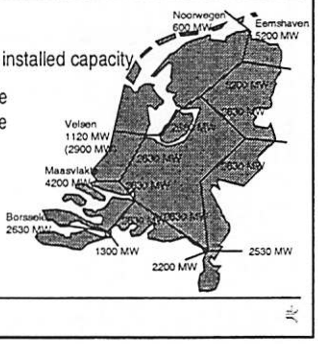
Present situation

Wind

- 1300 wind turbines, 400 MW installed capacity
- year 2020: 1500 MW onshore
  1250 MW offshore

Electricity structure

- Gas and Coal fired
- Demand 12000 MW
- APX



Program responsibility

Balance

Production + Buy + Import = Use + Sell + Export

- Program must be set 24 hours ahead
- Program changes allowed 2 hours in advance
- 1500 changes free, if more frequent: 200 Euro administration costs
- Wind power plants (>8MW) must have electricity programmes
- Program responsibility can be transferred

Costs of unbalance

Unbalance costs = energy component + incentive component

- Energy component
  - Buy electricity at peak load rate: 0.042 Euro/kWh
  - Sell electricity at base load rate: 0.020 Euro/kWh
- Incentive component: maximum 0.02 Euro/kWh
- If programme is underpredicted systematically, sell price is set to zero

After protocol period

- Bid for spinning reserve
- time dependent price per kWh
- cheapest unit first until unbalance disappears
- Price unknown but fair
- APX balancing market?

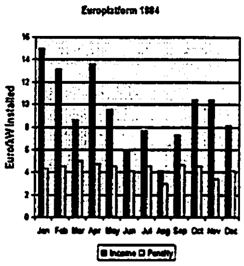
Consequences for Wind Farm owners & utilities

Prediction on basis of persistance

- annual income: 114 Euro/kW
- annual penalties: 51 Euro/kW (45%)

Total Netherlands: 20 Meuro

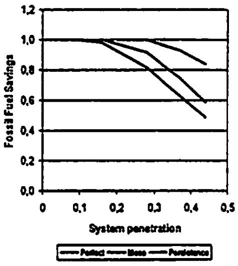
Wind power prediction!



Demand and wind power prediction

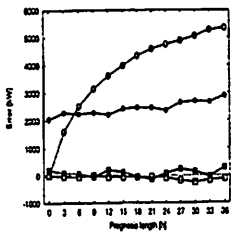
Noticeable influence at 10% local penetration

- System costs increase at higher penetration levels
- Penetration level is determined on a local scale, i.e. level of Program Responsibility
- Some "remote" areas have already high level of penetration



Prediction tools perform better than persistence

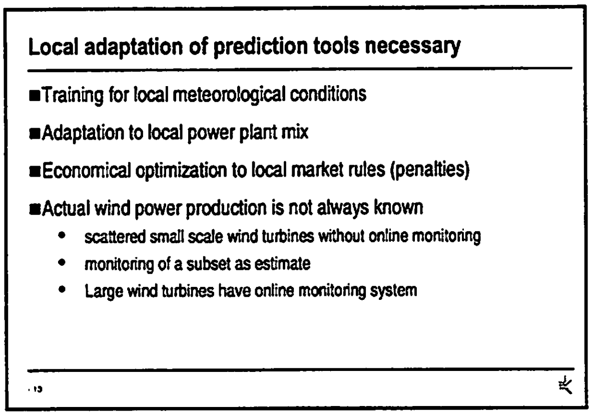
- For periods > 4 hours mesoscale models perform better than persistence extrapolation
- Prediction error constant over 36 hours
- MAE ~ 10% of installed capacity



Installed capacity 25 MW (source:Risoe)

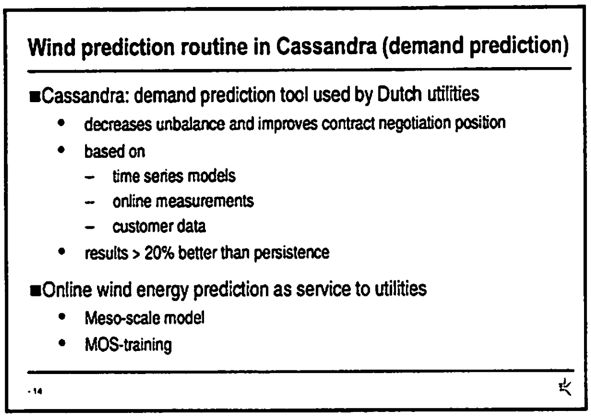
Towards a Dutch prediction service

Production and Demand



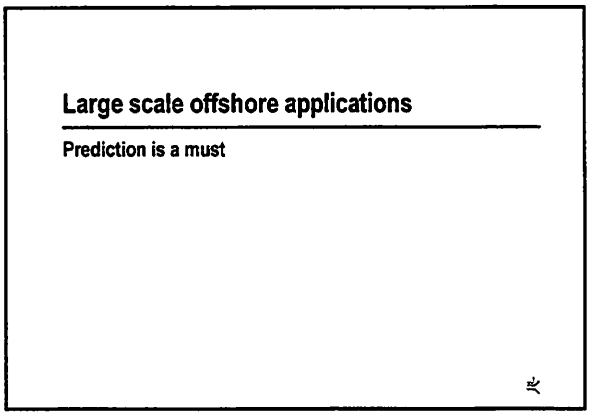
Local adaptation of prediction tools necessary

- Training for local meteorological conditions
- Adaptation to local power plant mix
- Economical optimization to local market rules (penalties)
- Actual wind power production is not always known
  - scattered small scale wind turbines without online monitoring
  - monitoring of a subset as estimate
  - Large wind turbines have online monitoring system



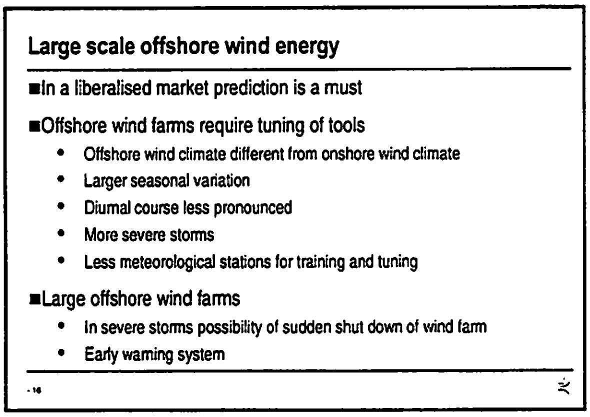
Wind prediction routine in Cassandra (demand prediction)

- Cassandra: demand prediction tool used by Dutch utilities
  - decreases unbalance and improves contract negotiation position
  - based on
    - time series models
    - online measurements
    - customer data
  - results > 20% better than persistence
- Online wind energy prediction as service to utilities
  - Meso-scale model
  - MOS-training



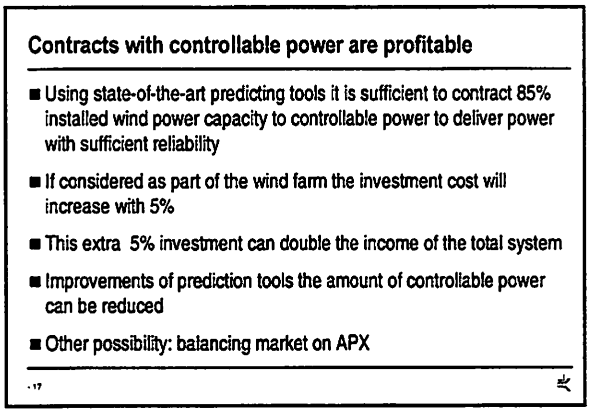
Large scale offshore applications

Prediction is a must



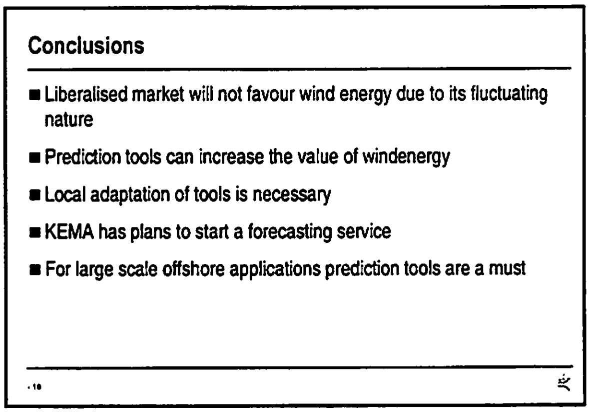
Large scale offshore wind energy

- In a liberalised market prediction is a must
- Offshore wind farms require tuning of tools
  - Offshore wind climate different from onshore wind climate
  - Larger seasonal variation
  - Diurnal course less pronounced
  - More severe storms
  - Less meteorological stations for training and tuning
- Large offshore wind farms
  - In severe storms possibility of sudden shut down of wind farm
  - Early warning system



Contracts with controllable power are profitable

- Using state-of-the-art predicting tools it is sufficient to contract 85% installed wind power capacity to controllable power to deliver power with sufficient reliability
- If considered as part of the wind farm the investment cost will increase with 5%
- This extra 5% investment can double the income of the total system
- Improvements of prediction tools the amount of controllable power can be reduced
- Other possibility: balancing market on APX



Conclusions

- Liberalised market will not favour wind energy due to its fluctuating nature
- Prediction tools can increase the value of windenergy
- Local adaptation of tools is necessary
- KEMA has plans to start a forecasting service
- For large scale offshore applications prediction tools are a must

ANNEX XI
Base Technology Information Exchange
Status Report no 1 2000
45th Meeting of Executive Committee
Sven-Erik Thor, April 18 2000

1. Introduction

The first half-year report 2000 from Annex XI covers the following items:

- Topical Expert Meeting No. 33
- Future meeting plans
- R&D strategies
- OWEMES conference

2. TEM on "Wind Forecasting techniques"

The 33rd Topical Experting Meeting, TEM, was held on the 3-4 of April 2000. It was hosted by NREL in Boulder, Colorado, USA. The subject of the meeting was "Wind Forecasting Techniques". At the meeting there were 20 participants giving 20 presentations.

Country representation was as follows:

• USA	7	• Netherlands	3
• Finland	1	• Germany	1
• Denmark	2	• Ireland	2
• Norway	2	• Spain	1
		• Sweden	1

After the presentations a discussion was held in order to try to identify the most interesting topics suitable for an IEA Annex. The different ideas were grouped into seven topics.

A.
- Benchmarking at different terrain types
- Test cases

B
- Validation
- Performance measures

C
- Prediction systems
- Uncertainties

D
- Education
- Dissimination
- Special topic meetings
- Utility acceptance

E
- Meso scale models
- Numerical weather prediction models
- Wind park output models

F
- Statistical techniques
- Up-scaling

G
- Value (monetary) of wind forecasting technique.

The topics were ranked by voting. Each participant had 3 votes. The result was:

	No. of votes	Rank No.
A	5	5
B	6	4 b
C	9	1
D	7	3
E	6	4 a
F	4	6
G	8	2

The meeting unanimously decided to propose the ExCo to start an Annex covering these issues. Lars Landberg was appointed to write the proposal text for the Annex together with Bruce Bailey and Henrik Madsen. The document shall be circulated among the whole group. Time plan is as follows:

- Put item on ExCo 45 Agenda (S-E Thor)
- Preliminary information to ExCo meeting in Sweden, may 2000. (S-E Thor)
- Final version of proposal ready beginning September
  Responsible Lars Landberg, send to P W-T in due time
- Distribute to ExCo (Patricia W-T.)
- Put item on ExCo Agenda (S-E. Thor)
- Present proposal at ExCo October meeting in Italy (L. Landberg)

3. Future meeting plans

In the autumn there will be two meetings arranged.

1. Topical Expert Meeting on Large-scale integration into the grid
2. Joint action on Aerodynamics.

4. R&D priorities / strategies

In the IEA Renewable Energy Working Partly there is presently a discussion on priorities/strategies for the renewable scene. As a part of that work our Ex Co has been asked to give a presentation on this subject form our horizon at a meeting in Paris in September.

As a preparation for this meeting a rough draft of priorities/strategies has been edited and will be presented to the ExCo meeting No. 45 in Sweden for discussion.

5. OWEMES conference

The 3rd conference on offshore wind energy in Mediterranean and other seas was held on Sicily on the 13-15 April 2000. IEA have been sponsoring the conference by letting the organisers use the IEA logo. The Operating Agent was as part of the sponsorship offered, and accepted, to be chairman for one of the sessions.

The conference was very appreciated and contributed in a positive way to the exchange of information. The number of participants was 160, representing mainly European countries.

List of participants

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