國外再生能源預測的現況與技術重點

中正大學電機系
吳元康

日期：107年6月28日(周四)

風力預測重點

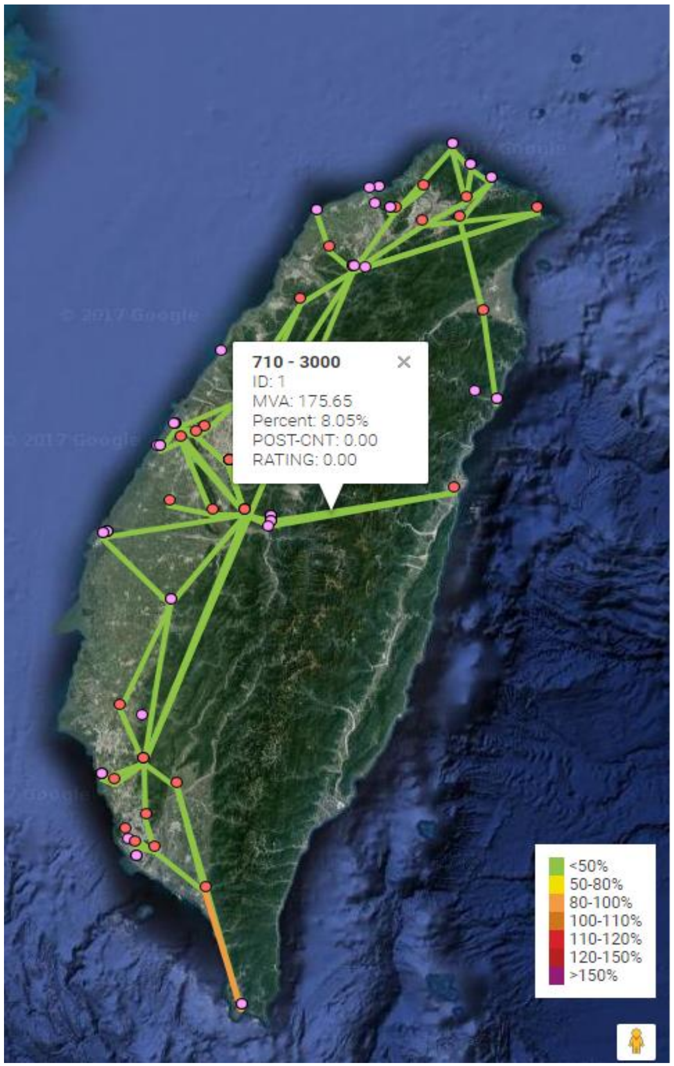
- 風力預測領前時間(Lead-Time)與其目的:
  - 極短期(seconds-minutes)、短期(several minutes-one hour)、中期(several hours-several days)、長期(Several days- one week)
- 風力預測誤差原因:
  - 模型精確性、風機動態/靜態特性曲線、輸入資料的相關性、風場內風機間干擾、風場風機的操作狀態、風場量測資料的穩定性、NWP數據的準確性
- 風力預測常用的方法
  - 目前大部分採用Hybrid models
- 國際間風力預測現況
- 風力 ramping預測 與 機率預測 重要性
- 國外電力市場(預測不準- 處罰機制)

風力預測領前(lead-time)與其目的

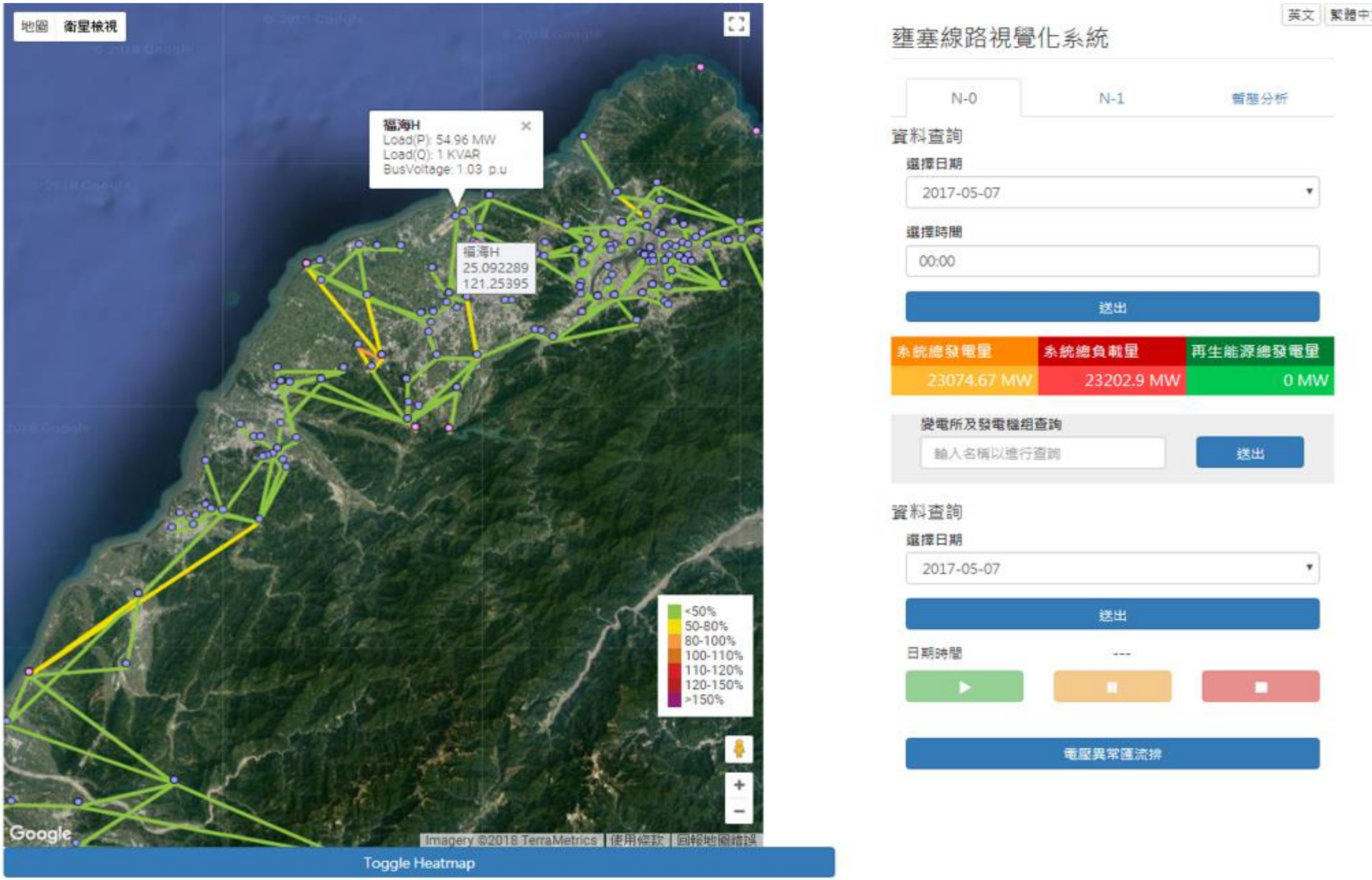
- 極短期(seconds-minutes)
  - 風力機控制(頻率調節)
- 短期(several minutes-one hour)
  - 電力系統操作安全
    - 短期備轉容量
    - 火力機組調度(Economic Dispatch)
    - 電力公司饋線調度
- 中期(several hours-several days)
  - 電力系統日前機組調度規劃
  - 電力系統日前線路調度規劃
- 長期(Several days- one week)
  - 電力系統燃料規劃、線路與發電機停檢修規劃

電力市場導入後，有更多可能的預測領前時間

風力預測可協助提前預測線路壅塞(1)

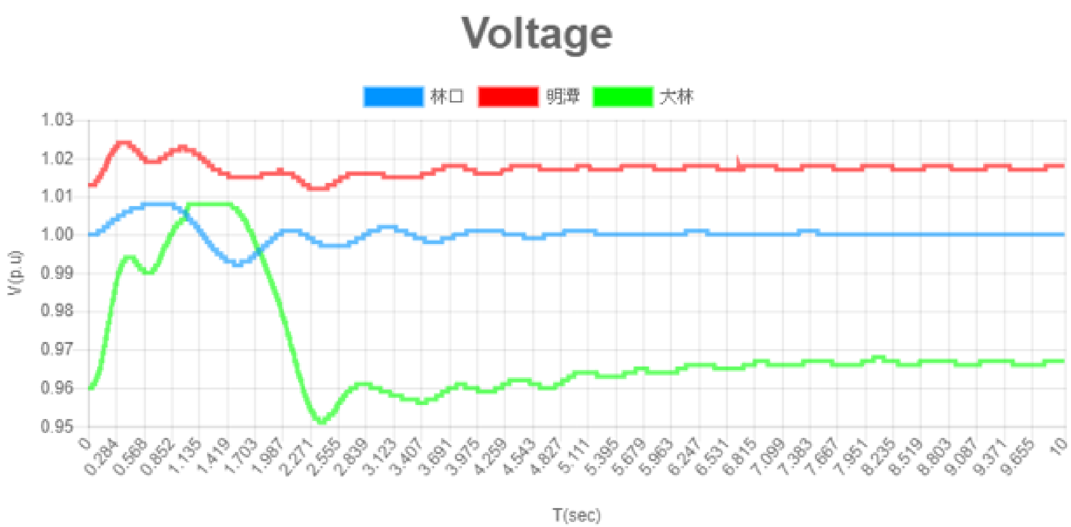


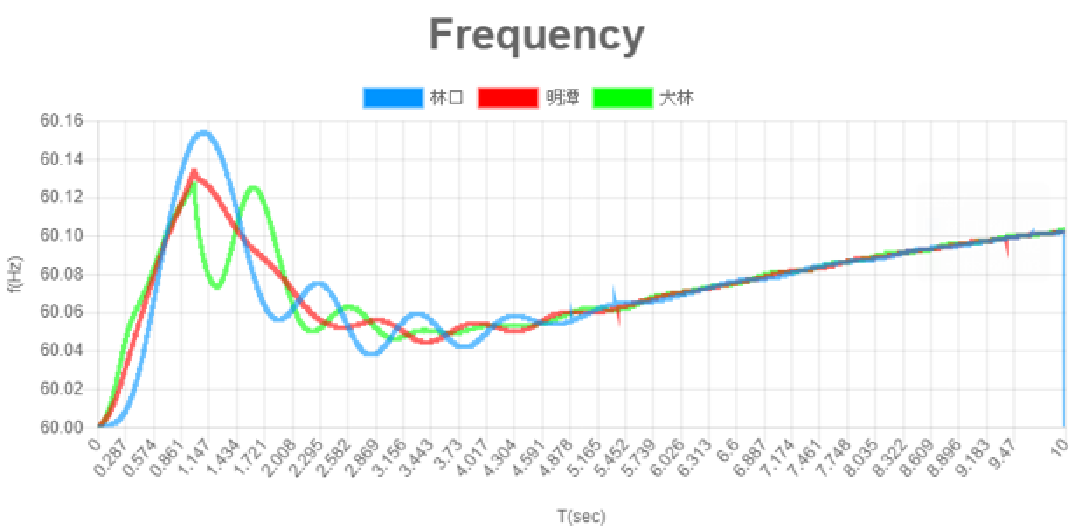
風力預測可協助提前預測線路壅塞(2)



風力預測可協助提前預測線路潛在的問題(電壓、穩定度)

風力預測可協助提前預測線路潛在的問題(電壓、穩定度)





英文 繁體中文

壅塞線路視覺化系統

N-0 N-1 暫態分析

資料查詢

選擇日期

2017-12-08

選擇時間

00:00

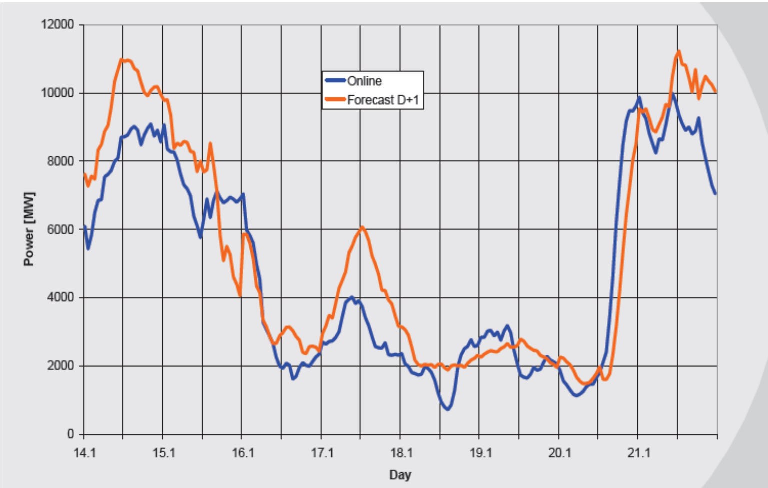
故障形式

機組故障

送出

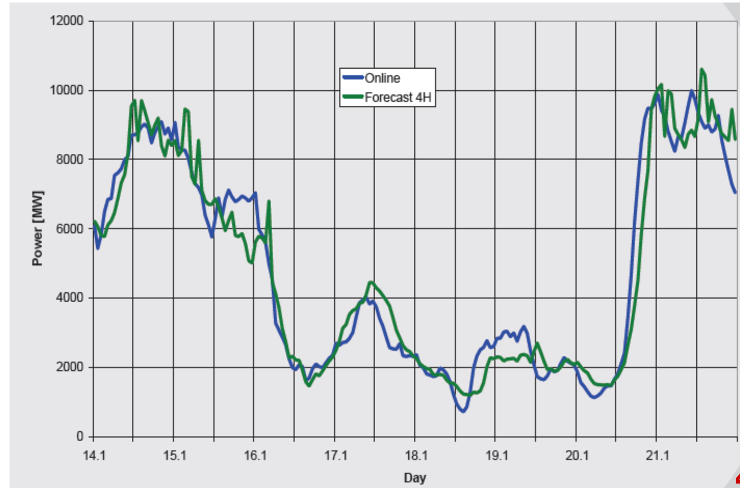
	林口	明潭	大林
最大電壓	1.008 p.u	1.024 p.u	1.008 p.u
最小電壓	0.992 p.u	1.012 p.u	1.008 p.u
最大頻率	60.154 Hz	60.134 Hz	60.127 Hz
最小頻率	60 Hz	60 Hz	60 Hz

Effect of forecasting lead-time



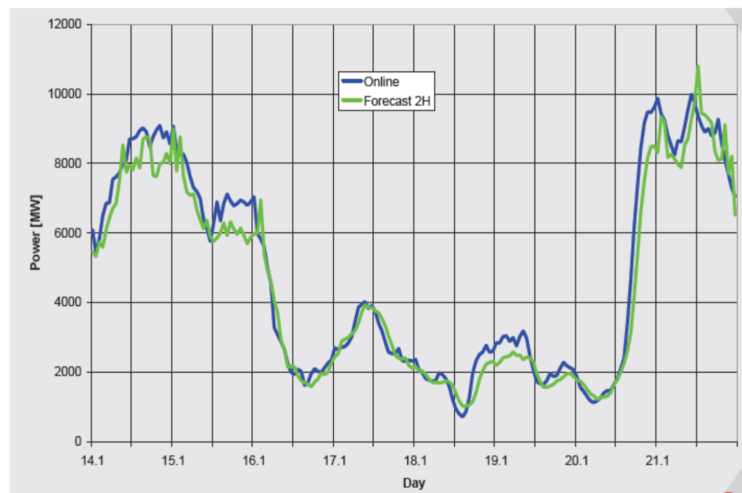
Wind generation – online, day-ahead forecast

One –day ahead



Wind generation – online, 4 hour forecast

4hr ahead

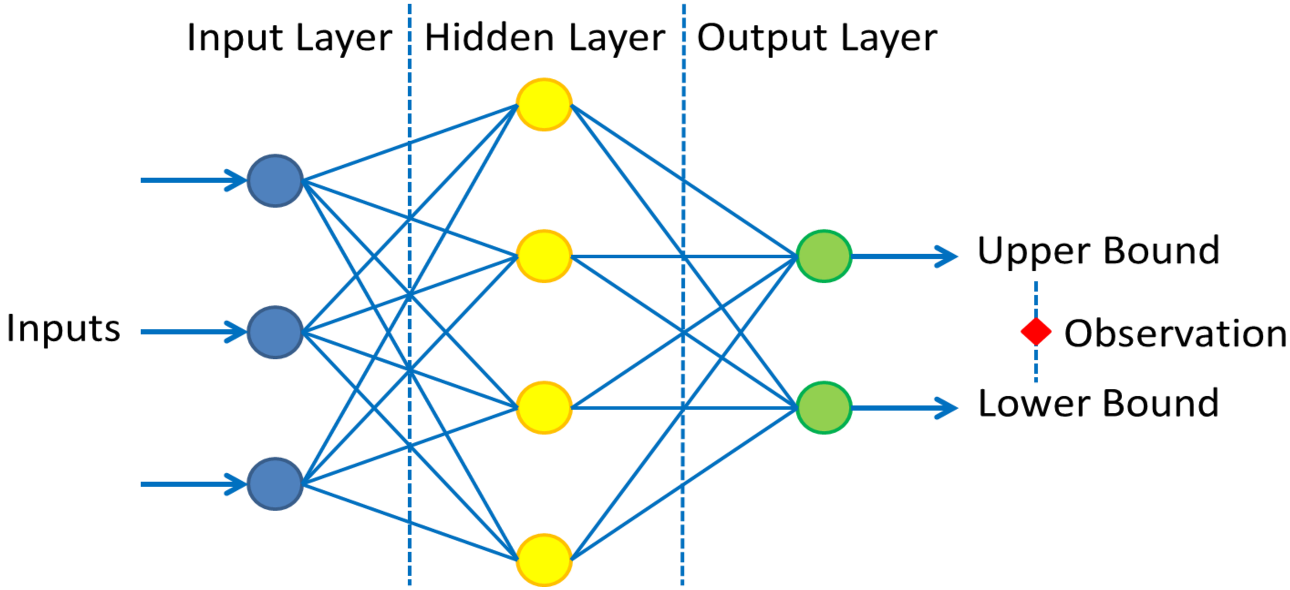


Wind generation – online, 2 hour forecast

2hr ahead

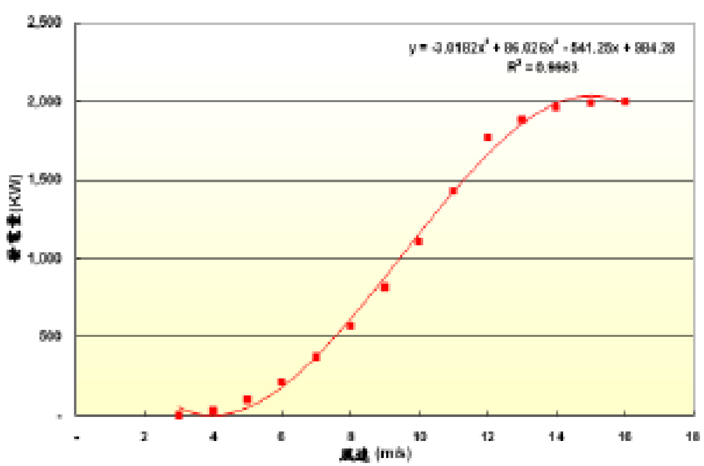
風力預測誤差原因(1)

模型精確性：模型架構、演算法（人工智慧、統計模型）

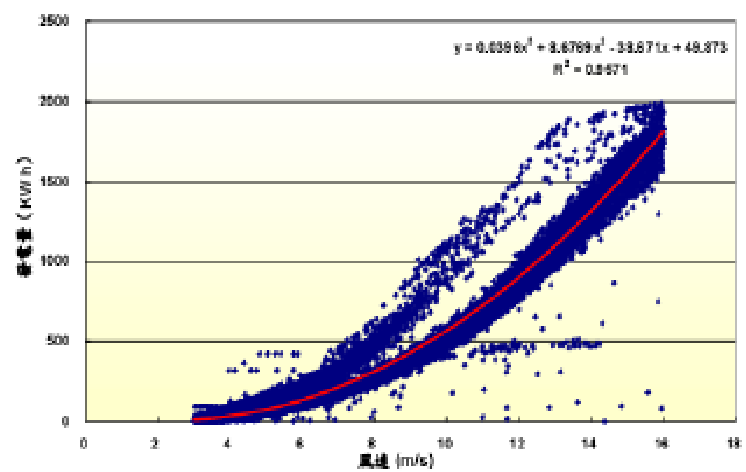


風力預測誤差原因(2)

- 風機動態/靜態特性曲線
  - 若是考慮由功率曲線直接從風速轉換成風力發電機組的發電量時，功率曲線動態/靜態的誤差亦是不容忽略的事實。
  - 靜態功率曲線之測定是原型機於製造風機組工廠測試期間重要資料，工廠內實驗風速與輸出功率之性能測試數據，在進行了迴歸分析後所得之三次或更高次迴歸方程式曲線。
  - 若由同一部風力發電機組實際運轉後，由實測之風速與瞬時出力數據所繪出之動態功率曲線，稱為動態功率曲線，在與工廠內部測試數據所得之靜態功率曲線互相比較後，可明顯看出，實際運轉後之風力發電機組，其風速與實際發電量之間具有頗大的離散特性

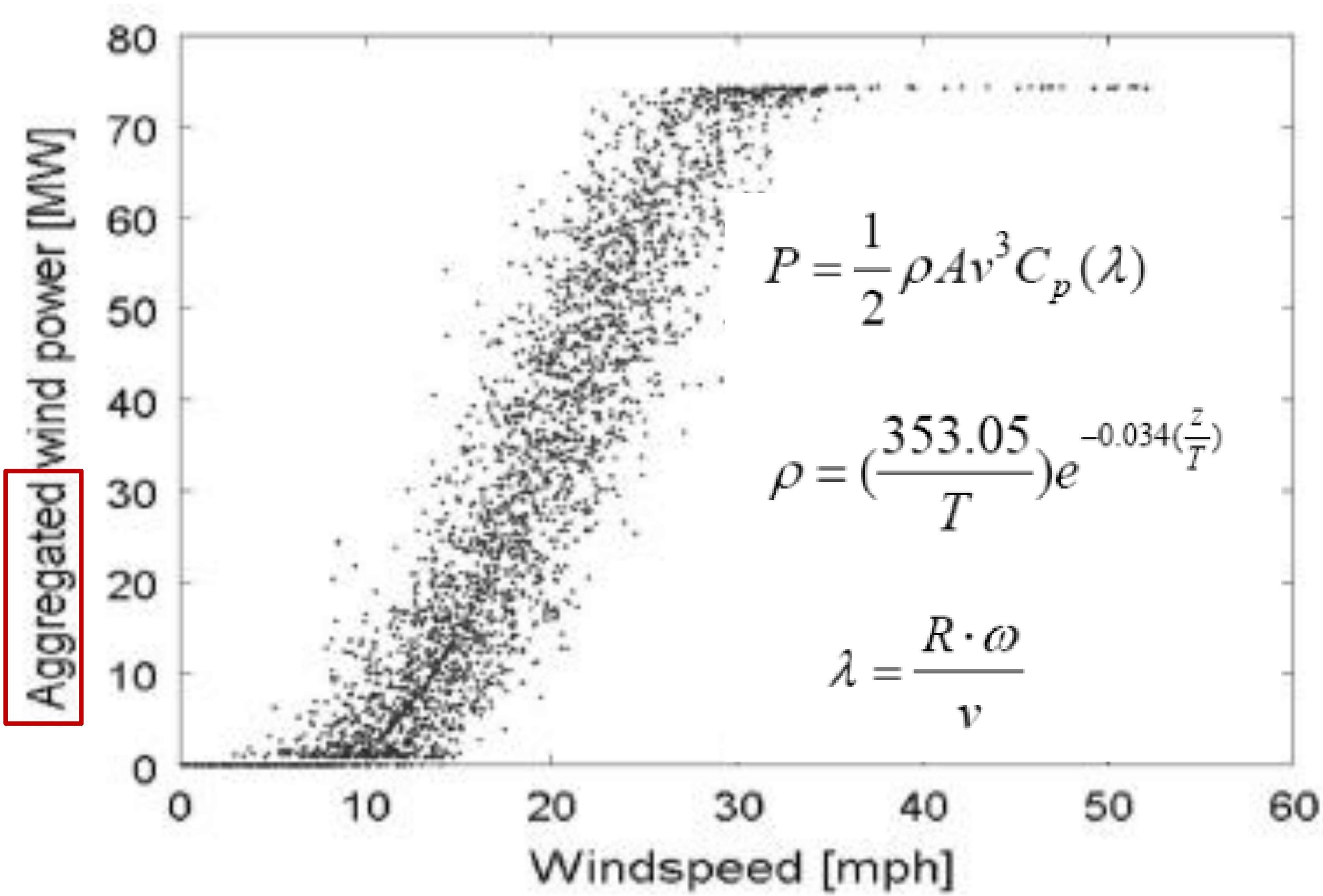


(a) 工廠原型機測試資料



(b) 實際量測資料

Aggregated wind power curve



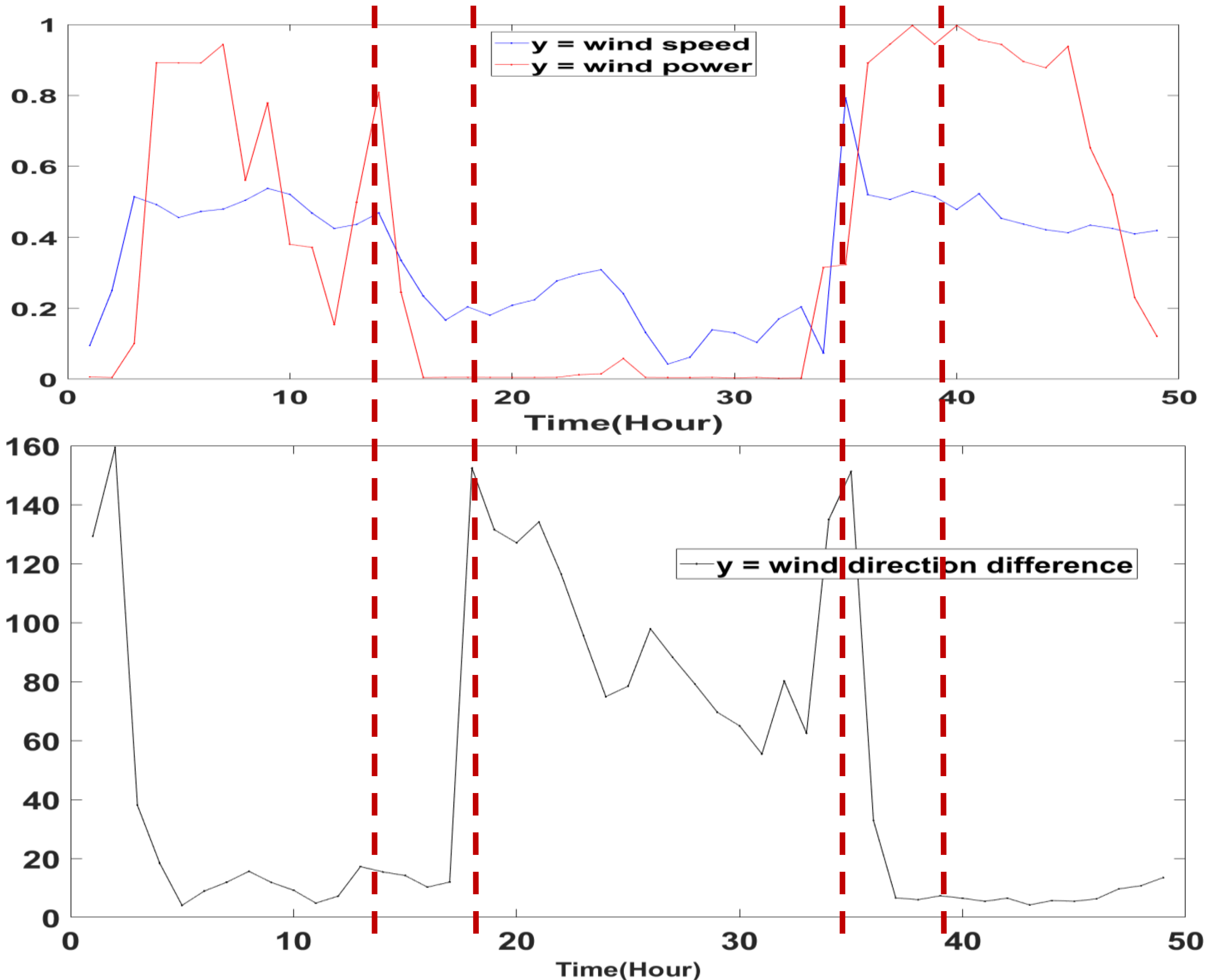
$$P = \frac{1}{2}\rho A v^3 C_p(\lambda)$$

$$\rho = \left(\frac{353.05}{T}\right)e^{-0.034\left(\frac{z}{T}\right)}$$

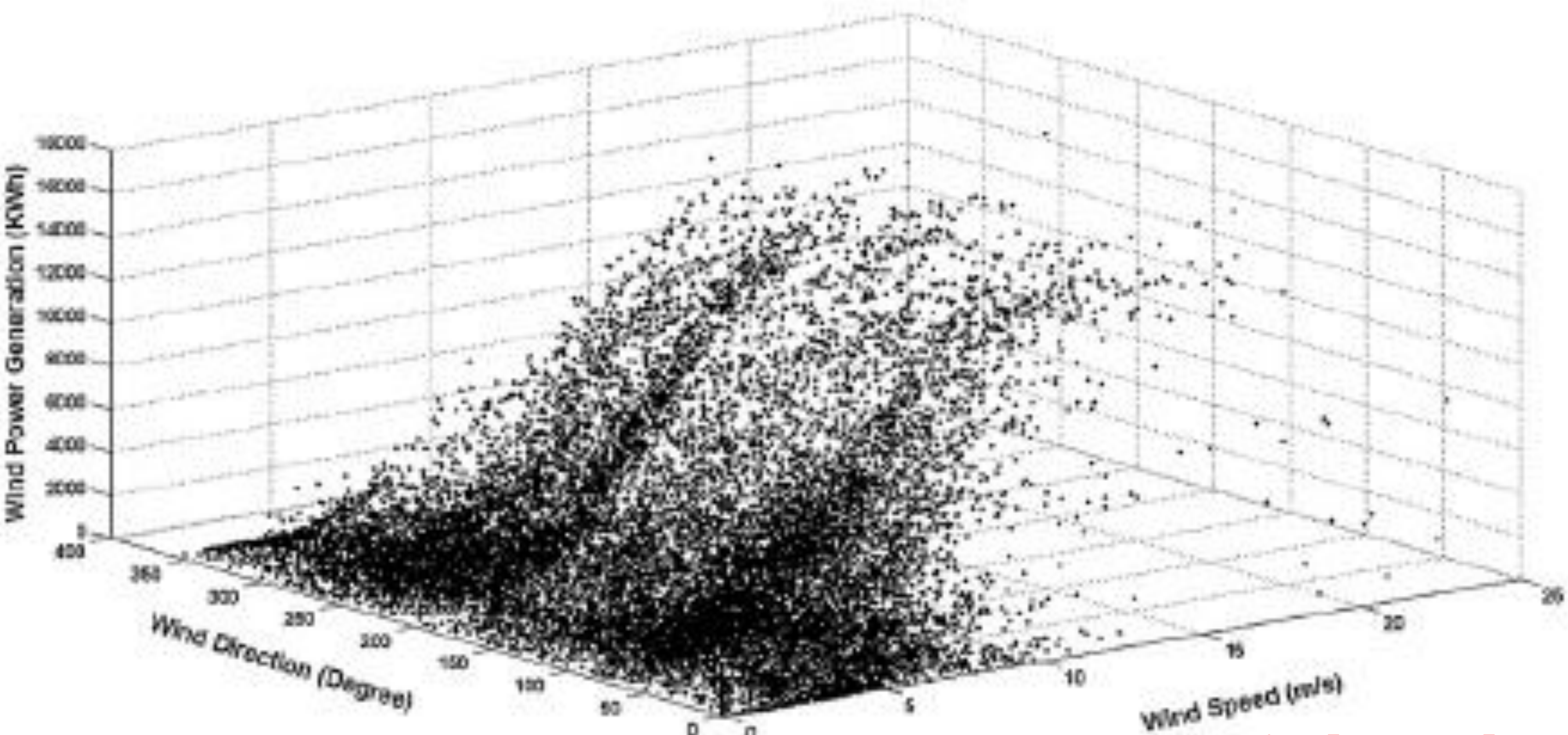
$$\lambda = \frac{R \cdot \omega}{v}$$

風力預測誤差原因(3)

- **輸入資料的相關性與重要性區別**
  - Example: day-ahead forecasting



Wind power with respect to wind speed and direction

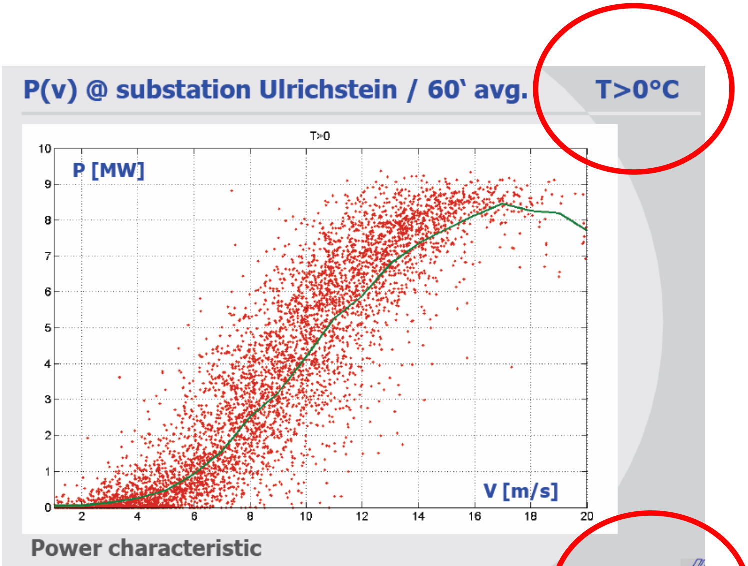


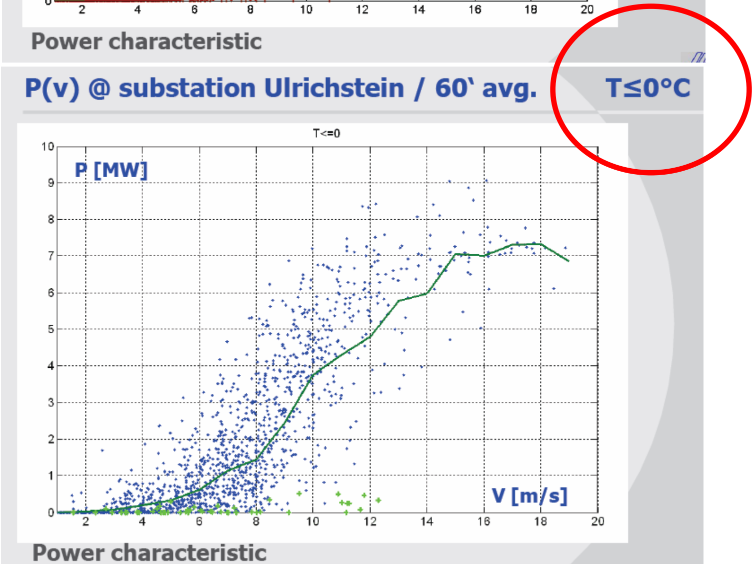
Wind Direction

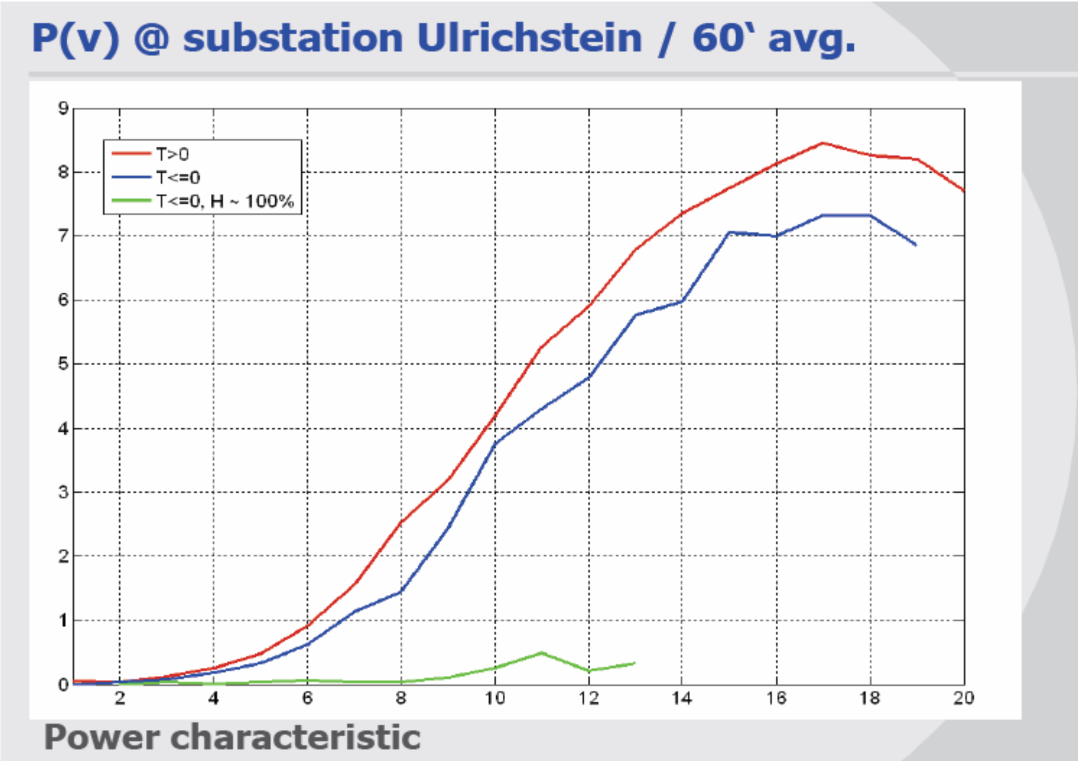
Wind speed

國外案例

Effect of temperature and humidity

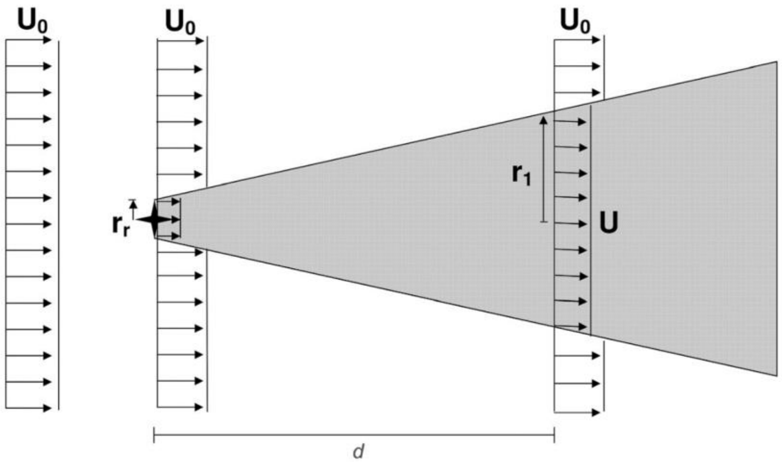


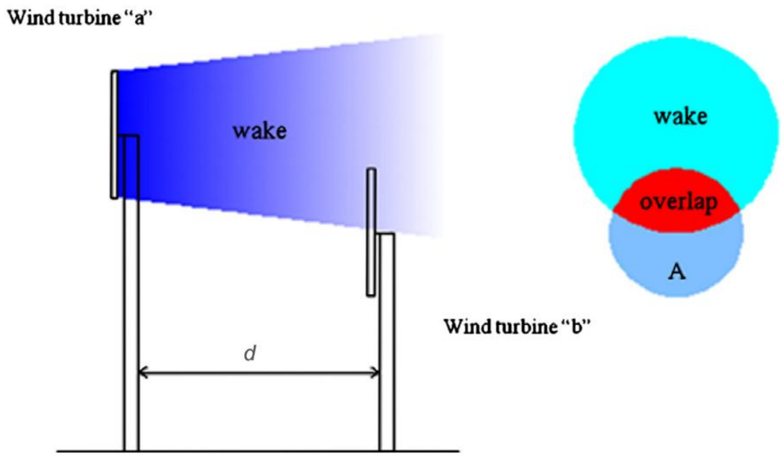


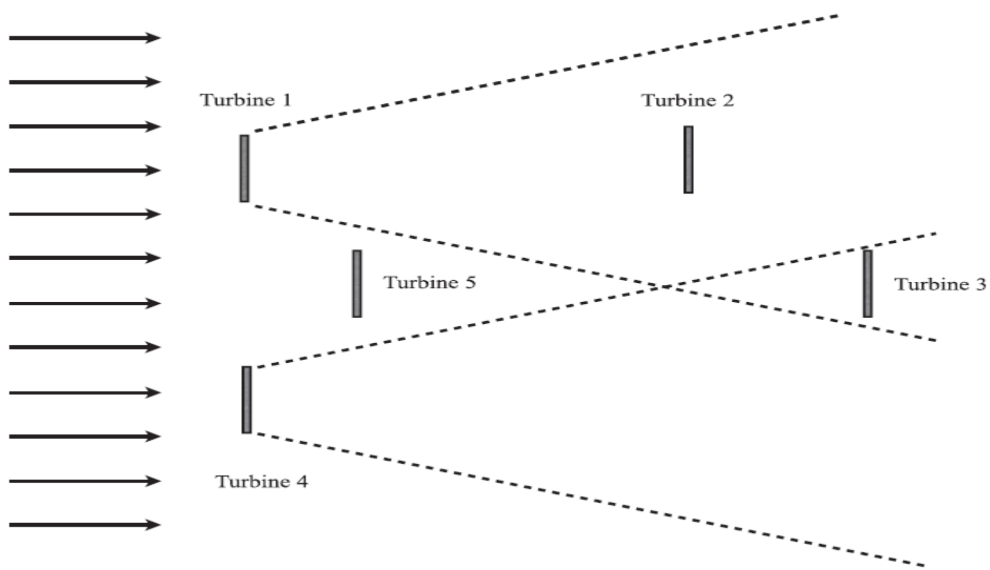


風力預測誤差原因(4)

- 風場內風機間干擾

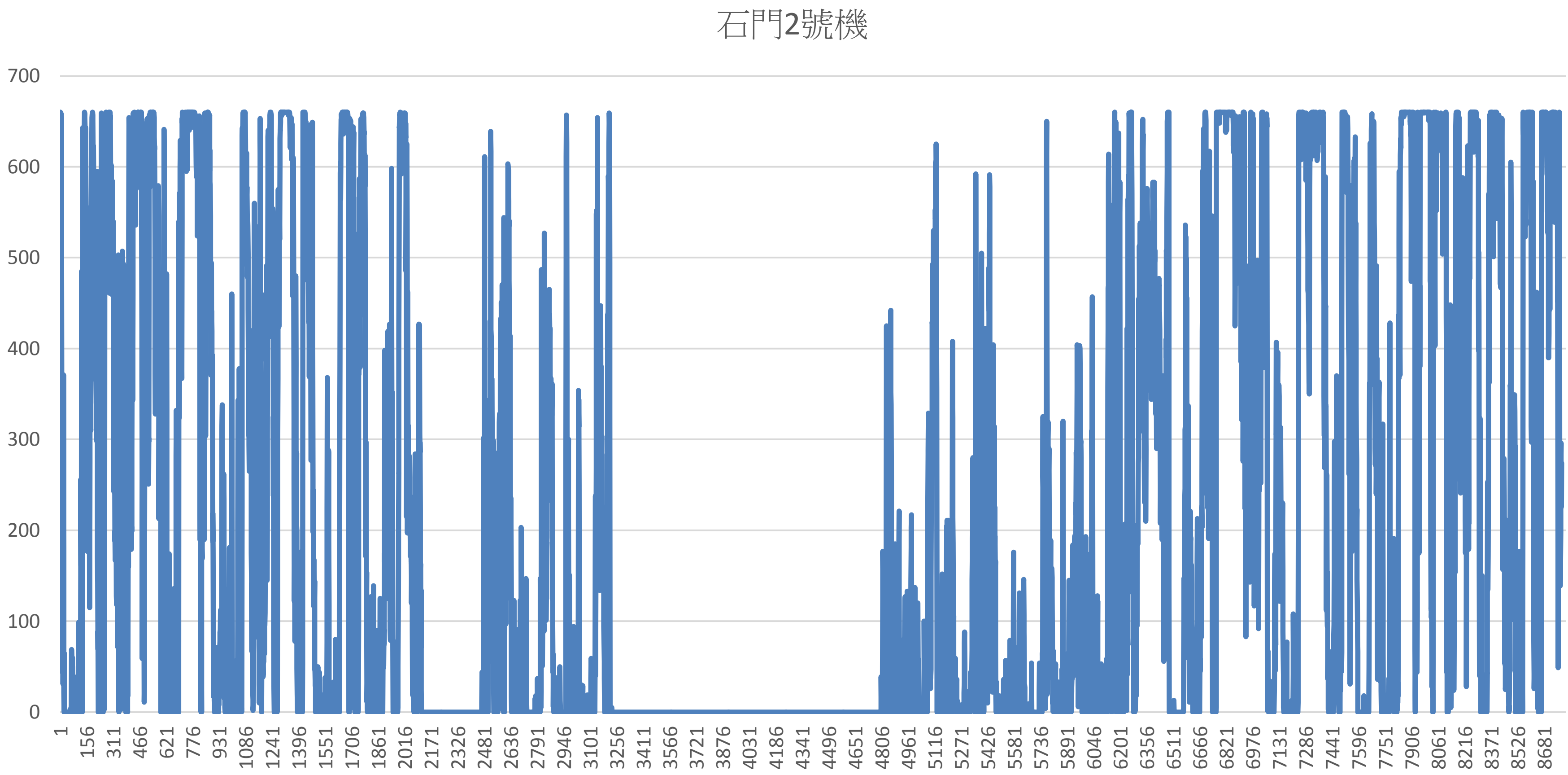






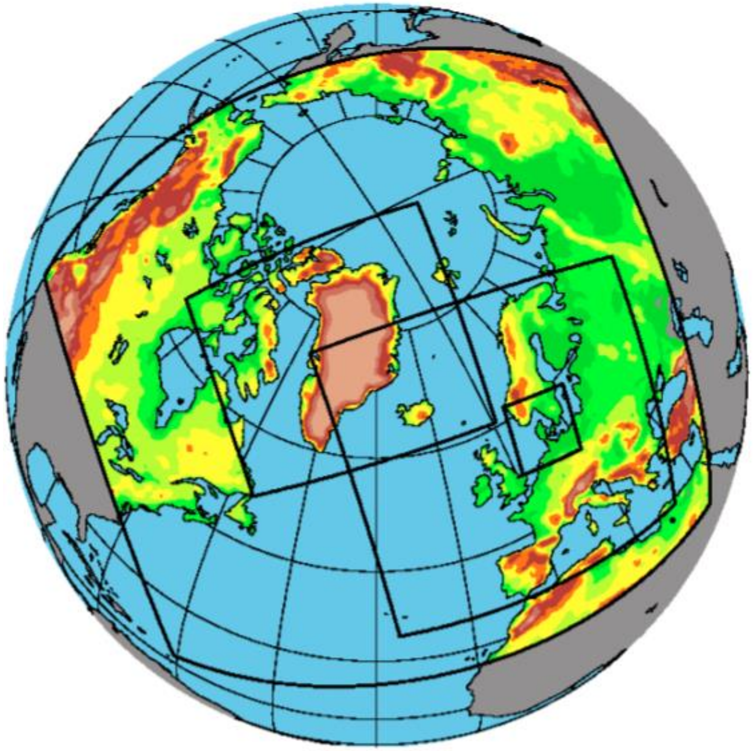
風力預測誤差原因(5)

- 風場風機的操作狀態
- 風場量測資料的穩定性

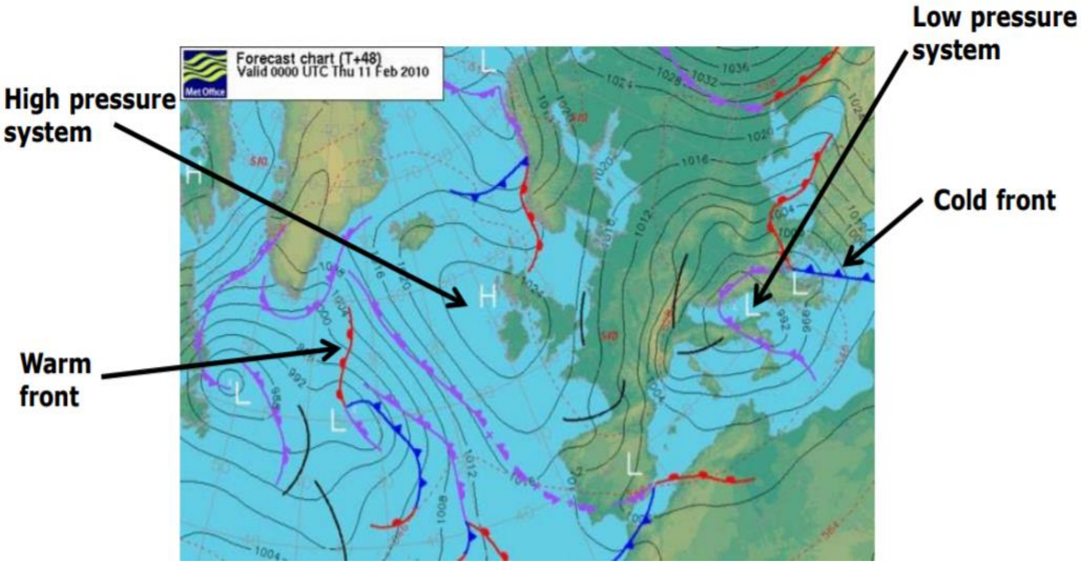


風力預測誤差原因(6)

Global scale meteorology



Synoptic scale meteorology



風力預測常用的方法

- Persistence models
- Numeric weather prediction (NWP) methods
- Statistical methods (ARIMAX, Grey,…)
- AI technology based on ANNs, Fuzzy logic, RNN,…
- Hybrid approaches
- Probabilistic forecasts

如何評估預測好壞

Methods to define forecasting errors- deterministic model

- *Normalized mean absolute error* (NMAE): This criterion gives equal weight to all errors and is easy to interpret in practice since it is directly related to the quantity of power not predicted.

$$\mathrm{NMAE}(h) = \frac{1}{P_{\mathrm{inst}} N} \sum_{t=1}^{N} |P(t+h) - \hat{P}(t+h|t)|$$

where $P(t+h)$ is the power measured at time $t+h$, $\hat{P}(t+h|t)|$ is the forecast of $P(t+h)$ computed at time t, N the number of computed forecasts, and | | denotes the absolute value.

- *Normalized root mean square error* (NRMSE), gives more weight to larger errors thus providing information on the relative size of the large errors:

$$\mathrm{NRMSE}(h) = \frac{1}{P_{\mathrm{inst}}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P(t+h) - \hat{P}(t+h|t))^2}$$

where P_{inst} denotes the installed capacity for which the forecasts are computed.

P_{inst} = installed capacity

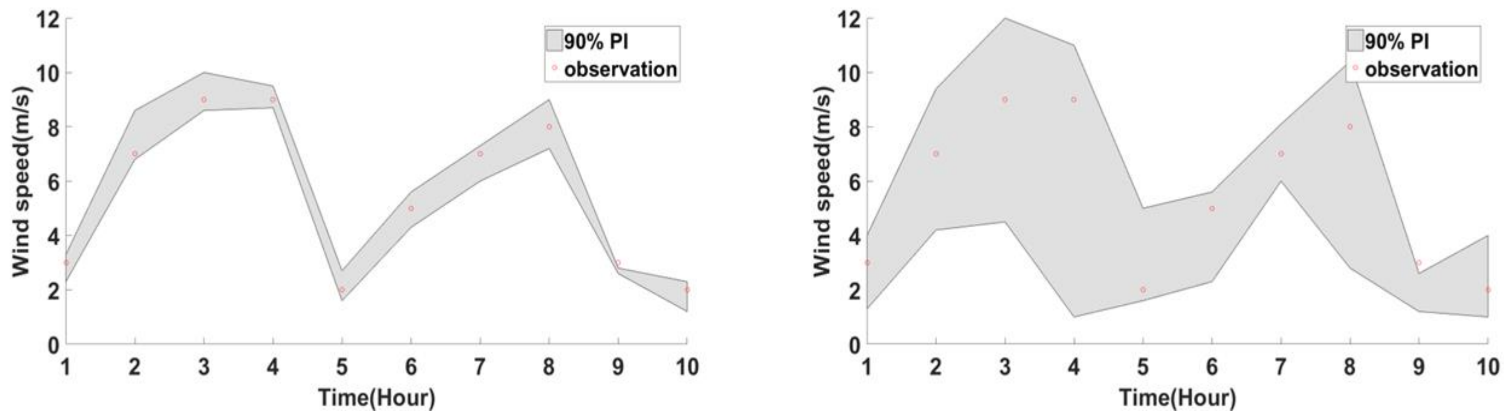
如何評估預測好壞
Probabilistic forecasting

– Prediction Interval Coverage Probability (PICP)

$$PICP = \frac{1}{N}\sum_{t=1}^{N} c_t \qquad c_t = \begin{cases} 1, y_t \in [L_t, U_t] \\ 0, y_t \notin [L_t, U_t] \end{cases}$$

- To maximize reliability, the PICP should be as close as possible to the nominal confidence level

Prediction Interval Normalized Average Width (PINAW)



Developed Wind Power Prediction Tools

No	Software Title	Developed institute	Method	Applied Area
1	WindFor	EMD Company (part-owner of ENFOR)	Hybrid : ANNs , Physical model and wind power domain knowledge (Time series, Statistical Feature and Feature Selection)	Many countries use windPro software and have a licence as picure,
2	RT Windmap	Meteodyn Company	ANNs & Statistical Analysis & Time series	China, India and USA
3	WPPT	Co-work between Elsam and the Department of Mathematicals Modeling at Technical University of Denmark	Statistical Analysis , Physical model and ARX models	North America, Europe (many countries), Asia, and Australia.

Developed Wind Power Prediction Tools

4	PredictWind App & Website	www.predictwind.com (Jon Bilger is a founder)	PWG/PWE wave forecast model and WAM model	USA ,Australia , Europe and New Zealand
5	FLOWSTAR-Energy	Cambridge Environmental Research Consultants (CERC)	Method was derived from theoretical work of Jackson and Hunt	UK government, EU, Asia
6	Wind Power Forecasting Using Edge Intelligence Software	Clixoo Solutions Private Limited (Oilgae,Energy Alternatives India and Solar Mango are Co-Founder)		Many companies from different countries use this software

Developed Wind Power Prediction Tools

7	Anemos wind power predictions software	ANEMOS TECHNOLOGIES (Founder is Philippe CROCHAT)	fuzzy neural networks & Statistical time-series approach	Australia, the US, the UK, Ireland,Canada, Denmark, Greece, France, Spain, and Portugal
8	SOMES	Utrecht University (Netherlands)	Statistical method	Netherland

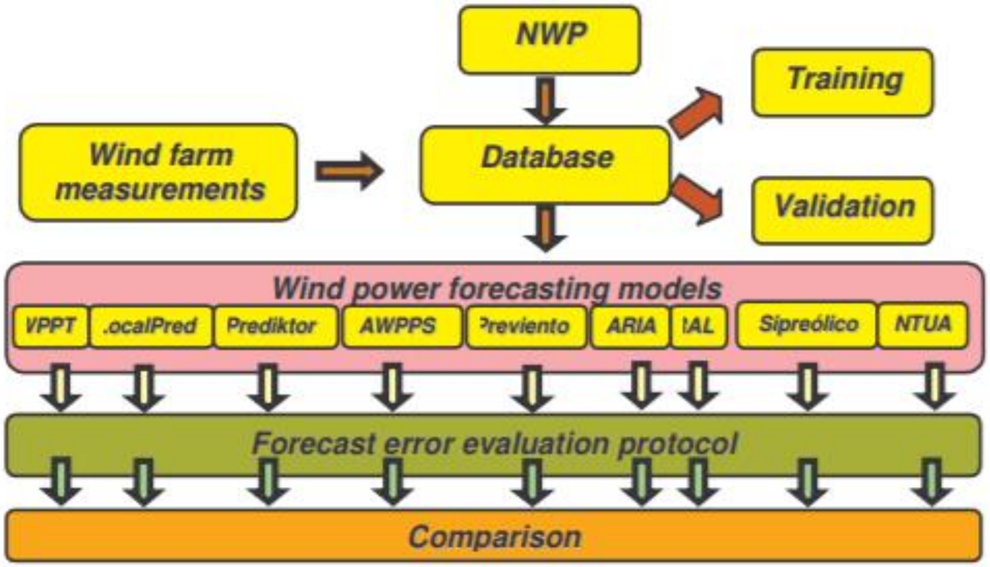
Combining many of the forecasting data from weather forecasting centers in Europe

歐洲結合多個氣象單位之預報資料
統合成一完整的氣象預測模型

Wind power forecasting in Germany

- Short term forecasting
  - One-day ahead: The forecasting result influences the 24 hour's electric quantity and bidding price of the next day
- Very-Short term forecasting
  - One hour ahead: the wind farms adjust the hour's generation plan based on the updated very-short term forecasting result in real time to correct the short term forecast

The basic idea of forecasting modelling contain physical and purely statistical approaches. On the new Anemos platform, the following models were implemented until today



Methods of wind power forecasting in Germany

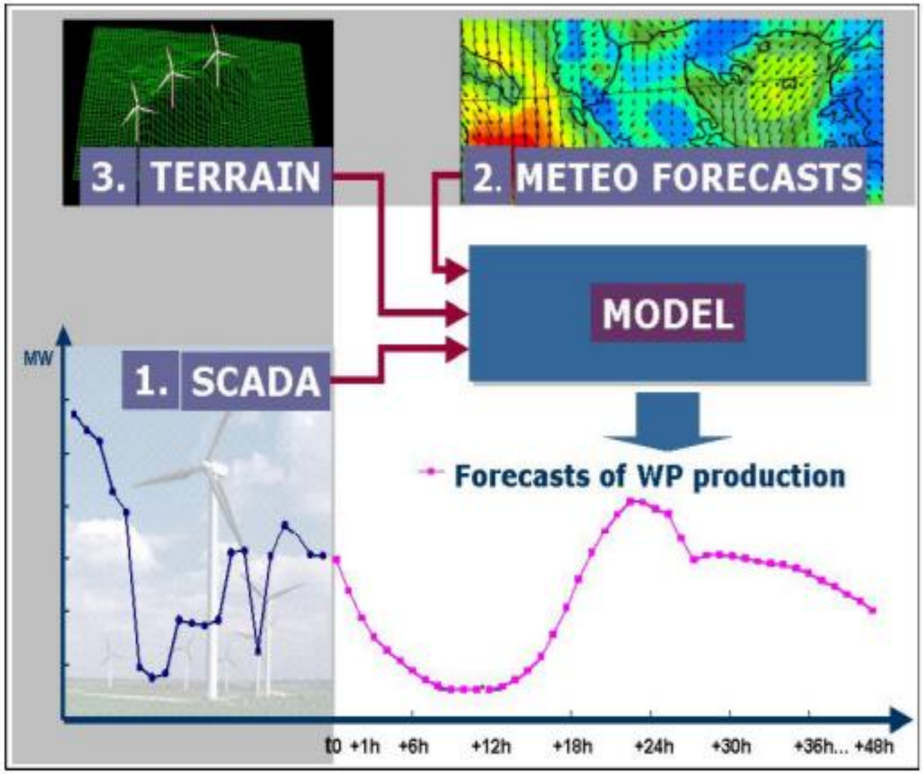


Figure 1: The various forecasting approaches can be classified according to the type of input (SCADA indicates data available on-line). All models involving Meteo Forecasts have a horizon determined by the NWP model, typically 48 hours.

(1): Short-term statistical approaches using only SCADA as input (horizons: <6 hours).
(2): Physical or statistical approaches. Good performance for >3 hours.
(2)+(3): Physical approach. Good performance for >3 hours.
(1)+(2): Statistical approach.
(1)+ (2)+(3): Combined approach.

Partners in the ANEMOS project

Performance of wind power forecasting should be less than 8.8% of power output which wind power plant can generate.

Wind power forecasting in UK

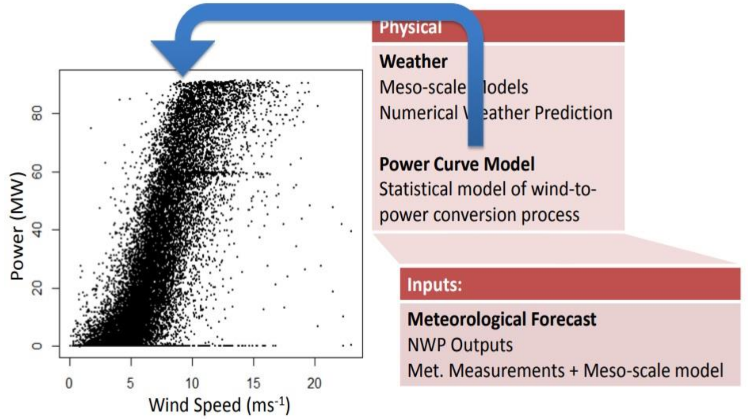
Time Scales

- Seconds (extremely-short-term)
  - Turbine/Farm Control
- Minutes (very-short-term)
  - Balancing and Transmission
- Hours (short-term)
  - Scheduling conventional plant
- Days
  - Day-ahead scheduling, large CHP operation
- Weeks
  - Maintenance
- Years
  - Investment/financing, cash flow etc.

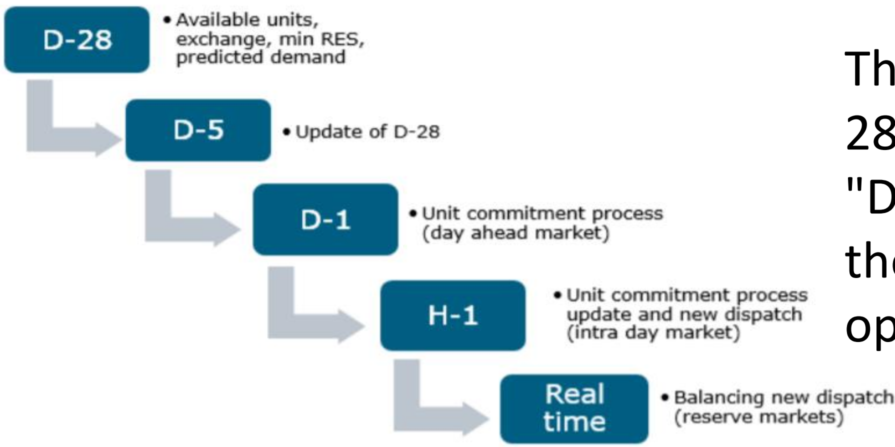
Not Covered Today

Covered Today

Not Covered Today



Wind power forecasting in Denmark



The relevant operational forecasting starts 28 days before operation – designated as "D-28", and the following figure illustrates the main activities from D-28 to real time operation.

D-1, morning before 9 AM

Input → **Process** → **Output**

Input

Generators:
Generation units:
- Availability
- Minimum
- Maximum

TSO:
Interconnectors:
- Firm capacity

RES generation:
- Forecasted production based on meteorological data

Demand:
- Forecast

Process

Every day:
Data is collected and power balance is calculated for the two Danish areas.
Result is evaluated and if necessary actions are taken.
Actions could be:
- Cancellation of maintenance work on grid or generators
- Forced availability of generators

Output

Acceptable forecasted power balance hour by hour the following **day**

H-1

Input → **Process** → **Output**

Input

Generators:
Generation units:
- Updated Scheduled production every 5 minute
- Min. and Max.

TSO:
Interconnectors:
- Scheduled exchange every 5 minute

RES generation:
- Updated forecasted generation every 5 minute

Demand:
- Updated Forecast every 5 minute

Process

For every time-step:
Power balance is calculated for the two Danish areas.

Result is evaluated and if necessary actions are taken.
Actions could be:
- Trade with neighbor's
- Cancellation of maintenance work on grid or generators
- Forced production

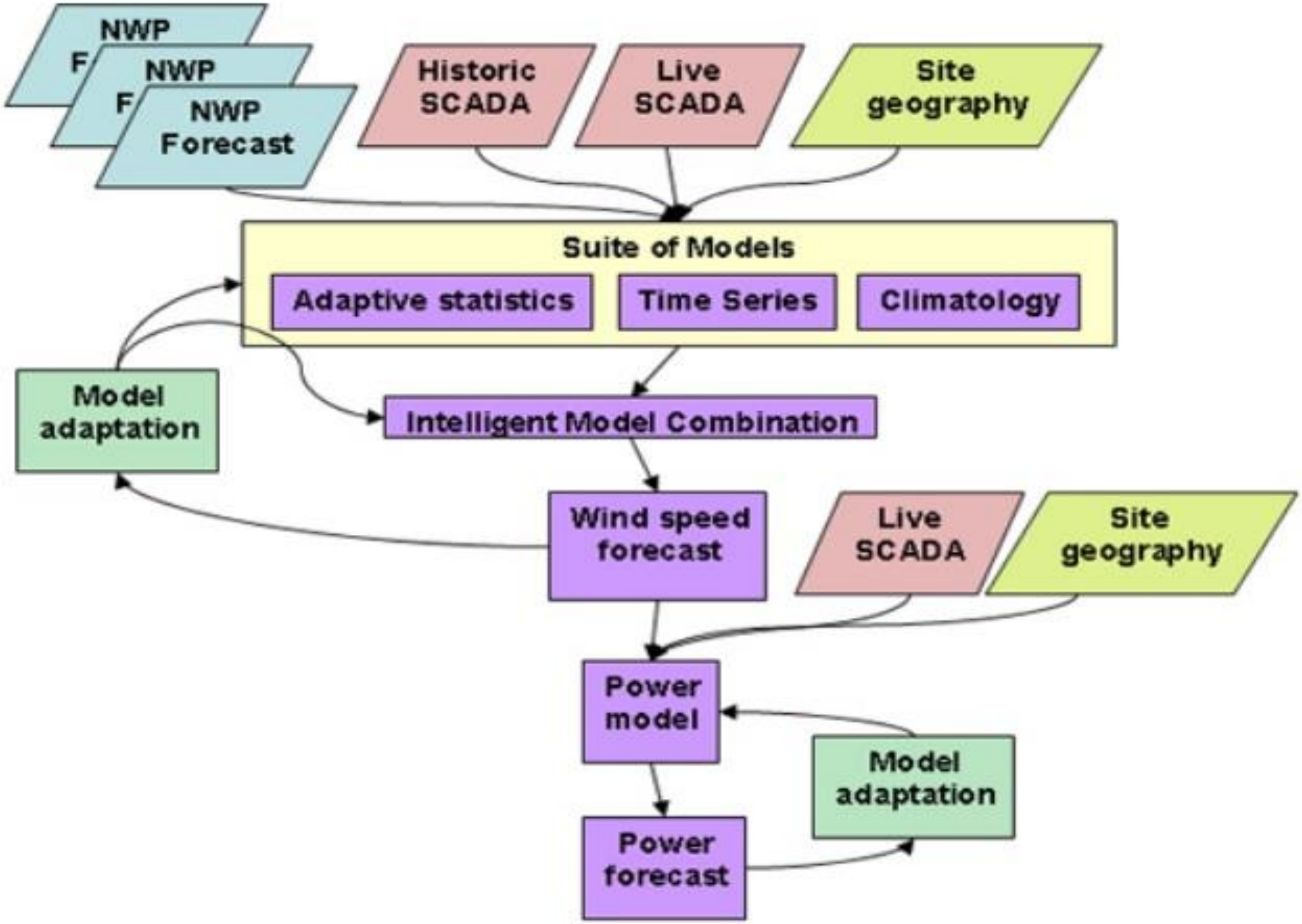
Output

Acceptable forecasted power balance every **5 minutes.**

Wind power forecasting in Denmark

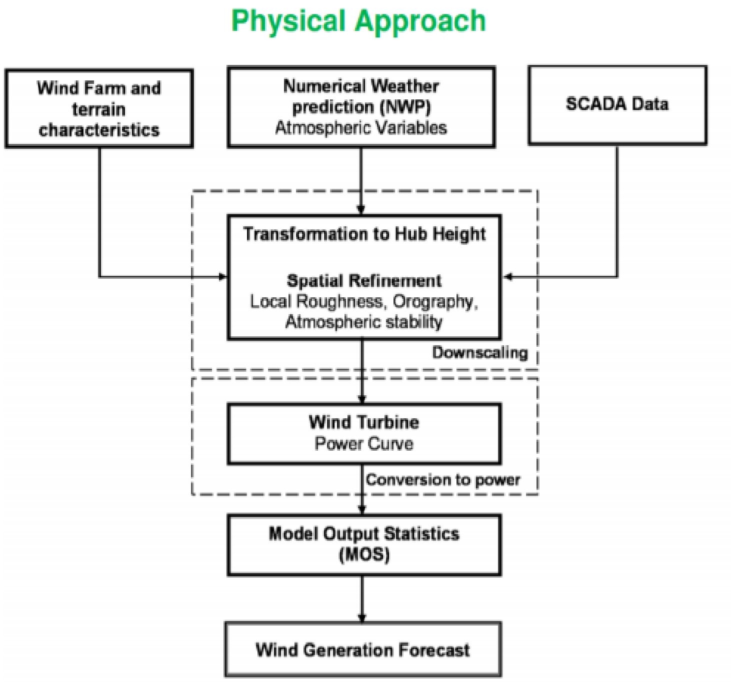
Suppose a wind front is arriving earlier than expected. If the front is moving from west to east, the arrival of the front is first seen by the westerly wind areas as an increasing offline forecast error. **If the model is correctly calibrated it is possible to use this information for the other wind areas,** i.e., we expect a similar increase in the offline forecast errors for the other wind areas in the near future, as the front sweeps across the country. This is the key idea behind the so-called spatiotemporal analysis, which is incorporated into the online wind power forecast.

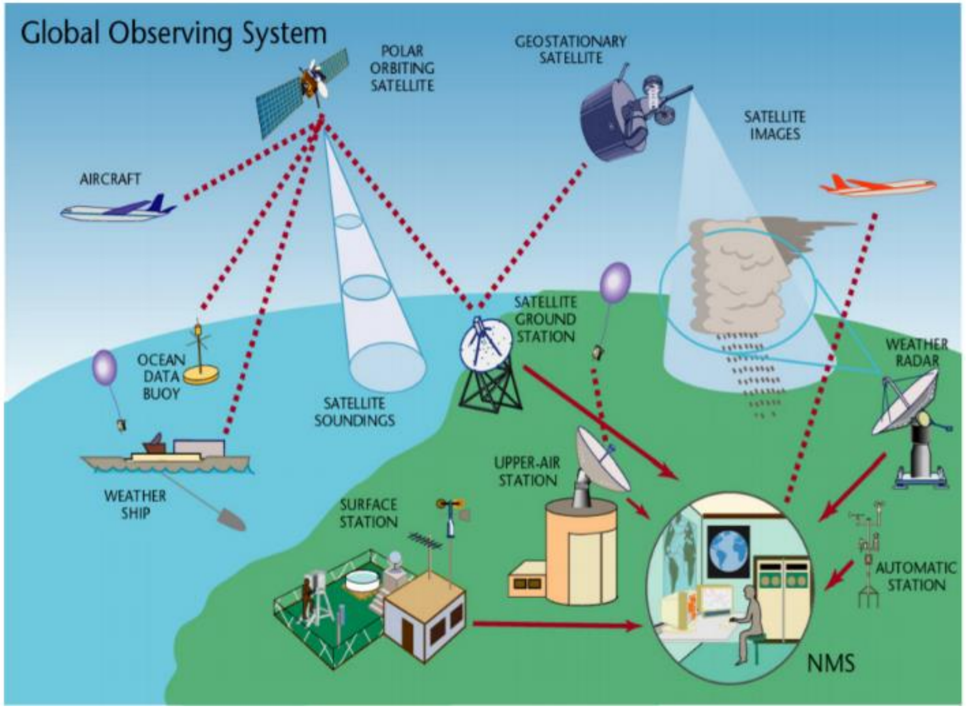
Wind power forecasting in France



Wind power forecasting in Ireland

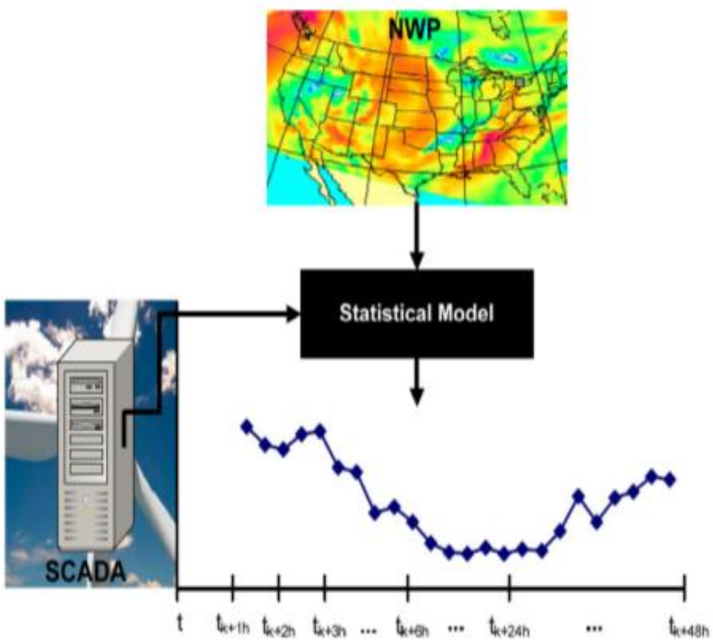
- Physical approach
  - It focuses on the description of the wind flow around and inside the wind farm, in addition to using the manufacturer's power curve in order to propose an estimation of the wind power output.
  - It consists of several sub models, which together deliver the translation from the NWP forecast at a certain grid point and model level, to power forecast at the considered site and at turbine hub height

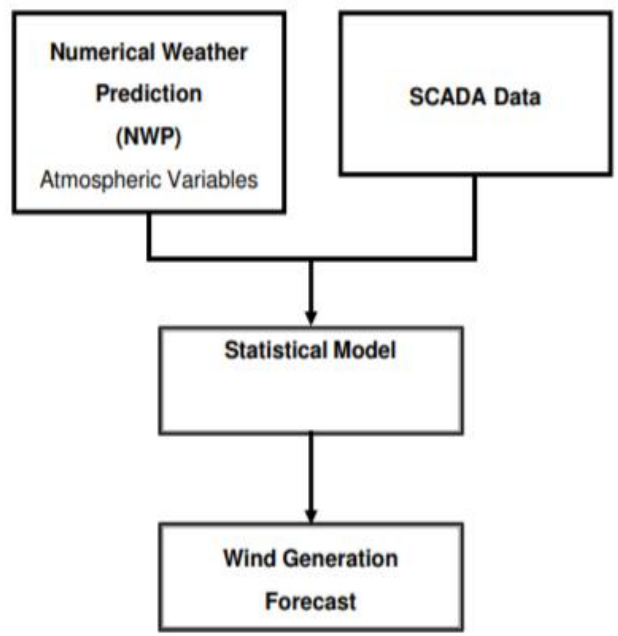




Wind power forecasting in Ireland

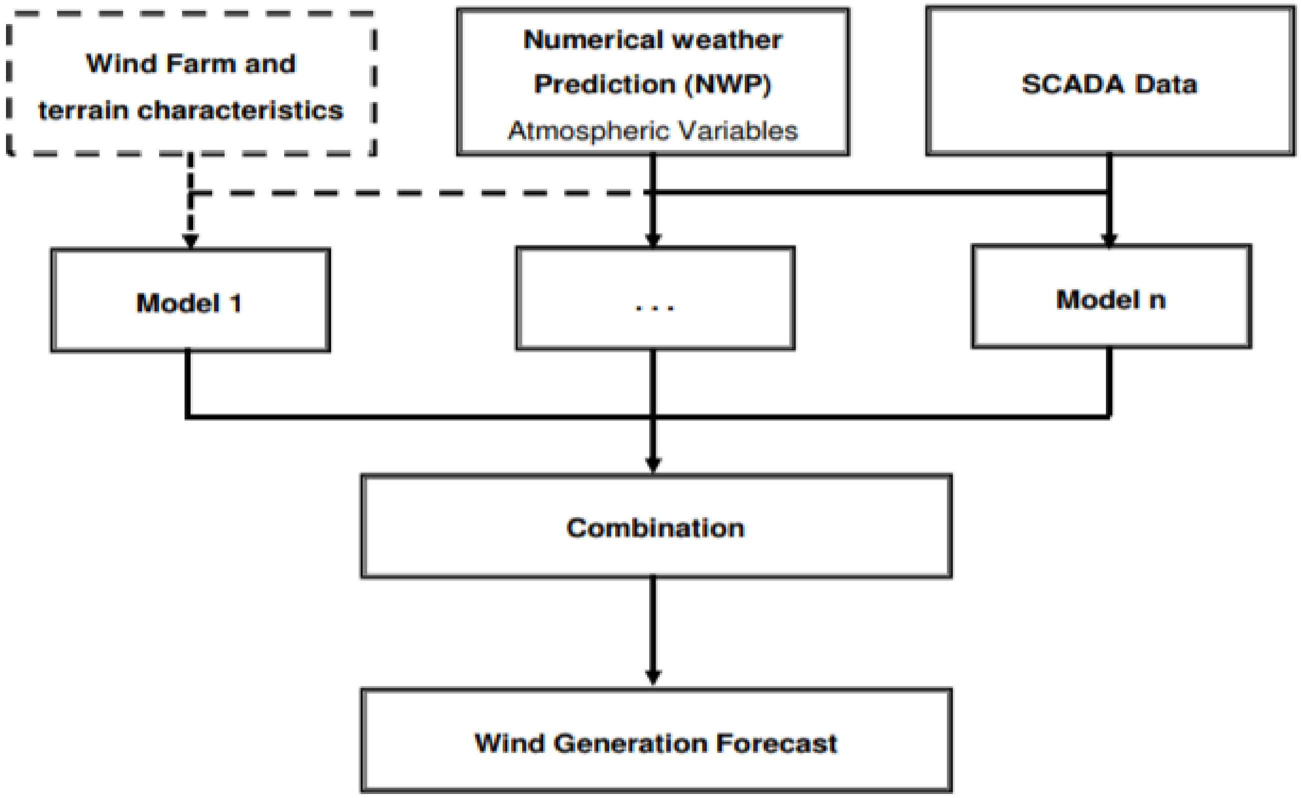
- Statistical approach
  - It consists of emulating the relation between meteorological predictions, historical measurements and generation output through statistical models whose parameters have to be estimated from data, without taking any physical phenomena into account.
  - Statistical block is able to combine inputs such as NWPs of the speed, direction, temperature, etc., of various model levels, together with on-line measurements, such as wind power, speed, direction, and others.





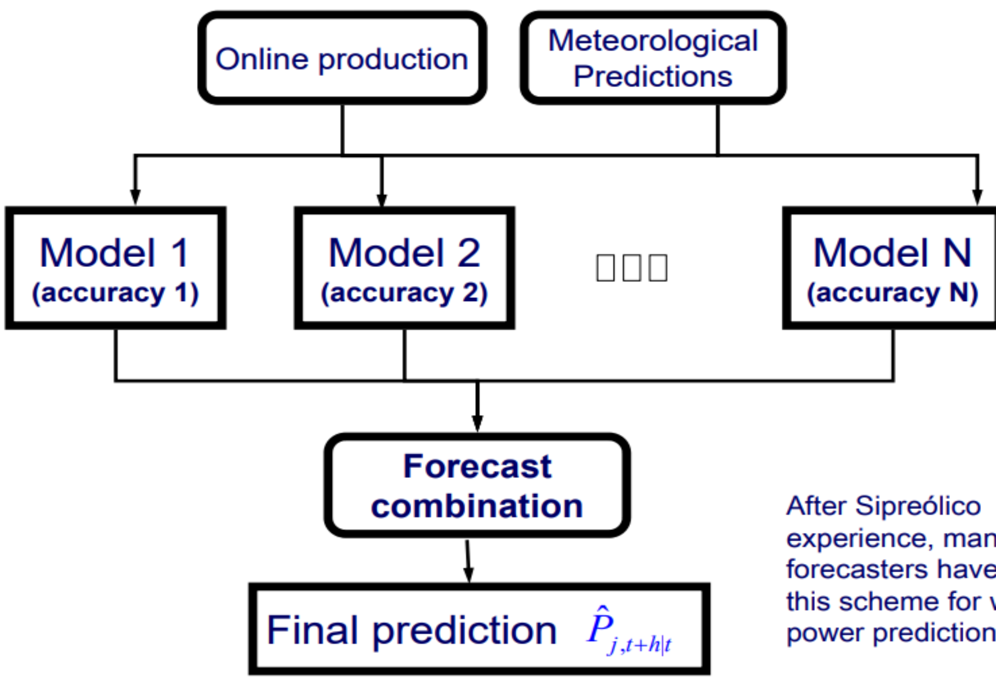
Wind power forecasting in Ireland

- Hybrid approach
  - There are some WPF systems that combine the two approaches in order to join the advantages of both approaches and thus improve the forecasts



Wind power forecasting in Spain

- REE use SIPREÓLICO model to do the forecasting which was developed by Universidad Carlos III de Madrid
- SIPREÓLICO use in 'Short term' statistical prediction tool (up to 48 hours)
  - Every hour, Sipre ólico updates the hourly predictions of more than 600 wind farms for the next 48 hours, using on-line production data and meteorological predictions.
  - On-line wind power predictions of individual wind farms
  - Too many wind farms to allow for individual model building



After Sipreólico experience, many forecasters have adopted this scheme for wind power prediction

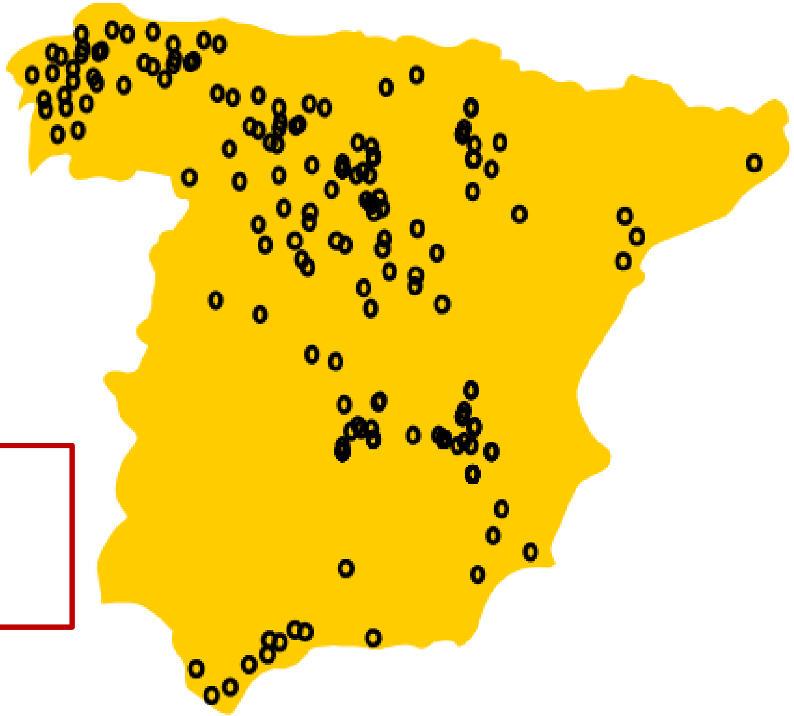
Wind power forecasting in Spain

Meteorological Predictions

- Wind speed (meters/second) and direction (degrees) at selected points.
- Hourly predictions for next 48 hours at more than 100 coordinates.
- Should be provided by a meteorological agency.
- Wind predictions are, nowadays, of <u>low quality.</u>
- REE buy the information from TWO independent meteorological agencies, using different sources of information, to gain accuracy.

Wind power forecasting in Spain

Online production



- **More than 600 wind farms**
- **The number of wind farms is constantly increasing: we have to be ready to predict new wind farms (with small datasets)**
- **Too many wind farms: it is not feasible to analyze them one by one**

Wind power forecasting in Spain

Model 1 (accuracy 1) | **Model 2 (accuracy 2)** | □□□ | **Model N (accuracy N)**

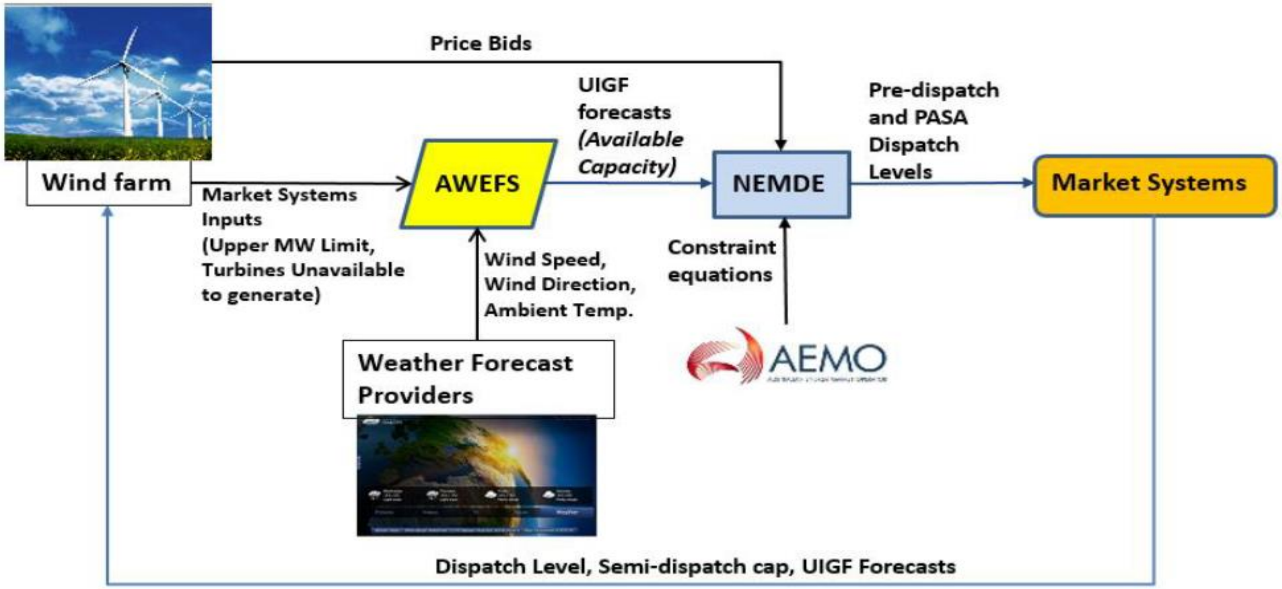
Alternative models are running in parallel

- Flexibility to adapt to different wind farms
- Flexibility to predict from short to long term
- Flexibility to situations with small or large data sets
- Adaptive and recursive estimation

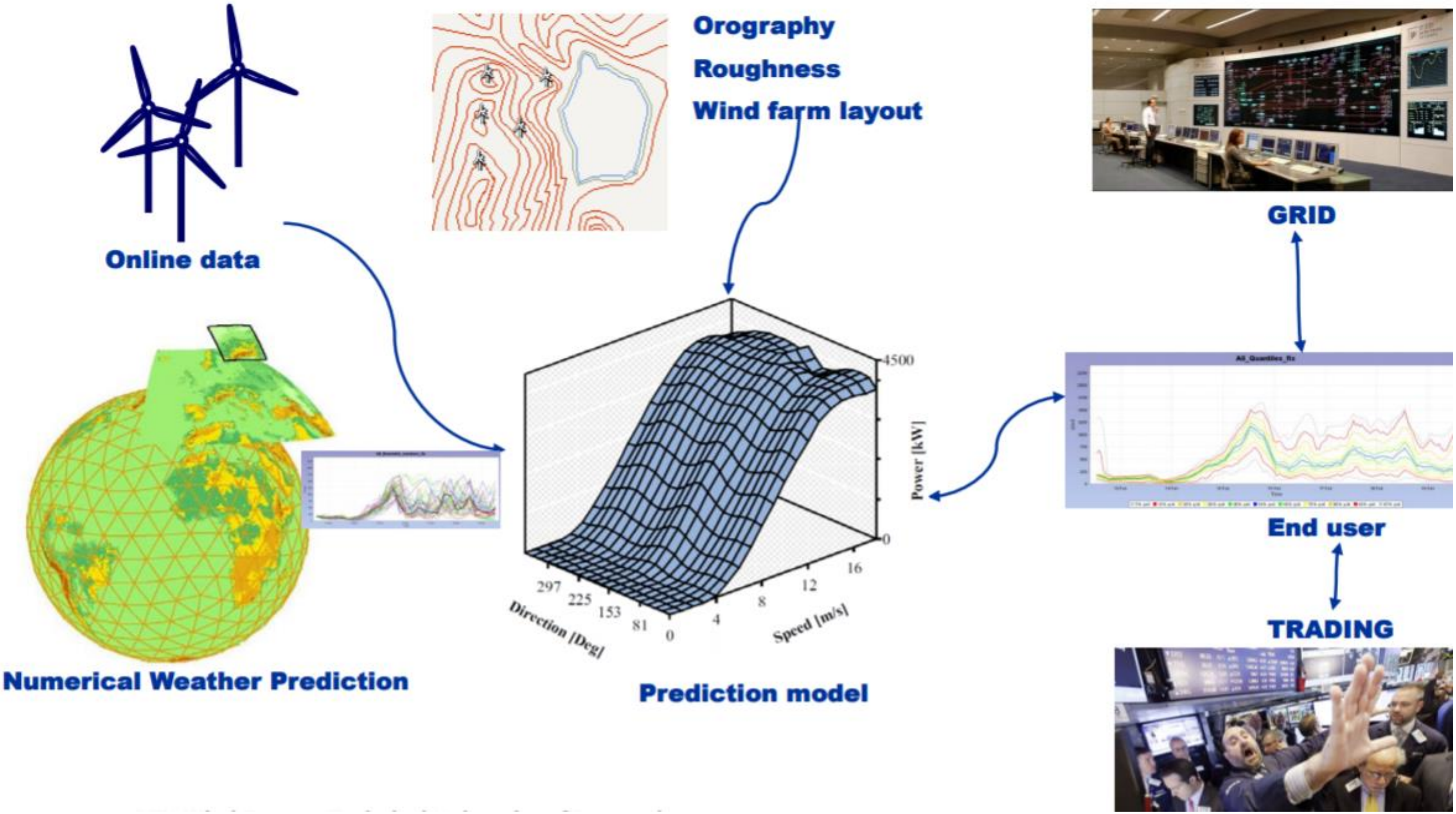
- Autoregressive models using ***on-line measurements***
- Parametric dynamic models with wind speed and direction
- Nonparametric (local regression) models with wind speed and direction

Wind power forecasting in Australia

- The Australian Wind Energy Forecasting System (AWEFS) produces forecasts from the following inputs:
  - Real-time SCADA measurements from the wind farms.
  - Numerical Weather Predictions from weather forecasters around the world.
  - Standing data from the wind farms.
  - Availability information provided by the wind farms, that includes turbines under maintenance and upper MW limit on the wind farm.

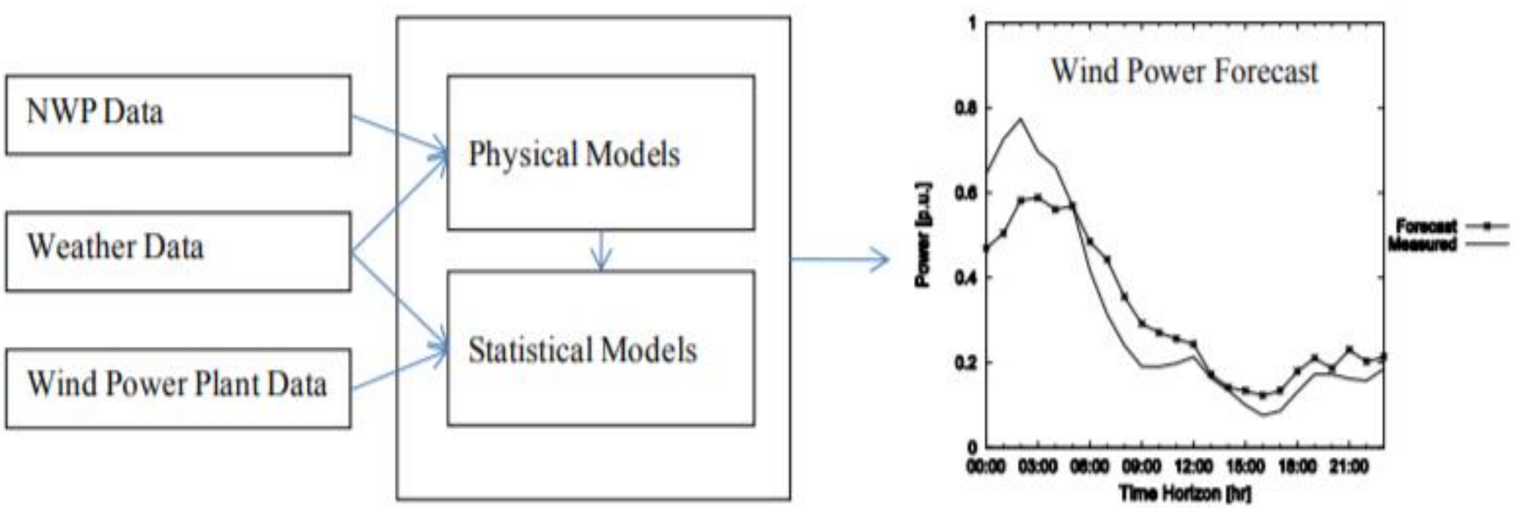


Wind power forecasting in Portugal



Wind power forecasting in ERCOT

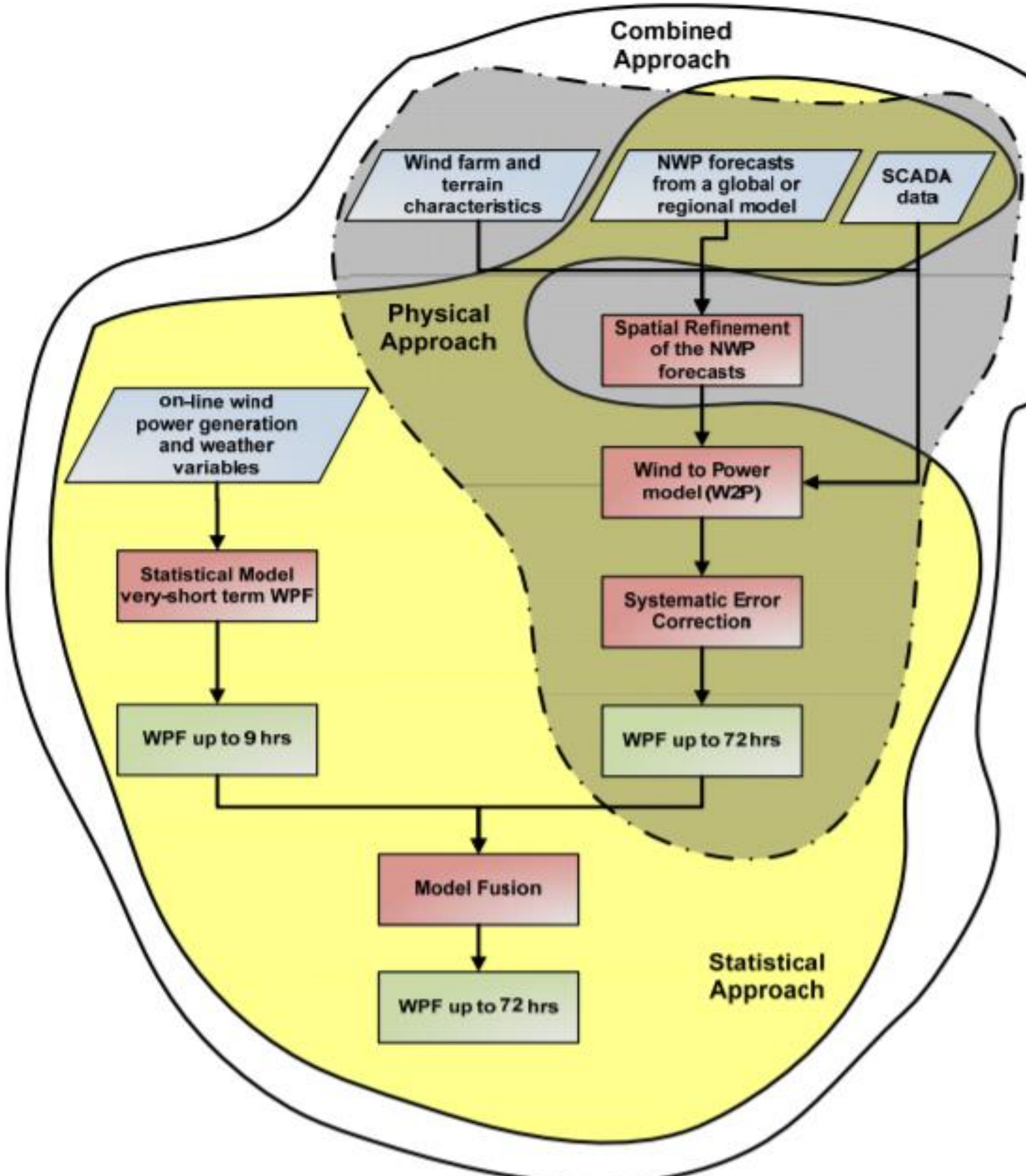
- The wind power forecasting in ERCOT electricity market is produced by AWS Truepower. United States Department of Energy and the National Oceanic and Atmospheric Administration were formed the Wind Forecasting Improvement Project (WFIP) and let AWS Truepower do it.
- A wind power forecasting uses input data from different sources, including results from numerical weather prediction (NWP) models, local meteorological measurements, SCADA data describing the real-time state of the wind power plants, and additional information about the characteristics of the wind power plants and the nearby terrain and topography.



Wind power forecasting in Nordic electricity markets

- The AleaWind is the forecasting model which was developed by AleaSoft. This model have the input base on NWP, History data measurements & generation output, wind speed, wind direction and other valuable weather data.
- After these data are fed in this model, then they will generate the wind power output base on Genetic Algorithms, Neural Networks and Statistics approach for each timeframe of electricity market. –

- UNCERTAINTY REPRESENTATION
  - **Probabilistic forecasts** consist of estimating the future uncertainty of wind power that can be expressed as a probability measure (e.g., quantile)
  - **Risk indices** provide comprehensive information on the expected level of forecast accuracy (the predictability of the atmospheric situation), an a priori warning on expected level of prediction error.
  - Scenarios of generation provide information on the development of the prediction errors through the set of look-ahead times and can also model the spatial and spatial-temporal interdependence of forecast uncertainty.


Combined Approach
Wind farm and terrain characteristics
NWP forecasts from a global or regional model
SCADA data
Physical Approach
Spatial Refinement of the NWP forecasts
on-line wind power generation and weather variables
Wind to Power model (W2P)
Statistical Model very-short term WPF
Systematic Error Correction
WPF up to 9 hrs
WPF up to 72 hrs
Model Fusion
Statistical Approach
WPF up to 72 hrs

IEA Wind Task 36 Forecasting

International Energy Agency (IEA) has several Energy Technology Networks, e.g. Wind Power.

Forecasting Task (36) runs 1/2016-12/2018 (and probably new phase after that).

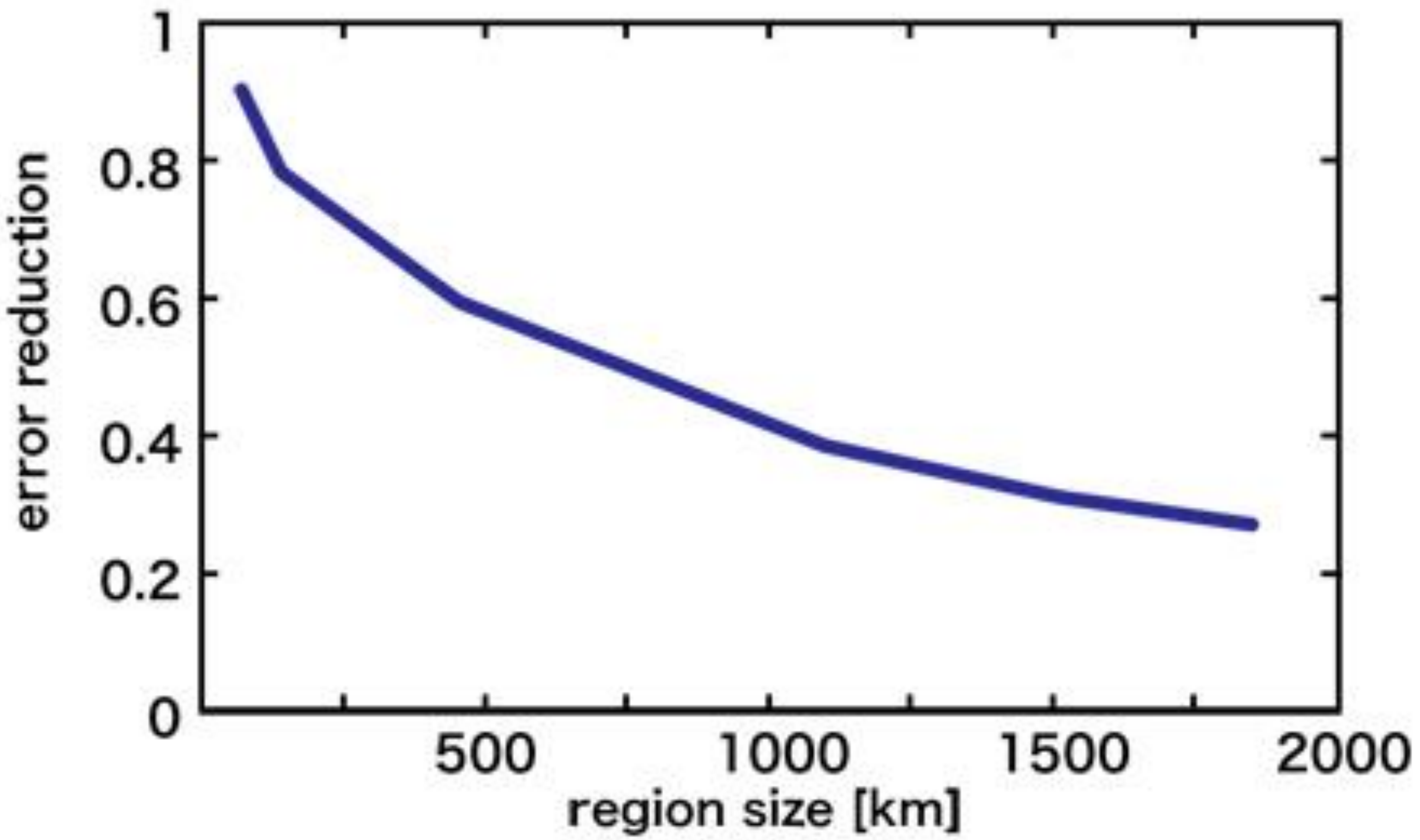
Some 200 people from weather services, operational forecasters, academia and end users (TSOs, operators, traders, ...).

Participation is open for IEA Wind member countries, but news are distributed via a mailing list (send mail to grgi@dtu.dk).

See details at www.ieawindforecasting.dk.

Spatial Smoothing Effect

The distributed range of wind turbines

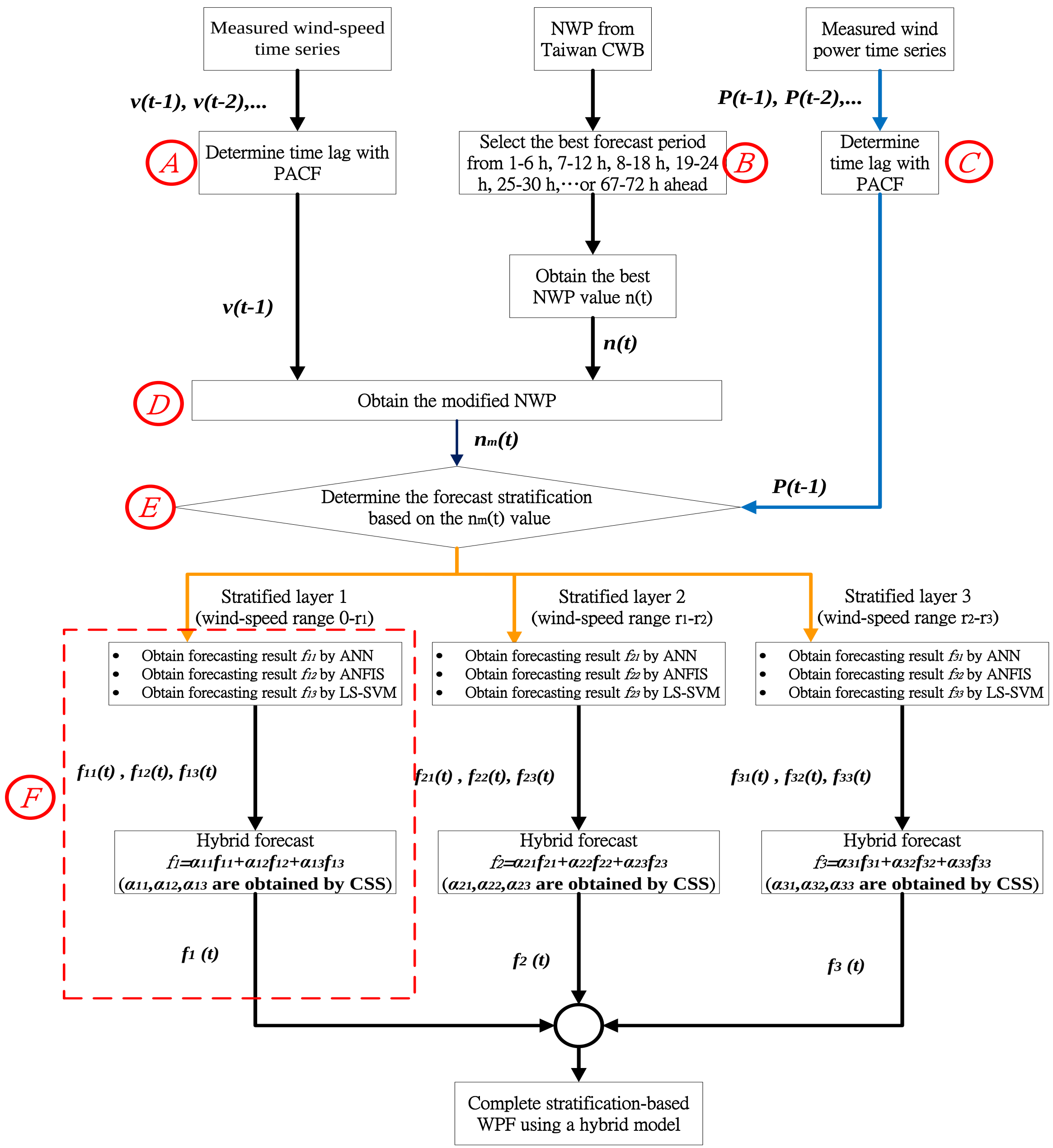


Effect of electricity market operation on the lead time of wind power forecasting

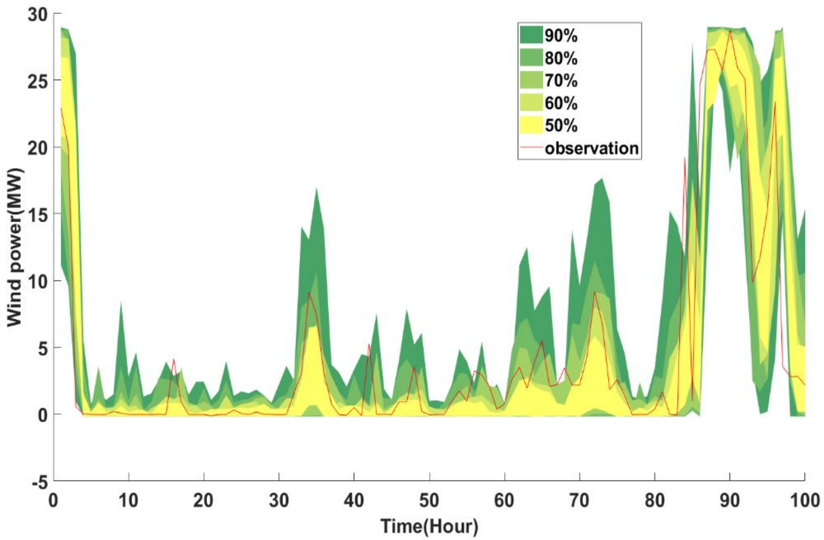
- 澳洲電力市場每隔5分鐘將依最新的系統狀況重新調度，因此5分鐘前的極短期風力預測模型將格外顯得重要。
- 英國BETTA電力交易市場機制規定在交易前1/2小時結束短期交易市場(spot market) 並進入平衡交易機制(balancing mechanism)，因此1小時前的風力預測將可提供風機發電業者重要的投標參考。
- 北歐市場(Nord Pool)與美國電力市場機制也以1日前及1小時前的標準交易市場為主。
- 因此在目前全球電力市場中，風力發電業者應至少具備1小時及1日前的風力預測技術，並搭配數分鐘前甚至數秒前的預測模型。

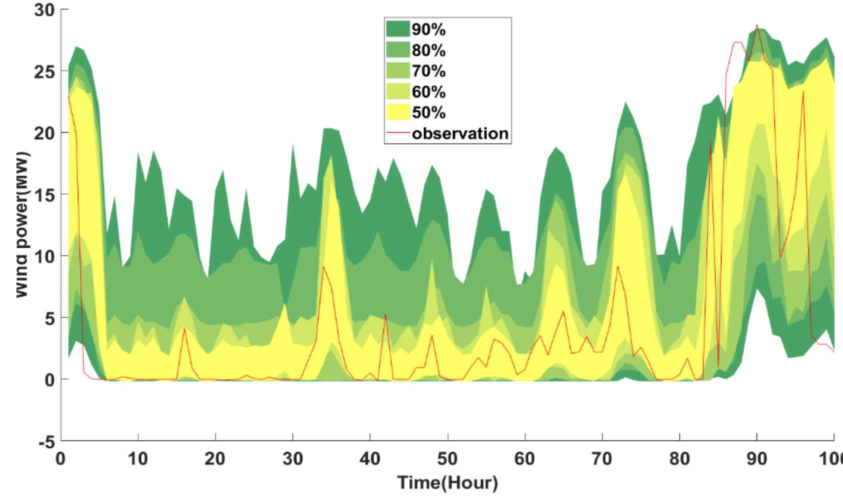
The role of wind power forecasting on the electricity markets

- 為了增進系統風力併接的效率，西班牙政府於2004年公佈新的併網規範- Spanish Royal Decree 436/2004 （簡稱R2），其增加對於風力機組額外的技術要求：其中針對任何大於10MW的風力裝置容量，必須在30小時前提供系統操作者風力輸出預測值；此預測值可持續修正直到前1小時為止。假設預測誤差高於20%以上，則風場操作者將必須罰以平均誤差成本的10%。


Measured wind-speed time series
NWP from Taiwan CWB
Measured wind power time series
v(t-1), v(t-2),...
P(t-1), P(t-2),...
A
Determine time lag with PACF
Select the best forecast period from 1-6 h, 7-12 h, 8-18 h, 19-24 h, 25-30 h,⋯or 67-72 h ahead
B
Determine time lag with PACF
C
v(t-1)
Obtain the best NWP value n(t)
n(t)
D
Obtain the modified NWP
nm(t)
E
Determine the forecast stratification based on the nm(t) value
P(t-1)
Stratified layer 1 (wind-speed range 0-r1)
Stratified layer 2 (wind-speed range r1-r2)
Stratified layer 3 (wind-speed range r2-r3)
Obtain forecasting result f11 by ANN
Obtain forecasting result f12 by ANFIS
Obtain forecasting result f13 by LS-SVM
Obtain forecasting result f21 by ANN
Obtain forecasting result f22 by ANFIS
Obtain forecasting result f23 by LS-SVM
Obtain forecasting result f31 by ANN
Obtain forecasting result f32 by ANFIS
Obtain forecasting result f33 by LS-SVM
F
f11(t) , f12(t), f13(t)
f21(t) , f22(t), f23(t)
f31(t) , f32(t), f33(t)
Hybrid forecast f1=α11f11+α12f12+α13f13 (α11,α12,α13 are obtained by CSS)
Hybrid forecast f2=α21f21+α22f22+α23f23 (α21,α22,α23 are obtained by CSS)
Hybrid forecast f3=α31f31+α32f32+α33f33 (α31,α32,α33 are obtained by CSS)
f1 (t)
f2 (t)
f3 (t)
Complete stratification-based WPF using a hybrid model

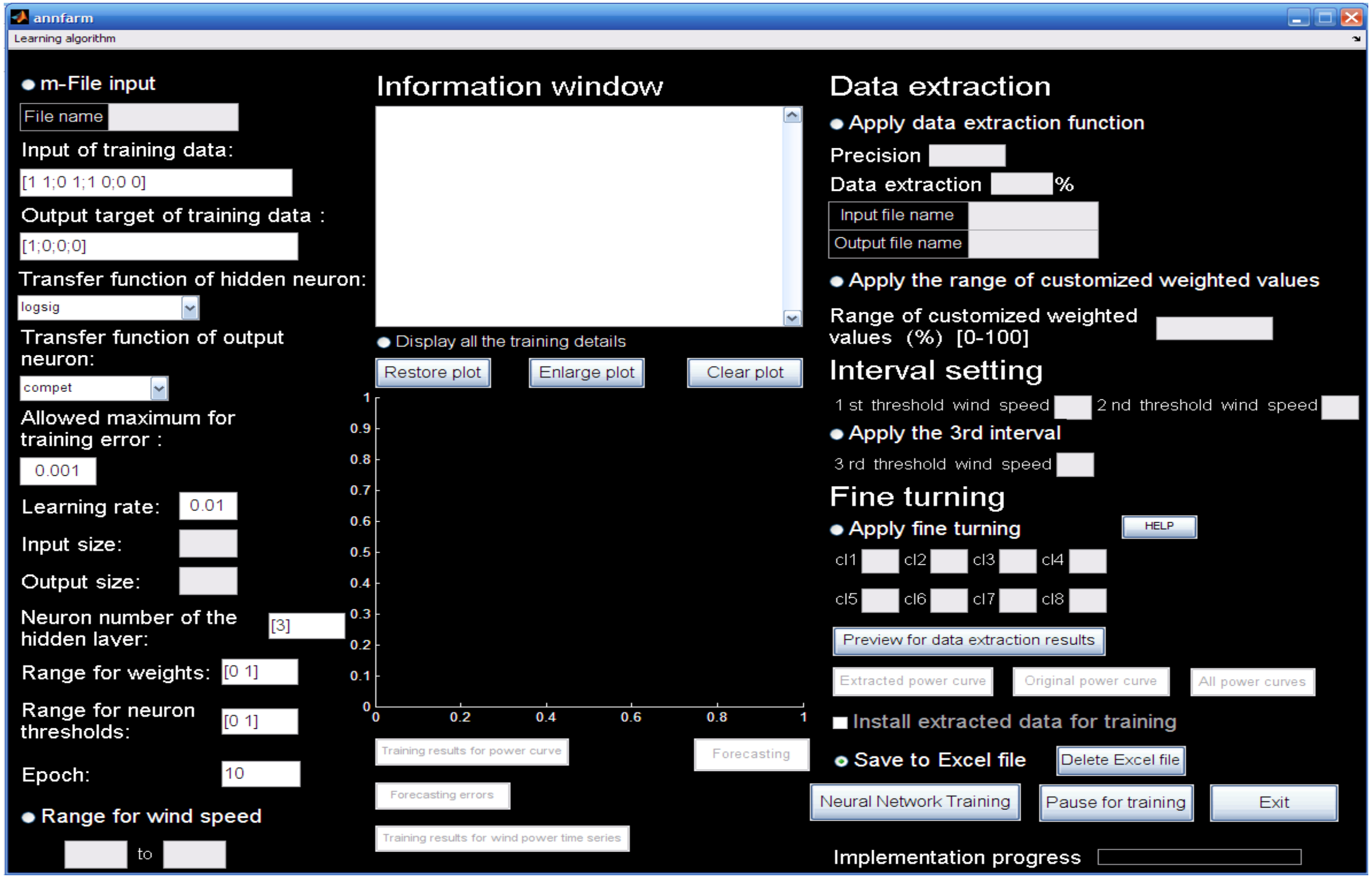
One-hour-ahead and one-day-ahead Probabilistic Wind power forecasting



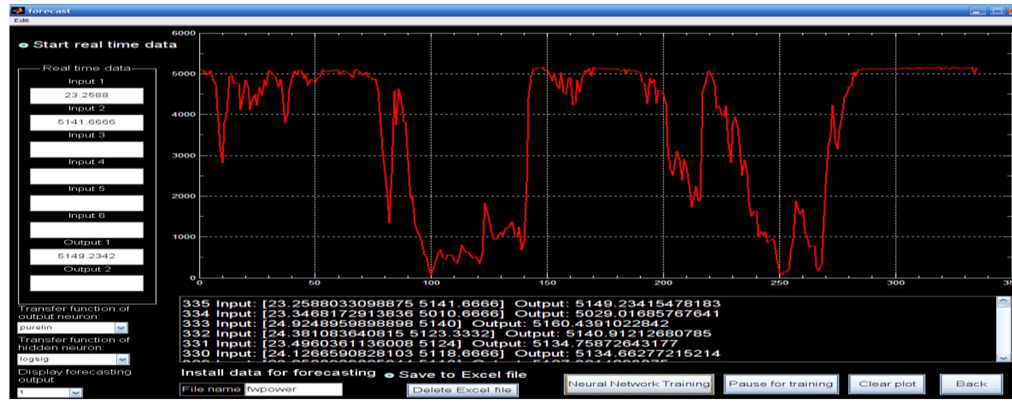


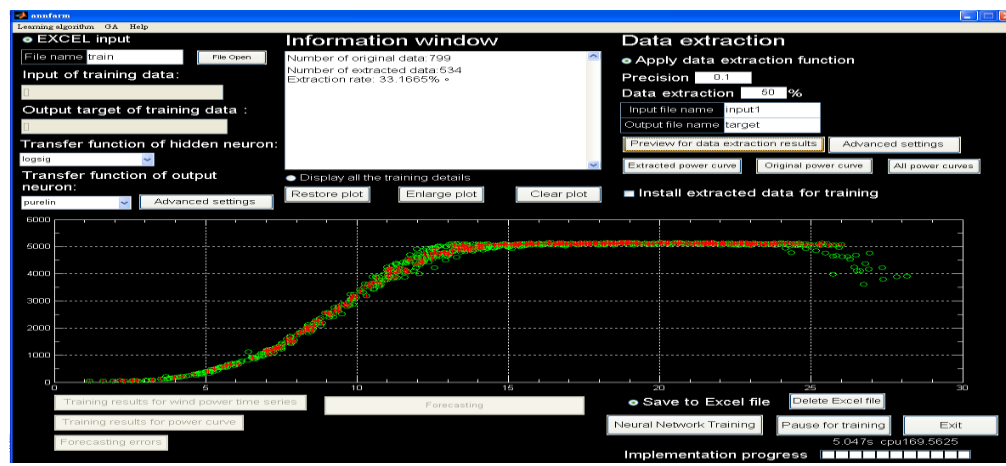
Confidence Level (%)	One hour ahead model			One day ahead model		
	PICP	PINAW	CWC	PICP	PINAW	CWC
50	57.19	9.94	**9.94**	60.42	19.09	**19.09**
60	61.82	12.32	**12.32**	63.26	25.68	**25.68**
70	70.55	16.15	**16.15**	85.42	30.59	**30.59**
80	81.16	20.38	**20.38**	82.77	44.26	**44.26**
90	90.24	29.90	**29.90**	92.05	54.87	**54.87**

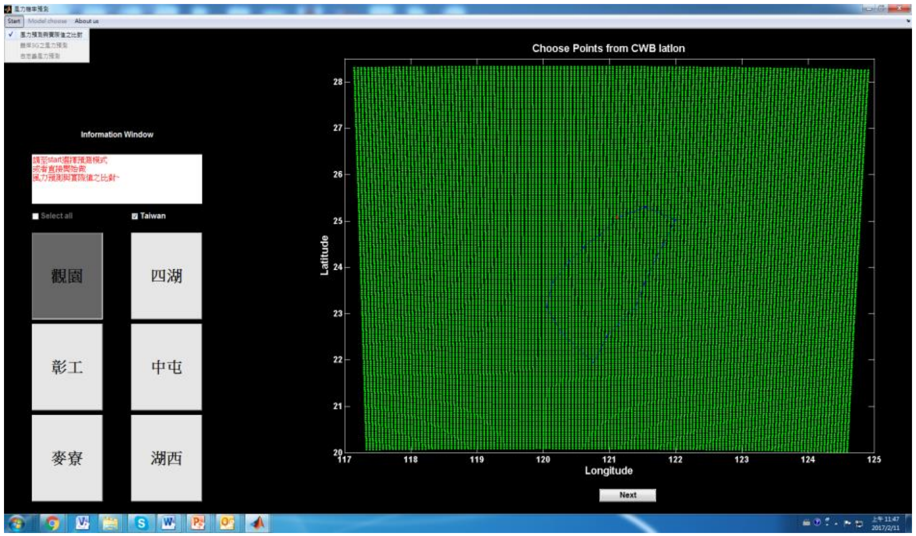
The main user interface of the design forecasting tool (The 1st edition)

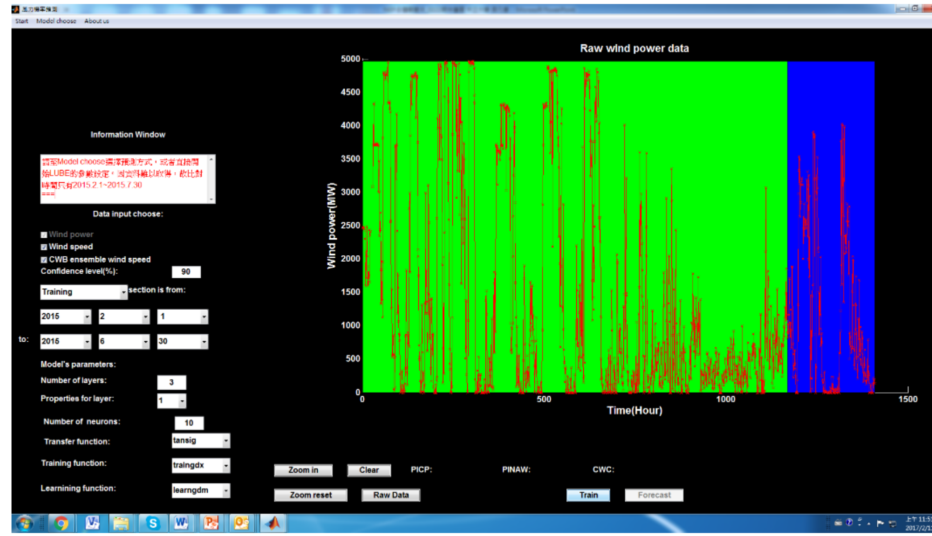


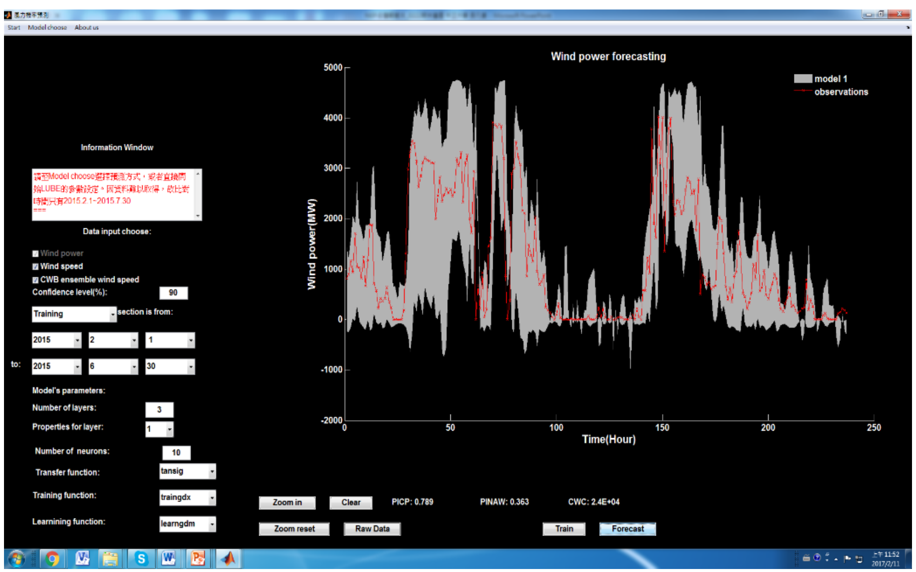
The main user interface of the design forecasting tool (The 2nd edition)

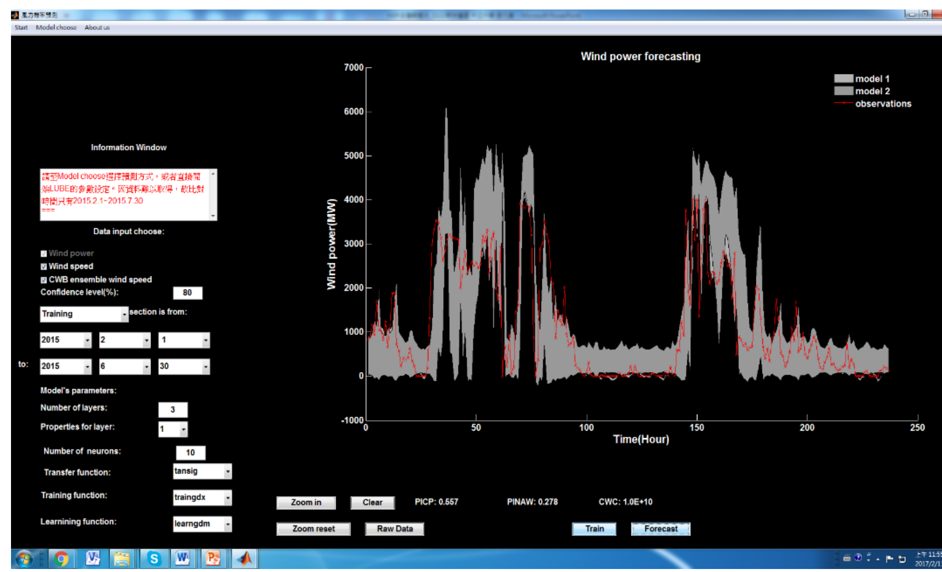





Choose Points from CWB latlon
Information Window
Select all
Taiwan
觀園
四湖
彰工
中屯
麥寮
湖西
Latitude
Longitude
Next


Raw wind power data
Information Window
Data input choose:
Wind power
Wind speed
CWB ensemble wind speed
Confidence level(%):
Training
section is from:
to:
Model's parameters:
Number of layers:
Properties for layer:
Number of neurons:
Transfer function:
Training function:
Learning function:
Wind power(MW)
Time(Hour)
Zoom in
Clear
PICP:
PINAW:
CWC:
Zoom reset
Raw Data
Train
Forecast


Wind power forecasting
model 1
observations
Information Window
Data input choose:
Wind power
Wind speed
CWB ensemble wind speed
Confidence level(%):
Training
section is from:
to:
Model's parameters:
Number of layers:
Properties for layer:
Number of neurons:
Transfer function:
Training function:
Learning function:
Wind power(MW)
Time(Hour)
Zoom in
Clear
PICP: 0.789
PINAW: 0.363
CWC: 2.4E+04
Zoom reset
Raw Data
Train
Forecast


Wind power forecasting
model 1
model 2
observations
Information Window
Data input choose:
Wind power
Wind speed
CWB ensemble wind speed
Confidence level(%):
Training
section is from:
to:
Model's parameters:
Number of layers:
Properties for layer:
Number of neurons:
Transfer function:
Training function:
Learning function:
Wind power(MW)
Time(Hour)
Zoom in
Clear
PICP: 0.557
PINAW: 0.278
CWC: 1.0E+10
Zoom reset
Raw Data
Train
Forecast

Solar power forecasts

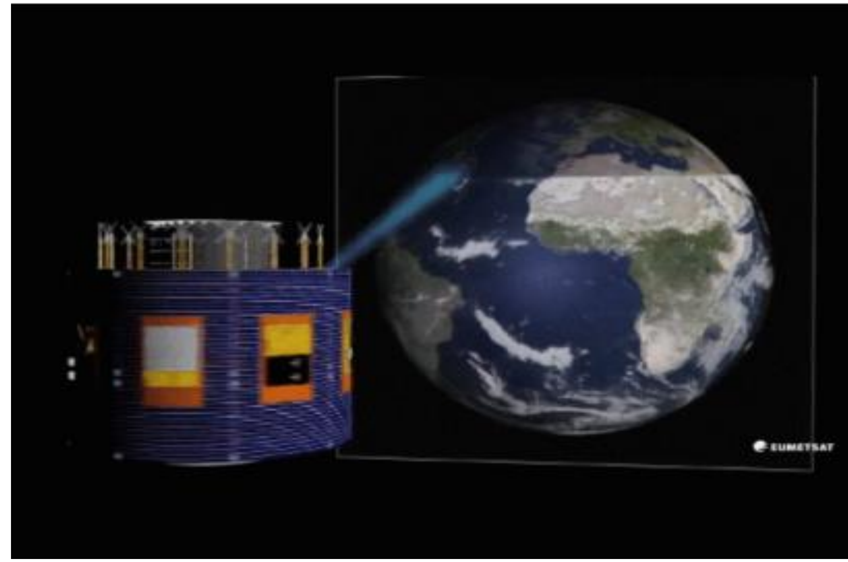
- 1) Statistical techniques (traditional linear models, neural networks, support vector machines, etc)
- 2) Earth observing satellites, such as MSG, nowcasting techniques
- 3) Geographical Information Systems (GIS)
- 4) Numerical weather forecast (NWP) models

Solar power forecasts

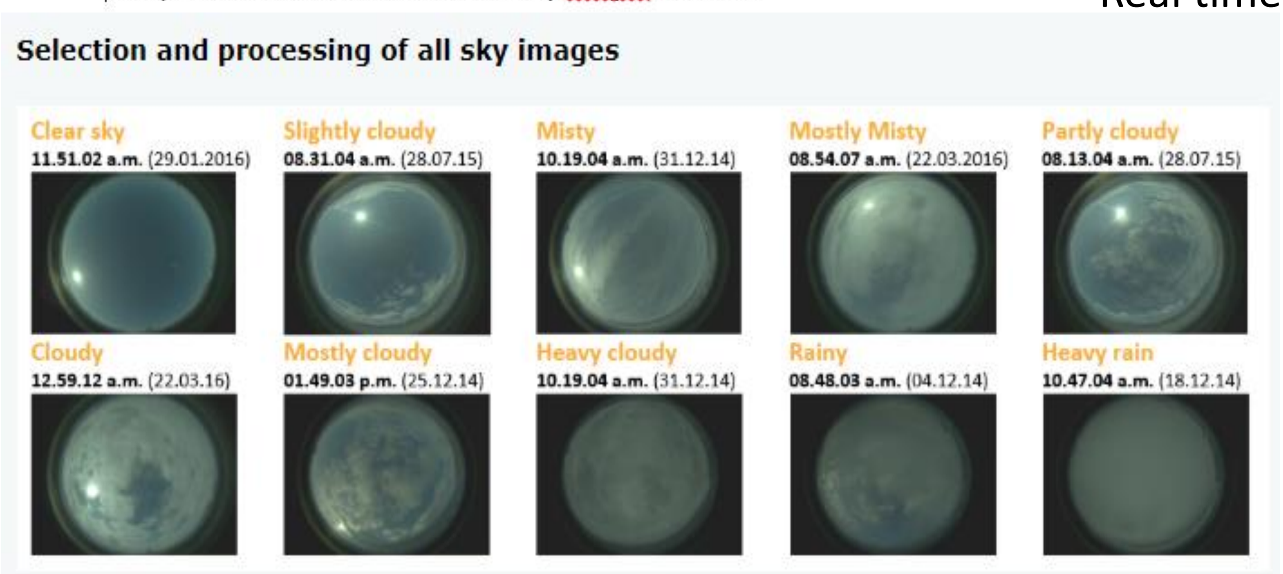
- Aeolis (Dutch)
- AleaSolar - AleaSoft (Spain)
- Datameteo (Italy)
- DNV GL short term solar power forecasting
- enercast (Germany) | Solar energy forecasting and Nowcasting (Worldwide)
- Enfor (Denmark)
- gWISE SOLAR - (Gnarum)
- IrSOLaV | Solar energy forecasting and Nowcasting (Worldwide)
- Solar Plant Generation Forecast (Meteologica)
- Meteo4energy (Czech republic)
- Nnergix | Accurate Solar Power Forecasts - Barcelona
- PVCAST | Short-term PV Energy Yield and Solar Radiation forecasting (Worldwide)
- PV_Forecast - Sheffield Solar | Solar photovoltaic forecast for GB
- RENES | Renewable Energy and Solar Radiation forecasting (Worldwide, Free-of-charge)
- Reuniwatt (France)
- Solargis| Solar Energy forecast and nowcast
- Solcast | Solar power forecast and solar radiation data with global coverage from hi-resolution satellites, via web API. Free trial, free data for researchers.
- Steadysun | Solar Production Forecasts Specialist (France)
- WPred (Canada)

Solar power forecasts

This picture show characteristic of Sky InSight machine.



Real time satellite images



Sky image

台灣部分風場的全年容量因數統計(Capacity Factor)

2016 年全年統計

	石門	林口	蘆竹	觀園	台中港	台中電廠	彰工	王功	麥寮	四湖	恆春	中屯	湖西	金門
CF (不排除連續為零的風力輸出)	13.4	25.5	28.1	33.9	13.1	14.0	28.8	30.1	25.5	24.4	29.2	26.0	32.1	24.2

2017 年全年統計

	石門	林口	蘆竹	觀園	台中港	台中電廠	彰工	王功	麥寮	四湖	恆春	中屯	湖西	金門
CF (不排除連續為零的風力輸出)	17.3	29.9	31.3	38.6	19.1	8.3	33.2	34.0	26.2	29.2	34.6	40.8	35.5	28.4

Thanks for your attentions