Il valore delle osservazioni e delle previsioni meteorologiche per le energie rinnovabili

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Energia e meteorologia vanno a braccetto

- Passing clouds
  - Drop in solar power

- Hurricanes
  - Disruptions to oil rig operations

- El-Niño
  - Changes in Demand Patterns

- Long term changes
  - Renewable Resource Assessment

Time Scale:
- Seconds
- Minutes
- Days
- Months
- Seasons
- Years
- Decades
Ma cosa significa la parola Meteorologia?

Il termine deriva dal greco μετεωρολογία, meteōrología, da μετέωρος metéōros, "elevato" e λέγω légō, "parlo", quindi "discorso razionale intorno agli oggetti alti". La parola μετέωρος ha un'etimologia incerta, forse da μετά metá "con, dopo" e αἴρω áirō "alzo".

The word "meteorology" is from Greek μετέωρος metéōros "lofty; high (in the sky)" (from μετα- meta- "above" and άείρω aeiro "I lift up") and -λογία -logia "-(o)logy", i.e. "the study of things in the air".

WORLD METEOROLOGICAL ORGANIZATION
WEATHER CLIMATE WATER

WEMC
World Energy & Meteorology Council
Global Final Energy Consumption

- Fossil fuels: 78.3%
- All renewables: 19.2%
  - Modern renewables: 10.3%
  - Traditional biomass: 8.9%
  - Nuclear power: 2.5%
- Biomass/geothermal/solar heat: 4.2%
- Hydropower: 3.9%
- Wind/solar/biomass/geothermal power: 1.4%
- Biofuels: 0.8%

Source: WEMC - Renewables 2016 Global Status Report
RE Share of Global Electricity Production

Non-renewables 76.3%

Renewable electricity 23.7%

Hydropower 16.6%
- Wind 3.7%
- Bio-power 2.0%
- Solar PV 1.2%
- Geothermal, CSP and ocean 0.4%

Based on renewable generating capacity at year-end 2015. Percentages do not add up internally due to rounding.

REN21 Renewables 2016 Global Status Report

WEMC World Energy & Meteorology Council
Strong growth in renewables

IRENA (2016)
Non solo aumento delle rinnovabili …

Efficienza energetica

Impatti su strutture energetiche
Significant science & technical challenges

An explosion in rooftop PV

Large-scale solar PV
PV Installations in Australia by postcode

APVI (2015)
Solar radiation – can be very highly variable
Important to measure PV panel temperature

PV production is highly dependent on the temperature of PV panels, which in turn depends on air temperature. As a rule of thumb, an increase of 20°C in PV panel temperature leads to a decrease in PV production of 10%.

PV panel temperature: $T_{PV} \approx \alpha \cdot GI + T_{air}$

with $GI$: Global Irradiance on PV plane, and $\alpha$ an empirical coefficient.
Australian National Energy Market

- Run by Australian Energy Market Operator (AEMO)
  - ~50GW installed capacity
  - Market coupled to physical operation at 5 min intervals
- Wind & Solar (now & 2030)
  - Wind ~4GW → 10GW
  - Solar PV ~5GW → 13 GW
- Wind forecasting since 2009 (AWEFS)
- Solar forecasting since 2014 (ASEFS)
With large quantities of intermittent generation this demand can exceed spinning reserve
- Normally supplied by conventional generators
Why Forecast Variable Renewable Power?

- From seconds to minutes
  - System control
  - Electricity system stability
- From minutes to hours
  - Alternative Generation scheduling
  - Storage system scheduling, peak shaving
- From hours to days
  - Alternative Generation scheduling, load shifting
  - Power system adequacy assessment
- From days to months to years
  - Power system adequacy assessment
  - Resource assessment
Observations – Ground
Observations – Space
Observations – Space (NASA & ESA)

Hundreds of millions of observations
Observations – You can set up your own!

- Data comes from the Solar Lab at Black Mountain in Canberra, Australia
- Tracking solar irradiance (direct, diffuse & global)
- Spectroradiometer
- Vaisala CL31 ceilometer records cloud base height and vertical profiles
- Sky camera
- 8 solar PV panels

Solar Tracker with 3 comp.
Ceilometer
Pyranometer on plane

Sky-cam
Spectro-radiometer
Physical/Mathematical Models

- Hundreds of equations
- Tens of thousands of lines of codes

Tens of thousands of lines of codes

Hundreds of equations
Physical/Mathematical Models

Wind turbine annual energy yield

Meteorological Variables for Energy

- Wind speed and/or direction
- Rainfall
- Sea level
- Humidity
- Air Temperature
- Cloudiness
- Short-wave radiation
- Snowfall and ice accretion
- Water Temperature
- Wave height
- River Flow
Energy and Meteorological ‘pairings’

**Demand**
- Air temperature
- Cloud cover
- Water vapour
- Albedo
- Nighttime lights

**Hydro**
- Soil moisture
- Precipitation
- Snow cover
- Elevation
- River/lake par
- Gravimetry

**Solar**
- Solar irradiance
- Cloud cover
- Water vapour
- Aerosols
- Albedo
- Air Temperature
- Land cover
- Elevation

**Biomass**
- Solar irradiance
- Air Temperature
- Precipitation
- Soil moisture
- Land cover
- Cloud cover
- Albedo
- Elevation

**Wind**
- Elevation
- Offshore winds
- Wave/currents
- Ocean altimetry

**Marine**
- Offshore winds
- Wave/currents
- Ocean altimetry

**Thermal**
- Air Temperature
- River/lake par

**Oil & Gas**
- Offshore winds
- Wave/currents
- Ocean altimetry
Historical Observations – Solar Radiation for NH

Table 2: Results of the regional trend analysis 1950-1985 and 1985-2009.

<table>
<thead>
<tr>
<th>Region</th>
<th>Trend [W/m² 10y]</th>
<th>R²</th>
<th>P (T-Test)</th>
<th>Trend [W/m² 10y]</th>
<th>R²</th>
<th>P (T-Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>-1.9</td>
<td>0.145</td>
<td>0.009</td>
<td>4.1</td>
<td>0.248</td>
<td>0.000</td>
</tr>
<tr>
<td>Germany</td>
<td>-1.2</td>
<td>0.070</td>
<td>0.206</td>
<td>4.6</td>
<td>0.211</td>
<td>0.001</td>
</tr>
<tr>
<td>Switzerland</td>
<td>-7.7</td>
<td>0.465</td>
<td>0.000</td>
<td>3.1</td>
<td>0.162</td>
<td>0.003</td>
</tr>
<tr>
<td>Asia</td>
<td>-5.9</td>
<td>0.430</td>
<td>0.000</td>
<td>1.4</td>
<td>0.133</td>
<td>0.177</td>
</tr>
<tr>
<td>India</td>
<td>-6.5</td>
<td>0.356</td>
<td>0.000</td>
<td>-5.4</td>
<td>0.331</td>
<td>0.001</td>
</tr>
<tr>
<td>Canada</td>
<td>-1.9</td>
<td>0.168</td>
<td>0.001</td>
<td>-0.2</td>
<td>0.008</td>
<td>0.909</td>
</tr>
</tbody>
</table>

Figure 1 shows seasonally corrected time series with smoothed values over 1 and 5 years. In this figure a gentle oscillation of the radiation values can be seen. Local maxima are visible around 1970 and 2003 (heat wave over Central and Western Europe).

Figure 1: Seasonally corrected time series with moving averages for 1 and 5 years for Europe.

4. Trends of 5, 10 and 20 year means

Similar to the trends of the monthly values also the trends of the 5, 10 and 20 year means show a big dependence on the station (Figure 2). Also here the dimming and brightening phase is clearly visible.

Monthly data, 1 year and 5 year running means
Historical Reanalysis – Solar Radiation (1981-2010)
Climate Projection – Solar Radiation (2050-2079)

Figure 5 – Linear trend for the mean sea level anomaly (in mm/10yr) over the period 1993-2011. Darker colours indicate significant values at the 95% confidence level.

Data source: TOPEX/Poseidon, Jason-1 and Jason-2 satellite missions.

Figure 6 – Projected annual mean changes over the period 2050-2079 under the low-range B1 emission scenario for 2-metre temperature (top left, in °C), precipitation (top right, in mm day\(^{-1}\)), solar radiation (bottom left, in W m\(^{-2}\)) and 10-m wind speed (bottom right, in m s\(^{-1}\)). Changes are computed as differences with respect to the 1970-1999 climate run results.

Numbers in parenthesis in the title indicate the number of models used for the averaging of each of the two periods considered.

Data source: CMIP3 model output.
Global radiation = Direct Beam + (Reflected diffuse + Backscattered diffuse + Transmitted diffuse) = Direct Beam + Diffuse radiation

The various radiation sources have different spatial distribution and spectral characteristics.
Pros & Cons of Solar Radiation Data Sources

**Satellite**

- **P:** Wide and frequent coverage (e.g. 5 km, 30 min)
- **P:** Algorithms specific for solar radiation
- **C:** Instantaneous (power) measure; DNI derived from GHI
- **C:** Technical limitations such as parallax, air composition
- **P:** Wide and frequent coverage (e.g. 5 km, 30 min)
- **P:** Flexible in choice of periods and domains
- **C:** Radiation schemes computationally expensive
- **C:** Models not tuned to produce best radiation

**Ground stations**

- **P:** Measure exactly the radiation received by the ground
- **P:** High frequency (energy) data (1-sec)
- **C:** Limited coverage
- **C:** Maintenance costs, particularly at remote locations

**Atmospheric model**
Blending of data sources

1. Satellite
2. Ground stations
3. Atmospheric model

WEMC
World Energy & Meteorology Council
Blending of solar radiation data sources

- Fit generalised additive model (GAM) to hourly ground station data:
  \[ k_m \sim f( k_s, k_c, \cos(\theta_z) ) \]

  - \( k_m \): measurements clear sky index
  - \( k_s \): satellite clear sky index (nearest grid point)
  - \( k_c \): weather model clear sky index (nearest grid point)
  - \( \theta_z \): solar zenith angle

  Cross validate at each ground station by reserving half the data.

Baseline model: satellite GAM  \[ k_m \sim f( k_s, \cos(\theta_z) ) \]

Davy et al. (2015)
Need to use RMSE improvement for GHI by including CCAM

Wagga Wagga GHI – SD changes relative to satellite

Miglioramento in tutte le 18 stazioni

Davy et al. (2015)
Meteorological products

- Re-analyses
- Now-casting
- Weather Forecast
- Monthly Forecast
- Seasonal Forecast
- Inter-annual Outlooks
- Climate Projections

Past: Minutes, Days, Months, Seasons, Years, Decades
Future: Weather Forecast, Monthly Forecast, Seasonal Forecast, Inter-annual Outlooks, Climate Projections
Building on Wind Forecasting at AEMO

AWEFS - ANEMOS Wind forecasting system

- Compulsory centralised forecasting
- 10 sec SCADA feed required
- Up to 200 wind farms
- Operational since 2008

Different forecasting techniques +
Wind to power conversion modules - unique to each wind farm
AWEFS Performance

![AWEFS NMAE forecast performance graph]

- **NMAE in Percent**
  - 0.00%
  - 2.00%
  - 4.00%
  - 6.00%
  - 8.00%
  - 10.00%
  - 12.00%
  - 14.00%
  - 16.00%
  - 18.00%
  - 20.00%

- **Time Horizons**
  - 5 minutes ahead
  - 1 hour ahead (60 min)
  - 4 hours ahead (240 min)
  - 12 hours ahead (720 min)
  - 24 hours ahead (1440 min)
  - 40 hours ahead (2400 min)
  - 6 days ahead (8640 min)
Solar forecasting techniques for different timescales

NMP – Numerical Weather prediction
Assessment – Solar Radiation Stations
Canberra Reference Site: ‘Solar Lab’

- Data comes from the Solar Lab at Black Mountain in Canberra, Australia
- Tracking solar irradiance (direct, diffuse & global)
- Spectroradiometer
- Vaisala CL31 ceilometer records cloud base height and vertical profiles
- Sky camera
- 8 solar PV panels
Canberra Solar radiation and power network

- Radford College (Fed 2010)
- Namadgi School (Nov 2011)
- Wombat Hill (Nov 2011)
- CSIRO Black Mountain (Mar 2012)
- WERU’s Solar Lab
  - Tracking solar/PV
  - Ceilometer
  - Spectro-radiometer
  - Sky camera
- Weetangera School (Jun 2013)
The Australian Solar Energy Forecasting System

Modelled Wind Speed @location…
Wind farm standing data eg. power curve

Modelled Solar Radiation input components (direct, diffuse) @location, physical distribution, time, date, other dependent data (panel temp)

Solar farm standing data eg. power curve + any fuel conversion, storage
ASEFS test results

Norwest

Black Mountain

Norwest
Alcuni risultati da studi di ricerca
Effect of aerosols (smoke) on PV

Canberra, 4th March 2014

Perry & Troccoli (2015)
Effect of aerosols on PV

Technology and Mean spectral ratio (smoky/clear)

- Single crystalline silicon (mono.Si): 0.9227
- Copper indium gallium selenide (CIGS): 0.9193
- Multicrystalline silicon (multi.Si): 0.9192
- Cadmium telluride (CdTe): 0.9157
- Gallium Arsenide (GaAs): 0.9108
- Amorphous silicon (a.Si): 0.9043
Cloud Motion Vectors

CMVs produced at Mildura site on 16/03/2014 at 0030, 0040, 0050 UTC

Derived CMVs compared to MISR instrument on TERRA satellite

Backward Processing

Forward Processing

Average

Courtesy UNSW
Daily Variability Index (DVI) Prediction

\[ DVI = \frac{\sum_{k=2}^{n} |GHI_k - GHI_{k-1}|}{\sum_{k=2}^{n} |CSI_k - CSI_{k-1}|} \]

DVI: daily variability index
GHI: global horizontal irradiance
CSI: clear sky irradiance

Huang et al. (2014)
Daily Variability Index (DVI) Prediction

The results at the nearest grid point are used.
CCAM outperforms GFS in forecasting of both GHI and DVI.
Important predictors include cloud and wind velocities.

Wagga Wagga – Inland temperate

Huang et al. (2014)
Solar NWP—pushing it to 5 days ahead

Monthly means for the three solar components

Bias based on clear sky index and zenith angle

Bias correction reduces error

Adelaide airport

Troccoli and Morcrette (2014)
Solar NWP—pushing it to 5 days ahead

Forecast score for ADELAIDE AIRPORT: GHI > 50%  
Forecast score for ADELAIDE AIRPORT: DHI > 50%  
Forecast score for ADELAIDE AIRPORT: GHI > 75%  
Forecast score for ADELAIDE AIRPORT: DHI > 75%

Non-corrected model (black), bias corrected over 2006 (green), bias corrected second half 2006 (red), persistence forecast (cyan)

Troccoli and Morcrette (2014)
Approcci di ricerca emergenti
Videocamere per la previsione di energia solare

1. Classificare Nuvole
2. Caratterizzare la distorsione della lente
3. Estrarre vettori di movimento delle nuvole
4. Estrapolare i vettori tenendo conto della distorsione della lente
5. Valutare tempo di copertura nuvole

High-resolution 180 degree panorama cameras (Mobotix Q24M)

Courtesy CSIRO
VIDEOCAMERA MOVIE

Courtesy CSIRO/ARENA
Sky camera network

- 10km radius: cover whole city with handful of cameras
- 15 sites around Canberra & Newcastle for ramp and irradiance forecasting
- Canberra sites co-located with: Pyranometer, PV arrays & weather stations
Il problema dell’immagazzinamento di energia
Compressed Air Storage

Huntdorf, Germany (290 MW) & McIntosh, Alabama (110 MW)
Sodium Sulphur (NaS) and Lithium-Ion Batteries

NGK 1.2MW/7.2 MWhr substation (upgrade deferral) system (6 hrs storage, NaS)

A123
2MW/0.5 MWhr Multi-purpose system (15 min storage)
Vanadium Redox Flow Battery – King Island Tasmania

VRB Power Systems
200kW/ 800 kWhr
(4 hrs storage)
Flywheel - Regulation Services

Beacon Power
20MW / 5MWhr
(15 min storage)
Summary of storage response times

Flywheel – $O$(msec)
Capacitors – $O$(msec)
Electrical – $O$(sec)
Pumped Water – $O$(min)
Pumped Air – $O$(10 min)

Response Time
Tests su cicli ricarica batterie
- NCAR wind power system for Xcel energy
  - Cost a few million USD, yielded an improvement of around 40% in forecast accuracy, which led to a cost saving of USD 49 million/yr
- NCAR solar power system for Xcel energy
  - A forecast improvement of ca 50% → cost saving of USD 820k/year
  - Projected to be USD 10-21 million/yr

Haupt et al. (2016)
Summary

- A huge amount of weather/climate observations and model output – though not so many for solar irradiance and wind speed above 10 m
- Accuracy of weather/climate products generally very good but need to understand limitations and their variability
- Wind and solar power forecasting proven to work in operational context for grid integration
Get involved!

http://www.wemcouncil.org/
Get in touch!

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