Solar and Wind resources estimation: an overview

Thierry Ranchin, Lucien Wald, Didier Mayer

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SOLAR AND WIND RESOURCES ESTIMATION: AN OVERVIEW

Thierry Ranchin, Lucien Wald, Didier Mayer
Center for Energetic studies,
Ecole des Mines de Paris
BP 207
06904 Sophia Antipolis cedex France

ABSTRACT: The renewable energies are of tremendous importance for the fight against greenhouse gas effects. They are also of paramount importance for the rural electrification and to open access to energy for all. Before making investment in this domain, there is a need for knowing their potential. This can only be achieved through the evaluation of natural resources of solar and wind energies. This paper presents some of the means and tools for estimation.

1. Introduction

Renewable energies are a challenge for durable development around the World. The use of solar and wind sources are growing to several hundred thousand of megawatts with hope of reducing the greenhouse gas effects. But data on resources are difficult to acquire and compile in some countries, and even their availability is problematic. This lack of data and knowledge have impacts on:

- policy and national planning favouring the development of traditional techniques of electricity production,
- security of supply of energy,
- large scale investment that can not be done without confidence on the potential of production.

Other problems are linked such as those related to the management of distributed generation of electricity (connection to the network reliability, safety, etc.) or to reliability of resources.

Hence, the evaluation of resources is a central point for a thoughtful and durable approach of energy development.

In this paper, we propose a small review of tools for measuring solar and wind resources. The usual measuring tools for solar radiation estimation are described and the benefits of using satellite data and modelling are shown through the application of the Heliosat method. The same approach is proposed for the evaluation of wind resources. The principal models used in Europe are presented and the benefits of prediction evoked. Some elements of conclusions are proposed

2. Tools for Solar resources estimation

Solar energy applications make use of Solar radiation. Solar radiation describes the radiation emitted by the Sun and reaching the ground after diffusion and absorption by the atmosphere. The spectrum of Solar radiation is composed by visible (0.4 - 0.7 μm), ultra-violet (0.3 - 0.4 μm), and infra-red (0.7 - 5 μm) wavelengths. Global Solar radiation is the solar radiation received on a plane surface. It is composed of direct and diffuse components. Global Solar radiation is the flux of solar radiation falling on a receiving surface from a solid angle of 2π sr.

2.1. TRADITIONAL MEANS FOR SOLAR RESOURCES ESTIMATION

Measuring instruments are designed for the whole range of wavelengths of solar radiation. But they react also to other wavelengths such as far infrared radiation emitted naturally by the atmosphere (atmospheric radiation) and by all natural bodies (ground radiation). These wavelengths, called terrestrial radiation, cannot be clearly separated from solar radiation.

Various instruments are used for the measurements of solar radiation:

pyranometers measure global, diffuse and reflected solar radiation,
pyrheliometers measure direct solar radiation at normal incidence,
pyrgeometers measure long-wave terrestrial radiation,
pyrradiometers measure the total radiation, solar and terrestrial.

Pyranometers are the most used instruments in meteorological stations for determination of the energy reaching the ground from the Sun. For allowing comparisons, all the measuring devices in stations should be calibrated. This task is far from being simple and should be regularly done.

Solar radiation is observed by the means of networks of meteorological stations. Various measurements can be made: cloud coverage, sunshine duration, global irradiation, the direct or diffuse irradiation, the spectral distribution of the irradiance etc. For irradiation measurements, the relative RMSE is approximately 3 to 5 percent if the station is well maintained. Costs for installation and maintenance of such networks are very high; consequently, there are a few measuring stations in the world. In the Western Europe and Northern America, where the situation is best, the average distance between stations is approximately 100 km. In Eastern Europe, the average distance is approximately 500 km and is approximately 1000 km in Africa. The situation is worse over the oceans. In the present situation, the irradiation over a particular site in the world is performed by interpolation / extrapolation of the measurements available and closest to this site.

Anonymous (1995) performed a study of the errors resulting from interpolation techniques for the assessment of global daily irradiation for agricultural purposes (agricultural policy for Europe). Using eight neighbouring stations, the root mean square error (RMSE) was 20 per cent in relative value. Supit (1994) reported relative RMSE of 15 - 25 per cent, using several techniques and five stations. Both authors and others stress the importance of the geographical and climate parameters upon the results and the importance of the adequacy between the spatial and temporal scales of the optical state of the atmosphere, the density of the network and the quantities to interpolate. The most complete study is that of Zelenka *et al.* (1992). Various techniques were defined and applied to six very dense networks in Europe and North America. For daily irradiation, relative RMSE of 15 per cent in July up to 40 per cent in January was found. Hulme *et al.* (1995), Beyer, Wald (1996) and Beyer *et al.* (1997) computed climatological means (respectively 30 and 10 years) of monthly means of respectively sunshine duration and daily irradiation using sophisticated interpolation methods calling upon satellite-derived estimates and 800 and 600 stations in Europe. The relative RMSE ranges from 5 per cent in July up to 11 per cent in January.
Several authors (Zelenka *et al.*, 1992; Hay, 1981, 1984; Hay, Hanson, 1985; WMO, 1981; Perez *et al.*, 1997) studied the extrapolation and interpolation errors as a function of the distance to the measuring stations. The errors are very similar for both cases, though the interpolation errors are lower. The larger the distance, the larger the RMSE. For global daily irradiation, the relative RMSE is 10 per cent for a distance of 16 km, 20 per cent for 64 km and 30-40 per cent for 256 km. For the global hourly irradiation, the errors are worse: 15 per cent for 4 km, 20 per cent for 16 km, 25 per cent for 64 km and 45 per cent for 256 km.

Mapping the solar radiation by interpolation / extrapolation of measurements is possible but leads to large errors, except if the network is dense. It should be noted that a deficient station might strongly affect the final map. Finally, interpolation / extrapolation techniques cannot reproduce radiation features that are smaller than twice the average distance between stations.

2.2. ESTIMATION BY MEANS OF SATELLITE

Several authors have shown the potentialities of the images of the Earth taken by the meteorological satellites for the mapping of the global irradiation impinging on a horizontal surface at the ground level. One advantage is that the errors in the estimates are constant throughout the mapped area, except in areas with highly variable relief or for very large areas, where illumination and observation angles may change dramatically. Consequently, an estimate of the quality may be provided for every site. Zelenka *et al.* (1992, 1999) and Perez *et al.* (1997) demonstrate that for the best methods, the irradiation assessed by satellite is better than that estimated from interpolation technique as soon as the distance to the stations is greater than 34 km for the hourly irradiation and 50 km for the daily irradiation.

Many methods were developed especially in the years '80s. Among them was the method called Heliosat, developed by Armines / ENSMP under the auspices of the European Commission (Cano 1982; Cano *et al.* 1986; Michaud-Regas 1986; Diabaté 1989). This method was among the most accurate methods as shown by several authors (Grüter *et al* 1986; Raschke *et al.* 1991). It was simple enough to widely disseminate in the world (Diabaté *et al.* 1988a b, 1989; Wald *et al.* 1992). It became popular and several modifications were proposed (Moussu *et al.* 1989; Obrecht 1990; Zelenka *et al.* 1992, 1999; Beyer *et al.* 1996; Fontoynont *et al.* 1997; Iehlé *et al.* 1997; Ineichen, Perez 1999).

The principle of the method Heliosat-I is the construction of a "cloud index" resulting from a comparison of what is observed by the sensor to what should be observed over that pixel if the sky were clear, which is related to the "clearness" of the atmosphere. At each pixel (i, j) of the current image at time t, a normalised count $CN^{*t}(i,j)$ is computed as:

$$CN^{*t}(i,j) = (CN^t(i,j) - CN0^t) / [I_0\, \varepsilon(t)\, (\sin \gamma_S(i,j))\, (\sin \gamma_S(i,j))^{0.15}]$$

where

- $CN^t(i,j)$ is the numerical count observed by the sensor at time t for this pixel (i, j), $CN0^t$ being what can be called the sensor zero (the numerical counts are not necessarily calibrated),
- $(\sin \gamma_S)^{0.15}$ is the clear sky transmittance (model of Perrin de Brichambaut, Vauge 1982).

This normalised count $CN^{*t}(i,j)$ is related to the apparent albedo $\rho^t(i,j)$ observed by the spaceborne sensor. In preparation to the determination of the cloud index $n^t(i,j)$, a reference map of the normalised count for clear sky is constructed (Moussu *et al.* 1989). It is also called the normalised count for ground, $CN^*_g(i,j)$. Given a time-series of images, it is evaluated at each pixel in a recursive fashion by minimising the variance between the digital counts and those resulting from the clear sky model, the cloudy cases being eliminated at each step (Cano *et al.* 1986). The cloud index is defined as a function of $CN^*_g(i,j)$, $CN^{*t}(i,j)$, and the typical normalised count of the brightest clouds tops CN^*_{cloud}:

$$n^t(i,j) = [CN^{*t}(i,j) - CN^*_g(i,j)\,] / [CN^*_{cloud} - CN^*_g(i,j))\,]$$

The computation of CN^*_{cloud} is performed using the inverse of the algorithm used for determining the reference albedo map and retaining only the cloudy areas. The histogram of this "only cloud" image provides an estimation of CN^*_{cloud}.
The clearness index $KT_h(i,j)$ may be defined for the hour h centred on t as:

$$KT_h(i,j) = G_h(i,j) / G_{0h}(i,j)$$

where $G_{0h}(i,j)$ is approximated by $I_0\ \varepsilon(t)\ \sin\ \gamma_S$, where γ_S is for the middle t of the hour. Care should be taken of the sunset and sunrise. Several previous studies did show a linear relationship between the cloud index and the clearness index, where the parameters A and B are positive and have been determined once for ever (Diabaté *et al.* 1988; Diabaté 1989):

$$KT_h(i,j) = -A\ n'(i,j) + B$$

This relationship between $KT_h(i,j)$ and $n'(i,j)$ leads to the computation of the global hourly irradiation $G_h(i,j)$.

The global daily irradiation $G_d(i,j)$ is computed from the set of hourly irradiations available for that day. The larger the number of images used per day, the lower the level of error. A model has been proposed by Diabaté (1989), using an analytical law fitted onto climatological hourly values. However most users adopted the following model. Let denote the horizontal daily irradiation outside the atmosphere by $G_{0d}(i,j)$ and the daily clearness index by $KT_d(i,j)$. $G_d(i,j)$ is then computed from the N assessments of the hourly irradiation $G_h(i,j)$ made during the day:

$$G_d(i,j) = KT_d(i,j)\ G_{0d}(i,j) = G_{0d}(i,j) \sum_{h=1}^{N} w_h KT_h(i,j)$$

where $w_h = \dfrac{G_{0h}(i,j)}{\sum_{h=1}^{N} G_{0h}(i,j)}$

It comes

$$G_d(i,j) = G_{0d}(i,j)\ \frac{\sum_{h=1}^{N} G_h(i,j)}{\sum_{h=1}^{N} G_{0h}(i,j)}$$

The method Heliosat-I is currently used by several institutes in Europe and elsewhere with geostationary satellites like Meteosat (Europe), GOES (USA) or GMS (Japan). A scientific network ensures collaboration between these institutes and improvements in the method. There is also a software, the Sun-UNIX version of it made at Armines / Ecole des mines de Paris being in public domain and available on an Internet server (*http://www-cenerg.cma.fr/tele*). A PC-based package including a satellite data receiver has also been developed and marketed by a French company.

There are several empirical parameters in the method Heliosat-I, especially in the computation of the apparent albedoes of the ground and clouds and in the follow-up of the changes of the ground albedo. The clear-sky model is also site-dependent. In this model, the optical state of the clear atmosphere is expressed by the sole exponent. As a basis, a value of *0.15* has been selected but other values may perform better. The parameters *c* and *d* in the relationship between $KT_h(i,j)$ and $n^t(i,j)$ may be adjusted by comparison with measurements made at meteorological stations. These parameters were well tuned during the construction of the method or of its varieties and this explains the good results attained by the authors when performing a comparison with ground observations. For example, according to Diabaté (1989), Diabaté *et al.* (1988) or Grüter *et al.* (1986), the typical relative error (RMSE) is about

- 7-18 percent for the assessment of the hourly irradiation,
- 10 percent or better for the monthly mean of the hourly irradiation,
- 10-15 percent for the assessment of the daily irradiation,
- 10 percent or better for the monthly mean of daily irradiation.

Rigollier (2000) performed a survey of the literature and reported the accuracy found by several authors when comparing irradiations measured by ground stations and irradiations derived from satellite data by various methods. She retained only the comparisons performed by authors, who were not the inventors of a method. Her work thus demonstrates the actual accuracy that can be attained by a naive implementation of a method.

2.3. EXAMPLE OF APPLICATION OF THE HELIOSAT METHOD

The Heliosat method was firstly applied to the Meteosat data.

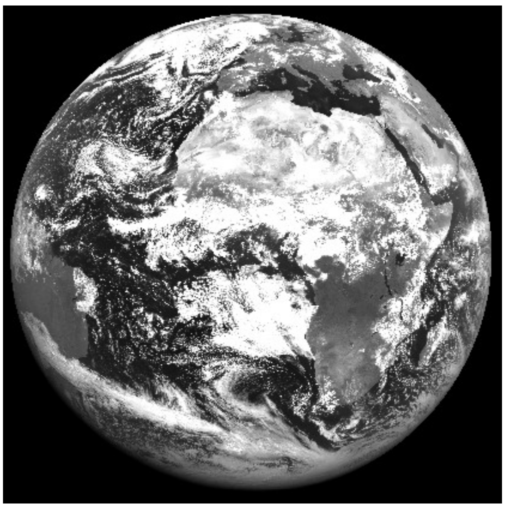

Figure 1 Meteosat original image in the visible channel acquired 1rst August 1992 at 11h30 GMT

Figure 1 presents an original image acquired 1rst August 1992 at 11h30. From this data, the cloud index is computed an the clearness index is obtained (Figure 2). Finally the global hourly irradiation is then obtained (Figure 3). From the time series provided by the Meteosat satellite (one image every half an hour) the global daily, weekly, monthly or yearly irradiation is obtained allowing the use of statistical information for different uses.

From the computation of these irradiation maps atlases were developed. An example of such an atlas is the European Solar Radiation Atlas (ESRA 2000a) Made on behalf of the European Commission, DG XII, JOULE II Programme. The atlas is oriented towards the needs of the users like solar architects and engineers, respecting the state of the art of their working field and their need of precise input data.

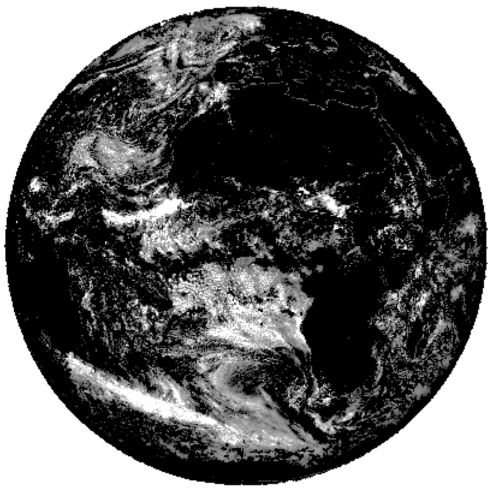

Figure 2. Clearness index computed from Figure 1 by the Heliosat method.

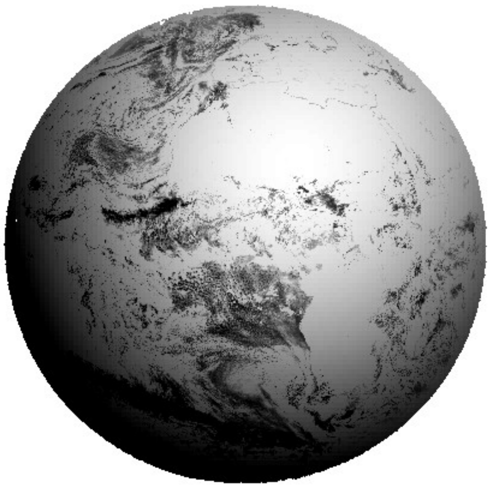

Figure 3. Global hourly irradiation computed by the Heliosat method

From best available measured solar data complemented with other meteorological data necessary for solar engineering, digital maps for the European continents are produced. It comprises a hard-copy atlas and a CD for PC, including the ESRA data base with the mapping in digital form, algorithms to calculate derived parameters and input files for engineering issues. It is complemented by a users guidebook (ESRA 2000a, 2000b).

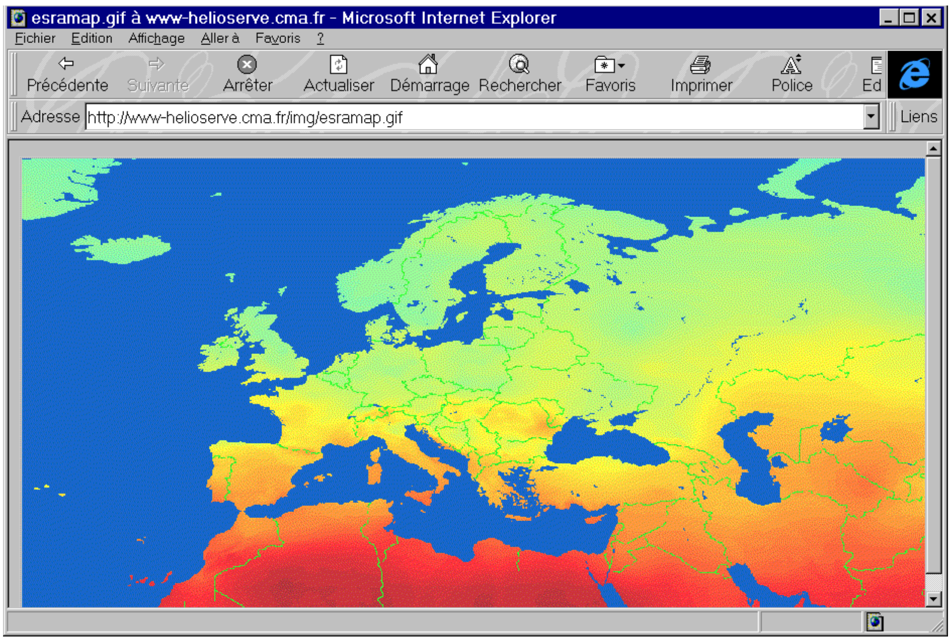

Figure 4. Map of the climatological average of the monthly mean of the daily sum of the global radiation received on horizontal plane for May.

Figure 4 is an example of the tools proposed by ESRA. From this kind of maps potential energetic resources can be derived. A set of Web services are designed to provide information on and tools for exploiting Solar radiation database (see e.g. http://www.helioclim.net, http://soda.jrc.it, http://www.satel-light.com).

3. Tools for Wind resources estimation

In this part are presented the way of obtaining wind resources. Wind resources start from the general estimation of the mean energy from wind over a large area and go till the mean annual production of a wind machine. In our paper we focus on the evaluation of wind parameters which are pre-required for wind resources estimation.

3.1. MEANS FOR WIND PARAMETERS ESTIMATION

Cup-Anemometers are certainly the most-used tools in the World for estimation of wind parameters. But these tools are liable to mechanical component deterioration. This leads to errors in wind speed are systematically biased to under representation of wind speed. Meteorological systematic tracking is considered a national baseline responsibility. Hence meteorological stations are also a basis of information on wind parameters. Some experience were also made with very interesting results on the use of anemometers with kites. Anemometers give access to a point-measurement and not to spatial information on the wind parameters.

But others tools were developed to try to catch a good representation of wind fields such as:

- *USA-1 (Ultra Sonic Anemometer).* This system is an anemometer measuring turbulent fluctuations of horizontal and vertical wind on a path of 10 cm.
- *Wind profilers*. During the last 20 years, so-called Doppler radars were systematically developed to probe the atmosphere and derive the wind profile (i.e., the speed and direction as function of height) from echoes of the transmitted radio waves produced by turbulence in the clear air. A wind profiler is the operational application of a radar originally developed by scientists for measuring the echo intensity and the wind profile up to about 30 km with height resolutions from 100 to 1500 m. Sequences of high power pulses are radiated in the vertical and in oblique directions. By analysing the received echoes, the radial velocity and the turbulence intensity can be computed. Observations from at least three directions are necessary to determine direction and speed of the wind.

- *SODAR (SOund Detection And Ranging)*. This system allows to obtain a 3-D profile of the wind parameters in the first hundreds of meters of the atmosphere. The SODAR processes the echo of an acoustic pulse which is directed into the atmosphere. The frequency shift of the echo varies according to the wind speed. This is the well-known DOPPLER effect. The echo intensity varies according to thermal turbulence and structure.
- *LIDAR (LIght Detection And Ranging)*. The transverse wind component is measured by projecting a series of beams which are evenly spaced in the transverse direction. The technique provides instantaneous velocities as well as mean velocities. Thus some turbulence quantities (e.g., turbulent intensities, Reynolds stresses, and higher moments or statistics) can be derived. In addition, particulate-related quantities can also be measured to obtain such quantities as cloud height and optical depth / reflectivity or boundary layer height and relative particulate loading with altitude. The vertical wind velocity is found from a correlation analysis. This tool is most often operated from an airborne platform.

The calibration of all tools for wind parameters measurement is mandatory to obtain possible comparison or combination of all the measures. But all these tools does not give a complete view of the wind configuration over a large area. Hence the only solutions is to use modelling tools for wind resources estimation.

3.2. MODELLING TOOLS FOR WIND RESOURCES ESTIMATION

Meteorological models such as those used by the ECMWF (European Centre for Medium-Range Weather Forecasts) allow to access to wind parameters statistics. In the European energetic domain, the most used model for wind resources estimation is certainly WAsP (Troen, Petersen, 1989; Bowen, Mortensen, 1996) from the Risoe National Laboratory (Denmark). It is based on the physical principles of flows in the atmospheric boundary layer and try to take into account the effect of the surface roughness, of obstacles and of terrain variations. In fact it is a combination of a set of models for each effect. Figure 5 presents the wind atlas methodology of WAsP.

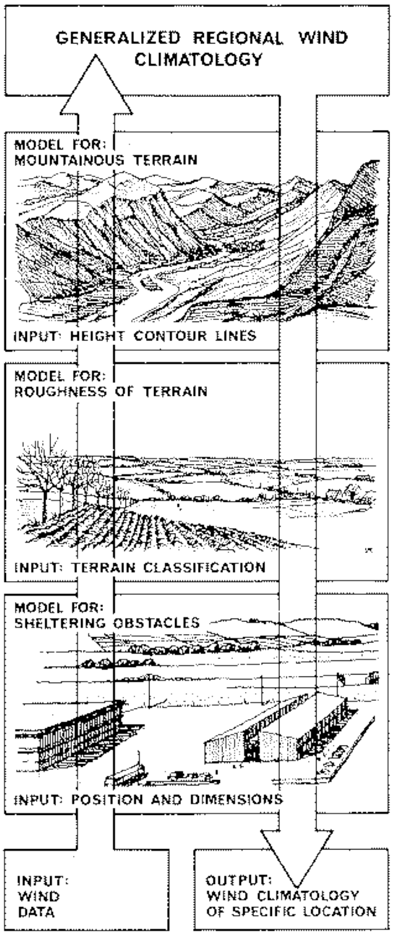

Figure 5. Wind atlas methodology of WAsP

WAsP consists of four main blocks of computation:

- *Analysis of raw data*. This option enables an analysis of any time-series of wind measurements.
- *Generation of wind atlas data*. Analysed wind data can be converted into a wind atlas data set. In a wind atlas data set the wind observations have been "cleaned" with respect to site specific conditions and reduced to standard conditions.
- *Wind climate estimation*. Using a wind atlas data set calculated by WAsP or one obtained from another source - eg. the European Wind Atlas - the program can estimate the wind climate at a particular point by performing the inverse calculation as is used to generate a wind atlas.

- *Estimation of wind power potential*. The total energy content of the mean wind (wind resource) is calculated by WAsP. Furthermore, an estimate of the actual, yearly mean power production of a wind turbine can be obtained by providing WAsP with the power curve of the turbine in question.

The main other family of models is based on Computational Fluid Mechanics (CFD). Examples of such models are Aria Local and Aria Wind from Aria Technologies(http://www.aria.fr). They are based on an implementation of the Navier-Stokes equations. Navier-Stokes models require considerable computational effort. It has been a serious drawback for their wide use. Even so, they constitute the most complete approximation and so they could be useful at least for checking and calibrating simpler models and to obtain good solutions when managing wind fields over complex terrains.

Aria Wind for example implements a linearised version of the Navier-Stokes equation and allows an accurate representation of 3D wind fields over complex terrain. It has two objectives:

- *At regional scale*: To provide a cartography of wind potential and define the best sites for wind energy production.
- *At local scale*: To define the pertinent implantation for the more convenient type of turbines. Precise calculation of each wind turbine production (kWh/year).

3.3. PREDICTION OF WIND RESOURCES

Accurate forecasting of the wind resource up to two days ahead is recognised as a major contribution for reliable large-scale wind power integration. Especially, in a liberalised electricity market, prediction tools enhance the position of wind energy compared to other forms of dispatchable generation. Nowadays, several tools have been developed for wind power forecasting (i.e. Zephyr, Predictor, Previento, WPPT, More-Care, Sipreolico and others). The state-of-the art tools are usually developed under the frame of specific applications. They are based either on physical (detailed terrain representation, roughness etc) or statistical modelling (i.e. black-box type of models based only on measurements). Physical modelling benefits from advances in the area of wind resource assessment.

In this important topic, a large European project, called ANEMOS (http://anemos.cma.fr) aims to develop advanced forecasting models that will substantially outperform current methods. Emphasis is given to situations like complex terrain, extreme weather conditions, as well as to offshore prediction for which no specific tools currently exist. The prediction models will be implemented in a software platform and installed for online operation at onshore and offshore wind farms by the end-users participating in the project. The project will try to demonstrate the economic and technical benefits from accurate wind prediction at different levels: national, regional or at single wind farm level and for time horizons ranging from minutes up to several days ahead.

4. Conclusion

The means and tools for estimation of solar and wind resources are numerous and potentially sufficient for assessing the potential of a specific area for solar or wind production of energy. Of course they do not provide an exact view of the situation, but they can help to plan new implantations of solar and wind farms. Connected with a tool allowing a geographical analysis of the energy potential of a country, such as geographical information system (GIS), this estimation will provide basis for a decision support system (DSS) if it includes the network description, the energy demand and some societal issues (Lamache and Vandenbergh 2000; Vandenbergh 1997) . Such a kind a tool exists and will help in a near future to propose economically and environmentally consistent solutions to provide energy to population.

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