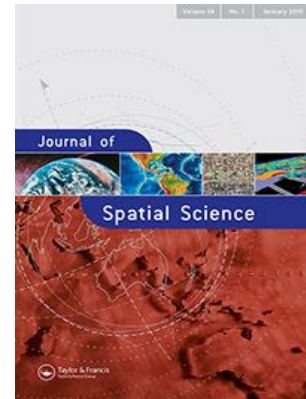


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in the Iberian Peninsula

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An Open Source Web Mapping Tool to Estimate Wind Energy in the Iberian Peninsula

Abstract: The main disadvantage of wind energy is its high spatial and temporal variability. This paper presents a web mapping tool to communicate to private users both the available wind resource and information to evaluate the suitability of several types of turbine for any point on the Iberian Peninsula. This tool performs on-the-fly three-dimensional interpolation of wind data from a 10 km horizontal grid database previously obtained using a regional climate model and generates a PDF report. It integrates several open-source GIS applications to build a coherent platform that performs advanced calculations and provides graphics and reports of high quality.

Keywords: Web mapping; wind energy; Iberian Peninsula; Geographic Information System; Open Source

1. Introduction

There is increasing demand for clean and renewable energy sources around the world due, among other reasons, to public concern about the availability and rising prices of fossil fuels, the need to reduce CO₂ emissions, one of the main contributory causes of Climatic Change (IPCC 2007), the need for national energy independence and economic instability due to fluctuations in the fossil fuels prices.

In this framework, wind energy may be regarded as one of the most suitable alternatives to traditional energy sources. Rodman and Meentemeyer (2006) stress its several reasons: (1) technological advances have reduced the cost of wind energy to the point where it can compete with conventional fuel sources; (2) there is a large variety of wind turbines that can operate with a range of different wind speeds, making wind a very scalable and flexible energy resource; and (3) such turbines can be installed by individual property owners or by communities in rural and remote areas enabling the decentralisation of power supplies.

One of the most studied environmental issues in Mediterranean countries is land abandonment (Thornes 2009); a problem that arises due, in part, to the financial problems faced by agriculture. For the aforementioned reasons, wind energy can be of use in supporting rural populations in the country land.

Nevertheless, one of the main disadvantages of wind power is the high spatial and temporal variability of the resource, meaning that it is necessary to develop easy to use instruments to evaluate the suitability of any area in the territory in terms of wind energy production. In this respect, a considerable amount of work has been devoted to the assessment of the available wind energy resources using GIS (Dominguez and Amador 2007). However, most studies have been concerned with large wind farms in a territorial planning framework.

Today, the availability of inexpensive small turbines for private use has created the need to make available the spatial and temporal distribution of the resource in question in the most efficient way. In particular, those wishing to install small wind turbines should be supported since individual users cannot address the cost associated with wind resource studies as performed by large companies or investors.

To help with this task, this paper presents a web mapping tool to communicate, in a straightforward way, information that can be used to evaluate the suitability of several types of turbine for any point of the Iberian Peninsula. This tool performs on-the-fly three-dimensional interpolations of gridded wind data obtained using a regional climate model with 10 km horizontal resolution. The model has been described in detail by Lorente-Plazas *et al.* (2012); in this paper we describe a GIS application developed to exploit the model and include additional data to improve its application. One of the most interesting features of the tool is that it can generate a wind resource report in PDF format for any point of the Iberian Peninsula, which can be downloaded by the user.

The web mapping tool is based on the integration of open source GIS applications to build a coherent platform. Several studies have previously analysed the corresponding advantages and disadvantages of open source software and proprietary software in environmental modelling and highlighted the benefits of the former (Weis 2006, Jolma *et al.* 2008, Steiniger and Bocher 2009). Mari *et al.* (2011) presented a wind-energy web-mapping system focused on wind farms and the planning of their allocation, while the purpose of the tool presented here is to support individual proprietors and small communities willing to install small wind turbines.

The main interest of the project is that it provides an easy to use tool for end users interested in estimating wind energy resources. The whole system is implemented using open-source software, a very inexpensive alternative that should facilitate its use in developing countries.

The paper is structured as follows. Section 2 provides an overview of GIS and web mapping technologies that publish spatial data on the Internet. Section 3 describes the database and the interpolation process used to obtain an estimation of the available resource. Section 4 describes the computer system in which the server was implemented. Section 5 explains how information flows between client and server. Section 6 describes the kind of reports that the system generates when a location is clicked on the map by the user. Finally, section 7 presents the main conclusions.

2. GIS and web mapping

A Geographic Information System (GIS) is a ‘powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes’ (Burrough and McDonnell 1998). According to Heimiller and Haymes (2001), a GIS is a useful tool both for assessing wind resources

and prior to installing wind turbines, because it uses the significant spatial components necessary in both cases. The objective of GIS wind analysis is usually to obtain a map with the distribution of the resource, which can then be represented as PDF maps or raster layers.

Several studies have been carried out from an energy point of view (Acker *et al.* 2007, Himri *et al.* 2008) or from a territorial perspective (Baban and Parry 2001, Heimiller and Haymes 2001, Hansen 2005, Ramachandra and Shruthi 2005, Rodman and Meentemeyer 2006, Acker *et al.* 2007, Byrne *et al.* 2007, Mari *et al.* 2011), in order to assess both the environmental limitations and the factors that can affect the profitability of the investments.

Other studies have integrated GIS technologies and diverse tools not just to assess but also to communicate the wind resource: for example the Canadian Wind Energy Atlas (Canada Environment and Climate Change 2016), the Republic of Ireland Wind Atlas (Brower *et al.* 2003, Wilson and Standen 2013) or the wind resource maps developed by the US Department of Energy (Flowers and Dougherty 2002). In Spain there are previous works such as that of Gastón *et al.* (2008) or the Spanish wind atlas (IDAE 2011). For its part, IDEA (2011) includes an analysis of the wind resource based on the Mesoscale Atmospheric Simulation System, in the form of an atlas allows on-line access to the information to a GIS web client.

One of the most important capacities of GIS is the possibility of publishing spatial data over the Internet, allowing multiple users to access it, and facilitating the updating of the data. The user can choose between several options and to interact with the map, enriching their experience in comparison with static paper maps. In the present century, several research groups, government organisations and large companies have been working on the implementation of Spatial Data Infrastructures (SDI) to allow users

to access spatial data; one of their main objectives is to give the possibility of sharing and improving spatial information, achieving greater interoperability between data and geographic services. Syntactic interoperability between systems based on standards, or semantics, ensures that contents are understood by any system. For example, Ulutaş *et al.* (2016) propose an ontology extension methodology to allow automatic data integration in SDIs from semantic web technologies instead of current technologies (syntactic web technologies).

SDIs include web mapping services which usually provide spatial data following three OGC (Open Geospatial Consortium) standards: WMS (Web Map Service) to display maps and images, WFS (Web Feature Service) to serve vector data and WCS (Web Cover Service) to serve raster data (Steiniger and Hunter 2012). The OGC is a consensus standards organisation that defines open specifications to distribute spatial information on the web to ensure interoperability between different systems. WPS (Web Processing Service) is another recently defined OGC standard intended as a solution to develop web-based geoprocessing modules and to share them on the web (Michaelis and Ames 2009). The service defines a standardised interface that facilitates the discovery of such processes and their use (Meng *et al.* 2010).

At the same time, there is a tendency to replace standalone applications by sets of integrated, smaller and more versatile applications that are able to work together transparently through any network. In this respect, Anderson and Moreno-Sanchez (2003) highlight several issues related with the use of proprietary web-GIS software. Open Source Software (OSS) provides several alternatives to proprietary software for the management of spatial information. Nowadays there is an appropriate OSS option for designing a web GIS infrastructure regardless of its level of complexity (Anderson and Moreno-Sanchez 2003, Steiniger and Bocher 2009). The use of Open Source

Software for implementing SDIs has been previously explored, between others (Anderson and Moreno-Sanchez 2003, Skelton 2010, Steiniger and Hunter 2012).

3. Data base

Figure 1 illustrates the workflow of the wind energy assessment system proposed. The following subsections describe this process, which begins when a location is clicked on the map by the user and the hub height of the wind turbine is introduced in the corresponding web form.

Wind data

The wind data included in the web tool were provided by in-situ observations from weather meteorological stations and simulations from an atmospheric model.

Data were provided by nine different regional weather agencies from the Iberian Peninsula (Portuguese data are not yet included). Data were purged following an exhaustive quality control based on Jiménez *et al.* (2010), after which 578 weather stations evenly spread over the whole target region (Figure 2) were selected.

Observations were unified to represent an hourly temporal resolution and 10 m above ground level values. More details about this dataset and the quality control applied can be found in Lorente-Plazas *et al.* (2015). The table that contains simulation data has 422 columns including: height above ground, station identifier, coordinates (X, Y), ground altitude over sea level, and 416 columns containing the frequency of winds in 16 compass directions and 26 speed values.

The model data were obtained using a modified version of the Fifth-Generation Pennsylvania State University National Center for Atmospheric Mesoscale Model (MM5; Grell *et al.* 1994), which is an atmospheric non-hydrostatic limited area model. Simulations have an hourly temporal resolution covering 1960 to 2007. Spatially,

atmospheric equations are resolved using a 10 km horizontal grid-cell (Figure 3) and 26 vertical levels related to air pressure. In the web tool, only the eight lowest levels are included (17.9, 53.8, 89.8, 125.9, 180.3, 253.5, 401.3 and 665.6 metres above ground level) since wind turbine heights are lower than the top of the atmosphere. The simulated wind data were validated using the observations described above, and reasonable agreement was obtained as regard wind speed and direction at different temporal and spatial scales (Lorente-Plazas *et al.* 2015). This data base has been used in some other studies that evaluate renewable energy resource variability in the Iberian Peninsula (Jerez, Trigo, Sarsa, *et al.* 2013, Jerez, Trigo, Vicente-Serrano, *et al.* 2013).

One of the main challenges of the web tool is to store all the wind data in the most efficient way in order to perform calculations at a low computational cost. Bearing this in mind, simulated winds were included by calculating a two-dimensional discrete function for each grid-cell point. This function takes into account the wind speed and direction histograms. Wind direction was split into 16 sectors and wind speed into 26 sections, meaning 416 possible cases. Wind data were stored in a table in PostgreSQL format with 125,000 rows (8x15,625). Each of the 15,625 points, which correspond to the number of grid cells in the spatial discretization to solve the fluid dynamics equations, has 8 entries corresponding to each vertical level. The observations from 578 automatic weather stations are included using a similar table with the objective of using real data to validate the results of the model and to provide the user of the web tool with an indicator of the quality of the model in the specific area of interest. This aim is achieved by including in the final report real data from the three weather stations that are nearest to the point of interest, which are compared with the model data.

Finally, the temporal evolution of the simulated monthly mean wind speed for each point is also stored in the database, enabling an estimation of the inter-annual

variability and the annual wind cycle to be included in the reports received by the user to estimate the accuracy of the results.

On -the -fly interpolation

As mentioned above, the main advantage of the web tool is its ability to evaluate the wind resource at a specific point only a few seconds after the user introduces the query in the web viewer. For this task, the wind field is first interpolated to the point of interest for the subsequent wind resource assessment.

The 3-dimensional grid of simulated wind data enables an easy interpolation to the point of interest. For this task, the web user can select the coordinates of the location and the hub height of the wind turbine (h_T). This information is sent to the Database Management System (DBMS) which first uses DEM data to obtain the real height (h_{DEM}) and then looks for the eight nearest points. These eight points correspond to the vertices of the cube which contains the point of interest, with four points at one vertical level and the other four points at the next level (Figure 4). Then the point of interest (K, L) is located at the height $L = h_{DEM} + h_T$ and at a K point with x_K latitude and y_K longitude. If the real height is lower than the model height ($h_{DEM} < h_{ter}$) the interpolation will be performed considering only the first $\sigma/2$ level.

Once the eight nearest points are found, the interpolation to obtain the distribution function at the specific point is performed. First, two horizontal interpolations are computed. Then, the two resultant averaged histograms are interpolated vertically. The horizontal interpolations are calculated as follow

$$\mathbf{W}_{K,l}(\theta, v) = \sum_{k=1}^4 \mathbf{W}_{k,l}(\theta, v) P_{k,l} \quad (1)$$

where $l = \sigma/2, \sigma/2 + 1$ and $P_{k,l}$ are the weights defined by:

$$P_{K,l} = \frac{\exp(-\alpha d_{k,l})}{\sum_{i=1}^4 \exp(-\alpha d_{k,i})} \quad (2)$$

where $d_{k,l} = \sqrt{(y_k - y_K)^2 + (x_k - x_K)^2}$ and $\alpha = 150$ is a constant.

Once the horizontal interpolation has been computed for $\sigma/2$ and $\sigma/2 + 1$ vertical levels, the vertical interpolation to the interest point is given by:

$$\mathbf{W}_{K,L}(\theta, v) = \mathbf{W}_{k,\sigma/2}(\theta, v)T_{\sigma/2} + \mathbf{W}_{k,\sigma/2+1}(\theta, v)T_{\sigma/2+1} \quad (3)$$

where the weights are defined by:

$$T_l = \frac{1/H_l}{1/H_{\sigma/2+1} + 1/H_{\sigma/2}} \quad (4)$$

where $H_{\sigma/2} = h_T - z_{\sigma/2}$ and $H_{\sigma/2+1} = z_{\sigma/2+1} - h_T$. Finally, the interpolated 2-D histogram is normalized by:

$$\bar{\mathbf{W}}_{K,L}(\theta v) = \frac{100\mathbf{W}_{K,L}(\theta, v)}{\sum_{j=1}^{416} \mathbf{W}_{K,L}(\theta, v)} \quad (5)$$

An analogous interpolation method is used to obtain the 2D-histograms for the monthly temporal series $\mathbf{S}_{K,L}(t)$ (without normalization).

Wind resource assessment and wind power estimation

The interpolated functions $\mathbf{W}_{K,L}(\theta, v)$ and $\mathbf{S}_{K,L}(t)$ allow the wind resource to be assessed for almost 50 years at the specific point where the user is interested in installing the SWT. The assessment of the wind resource consists of evaluating the hourly wind speed histograms, the inter-annual variability and the wind roses for the complete simulated period. The mesoscalar models (or regional models) generally used to wind energy assessment are atmospheric models not specifically designed to this end. The outputs of such models need to be post-processed in order to obtain the diagnostic

variables and statistical metrics relevant in the wind assessment. In general, wind mapping tools show some of this information directly at the grid points used by atmospheric models discretization. One of the main advantages of the web mapping tool presented here is that wind assessment is provided at the interesting point where the SWT want to be installed by using the interpolation method described above.

Characterising the wind speed histograms is important because the wind power and the power curve of the SWT can be estimated with the provided information. With the averaged bidimensional histogram ($\bar{\mathbf{W}}_{K,L}$), each bin of the wind speed histogram is directly obtained by $freq(v_j) = \sum_{i=1}^{16} \bar{\mathbf{W}}_{K,L}(\theta_i, v_j)$. With this procedure, the wind speed histogram is computed for the specific point (K,L) where the user is interested in installing the wind turbine. In addition, this histogram is fitted to the Weibull distribution widely used in wind power, which is characterised by the shape and scale parameters. The values of these parameters are also provided in the wind resource assessment. Several studies have demonstrated that the Weibull distribution accurately represents the hourly frequency distribution of the wind speed (e.g. Carta *et al.* 2009, Jiménez *et al.* 2011).

In wind resource assessment, it is also important to inspect the histogram of the wind direction as a function of the wind speed, i.e., a wind rose. The wind directions are divided into 16 bins and the wind speed into 5 bins of 5 ms^{-1} , a bin with calms (wind speed lower than 1 ms^{-1}) and a bin with the wind speed higher than 25 ms^{-1} . To identify the predominant wind direction the shadow effects of obstacles must be avoided such as trees or buildings that would affect the wind power efficiency.

The final step of the wind resource assessment is to inspect inter-annual variability taking advantage of the availability of almost 50 years of simulated wind fields. Using the interpolated function $\bar{\mathbf{S}}_{K,L}(t)$, the monthly mean and 12 month run

median wind speed series for the simulated period are computed. The estimation of the inter-annual variability of the wind resource allows the user to evaluate fluctuations of the wind turbine electricity output from one year to another. It also provides an estimation of the representativeness of the period when wind records are available in the subsequent validation of the simulation.

Once the wind resource has been characterized and evaluated in the specific area of interest, the next step is to estimate the amount of energy that a typical wind turbine can produce. Various sizes and makes of wind turbine can be examined to find the most suitable for a given need. Wind power is estimated with the information of the power curve of a wind turbine and the interpolated function $\bar{W}_{K,L}(\theta_i, v_j)$. The power curve gives the electric power $P(v_j)$ generated by the wind turbine for a given wind speed v_j .

From the wind speed distribution, the hours that the wind blows with a v_j in a year is given by:

$$h(v_j) = freq(v_j)87.60 \quad (6)$$

Taking into account the power curve the energy production for v_j is:

$$e(v_j) = h(v_j)P(v_j) \quad (7)$$

hence, the total annual energy is $E = \sum_{j=1}^N e(v_j)$. Once the energy production per hour is computed, some other fundamental parameters that characterise the annual production can be evaluated.

The *availability* (AV) is the percentage of hours that the wind turbine is working. It could also be defined as the number of hours per year that the wind speed is between the

cut-in wind speed and the cut-out¹ wind speed of the turbine.

$$AV = \frac{100 \sum_{j=0}^N h(v_j)}{8760} \quad (8)$$

The *equivalent hours (HEQ)* are the number of hours that the turbine is working for a given period (one year) with full capacity:

$$HEQ = \frac{E}{P_N} \quad (9)$$

where P_N is the nominal power. The definition of the nominal wind speed is controversial and could be defined as the lowest speed at which the wind turbine reaches its nominal power output. Above this speed, higher power outputs are possible, but the rotor is controlled to maintain a constant power to limit loads and stresses on the blades.

The *capacity factor (CF)* represents the real percentage of energy generated during a year divided by the theoretical maximum production and is given by:

$$CF = \frac{HEQ}{8760} \quad (10)$$

Analogous to the wind rose, we can create wind energy and wind power roses. For this, the wind power is divided into seven bins of 0.5 kW intervals, with one bin covering powers greater than 2.5 kW, while for the wind energy each bin has a range of 300 kWh, with one bin for energies greater than 1200 kWh.

¹ The cut-in wind speed is the minimum wind speed at which the turbine blades overcome friction and begin to rotate. Cut-out speed is the speed at which the turbine blades are brought to rest to avoid damage from high winds.

Additional layers

The objective of the system is for it to be useful for a wide range of users in the most convenient way. That is the reason why, instead of including several different layers that could distract the user or even reduce the system efficiency, it was decided to include only the strictly necessary information (Table 1). All the available data are used to locate the points of interest or as inputs to run the model. However, the tool can add new information from WMS from other IDEs using a plug-in, which is available to the client.

4. System Description

The system proposed in this paper is an integration of several components. Besides the usual Mapserver and PostGIS approaches to build most Open Source web mapping systems, other programs, such as R or Latex, are included to increase computation capabilities, and the ability to create graphics or to prepare high quality reports.

The system was installed in a relatively inexpensive computer (Table 2). Several software components were required (Figure 5), the basic component was the operating system and the obvious choice was the open source system Linux, in this case the Debian distribution; Apache 2 was used as web server.

The platform used to create the spatial Internet application was MapServer (Lime 2008), one of the most widely used Open Source applications to create web mapping sites. It can read and serve spatial data in several formats using the GDAL library (Warmerdam 2008) and make on-the-fly reprojections using the Proj4 library (Evenden 1990).

The user interface was created using p.mapper (Burger 2010), a development framework that uses PHP on the server side and JavaScript, with embedded PHP, on the

client side. The interface provides access to the usual tools for a web mapping client such as zoom, pan, spatial configuration, advanced query, etc., and has been used in several web mapping projects, including at least one other wind energy oriented project (Mari *et al.* 2011).

We used GRASS (Neteler and Mitasova 2008, Neteler *et al.* 2012) to store raster data. This is a desktop GIS mainly used to store, analyse and visualise geospatial information, and for image processing and spatial modelling.

The relational DBMS PostgreSQL (PostgreSQL Global Development Group 2017) was chosen to store the aforementioned wind tables since it is considered to be the most powerful Open Source DBMS. PostGIS, developed by Refractions (Obe and Hsu 2015), is an extension to PostgreSQL which adds spatial capabilities by adding spatial data types, functions, operators and indices for spatial data handling. PostGIS 2 was used as the storage format of the vector layers.

One of the problems of PostgreSQL-PostGIS is its limited mathematical or graphic capabilities. In this respect, R (R Core Team 2016) is a GPL statistical modelling program that includes graphical tools, exploratory analysis and an efficient object-oriented programming language (Crawley 2005). One of the strengths of R is the ease with which well-designed plots can be produced. R was used in this web mapping tool to create graphics that are included in the final report. One of the most interesting features of R for the purposes in mind is the possibility of embedding R functions in PostgreSQL using PL/R, which is a PostgreSQL language extension that allows users to write PostgreSQL functions and aggregate functions in the R statistical computing language.

The PL/R function is based on several R functions, some of them were developed for this project while others are found in the R packages plotrix (Lemon

2006) for advanced graphical functions, *rgdal* (Bivand *et al.* 2016) as an interface with GDAL library, *quantreg* (Koenker 2016) to calculate quantile regression and *gnlm* to fit data to the Weibull distribution (Yssaad-Fesselier and Knoblauch 2006). All these functions are integrated in the main function, their purpose being to generate histograms, legends, wind and energy roses and to interpolate the data.

The PL/R function embedded in PostgreSQL generates a large quantity of data and figures that need to be organised in a report the user can download. In this case, Latex, a document formatting language based on TEX, was used. The main advantage of this solution is that the compilation of the report can be integrated directly in the working environment using an R system call, so all the processes - from obtaining the coordinates to the generation of the final report - are triggered by an SQL query sent by the client.

Several techniques are included to increase the efficiency of the tool. For example, AJAX (Asynchronous JavaScript and XML) is used on the client-side to allow asynchronous communications with the server using JSON (JavaScript object Notation) as the data interchange format rather than XML. For its part, FastCGI is a protocol for improving the interaction of client programs with a web server, allowing the server to handle several web page requests at the same time. Finally, Tilecache is used to organise large images in tiles, while keeping them in the memory for further requests.

5. Information flow

The flow of information between client and server and within the server is illustrated in Figure 5. When users access the client application (Figure 6), they can interact with it, display the available spatial layers, and query for information about them. However, the most important use, the evaluation of the wind resource, begins when the user enters, in

a web form, the turbine model and height. The coordinates can be entered using a form or by clicking on the map. This information is sent to the server using JSON.

When the server receives this information, the calculation process begins. The coordinates are used to obtain the hub altitude at the point of interest by means of a query to the GRASS layer, while a query is sent to the PostgreSQL DBMS to obtain the three nearest weather stations and the eight model grid points nearest to the location in question.

The PL/R function is then used to analyse the data. The bidimensional distribution function of wind speed and direction for the entered point is obtained by interpolating the distribution functions of the eight nearest 3D points. These eight points are the vertices of a cube containing the point of interest (four on the vertical level above the point of interest and other four on the vertical level below). The horizontal interpolation is done first, it is simply a weighted average using the squared inverse distances as weights is made first. Later, the vertical interpolation is carried using a logarithmic regression model.

Once the information has been processed, the next step is to generate all the elements that compose the final report, including texts, figures and tables. Several functions are used to plot figures, make format conversions, and generate the location maps using Mapscript. Several figures are produced based on the results of the interpolation: mainly histograms of wind speed, fitted using the Weibull distribution, and temporal series. All the elements produced are finally integrated into a Latex template to produce the final report in PDF format, which is returned by the server to the web client.

6. Results analysis

The main result of the project was satisfied in the form of a web mapping tool that can be accessed through the web page <http://meteo.inf.um.es/eoloeng/map.phtml>. Figure 6 shows the interface that enables users to access the server. This client was programmed using p.mapper. Among the set of functionalities offered by the client program are: navigation, search, distance and area measurements, labelling, drawing, etc. Of greatest interest is the fact that the user can:

- Dynamically load the data available on the server.
- Print the view as a map.
- Download the map in Geotiff format.
- Identify and select spatial objects and open the attribute tables linked to them with the possibility of exporting them in txt or PDF format. The weather stations have a hyperlink for summaries of the wind data.
- Send advanced queries from a graphic SQL builder.

The client program allows to locate any point of interest to be located using orthophotos or the land properties map. Once the point has been located, the data are sent to the server using a web form or by clicking on the map. The response of the server is in the form of a report that provides an analysis of the wind resource at the point of interest. Figures 7 to 9 show some of the elements included in such a report. Finally, Figure 10 shows an example of the kind of report produced by the server. It includes:

- An evaluation of the selected point, including a summary of its location and the most relevant data (Figure 8(a)).

- An assessment of the wind resource (Figures 7 and 10(b)), including a histogram of frequencies adjusted to the Weibull distribution function, the wind rose and the monthly series, including a moving median, for the whole simulated period (1960-2007).
- A comparison of the model output with real values for the 3 nearest stations (Figures 8 and 10(c)), including a representation of the daily and annual cycles of the wind speed. The user can use this information to estimate the accuracy of the model in the surroundings of the location of interest. While the fact that only 578 weather stations are available and that the coarse resolution of the model introduces some uncertainties in the accuracy estimation, the flatness of the terrain in most of Spain reduces this uncertainty. It would obviously be desirable to have more weather stations than those available at the moment.
- A study of the potential wind power. An example using the Sonkyo turbine is shown in Figures 9 and 10(d). The table with wind speeds and the predicted energy production of the turbine are complemented by two compass roses representing energy and power.

The whole implementation was documented and programmed using scripts, thus facilitating the scalability of the system or its portability.

7. Conclusions

The present work describes a web-mapping tool that can be used to access the wind energy potential in Spain. The tool was developed in the framework of the PSE-120000-2007-14 MINIEOLICA project funded by the Spanish Ministry of Science and Innovation. The system was conceived as an interactive tool for free access on the Internet for potential small wind turbine users, although it can also be used for other

applications.

Several open source applications are integrated to create a coherent tool that can make advanced computations, and provide graphics and high quality reports, which is the main difference of this project compared with conventional web mapping applications that simply provide map viewing and querying potential.

The use of PostgreSQL to store massive tables has enabled us to improve several aspects (for example usability, remote access, response time or integration with other applications) compared with other traditionally used standard formats such as GRIB (Gridded Binary or General Regularly-distributed Information in Binary form) or NetCDF (Network Common Data Form).

Another noteworthy feature is the creation of Latex reports integrating the tables, figures and text generated by the R functions into a Latex template. Latex is a very powerful document preparation system that allows users to create high-quality professional documents. In this case, it was decided to keep the formatting simple, more sophisticated designs are possible.

The centralised design of the tool contrasts with the increasing use of the Web Processing Service (WPS) in similar projects. We consider that the execution of geo-processes in the server rather than using WPS is efficient enough for the objectives of this project.

The web tool has some limitations and further improvements will be considered in future works. One of the main drawbacks is related to the coarse resolution of the simulation, which is unable to capture the effects of topography on winds. To address this issue several strategies can be adopted such as (1) increasing the spatial resolution, (2) improving the model performance, (3) developing a technique to correct the outputs of the model based on more detailed information of the terrain, such as roughness length

or (4) introducing the RCM outputs into microscale diagnosis models such as WASP or CALMET.

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Disclosure statement

There is no potential conflict of interest for any of the authors

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Tables with captions

Table 1. Additional layers in the server. The first one is used to obtain the height of the point of interest, the others are just to help the user in the location.

Information	Format	Source
DEM	GRASS Raster	Spanish map authority (IGN)
Regional boundaries	PostGIS	IGN
Land properties	WMS (FeatureInfo capability)	Spanish land registration authority (D.G. Catastro)
Orthophotograph	WMS	IGN
Satellite image	WMS	IGN

Table 2. Hardware of the server.

Element	Description
Processor	P i7 8 cores 2.93GHz
RAM	8 Gb. PC-667 DDR2
Graphic card	ATI Pro Sapphire 1024Mb
Storage	HD 1 Tb (4X250Gb)
O.S.	Linux Debian 8
File system	Ext3

Figures with captions

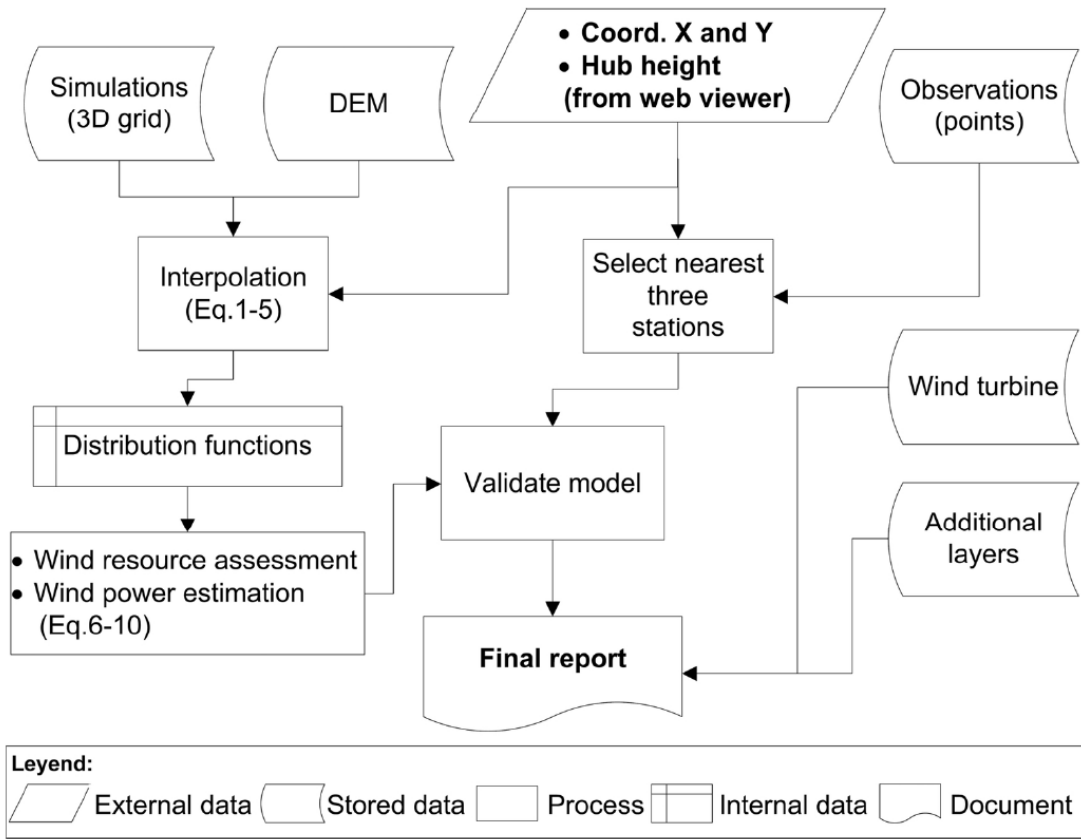


Figure 1. Workflow of wind energy assessment system proposed.

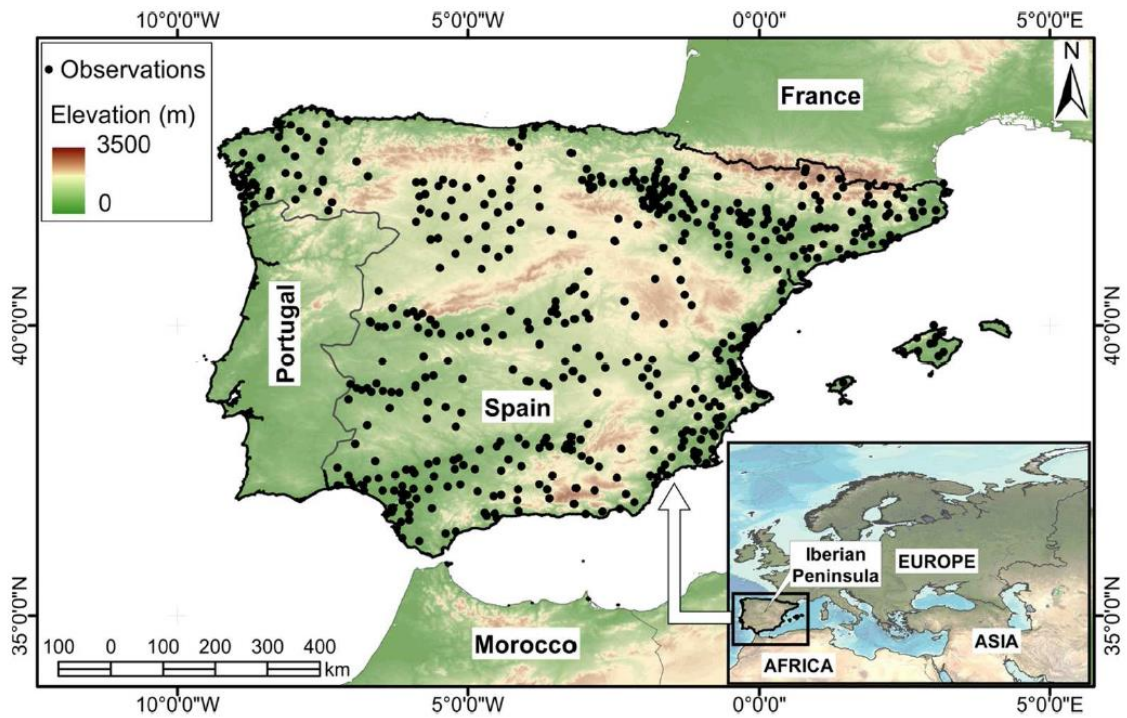


Figure 2. Spatial distribution of observations points with information about wind direction and wind speed for different heights.

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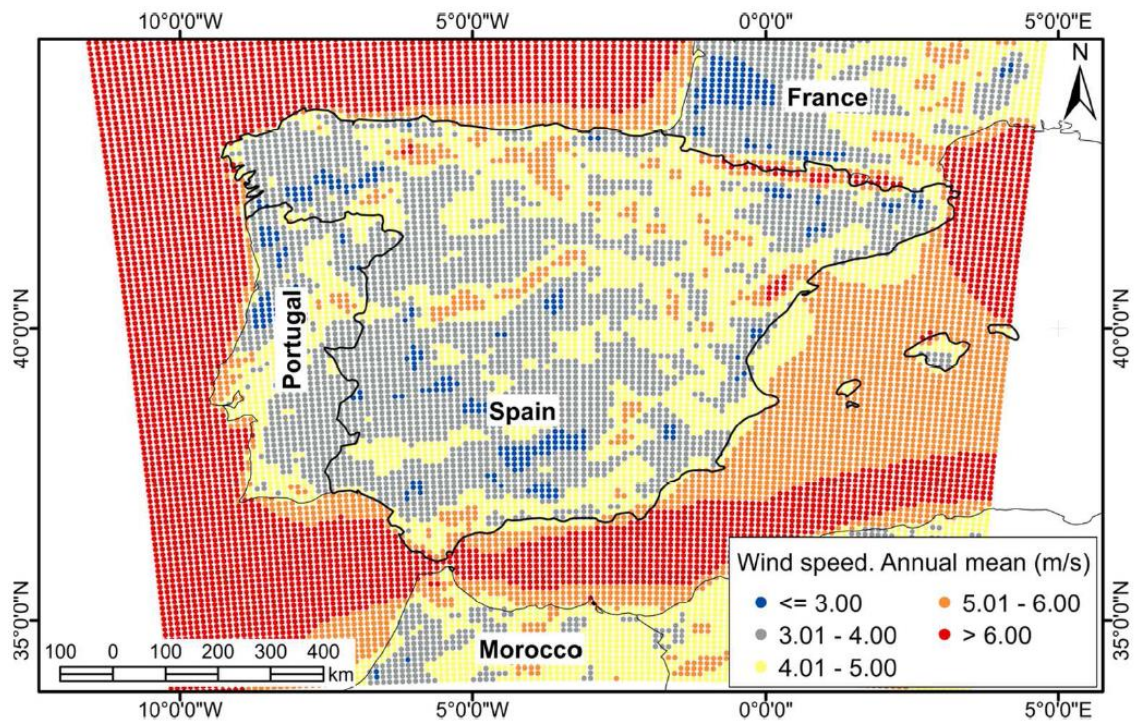


Figure 3. Spatial distribution of the grid points for the MM5 model with information about wind direction and wind speed for different heights.

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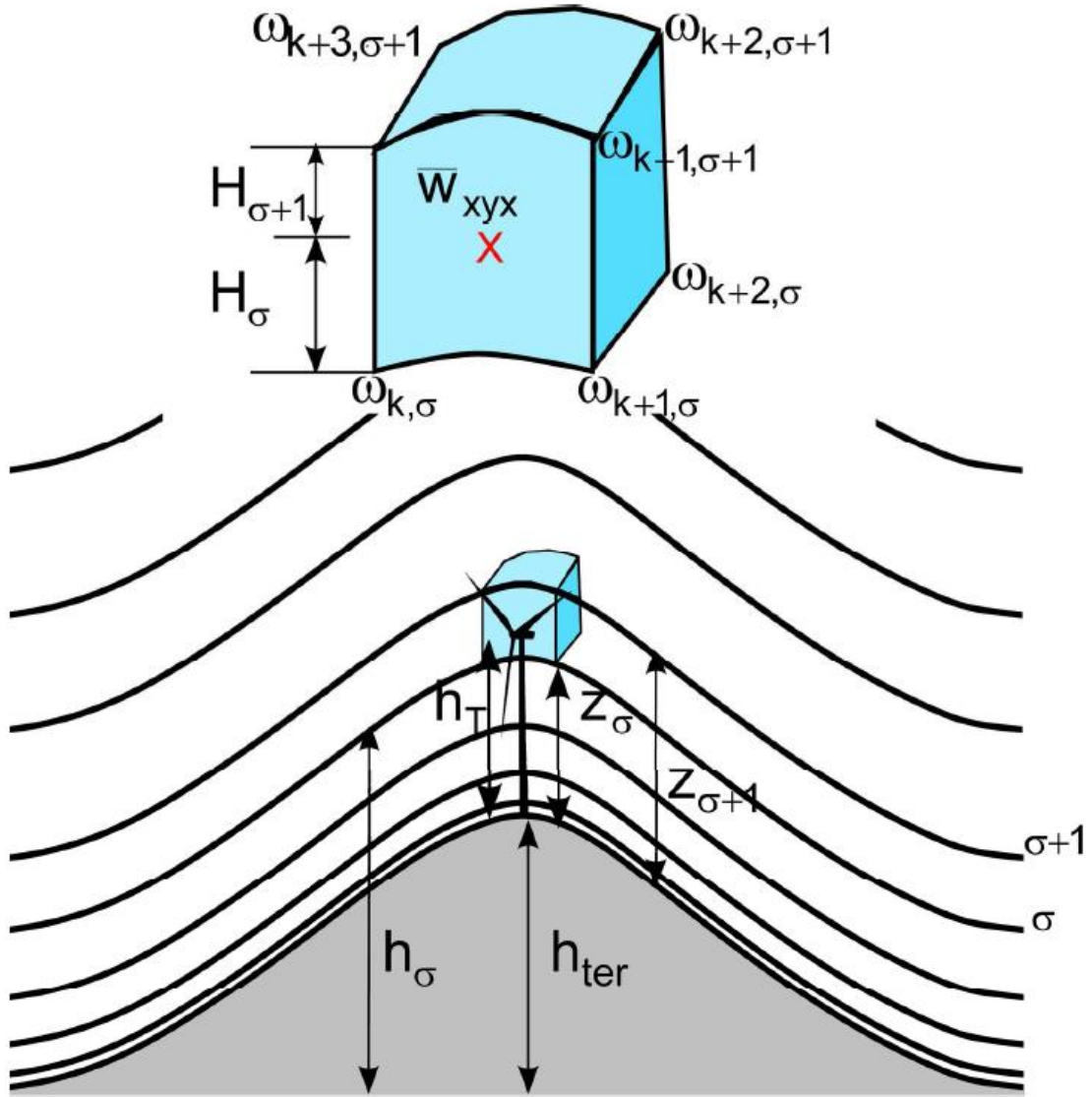


Figure 4. On-the-fly interpolation of the bidimensional histograms ($\mathbf{W}_{k,l}(\theta, v)$) using the eight nearest grid-points located between two sigma vertical levels. The terrain height (h_{ter}) is showed in gray shadow, the lines following the terrain are the σ levels at h_σ height above the sea level and at z_σ above the ground and h_T is the hub height of the wind turbine.

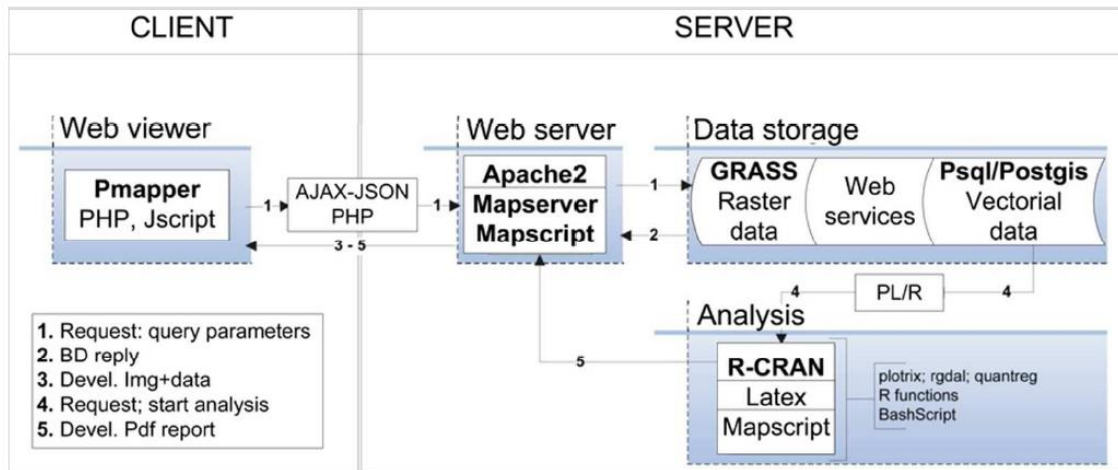


Figure 5. Conceptual scheme of the programs used and information flow.

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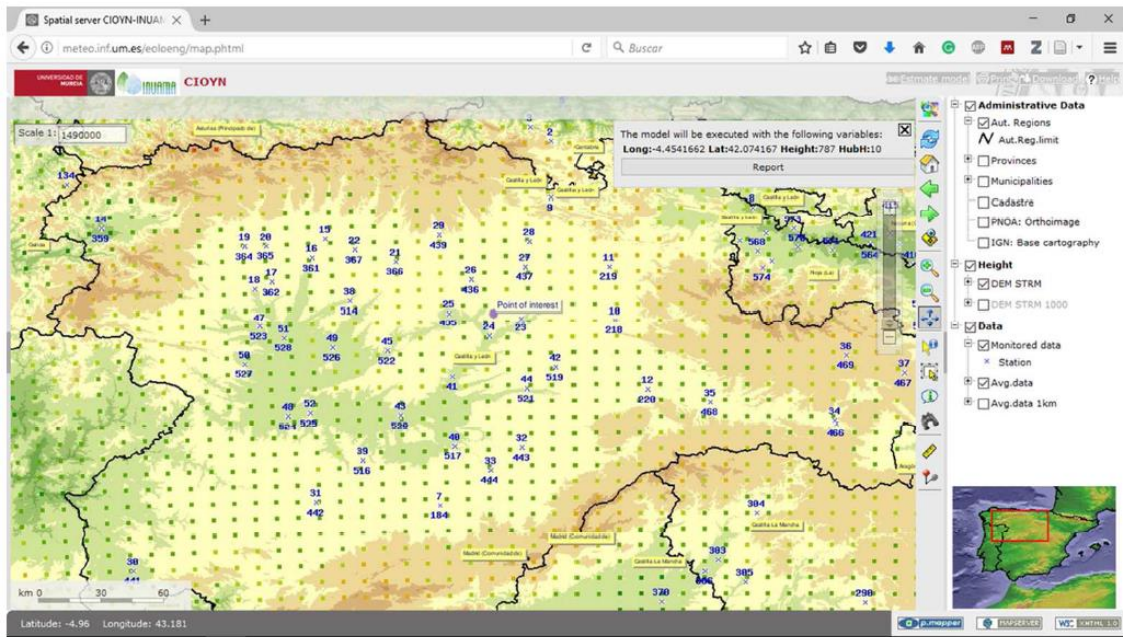


Figure 6. Example of the implemented web client example corresponding to the Northwestern sector of the Iberian Peninsula (Autonomous Region of Castilla y León).

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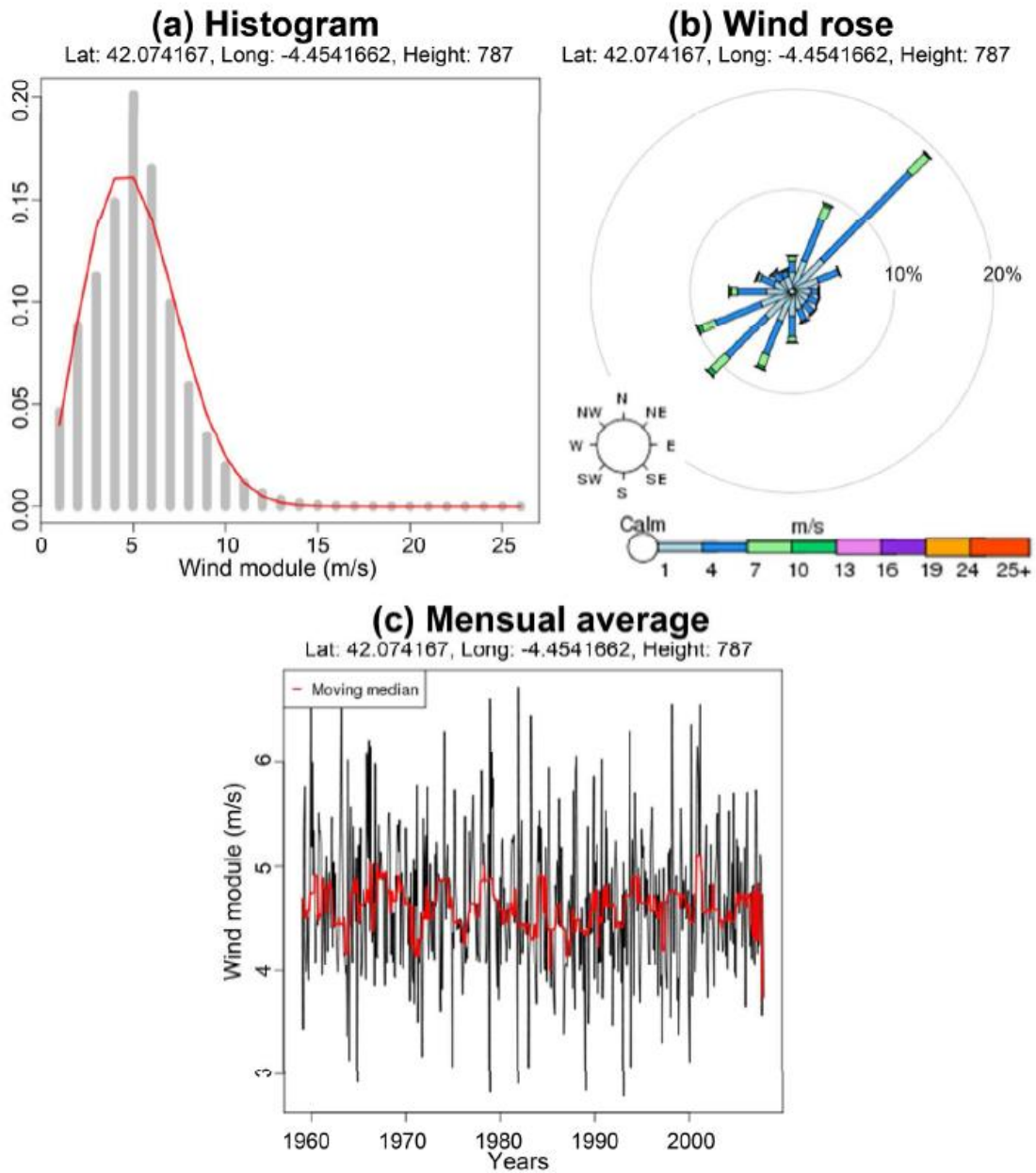


Figure 7. Plots included in the report at the location of interest.

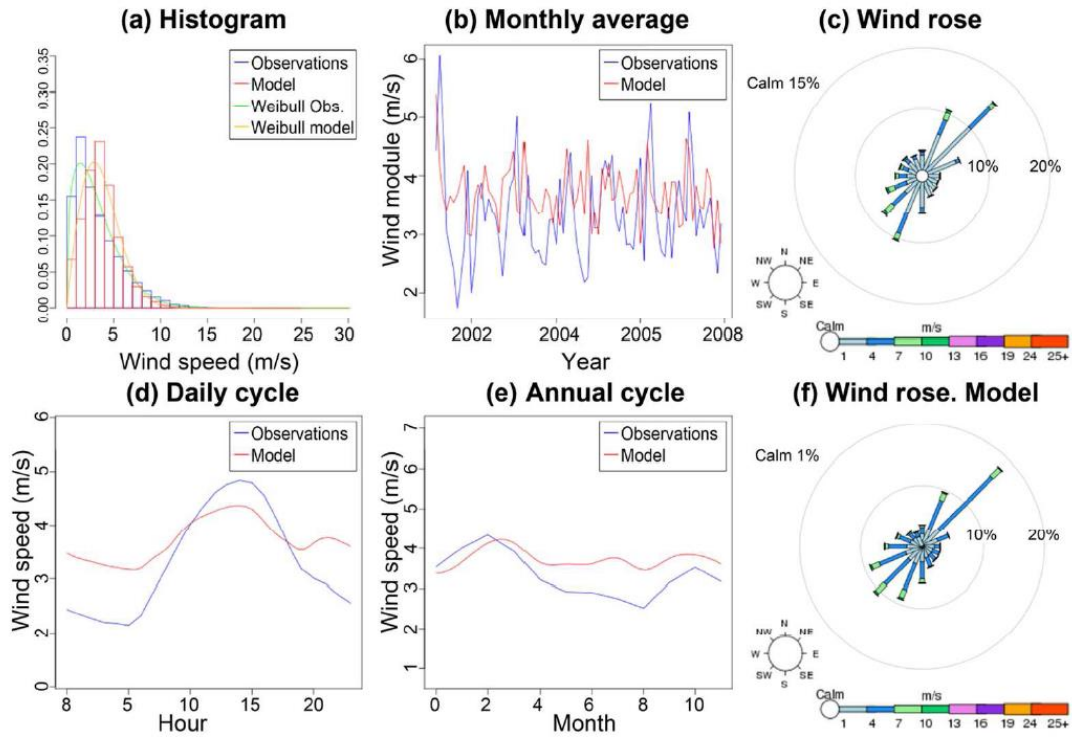


Figure 8. Representation included in the report of the daily and annual cycles of the estimated wind speed. Detail of the nearest weather station (id: 24) to the location of interest.

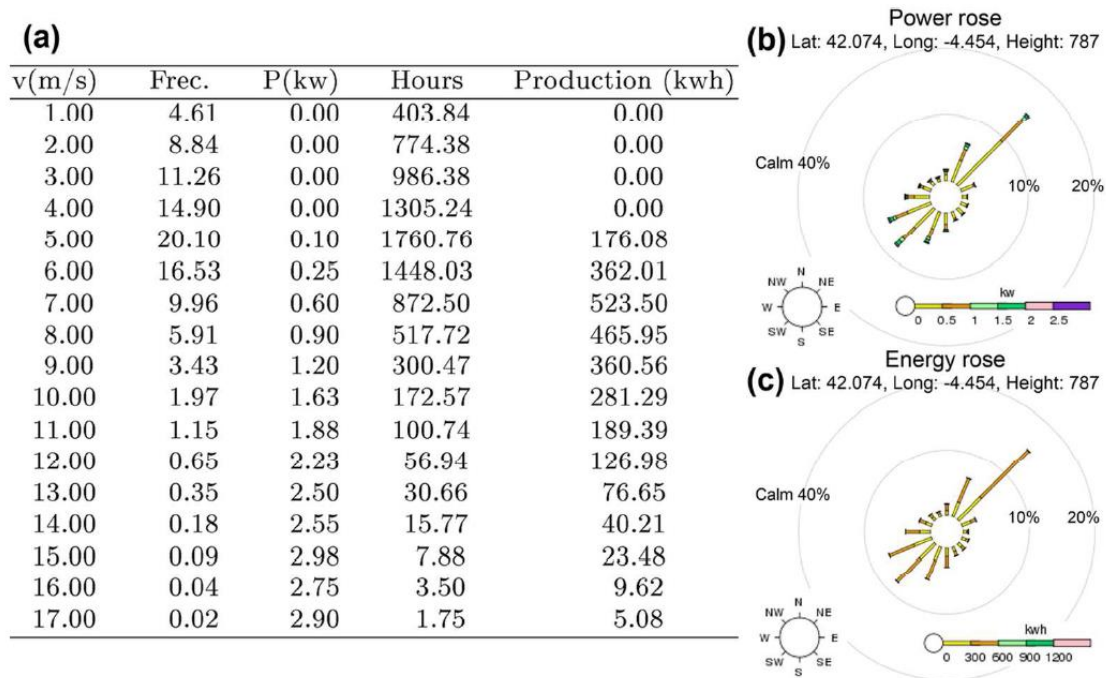


Figure 9. Turbine efficiency analysis in the report produced by the web mapping tool.

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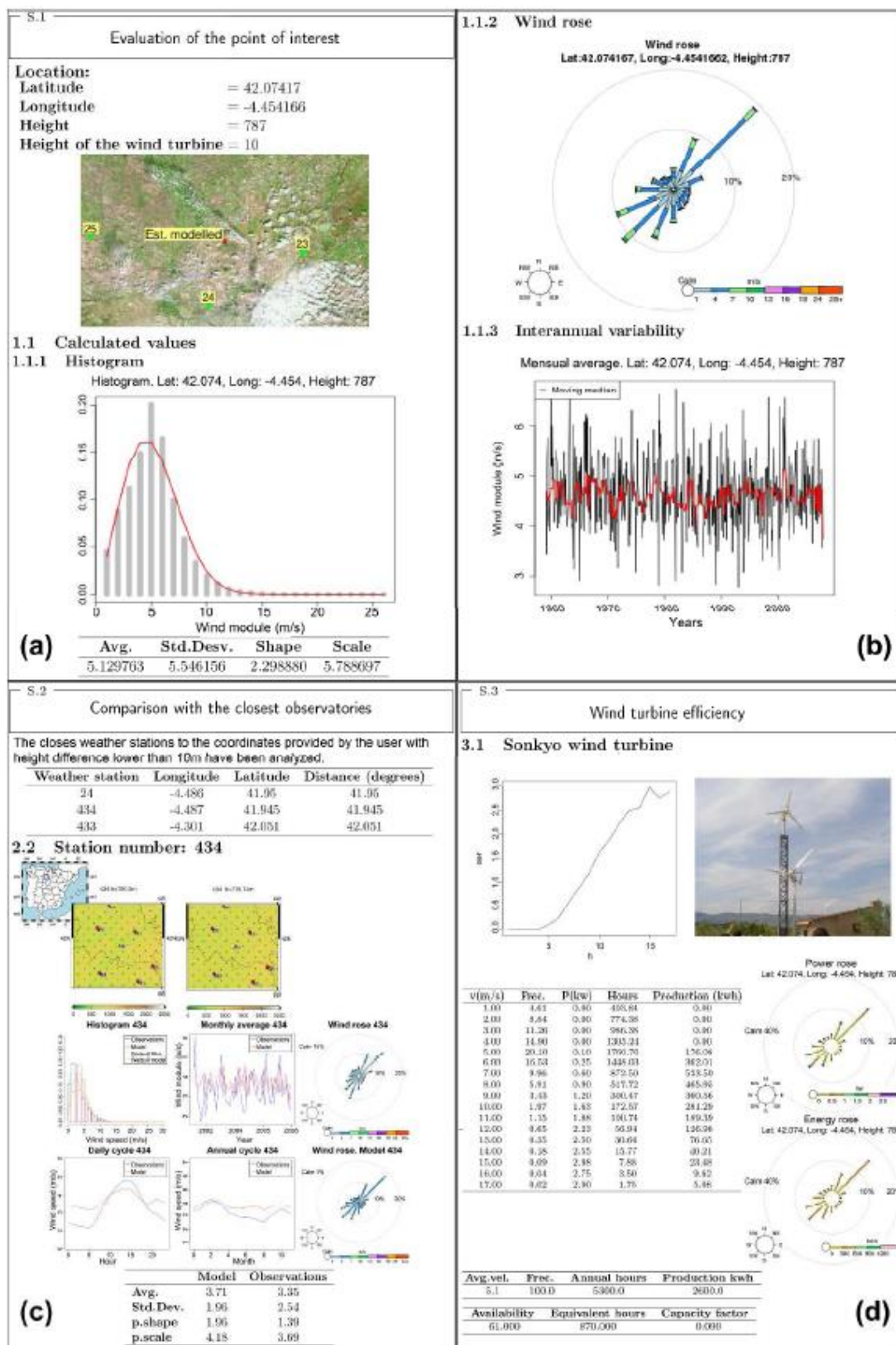


Figure 10. Complete report produced by the web mapping tool, with the results of the wind potential of the identified point.