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Development and Application of an Integrated Wind Resource Assessment Tool for Wind Farm Planning

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Abstract- An integrated wind resource assessment tool has been developed to help public operators and private investors in wind farm planning. The two-parameter Weibull probability density function is used to calculate wind speed frequency distribution. The system takes advantage of an integrated database including an updated list of more than 200 windgenerators manufactured by the most experienced worldwide companies. Main wind resource and turbine-converted energy indicators are computed, such as mean wind speed and power density, Weibull's scale and shape factors, Betz annual specific energy, availability and capacity factors, annual energy production, and full-load hours. A comprehensive energy report is eventually created for any site, including plots and tables such as wind rose and Joint Frequency Functions, Weibull's wind speed distribution and cumulated probability, annual energy production vs. turbine power curve. Thereby, the system is suitable for on-site pre-feasibility studies. Furthermore, it operates according to a point-by-point fashion, as it may be routinely run in an automated mode for a large number of points over the study area. This later enables main wind energy contouring maps to be plotted. The system has been applied to perform a wind turbine comparison aimed at detecting the site most efficient windgenerator within a number of works. As a benchmark, an extensive application of the developed system has been carried out to assess the large-scale wind potential of Tuscany region, Italy. Hourly wind estimates calculated by the coupled Weather Research and Forecasting (WRF) and CALMET models at a 2-Km resolution have been processed by the system over the region through a 4-year time period.

Keywords- Wind resource assessment; Wind energy assessment tool; Wind farm planning; Pre–feasibility studies; Turbine database; Energy report.

1. Introduction

The typical approach to assess the expected wind energy output of a wind turbine on a site is to pair the wind speed frequency distribution over the site and the turbine's power curve [1-6]. The two-parameter Weibull probability density function is the most commonly used and widely adopted continuous mathematical function in wind power studies [7-8]. It proved to fit the real wind speed distribution better than the lognormal, gamma and Rayleigh models [2,9]. In other words, most wind speed distribution characteristics at any site can be properly described by two parameters, i.e., the scale factor (c) and the shape factor (k). On the other hand, the increasing knowledge of wind turbine characteristics and actual on-site performances [1-5,8,10-15], along with turbines technical specifications (power curve, hub height, cut-in and cut-off speeds, rated power, etc.) easily accessible at the manufacturers websites, allowed characteristics of a number of commercially available windgenerators to be collected in structured archives as "ready-to-use" for applications, as shown, e.g., in [1,3,12]. Therefore, by combining the Weibull wind speed distribution with rather few turbine parameters, various studies were carried out worldwide to assess the expected wind energy output on a site and thus the economic viability of the project [1-8]. However, in spite of applying statistical formulations or graphical methods merely developed for the case under study, integrated computer programs purposely designed to thoroughly perform wind resource potential and wind energy yield were suitably developed, such as [16], where an integrated analytical method for calculating the wind energy potential in Syria is described based on more than 20 wind data measuring stations at 10 m a.g.l. Another example is given by a web tool entitled “Wind Energy Assessment Tool” developed by Bhuiyan et al. [17], which was tested to prepare a technical assessment of the energy generation for a sample wind turbine of 1 kW in Southern Bangladesh.

In principle, the finest wind energy potential assessment should result from long-term wind measuring campaigns at the site where the turbines are planned to be installed. However, since such an information is rarely available, data interpolations from wind measurements by the closest wind monitoring sites were performed, either by using simple spatializations [8] or more complex statistical techniques such as, e.g., measure-correlate-predict or artificial neural network [18-22]. Unfortunately, unless the terrain is flat and the land-surface characteristics are uniform, the distance over which existing wind information is useful is quite limited. In most cases, numerical methods with high-resolution grid sizes are needed, particularly over complex terrains and in case large-scale turbine classifications (and thus relevant heights above the ground) are under examination. As a matter of fact, numerical model simulations can produce 3-D wind field descriptions that cannot be obtained from extensive measurements. They can describe the changes induced on wind field from topography and land cover variations [23].

The use of modelled wind estimations proved to provide wind energy assessments being comparable with those based on experimental data, as shown, e.g., in [23-29]. In any case, a large number of wind measuring or estimating points should be available to carry out a high-resolution wind classification of a region [23-26], as well as a flexible and powerful computation tool to perform a detailed wind energy analysis. To achieve such a goal, an integrated wind resource assessment tool has been purposely developed, which is able to calculate all primary wind energy indicators, as well as eventually create for any site a comprehensive energy report including plots, tables and numerical values.

2. Methods

Weibull distribution can be characterized by its probability density function f(V) and cumulative distribution function F(V), as given in the following equations:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

$$F(v) = \int_0^{\infty} f(v)dv = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

where c is the scale parameter, k the shape parameter, and v is wind speed. Starting from frequency distribution of observed v records, Weibull’s c and k parameters can be calculated by using the least-square method [30], which was demonstrated, e.g., by Justus et al. [31], to best fit the observed distribution. The knowledge of c and k enables f(v) to be drawn for each v bin. Also, by applying formulations reported, e.g., in [32], the computation of most probable wind speed (v_{mp}) and wind speed carrying maximum energy (v_{maxE}) is straightforward:

$$v_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{3}$$

$$v_{\max E} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{4}$$

For a unit area A of the turbine rotor, power available P(v) in the wind stream of velocity v is given by [32]:

$$P(v) = \frac{1}{2}\rho A v^3 \tag{5}$$

where ρ is the air density. Mean wind power density (PD) of a site based on a Weibull probability density function can be expressed as:

$$PD = \frac{P}{A} = \int_0^{\infty} P(v) f(v) dv = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \tag{6}$$

where Γ denotes the Gamma function.

Once wind power density of a site is given, the wind energy density for a desired duration can be expressed as [8]:

$$E_T = PD * T = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) * T \tag{7}$$

where T is the time period, equal to 8760 for a 1-year duration.

The theoretically maximum power that can be extracted from the wind is expressed by the Betz specific mean wind power [8]:

$$P_{Betz} = \left(\frac{16}{27}\right)\frac{1}{2}\rho \bar{v}^3 \tag{8}$$

where is mean wind speed averaged over the full sample of observed v records. After multiplying P_{Betz} by T=8760, the Betz annual specific energy E_{Betz} can be achieved:

$$E_{Betz} = P_{Betz} * T = P_{Betz} * 8760 \tag{9}$$

Capacity factor (CF) is a crucial index for assessing the performance of a wind turbine at a given site. It is defined as the ratio of the energy actual production of a turbine (E_{TA}) over a given duration T, or turbine’s Annual Energy Yield (AEY) when commonly assuming T=8760, to the energy that could have been produced if the machine would have operated at its rated power (E_{TR}) throughout the same period [32]:

$$CF = \frac{E_{TA}}{E_{TR}} \tag{10}$$

The knowledge of CF enables Full-Load Hours (FLH) to be calculated after multiplying CF by the number of hours in one year (T=8760):

$$FLH = CF * T = CF * 8760 \tag{11}$$

Availability factor (AF) is another fundamental parameter to assess turbine's perfomance at a site, which accounts for the percentage of time that a wind turbine is operating, depending on wind turbine characteristics and wind energy potential. For a turbine having the cut-in speed vi and cut-off speed vo, AF is the probability of P(vi ≤ v <vo), which can be calculated using the following equation [8]:

$$AF = \int_{v_i}^{v_o} \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] dv \tag{12}$$

3. System Description

3.1. Architecture

The architecture of the developed integrated wind resource assessment tool is shown in Fig. 1. It consists of two integrated databases, relating to stations and wind turbines, respectively, a run management and stations database connecting module, a wind data import and processing tool, and eventually a computation core designed to perform the wind energy analysis. System's final result is the dynamic creation of an overall indicators spreadsheet for all stations, as well as a number of summarizing energy reports, one for any station, which include all main plots and tables.

Please note that in this work the term "station" is generalized and meant to be as whatever location or point where wind data or estimates are available to be processed.

3.2. Integrated Databases

The system is supplied by two integrated databases, i.e., a stations and a wind turbines database (see Fig. 1). In Table 1 the structure of the stations database is depicted, which is basically made of groups (G) of paired tables, where the first table include all station geographical features such as location, coordinates, elevation and roughness class, while the second table include wind data beginning and ending date, and file name. As a matter of fact, wind data resulting from various sources (subscript s) may be imported in the stations database, e.g., experimental data and/or model-calculated estimates by national or local offices/agencies, and therefore pairs of tables may be linked according to any wind data group (G_s) depending on specific user's application features.

Table 2 summarizes the structure of the wind turbines database, which consists of three tables: (i) a general one, including turbine's manufacturer and model, (ii) a geometric and operative parameters table, and (iii) the table where the turbine power curve per wind speed class is explicitly specified.

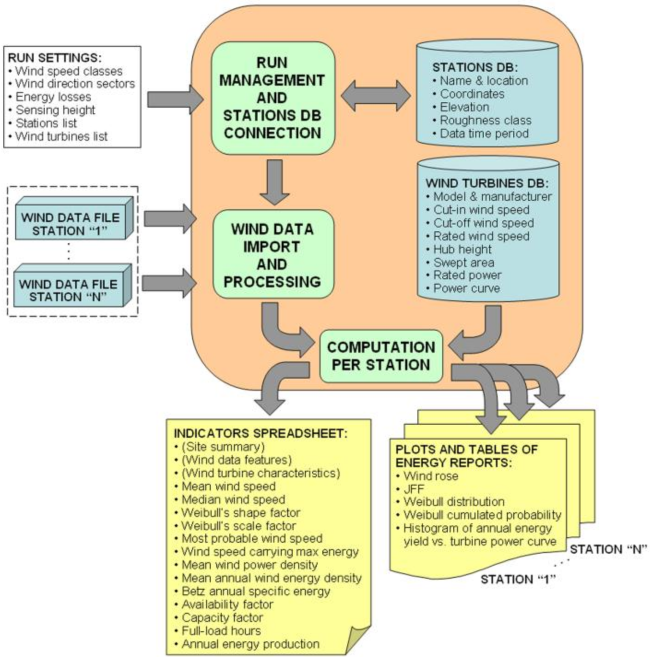

Fig. 1. Architecture of the developed integrated wind resource assessment tool.

Table 1. Structure of the integrated stations database

Table per G_s data group	Field	Example
Station	Location	Santa Fiora
	Province	Grosseto
	X-coordinate	1715.031 km
	Y-coordinate	4748.512 km
	Elevation	1115 m
	Roughness class	2
Time period	Beginning date	01/01/2004
	Ending date	31/12/2007
	Data file name	9513_CMET_01012004-31122007.csv

Table 2. Structure of the integrated wind turbines database

Table	Field	Example
General	Location type	On-shore
	Axis	Horizontal
	Power size	Large
	Manufacturer	VESTAS
	Model	V80
Parameters	Number of blades	3
	Cut-in wind speed	4 m/s
	Cut-off wind speed	25 m/s
	Rated wind speed	15 m/s
	Hub height	78 m
	Rotor diameter	80 m
	Swept area	5027 m^2
	Rated power	2000 kW
Power curve	No. wind speed classes	25
	Power output at 1 m/s	0 kW
	…	…
	Power output at 25 m/s	2000 kW

All turbines characteristics have been derived from technical documentation available at manufacturers' official websites. It is to be remarked that the wind turbines database includes an updated list of more than 200 windgenerators manufactured by the most experienced worldwide companies, working both on-shore and off-shore, ranging from small to large power size. Therefore, the user is enabled to perform a wide range of different applications suitably complying with his own needs.

3.3. Run Settings

Before running the system, a preliminary definition of a number of application settings is required. In particular, wind speed classes and wind direction sectors have to be set, as well as wind sensing height and expected energy losses. Concerning the latter, losses due to turbulent wakes, blade soiling, icing, aerodynamics, system control, grid connection dependent electric faults, turbine maintenance and availability are taken into account based on values suggested in literature [11,14,33], as well as air density reduction. In particular, the latter is calculated as a function of site mean air pressure (and thus elevation) and temperature, according to the formulation proposed by [34].

The system is driven in an automated mode by means of two independent lists, i.e., the stations and turbines ones, which enable multi-purpose applications to be easily performed. For example, particular cases apply when either a list of stations is processed for a given windgenerator model (addressing spatial wind potential assessment), or a list of turbines is entered out of a given wind dataset (aiming at on-site turbine efficiency comparison).

3.4. Input Wind Data

In Table 3 the structure of station-specific hourly wind data input files is presented, including wind speed and direction values on each processed station, whose features are derived from the stations database via the "Station ID" field, which is the primary key the access to the database is made. Wind data file may be either an MS Excel (.xls) spreadsheet or a simple ASCII comma-separated or space-separated text file (.csv, .txt, .prn). At this stage a number of data check are run, including invalid file format, missing or invalid data values, non-consecutive date or hours or sensing heights, etc. A possible data inconsistency results in a fatal error causing an alert message to be displayed to the user and the system execution to be stopped.

Table 3. Structure of station-specific hourly wind data input files

Field	Unit	Format
Station ID	-	I5
Date	-	DD/MM/YYYY
Hour	-	00-23
Sensing height	m	-
Wind speed	m/s	-
Wind direction	°N	-

It is to be highlighted that multi-level data may be processed as well, i.e., vertical wind profiles, as the user is offered the possibility of choosing the preferred data vertical level.

3.5. Computation Core

System's main core is given by a computation tool designed to run a detailed wind energy analysis. Such a tool has been developed according to current literature and state-of-the-art statements in wind energy field [1-12]. The two-parameter Weibull probability density function is used to calculate wind speed frequency distribution. Expected electric energy converted by the windgenerator is eventually computed once relatively few turbine parameters are entered, such as hub height, cut-in and cut-off speeds, rated power, swept area, as well as power curve.

The program's run procedure is divided into four main sections (see Fig. 1), namely:

(1) wind data import and processing;
(2) computation of wind speed statistics, Weibull distribution functions and Betz parameters;
(3) computation of expected turbine-converted wind energy;
(4) creation of indicators spreadsheet and energy reports.

It is noteworthy that, in the most general case, the above flow chart applies to any station and any turbine. Thereby, it works recursively for the product of both, which allows the program to be potentially applied for as large number of stations and turbines as the user likes.

The system is a mere computation tool as it is not supplied by a microscale or Computational fluid dynamics (CFD) model providing as input a properly arranged wind field. Nevertheless, its computation section was tested by comparing its produced results with the corresponding computation section of worldwide currently used softwares such as, e.g., WAsP (Wind Atlas Analysis and Application Program) [35].

3.6. Numerical and Graphical Outputs

Main wind resource and wind energy indicators are calculated for all stations, such as mean wind speed and power density, Weibull's scale and shape factors, Betz annual specific energy, as well as turbine-related availability and capacity factors, annual energy production and full-load hours. All these output indicators, along with input site summary, wind data features and turbine characteristics, are part of a purposely created MS Excel (.xls) spreadsheet, whose detailed structure is depicted in Table 4, where each record actually refers to any processed station.

Furthermore, for any station main plots and tables are calculated, such as wind rose and related Joint Frequency Functions (JFF), Weibull's wind speed probability density function and cumulative distribution function, histogram of annual energy production vs. turbine power curve. As a matter of fact, eventually a number of comprehensive output energy reports is dynamically drawn up, one for any station, as depicted in Table 5, either as MS Word (.doc) documents or (.html) web pages, including plots, tables and numerical values. It is to be noticed that, in the event energy reports are set to be created as web page (.html) files, a further (optional) field may be entered in the station-specific record of the output spreadsheet file, as shown in the last row of Table 4. This enables a direct hyperlink to the station-specific energy report to be easily activated from the spreadsheet itself to help the user have a comprehensive, graphical idea of wind energy pattern and turbine performance over the station site.

Table 4. Run summary and wind energy indicators included in the output spreadsheet

Type	Parameter	Symbol	Unit	Example
Input: site summary	Station ID	*ID*	-	9513
	Location	-	-	Santa Fiora
	X-coordinate	X	km	1715031
	Y-coordinate	Y	km	4748512
	Elevation	H_{asl}	m	1115
	Air density	ρ	kg/m^3	1.073
	Total energy losses	-	%	12.41
Input: wind data	Processed time period	-	-	01/01/2004-31/12/2007
	Processed data sample	-	h	35064
	Valid data sample	-	h	34890
	Valid data percentage	-	%	99.50
	Sensing height	H_{agl}	m	75
Input: wind turbine	Manufacturer	-	-	VESTAS
	Model	-	-	V80
	Rated power	P_r	kW	2000
	Hub height	H_{hub}	m	78
	Swept area	A	m^2	5027
Output: site wind resource	Mean wind speed	v	m/s	7.43
	Median wind speed	$\langle v \rangle$	m/s	6.62
	Weibull's shape factor	k	-	1.48
	Weibull's scale factor	c	m/s	8.29
	Most probable wind speed	v_{mp}	m/s	3.87

	Wind speed carrying max energy	v_{maxE}	m/s	14.77
	Mean wind power density	PD	W/m^2	494.87
	Mean annual wind energy density	E_T	kWh/m^2	4335.09
	Betz annual specific energy	E_{Betz}	kWh/m^2	2686.57
Output: turbine-converted wind energy	Availability factor	AF	%	71.4
	Capacity factor	CF	%	30.3
	Full-Load Hours	FLH	h/y	2661
	Annual Energy Yield	AEY	MWh/y	5176
	Energy produced over the period	E_{tot}	MWh/period	22443
Output: energy report[a]	Energy report web page file name	-	-	9513.html

[a] Optional field.

Table 5. Plots and tables included in the output energy reports

Object	Description
Plot	Wind rose
	Weibull probability density function
	Weibull cumulative distribution function
	Histogram of annual energy production vs. turbine power curve
Table	Site summary
	Joint Frequency Functions (JFF)
	Site wind statistics
	Turbine-related energy statistics
	Wind speed frequency and probability distribution vs. energy yield

4. System Benchmark

4.1. Application Features

An experimental version of the developed system has been applied to assess a wind turbine performance comparison in the energy efficiency assessment of a wind plant installation in the Livorno harbour, Italy [36]. A system's definitive version has been later applied to detect the site most efficient windgenerator within various works, e.g. [37-39]. Within this turbine comparison the user is helped in his models selection by filtering the turbine database by location (on-shore or off-shore), rated power range and hub height range. As a sample, Table 6 reports the system output of the wind turbine comparison performed by the site of Piombino (Italy) to detect the site most efficient model with 100-m hub height, regardless of rated power [39]. This comparison suggested to adopt the 2050-kW Repower MM92 wind turbine [40], featuring the highest CF (25.10%), as the reference windgenerator for site wind energy computations.

Furthermore, the system has been extensively applied by the LaMMA Consortium in the framework of the "WIND-GIS" project promoted by the Tuscany Regional Authority to assess the large-scale wind potential of Tuscany region, Italy. In particular, system's calculations become the basis of a purposely developed Geographic Information System (GIS) based interactive web decision support system for planning wind farms in Tuscany [41]. Hourly wind estimates calculated over the region by the coupled Weather Research and Forecasting (WRF) [42] and CALMET [43] models at a 2-Km resolution have been processed by the system over a 120x107 (12840) points computation grid. The system was applied in an automated mode through a 4-year time period (01/01/2004 to 31/12/2007), i.e., over a total of 35064 hours.

Table 6. Wind energy yield comparison based on observations performed at 100 m by the Piombino site (Italy) using different 100-m hub height windgenerators sorted by rated power (01/01/2001-31/12/2001)a

Windgenerator	P_r (kW)	D (m)	v_i (m/s)	v_r (m/s)	v_o (m/s)	AF (%)	CF (%)	AEY (MWh/y)
Fuhrlander FL1500-77	1500	77	4	12	20	65.82	21.92	2882
Nordex S77	1500	77	3	13	25	78.13	21.70	2853
Repower MD77	1500	77	3	13	20	78.10	21.51	2828
AAER A-2000-71	2000	71	4.25	14	25	62.70	14.78	2591
AAER A-2000-80	2000	80	3.5	13	20	72.06	19.30	3384
AAER A-2000-84	2000	84	3.25	12	20	75.11	21.41	3753
Enercon E82	2000	82	2	12	28	88.91	22.64	3970
Gamesa G80-2.0	2000	80	4	17	25	65.85	19.42	3404
Gamesa G87-2.0	2000	87	4	17	25	65.85	22.25	3901
Gamesa G90-2.0	2000	90	3	17	21	78.11	23.67	4150

Repower MM82	2050	82	3.5	13	25	72.09	20.54	3601
Repower MM92	**2050**	**92.5**	**3**	**12.5**	**24**	**78.14**	**24.89**	**4363**
Vestas V80-2.0	2000	80	4	15	25	65.85	19.42	3404
Suzlon S88-2100	2100	88	3	14	25	78.13	20.86	3839
Enercon E70	2300	70	2	15	28	88.91	16.26	3278
Nordex N90	2300	90	3	13	25	78.13	20.66	4165
Fuhrlander FL2500-100	2500	100	4	12	25	65.85	23.83	5222
GE Energy 2.5	2500	100	3.5	12.5	25	72.09	21.34	4676
Nordex N100	2500	99.8	3	12.5	20	78.10	22.86	5009
Repower 5M	5075	126	3.5	13	25	72.09	16.92	7415

[a]Total energy losses accounted for energy yield are 8.83%, resulting from the following: 0.33% (air density), 2.00% (control system), 3.00% (unavailability and maintainance), 2.50% (electric losses), 1.00% (other losses).

4.2. Wind Energy and Turbine Output Sample Results

As far as the station–specific output energy reports are concerned, herein some of graphical outputs carried out within the "WIND–GIS" project will be presented as a sample.

In particular, focusing on the site of Abbadia San Salvatore at the height of 75 m a.g.l. (01/01/2004 to 31/12/2007), Fig. 2 shows the related wind rose, whereas in Fig. 3 the wind speed frequency distribution vs. Weibull–fit is plotted, also reporting maximum and mean wind speed, Weibull's shape and scale factors, as well as Betz mean specific power and annual specific energy. Furthermore, once the VESTAS V80 2–MW rated turbine has been chosen [44], in Fig. 4 the histogram of energy production vs. turbine power curve per wind speed class is plotted, also displaying the total energy produced over the full 4–year period and the estimated annual energy production.

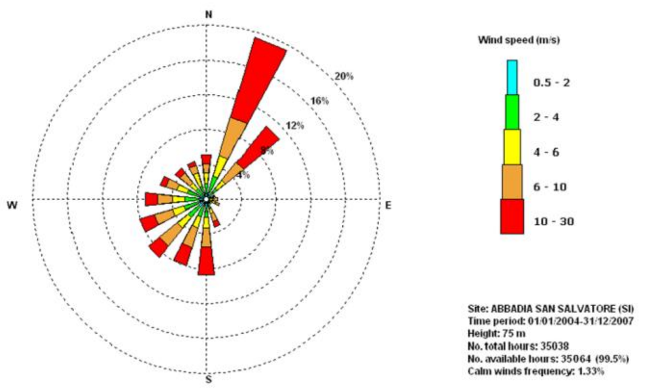

Fig. 2. Energy report sample: 75–m wind rose over the site of Abbadia San Salvatore (01/01/2004–31/12/2007).

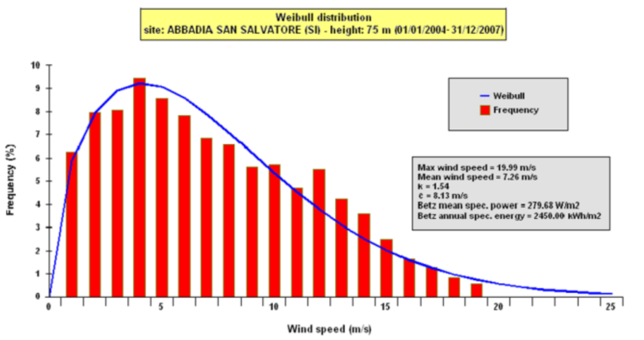

Fig. 3. Energy report sample: 75–m wind speed frequency distribution vs. Weibull–fit over the site of Abbadia San Salvatore (01/01/2004–31/12/2007).

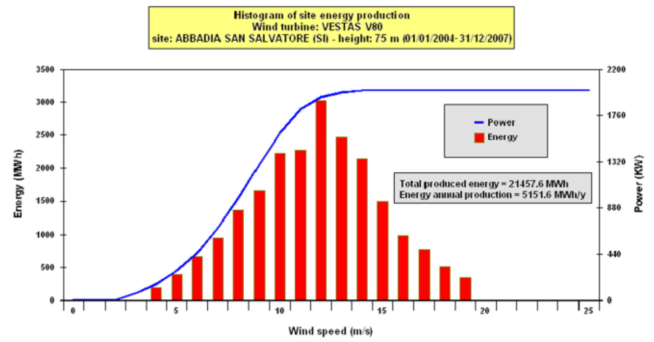

Fig. 4. Energy report sample: 75–m histogram of energy production vs. turbine power curve over the site of Abbadia San Salvatore (VESTAS V80 [44], 01/01/2004–31/12/2007).

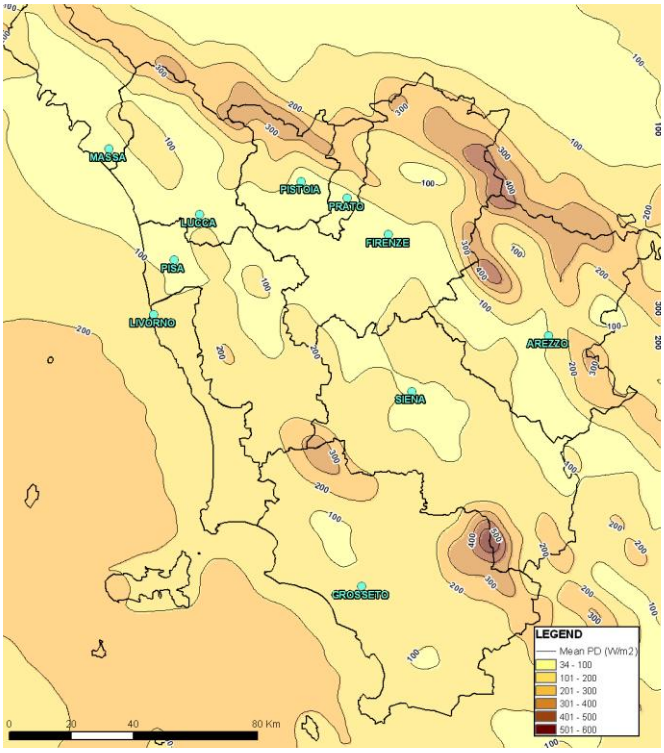

Fig. 5. Map of calculated mean power density at 75 m over the Tuscany region (01/01/2004–31/12/2007).

In addition to single station detailed analysis, once a number of available gridded points is large enough to be processed, main wind energy long–term contouring maps may be plotted over the study area. This was the case of the aforementioned Tuscany region application [41], where main wind energy indicators calculated over the processed gridded points and gathered in the spreadsheet file were used to create a number of contouring maps. As a sample, in Fig. 5 the map of mean power density (PD) is presented. Based on the selected windgenerator [44], in Fig. 6 the map of Full–Load Hours (FLH) is shown, i.e., the number of hours per year the wind turbine works at rated power. Actually, as given in Eq. 11, FLH is equivalent to the capacity factor (CF), i.e., the ratio of the annual energy yield to the product of rated power and 8760 hours (Eq. 10). Furthermore, the overlap of a number of layers such as environmental, landscape, and archaeological restricted areas as well as electric grid enables a more reasonable location of areas actually eligible for wind exploitation to be made as both exclusion and economic criteria can be also analyzed and eventually satisfied

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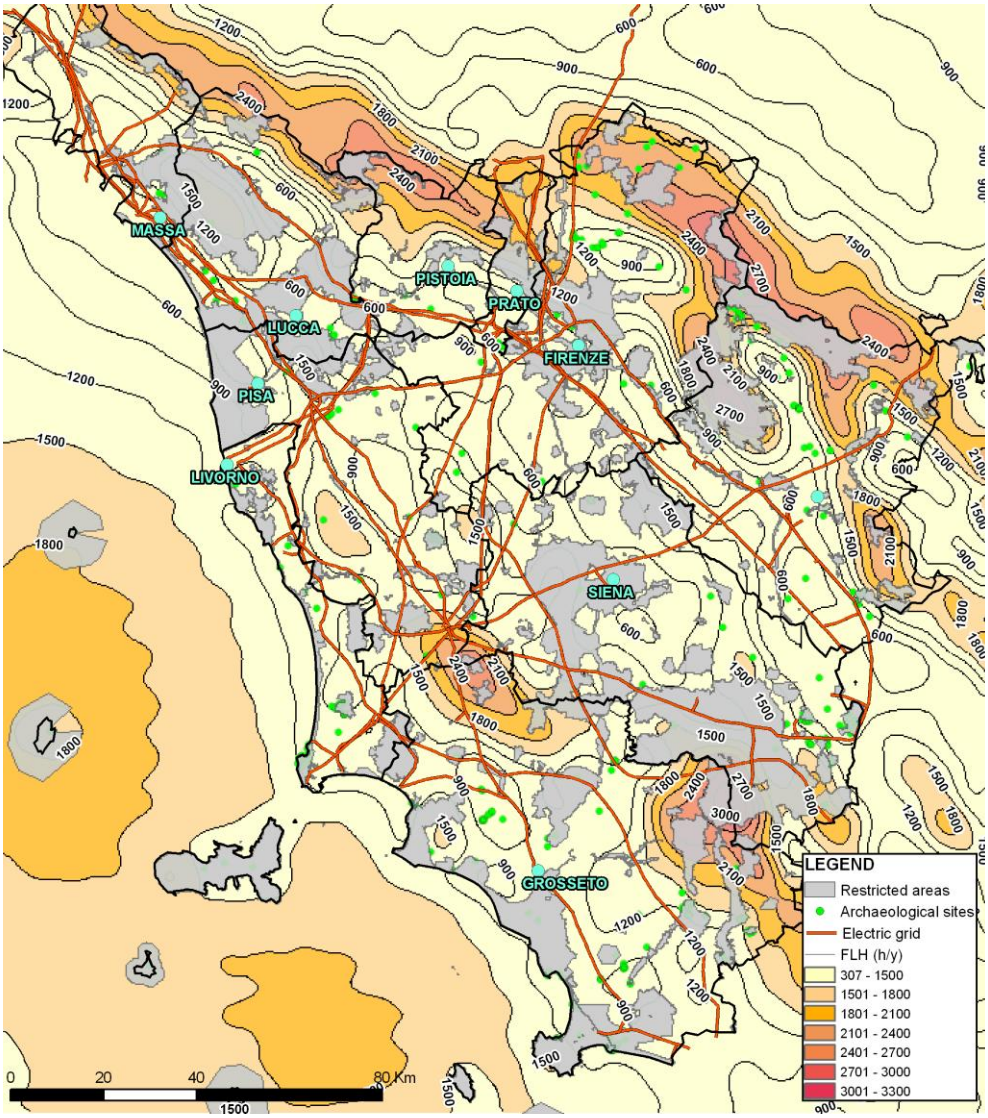

Fig. 6. Map of calculated full–load hours at 75 m over the Tuscany region for VESTAS V80 turbine [44] (01/01/2004–31/12/2007).

4.3. Technical Features

The system has been developed by using MS Visual Basic for running on Windows platform. In particular, the system is designed as an ActiveX control which, once launched, activates an Internet Explorer (.html) working environment. As a sample, in Fig. 7 a screen snapshot is captured while the system is running over the station of Santa Fiora at 75 m level (01/01/2004-31/12/2007), where in particular the first “General” tab is shown in evidence. Incidentally, the characteristics of the chosen windgenerator (VESTAS V80) are those reported in the “Example” column of Table 2, while the summary output results over this station are shown in the “Example” column of Table 4.

Fig. 7. Sample screen snapshot of system's environment captured while running.

On the other hand, the system takes advantage of the embedded MS Jet database engine to make the access to the integrated databases.

Bearing in mind the program's run procedure described in § 2.5, the computation of wind speed statistics and Weibull distribution functions (section #2) proved to require the highest time consumption. However, since the program works recursively for any station and any turbine, the

station to perform all station-specific computations, i.e., one record in the overall spreadsheet file and one energy report for each station (see Fig. 1). The system's automated run over 12840 stations through 35064 hours approximately required 7 days to be successfully brought to an end. As a final result, it produced a 12840-record spreadsheet file and 12840 energy report web page files. However, time consumption proved to be dramatically lower in the case the creation of all energy reports was disabled.

5. Future enhancements

A number of possible system's future enhancements could be performed. For example, the implementation of wind speed vertical extrapolation methods (based on power law or logarithmic law) as a function of site roughness would

greenhouse gas emission reduction, also useful to quantify possible annual incentives/credits, could be easily implemented, too. A further improvement might concern the assessment of on-site wind turbulence, particularly by means

machine's 100% CPU usage is completely released at each step, which makes the processing handle to be particularly efficient.

Referring to the benchmark features described in § 3.1, the system was tested on a dedicated Pentium 4, 2.40 GHz, 504 MB RAM PC with Windows XP on board. After the turbine model was set, it took approximately one minute per

enable to extrapolate observed wind speeds from the available heights (10-40 m) to the increasing hub height of modern wind turbines (50-100 m). To reduce the project risk, a full uncertainty analysis of power system might be incorporated, e.g., to account for those uncertainties described in [45]. Therefore, the computation of related expected annual energy yield by a probability of, e.g., 75 or 90% (P75, P90) could be implemented. Another possible enhancement might be the integration of a specific section focused on the wind farm economic analysis, and thus life cycle assessment. Once all project initial, annual and periodic costs have been quite accurately quantified and scheduled, this could be achieved through the computation of financial feasibility indicators such as energy pay back time, Return On Investment (ROI), Net Present Value (NPV), debt service coverage, Benefit-Cost (B-C) ratio, as well as yearly cumulative cash flow. The computation of wind farm related of parameters such as turbulence intensity, gust factor, standard deviation of wind direction, as well as the turbulence intensity vs. mean wind speed plot. Since this task can be accomplished provided that 10-min mean wind data are available, a substantial change would be necessary in the system's import and processing time step, which at the moment is 1-hour, actually (see Table 3 for example). The system's database module structure also allows new turbine manufacturers and/or models to be imported in the turbines database.

On the other hand, the system is designed to be dynamically supplied by a numerical model able to provide a properly arranged input wind field.

As shown in Table 4, the output spreadsheet is structured as to geographically characterize any station. In other words, since any record is supplied with coordinates, wind energy contouring maps may be easily plotted later, as performed in the current application (Figs. 5 and 6). This is a fundamental feature of the developed tool as it is naturally conceived to be integrated into a GIS-based decision support system in the future, such as, e.g., [46-50], as well as into a dynamic and interactive GIS-based wind resource mapping system available on the web, such as, e.g., [51-55].

Another possible enhancement of the developed system might be its implementation as an on-demand web tool to immediately calculate on-site wind resource and turbine-converted energy indicators, as well as create an energy report. In particular, once integrated into a weather (and thus wind field) web forecasting service, the system might predict expected wind energy production as well. The latter could be particularly useful to forecast the lowest yearly or monthly wind speed periods, and therefore when to possibly plan the turbine maintenance operations to minimize electric losses.

6. Conclusion

In the present work the development and application of a wind resource assessment tool is described, which is designed to help public operators and private investors in wind farm planning. Besides the computation of main wind resource and turbine-converted energy indicators filling in an overall output spreadsheet, the system is able to dynamically draw up a comprehensive energy report for any site, including plots, tables and numerical values. Since working according to a point-by-point fashion, the system may be routinely run in an automated mode for a large number of points over the study area, thus enabling wind resource and wind energy contouring maps to be later plotted for potential assessment purposes.

The system proved to be a powerful and flexible tool for on-site pre-feasibility studies, as it quickly returns comprehensive responses in terms of territorial-integrated wind energy assessment. As a matter of fact, the user is enabled not only to easily locate sites eligible for exploitation, but also be returned a number of possible different energy scenarios to analyze and choose from. In addition, the user is offered a wide range of wind energy applications to be carried out. Besides performing a numerical model based high-resolution wind energy classification of an area for a given turbine model, as described in the present work, it is possible to compare wind energy results in the case both experimental and estimated data are processed altogether. Since the system may be driven by a wind turbines list, too, it might be also used to assess a turbine performance comparison for a given wind dataset to detect the site most efficient windgenerator. When data sensing height (and thus turbine hub height) is set, performances resulting from turbines with different rated powers can be compared as well.

As a definitive benchmark, an extensive application of the developed system (12840 points over 35064 hours) has been carried out to assess the large-scale wind potential of the Tuscany region, Italy. As a result, system's calculations become the basis of a purposely developed GIS-based interactive web decision support system for planning wind farms in Tuscany.

However, a number of possible system's future enhancements could be performed. Internal improvements might address the following features:

(1). implementation of wind speed vertical extrapolation methods;
(2). assessment of uncertainty analysis;
(3). assessment of wind farm economic analysis;
(4). assessment of on-site wind turbulence;
(5). addition of new turbine manufacturers and/or models in the turbines database.

On the other hand, the system is naturally conceived to be:

(6). dynamically supplied by a numerical code providing a properly arranged input wind field;
(7). integrated into a GIS-based wind resource decision supporting system;
(8). integrated into an interactive GIS-based wind resource mapping system running on the web;
(9). implemented as an on-demand web tool to calculate on-site energy indicators;
(10). implemented as a wind energy production forecasting tool.

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