

V. RENEWABLE ENERGY SOURCES

BALANCE OF SOLAR AND WIND ENERGY SOURCES

Ludmil Stoyanov, Gilles Notton, Vladimir Lazarov

Abstract: In a hybrid system, the solar and wind power productions are used together increasing the system reliability. This work shows how solar energy and wind energy can be complementary (or not) using hourly values of wind speed and solar irradiation collected in 13 sites located in Bulgaria and Corsica. The renewable potential of these sites is estimated and their complementarity nature is studied at various time scales. The results show that wind and solar energy do not support always each other and depends largely on the season, on the site and on the time scale.

Keywords: hybrid systems; solar energy; wind energy; renewable energy sources

1. INTRODUCTION

The common drawback with solar and wind energy is their unpredictable nature. As specified by Ozdamar *et al* [1], the biggest problem in separately use of wind and solar energy is their discontinuity: A solar energy system, itself, cannot provide a continuous source of energy due to the low availability during the no-sun period and during winter; a wind system, itself, cannot satisfy constant load demands due to different magnitude of wind speed from one hour to another. In order to achieve the high energy availability required in some application such as: lighting, electrification of remote areas and telecommunications it is necessary to oversize the rating of the generating system. On the other hand it is possible to use hybrid system for which two or more renewable energy sources are exploited together. Hybrid systems were, at first, used only for remote systems but today, there is a trend to update the existing one source system (PV, Wind, hydro) into hybrid system also for grid connected applications. In the case of remote electrification, the hybrid renewable energy systems can include energy storage.

Sizing such hybrid systems is much more complicated than for single source systems, due to the high number of variables that have to be considered for the optimal design. A good review on renewable energy hybrid systems researches was performed [1-3]. More recent works [4-8] show the importance of meteorological data and load repartition on the sizing and performances of the hybrid system.

In general, the variations/fluctuations of solar and/or wind energy generation do not match the time distribution of the load demand on a continuous basis. But, moreover, the wind and solar resources are not always complementary. This complementary nature of the wind and solar resource in the US was

examined as early as 1981 by Aspliden [9] and by Reichling and Kulacki [10]. Special attention was paid to the energy sources complementarity issue in studies of Wind/Solar hybrid systems [1, 10-13].

The aim of this work is to see if solar energy and wind energy are complementary in using annual average hourly values for wind speed and solar irradiation collected in 13 sites located in Bulgaria and Corsica. The load distribution will be not taken into account; only the distribution of wind and solar sources will be studied. Monthly and daily correlation between these two resources will be analysed.

2. PRESENTATION OF THE SITES

This work was realized in the frame of collaboration between the University of Corsica (France) and the Technical University of Sofia (Bulgaria). In the present investigation, hourly wind speed and solar radiation measurements, made at various meteorological monitoring stations in Bulgaria (8 sites) and Corsica (5 sites) were used. The situation of the studied areas is shown in Fig. 1 and the altitude and geographical coordinates in Table 1.

Bulgaria is a small country located in south-eastern Europe in the Balkan region, its surface is 110 994 km² (22% of the peninsula surface) and its capital is Sofia. It is located between 41°11' and 44°11' N and between 22°22' and 28°37' E. Its relief is varied with 378 km of coastline and 5 chains of mountains with a height of over 2000 m and 31 summits above 2 700 m. This relief implies a very different climate compared to the European Mediterranean climate often present at this latitude. The Balkans stop cold air from the north, but the mountains Rila, Pirin and Rodopi limit the profitable influence of the Mediterranean Sea.

There are four seasons: cold and humid winter with average temperatures around 0°C, a dry and hot summer with average temperatures of 23°C and sunny autumn and spring.

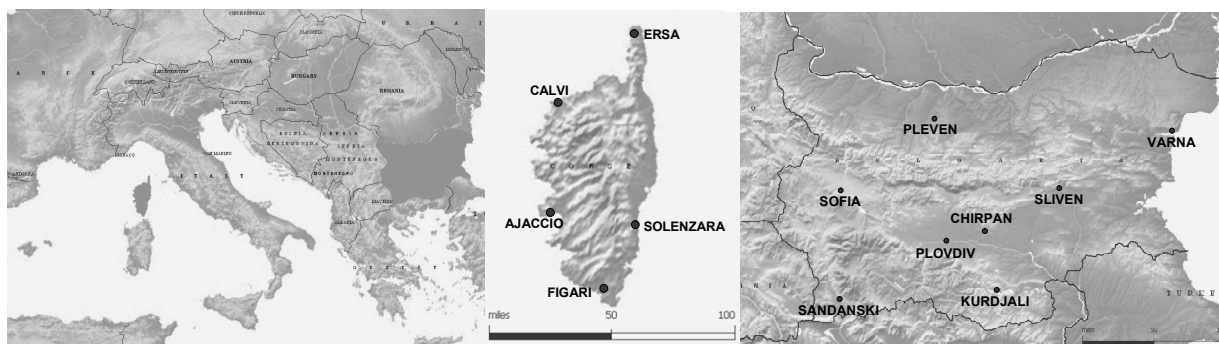


Fig. 1. Situation of the studied areas

Table 1. Geographical coordinates of studied sites.

Country	City	Longitude	Latitude	Altitude
Corsica	Ajaccio	8°44'27" E	41°55'29" N	10 m
	Calvi	8°45'38" E	42°34'0" N	12 m
	Ersa	9°23'4" E	42°58'27" N	213 m
	Figari	9°8'2" E	41°29'16" N	127 m
	Solenzara	9°22'39" E	41°50'4" N	7 m
Bulgaria	Chirpan	25°19'58" E	42°12'15" N	176 m
	Kurdjali	25°22'49" E	41°38'34" N	383 m
	Plevna	24°37'49" E	43°25'03" N	109 m
	Plovdiv	24°46'00" E	42°08'24" N	330 m
	Sandanski	23°16'44" E	41°34'22" N	618 m
	Sliven	26°19'54" E	42°41'29" N	431 m
	Sofia	23°19'17" E	42°42'25" N	610 m
	Varna	27°54'26" E	43°12'21" N	52 m

The Bulgaria annual average temperature is 10.5°C and this country receives between 2000 and 2400 hours of sunlight per year. The annual average precipitations are within the limits of 500 to 800 mm in the plains, and from 1000 to 1400 mm in a mountainous area. The global solar irradiation varies between 1400 and 1600 kWh/m² per year.

With its 8680 km² and an average altitude of 568 m, Corsica is the smallest, but the most mountainous of the 3 big occidental Mediterranean islands. The island is 183 km long from 41°19' to 43° N, and 83.5 km large from 6°31' to 7°13 E. Mediterranean by its situation, Corsica is alpine by its structure. The central fold, of North-Northeast direction, South-Southeast direction which splits Corsica into 2 parts, forms an important barrier which can be crossed over by passes often situated at a height of more than 1 000 m and, with snow in winter. As 10 peaks exceed 2 000 m, the most important being Monte Cinto with 2 710 m and Monte Rotondo with 2 625 m, this island is described as "a mountain in the sea". Corsica has

more than 1 000 km of coastal area (14% of the total French coasts). Corsica fits naturally into the Mediterranean climate zone with subtropical or temperate affinities according to the season. The importance of its relief introduces striking contrasts, the fundamental type evolving from a maritime Mediterranean climate to an alpine climate within only a few kilometres. Corsica has a high level of solar irradiation (average daily horizontal solar irradiation around 4.2 to 4.4 kWh.m⁻²).

3. RENEWABLE ENERGY POTENTIAL ON THE 13 SITES.

Average hourly values for wind speed and horizontal solar irradiations were used for this analysis and were calculated from 3 or 5 years of meteorological data according to the site.

3.1. Wind potential

The wind potential is presented in term of wind distribution and not in term of wind energy values

because it is more usual for a wind potential estimation. Using the Weibull model [14], time series data for one year are analyzed and distributional parameters are estimated for probability distributions.

The Weibull and Rayleigh probability density functions are commonly used and widely adopted [14-16]. Herein the Weibull distribution is used since the Rayleigh distribution is only a subset of it. The Weibull probability density function is a special case of a generalized two parameters gamma distribution. The Weibull distribution can be characterized by its probability density function $f(V)$ and cumulative distribution function $F(V)$ in the following formula:

$$f(V) = \left(\frac{k}{A}\right) \left(\frac{V}{A}\right)^{(k-1)} \exp\left[-\left(\frac{V}{A}\right)^k\right] \quad (1)$$

$$F(V) = 1 - \exp\left[-\left(\frac{V}{A}\right)^k\right] \quad (2)$$

where A is the scale parameter in m/s, k is the unitless shape parameter and V the wind speed.

If the probability function is already known, the average wind speed and the standard deviation are defined by:

$$\bar{V} = \int_0^{\infty} V \cdot f(V) dV = A \Gamma\left(1 + \frac{1}{k}\right) \quad (3)$$

Where $\Gamma(x)$ is the well-known Gamma function defined by:

$$\Gamma(x) = \int_0^{+\infty} t^{x-1} \exp(-t) dt \quad (4)$$

Others interesting wind speeds can be computed:

- the most probable wind speed V_{mp} representing the most frequent wind speed expressed by [16]:

$$V_{mp} = A \left(\frac{k-1}{k}\right)^{1/k} \quad (5)$$

- the wind speed carrying the maximum energy $V_{\max,E}$ expressed by :

$$V_{\max,E} = A \left(\frac{k+2}{k}\right)^{1/k} \quad (6)$$

- The median wind speed V_{med} , the speed dividing in two equal parts the wind speed distribution:

$$V_{med} = A \ln(2)^{1/k} \quad (7)$$

We calculated the two Weibull coefficients and the four previous wind speeds for 8 sites in Bulgaria and 5 sites in Corsica (see Table 2). The wind speed distribution and the corresponding calculated Weibull distribution have been plotted in Figs. 2.a and 2.b for respectively Bulgarian and Corsican sites. All these sites differ at the same time from an energy point of view and from a wind speed distribution point of view making this study more universal.

Comparing the various studied sites, we note that the wind potential variability is important because the annual average wind speed varies between 1.77 m/s for the worst site (Sandanski, Bulgaria) to 7.11 for the best one (Ersa, Corsica) and the k parameter is between 0.99 for Sandanski (Bulgaria) to 1.78 for Pleven (Bulgaria).

Table 2. Wind speed and Weibull coefficients for each site

Station	Reference	$\bar{V}$	V_{mp}	V_{med}	$V_{\max,E}$	A	k
Chirpan	A	1.93	0.09	1.42	5.63	2.02	1.04
Kurdjali	B	2.66	0.74	2.14	6.30	2.88	1.23
Pleven	C	4.32	3.08	4.00	7.51	4.91	1.78
Plovdiv	D	2.66	0.82	2.15	6.14	2.88	1.26
Sandanski	E	1.72	*	1.23	5.37	1.77	0.99
Sliven	F	2.10	0.16	1.56	5.94	2.20	1.06
Sofia	G	2.36	0.30	1.79	6.37	2.50	1.11
Varna	H	3.30	1.99	2.96	6.25	3.74	1.59
Ajaccio	I	3.50	1.74	3.03	7.11	3.91	1.45
Calvi	J	3.90	2.11	3.41	7.63	4.35	1.51
Ersa	K	7.11	4.89	6.54	12.66	8.10	1.72
Figari	L	5.96	3.39	4.77	9.64	5.94	1.65
Solenzara	M	3.13	1.36	2.65	6.61	3.46	1.38

* impossible to calculate

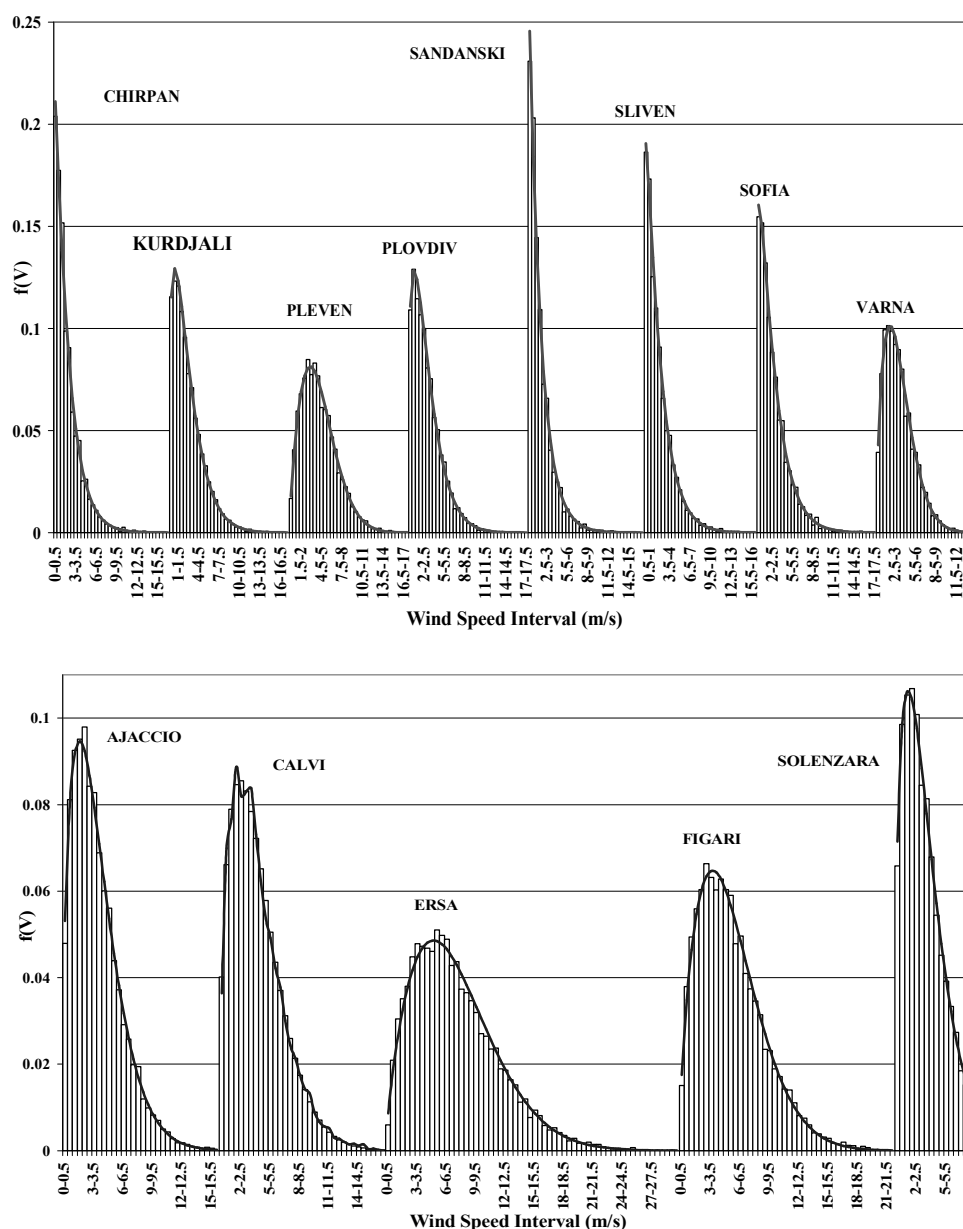


Fig. 2. Weibull distribution for the 8 sites in Bulgaria and 5 sites in Corsica

3.2. SolarPotential

We plotted in Fig. 3 monthly mean values of the daily horizontal solar irradiation. The variability of the solar potential from a site to another is less important than for the wind potential. However, we note some differences concerning the annual mean value of the daily irradiation from 3.25 for Sofia to 4.29 for Figari i.e. a variation of about 25%. Moreover, the monthly repartition of the solar irradiations shows some variations according to the site. The Bulgarian and Corsican sites being at the same latitudes the variation noted for horizontal irradiations must be the same for other inclinations of

the plane. But, we prefer to use hourly horizontal irradiations because these data are more easily available and the utilization of titled solar irradiations need to use complex methods to convert horizontal data to tilted data with not always a good precision.

4. COMPLEMENTARITY OF TWO RENEWABLE RESOURCES

The problem of the solar or wind generation system is the variability in power production caused by the time-varying renewable resource. Combining wind and solar together in a hybrid power plant can help to smooth this variation.

The amounts of solar radiation on the unit area of the horizontal plane surface and amount of wind energy on the unit area of a cross-section of the turbine propeller are compared.

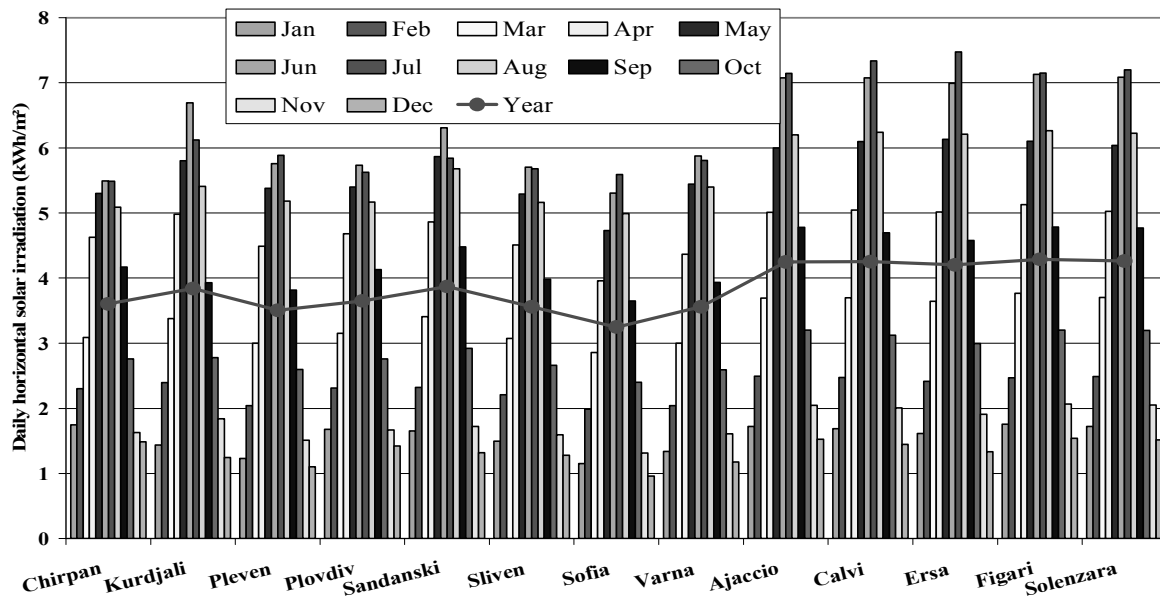


Fig. 3. Daily horizontal global solar irradiations

Balance of the wind energy and solar energy have been studied using previous measured data of total solar radiation on a unit of horizontal plane and hourly wind velocity on the wind turbine of 10 m high because it is generally the height of the measurement tower.

At first, we calculate for each hour the amount of wind energy during Δt per the unit of cross-sectional area given by the following equation:

$$E_{wind} = \frac{1}{2} \rho_a V^3 \Delta t \quad (8)$$

with the air density $\rho_a = 1.23 \text{ kg/m}^3$.

It is obvious that we cannot compare quantitatively the wind energy per unit of cross-sectional area and the solar energy per unit area of horizontal plane surface because the two unit areas do not refer to the same type of surface.

At first, we observed the variation of the two renewable resources on a monthly time step: thus, we want to see if during a no-sunny month (in winter) the wind power is higher than during sunny period.

To quantify the quality of the complementarity between the two renewable resources two parameters are used:

- a first one which quantifies the temporal simultaneity of solar and wind energy productions: the correlation coefficient defined by:

$$CC = \frac{\left[\sum_{i=1}^N (y_i - \bar{y})(x_i - \bar{x}) \right]}{\left\{ \left[\sum_{i=1}^N (y_i - \bar{y})^2 \right] \left[\sum_{i=1}^N (x_i - \bar{x})^2 \right] \right\}^{1/2}} \quad (9)$$

where y_i and x_i are the i^{th} monthly mean values of the daily wind energy and daily solar irradiation values at same time month i , $\bar{y}$ the mean value of the wind energy and $\bar{x}$ the mean value of the solar irradiation.

- a second one which quantifies the relative ratio between the two annual quantities of renewable energy received and defined by

$$R = \frac{\bar{E}_{solar}}{\bar{E}_{wind}} \quad (10)$$

where $\bar{E}_{solar}$ and $\bar{E}_{wind}$ are respectively the annual average of daily solar irradiation per m^2 and daily wind energy per m^2 .

More CC is near 1, more the two renewable sources vary in the same way. For us, a good site will be a site for which it exists a negative correlation between the availability of solar irradiation and wind energy i.e a site for which the correlation coefficient is near to “-1”.

For each meteorological station, we plotted in Fig. 4a and Fig. 4b the monthly wind energy per unit of cross-sectional area and the monthly solar energy per unit area of the horizontal plane surface.

Only four stations present a negative correlation between solar and wind energy: Pleven (CC = -0.225), Sliven (CC = -0.587), Solenzara (CC = -0.747) and Ersa (CC = -0.903); but, between these four sites, only

Pleven has an interesting wind potential and Ersa is the best site from a complementarity point of view at a monthly scale.

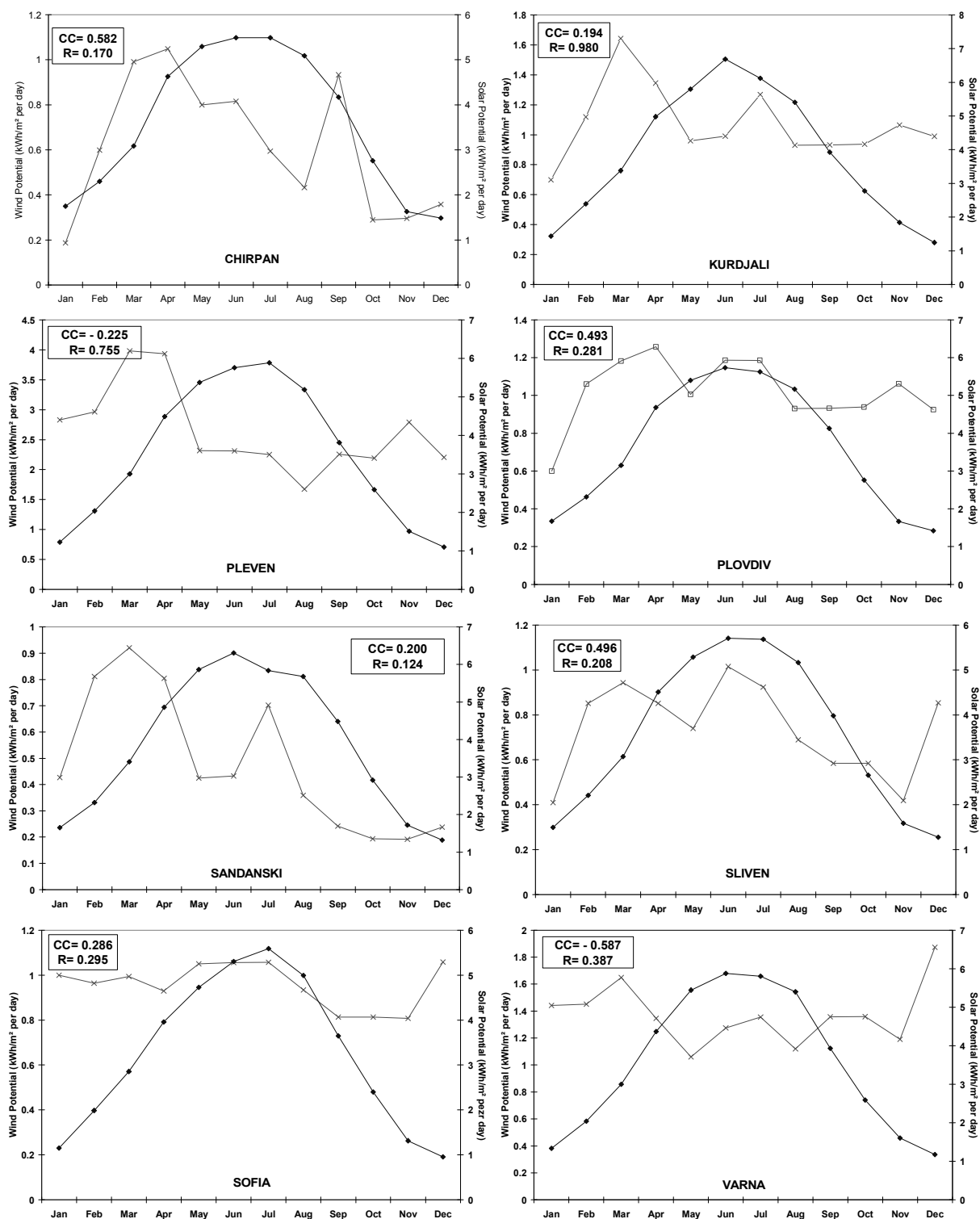


Fig. 4a. Monthly variation of solar and wind energy for Bulgarian sites

The monthly solar irradiation, for a given month, does not vary very much from a site to another one, thus the ratio R can be considered as representative of the renewable energy available on the site.

Now, it seems interesting to observe the variations of the two resources hour per hour throughout the day. We calculated for each month, the monthly mean value of the hourly wind and solar energy. Then, for each month, we computed the two previous parameters: the correlation coefficient CC defined by Eqs. (9) with some modifications y_i and x_i are the i^{th} hourly values of wind energy and solar irradiation values at same hour i and the ratio R is the daily wind energy on the daily solar energy according to Eq. (10). The ratio R is

useful to judge how wind energy can complete the solar energy in term of quantity but it seems not sufficient to quantify the renewable energy available for the given month on a given site. Thus, we introduce a new parameter, the product of the daily wind energy by the daily solar energy. This parameter, even if its dimension (Wh^2/m^4) does not correspond to a habitual size, its meanings is easier: it is linked to the renewable potential of the site. We don't choose to add the two energies because a previously said, the wind energy per unit of cross-sectional area and the solar energy per unit area of the horizontal plane surface cannot be compared in size and cannot be added.

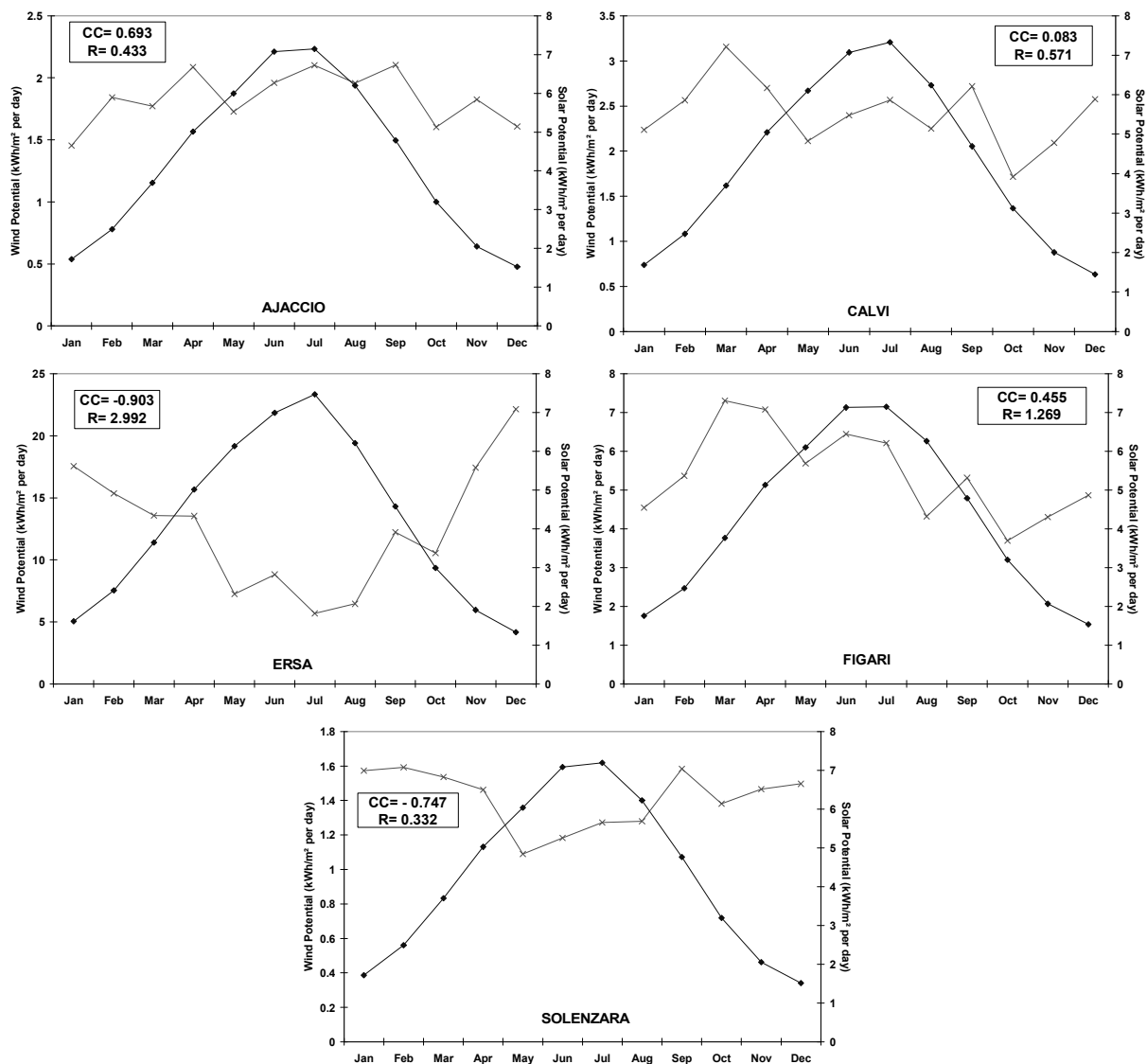


Fig. 4b. Monthly variation of solar and wind energy for Corsican sites

In Fig. 5, we show, for each month, the results of the analysis of complementarity at the daily scale.

The correlation coefficient CC is on the X-axis, the Ratio R is on the Y-axis and the size of the bubble is

linked to the multiplication of the two energies per m^2 . Thus, more the bubble is big, more the renewable potential of the site is high. More the bubble is to the left of the graph, more the solar source and the wind source support each other in the

time during the day. More the bubble is located upwards, more the wind energy completes the solar energy in term of quantity. The letter into or near the bubble corresponds to the meteorological station (see Table 2).

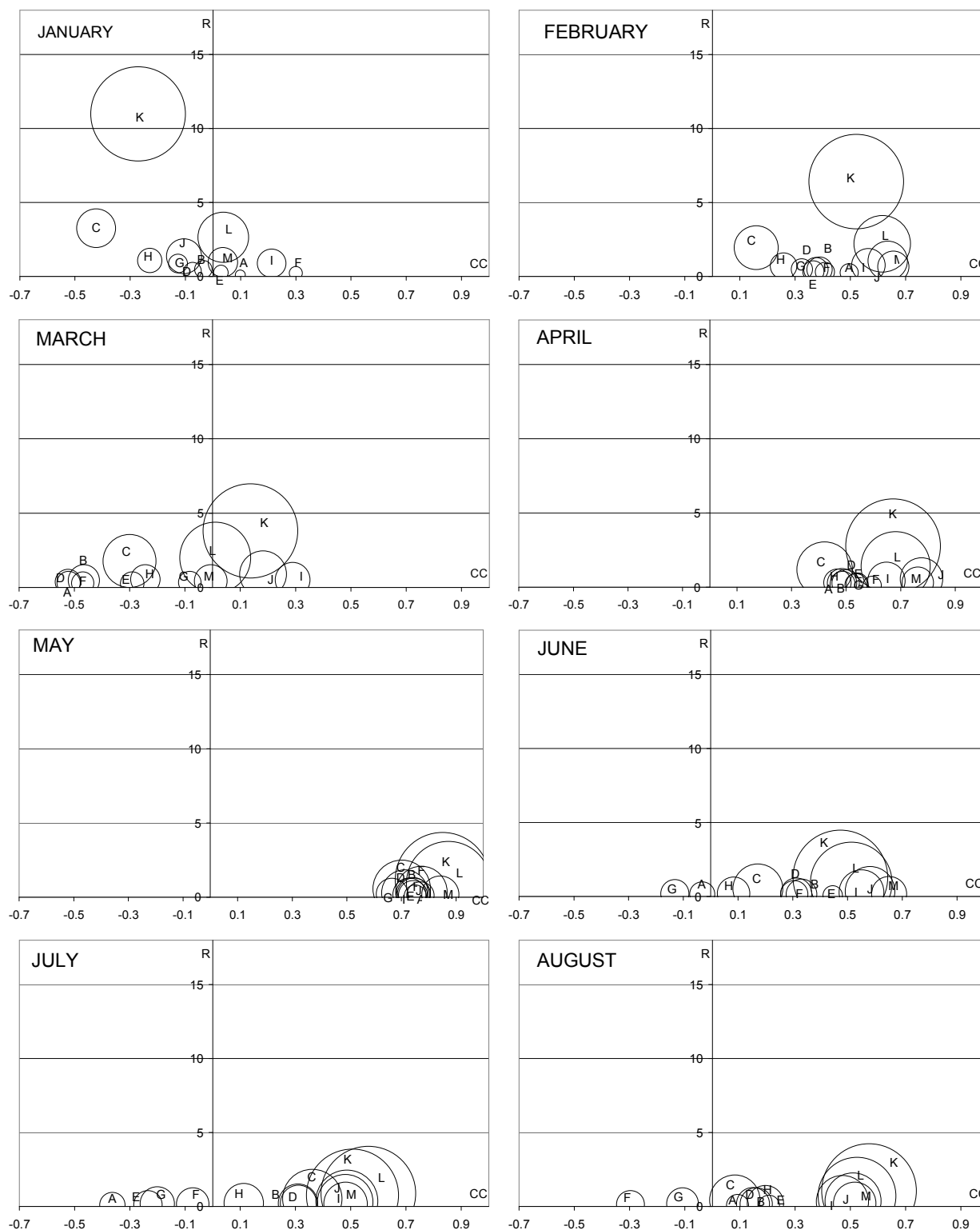


Fig. 5.a Complementarity of renewable sources at daily scale (January to August)

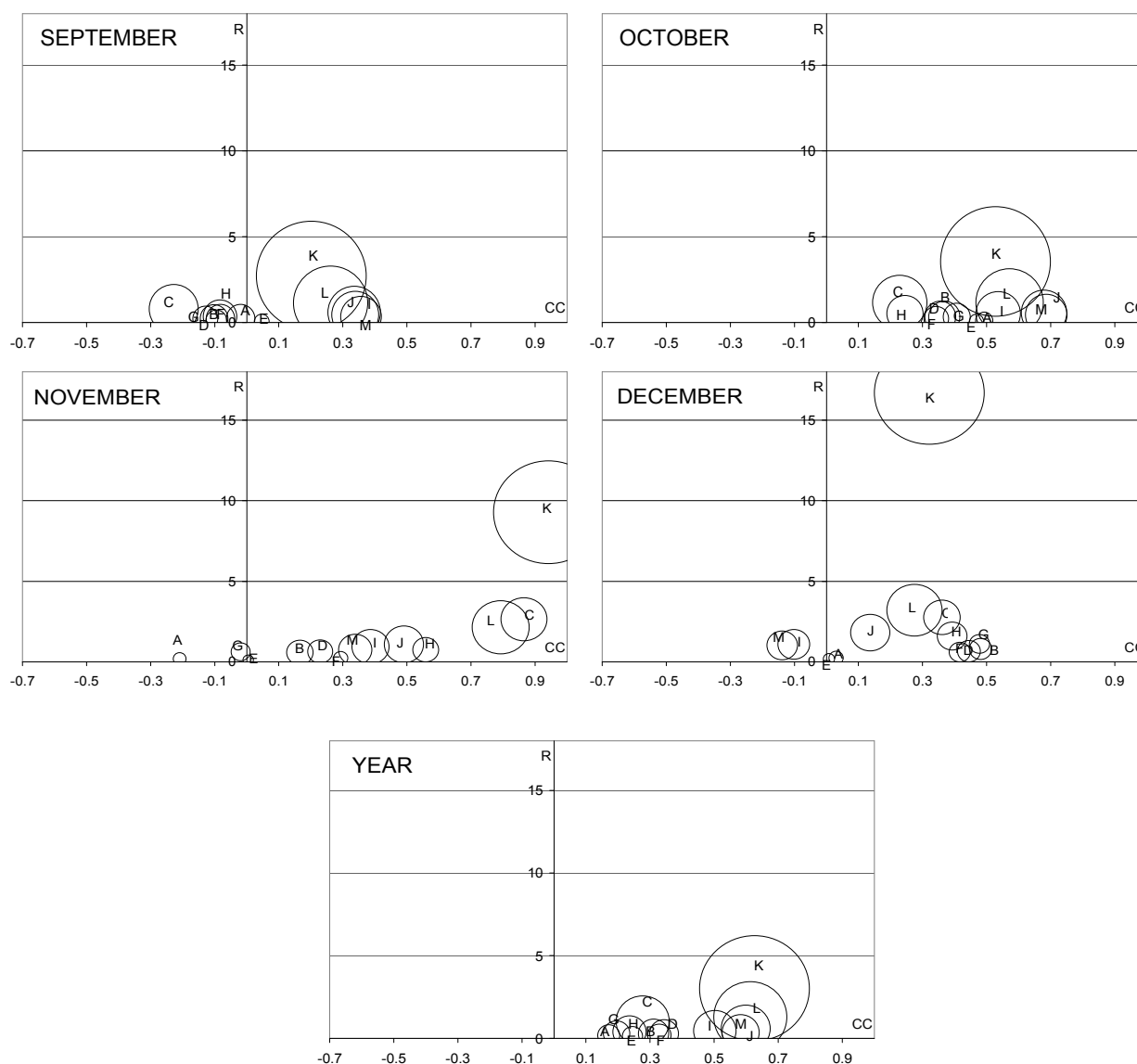


Fig. 5.b Complementarity of renewable sources at daily scale (September to December and annual)

We note a high difference of the bubble position and size according to the month, the complementarity of the two renewable resources during the day depends on the month and it is difficult to give a general conclusion for a given site without observing what happens month by month.

In Table 3 the extreme values for each parameters that vary widely according to the site and the month are reported. Moreover, we can think that the coefficients R and P are linked but even we observe that the minimum and the maximum values of R and P are obtained for the same station, they have not been reached for the same month.

To illustrate the influence of the daily repartition of the two energies on the three parameters values, we plotted in Fig. 6, as an example the daily variation of

the solar and wind energy per m^2 for Ersa in November and for Sliven in March. First observation: the daily repartitions of the average hourly wind speed and of the wind energy are very different; if the average wind speed is relatively constant, this is not the case for the wind energy; it is due to the fact that the monthly average of the hourly wind energy is an average of values proportional to the cube of the wind. For Ersa in November, we observe simultaneity between the solar and the wind productions and consequently a high positive value of CC , for Sliven in March the two productions are nearly in opposite phase. For R and P , it is easy to see the difference between the two sites for the two given months.

Table 3. Minimum and maximum values of the three parameters

	Minimum	Maximum
CC	-0.611	0.934
	Sliven (03)	Ersa (11)
R	0.054	16.59
	Sandanski (09)	Ersa (12)
P	314000	68539252
	Sandanski (12)	Ersa (04)

(number) = number of the month

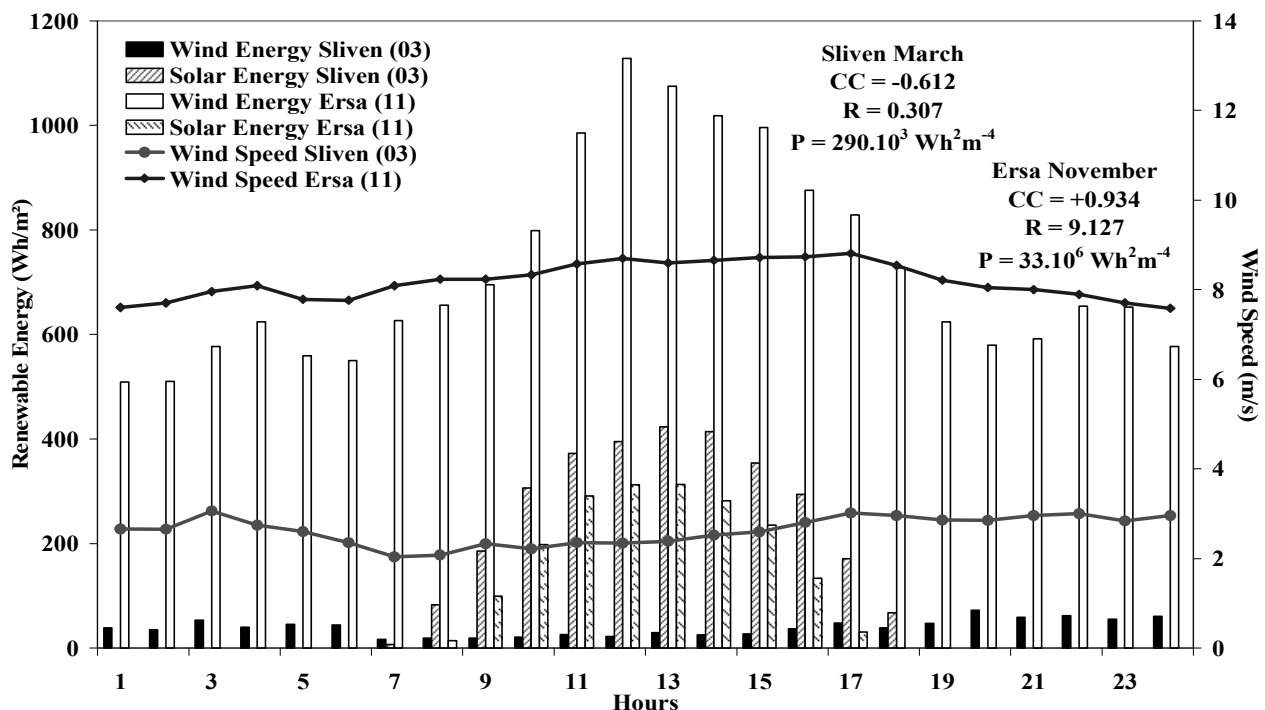


Fig. 6. Two examples of wind and solar energy daily repartition

5. CONCLUSIONS

To realize this study, we defined and used three parameters to characterize the site during a given period. The study has been conducted at monthly and daily scale. The Ersa station, in Corsica, solar energy and wind energy support each other very well each month; but, during the day, it is not the case excepted for January and March. For Sofia, it is the opposite, the complementarity is relatively good at the daily scale during 7 months per year, but not at a monthly scale and moreover, unfortunately, the renewable potential of this site is not very high.

As a result of examination of all tables and figures, it can be seen that it is impossible to conclude in a general way about the complementarity of the two

renewable resources: solar resources and wind resources. It depends on the site, on the period and on the considered time step.

For a more complete work, it would be necessary to introduce in this study the load curve i.e. the variation of the load to supply versus the time because it would be interesting to look for a positive correlation between utility electric demand and the availability of electricity generated from solar and wind. It will be interesting to see if either just solar energy system or just wind energy system can satisfy constant load demands for national grid and/or to satisfy a load in remote production or if wind and solar energy systems can be used as a combined system to meet this energy demand.

Moreover, if we can consider, with a good approximation, that there is proportionality between the photovoltaic production and the solar irradiation, it is not right for wind turbine production because the electrical production must take into account the power profile of the wind turbine.

These two topics, simultaneousness between the renewable resources and the load consumption on the one hand and the influence of the wind turbine power curve on the complementarity between the electrical production of the wind turbine and of the photovoltaic system on the other hand, will form the subject of two future studies.

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БАЛАНС МЕЖДУ СЛЪНЧЕВИ И ВЯТЪРНИ ЕНЕРГИЙНИ ИЗТОЧНИЦИ

Людмил Стоянов, Жил Нотон, Владимир Лазаров

Abstract: В хибридни системи използването на произведената енергия от два източника – слънчевите и вятърните генератори, увеличава надеждността на системите. Тази статия разглежда взаимното допълване (или не) между слънчевата и вятърната енергия, използвайки почасови данни за скоростта на вятъра и слънчевата радиация, измерени на 13 места в България и Корсика. Оценен е енергийният потенциал на възобновяемите източници в тези места и е изследвано взаимното допълване при различни времеви мащаби. Резултатите показват, че енергиите от Слънцето и вятъра не винаги се допълват, като допълването им зависи силно от сезона, мястото и времеви мащаб.

Ключови думи: хибридни системи, слънчева енергия, вятърна енергия, възобновяеми източници на енергия

Assoc. Prof. Ludmil Stoyanov

Laboratory on Renewable Energy Sources
Faculty of Electrical Engineering
Technical University of Sofia
8, Kl. Ohridski Blvd.
1000 Sofia
Bulgaria
Tel: +359.2.965.24.65
Fax: +359.2.962.44.07
email: ludiss@tu-sofia.bg

Assoc Prof. Gilles Notton

Research Centre of Vignola
University of Corsica
UMR CNRS 6134
route des Sanguinaires
F20000 Ajaccio
France
Tel: +33.4.95.52.41.52
Fax: +33.4.95.52.41.42
e-mail: gilles.notton@univ-corse.fr

Prof. Vladimir Lazarov

Laboratory on Renewable Energy Sources
Faculty of Electrical Engineering
Technical University of Sofia
8, Kl. Ohridski Blvd.
1000 Sofia
Bulgaria
Tel: +359.2.965.24.59
Fax: +359.2.962.44.07
email: vl_lazarov@tu-sofia.bg

доц. Людмил Стоянов

Лаб. по Възобновяеми Източници на Енергия
Електротехнически Факултет
Технически Университет – София
бул. Кл. Охридски 8
1000 София
България
Тел: +359.2.965.24.65
Факс: +359.2.962.44.07
имейл: ludiss@tu-sofia.bg

доц. Жил Нотон

Изследователски център Виньола
Корсикански Университет
ЮМР ЦНРС 6134
рут де Сангинерс
Ф20000 Аячо
Франция
Тел: +33.4.95.52.41.52
Факс: +33.4.95.52.41.42
имайл: gilles.notton@univ-corse.fr

проф. Владимир Лазаров

Лаб. по Възобновяеми Източници на Енергия
Електротехнически Факултет
Технически Университет – София
бул. Кл. Охридски 8
1000 София
България
Тел: +359.2.965.24.59
Факс: +359.2.962.44.07
имейл: vl_lazarov@tu-sofia.bg