

**Research
Article**

On the Wind Power Rejection in the Islands of Crete and Rhodes

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wind power penetration;
wind energy rejection;
isolated power systems

Crete and Rhodes represent the two biggest isolated power systems in Greece. The energy production in both islands is based on thermal power plants. The annual wind energy rejection percentage is calculated for Crete and Rhodes in this paper. The rejected wind energy is defined as the electric energy produced by the wind turbines and not absorbed by the utility network, mainly due to power production system's stability and dynamic security reasons. A parametric calculation of the annual wind energy rejection percentage, in terms of the installed wind power, the power demand and the maximum allowed wind power instant penetration percentage, is accomplished. The methodology takes into account (i) the wind power penetration probability, restricted by the thermal generators technical minima and the maximum allowed wind power instant penetration percentage over the instant power demand; and (ii) the wind power production probability, derived by the islands' wind potential. The present paper indicates that isolated power systems which are based on thermal power plants have a limited wind power installation capacity—in order to achieve and maintain an adequate level of system stability. For a maximum wind power instant penetration percentage of 30% of the power demand, in order to ensure an annual wind energy rejection percentage less than 10%, the total installed wind power should not exceed the 40% of the mean annual power demand. The results of this paper are applicable to medium and great size isolated power systems, with particular features: (i) the power production is based on thermal power plants; (ii) the power demand exhibits intensive seasonal variations and is uncorrelated to the wind data; (iii) the mean annual power demand is greater than 10 MW; and (iv) a high wind potential, presenting mean annual wind velocity values greater than 7.5 m s^{-1} , is recorded. Copyright © 2007 John Wiley & Sons, Ltd.

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Introduction

Crete and Rhodes are the two biggest islands in Greece, as far as the populations and the socioeconomic activities are concerned. The islands' local economies are based mainly on tourism (especially in Rhodes), agriculture, commerce and small industries (Crete).

The developing socioeconomic activities in both islands are reflected in the annual energy consumptions characteristic features. The two islands exhibit the highest annual energy consumptions and power demand peaks in the insular Greek territory.^{1,2} Both islands constitute isolated power production systems. All the consumed energy is produced on their respective landmasses.

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In Crete and Rhodes, the wind power penetration is limited by the following:

- the demand for uninterrupted power production and the produced power quality;
- the isolated power systems peculiarities; and
- the wind stochastic nature.

Despite the improved wind generators' behaviour concerning the produced power quality and the utility network compatibility, the wind stochastic nature does not allow the achievement of high wind power penetration.^{3–10} Moreover, wind energy rejection in isolated power production systems is significant because:

- the power demand exhibits intensive seasonal variations and it is uncorrelated to the weather conditions. In the cases of Crete and Rhodes, these are imposed mainly by the touristic sector, due to which the power demand increases considerably during summer (as a result the correlation coefficient between the actual wind velocity at different sites and the power demand of Crete was in all cases less than 0.20; approximately 50% had an absolute value less than 0.05). The total installed wind power in a Greek isolated power system during a year is not permitted to be over the 30% of the maximum annual power demand of the previous year. In an isolated power system with intensive seasonal power demand variations, the power demand during low power demand seasons will be significantly lower than the maximum power demand. Hence, the installed wind parks will be underemployed during the low power demand seasons, exhibiting high wind energy rejection.
- the requirement for power production system dynamic security and stability imposes an upper threshold to the thermal production substitution from the wind power. The stability of an isolated power production system is affected negatively for increasing ratios of wind power penetration over the total power demand (especially when it exceeds an upper limit). In these cases, a sudden power production loss, probably caused by an abrupt wind velocity gust or a turbine blade damage, may result in a partial or total blackout, if the system is not sufficient to undertake in a short time period the power production loss. Therefore, in order to ensure the stability of the system, a wind power penetration upper limit relative to the power demand is set.

These constraints may lead to considerable wind power rejection in isolated power systems. The wind power rejection depends on the total installed wind power in the isolated power system and the power demand scale.

Despite the above constraints, both Crete and Rhodes represent highly attractive territories for wind parks installations. This is due to the excellent wind potential and the increased power demand in both islands. The present paper investigates the ability of the two islands to accept new wind parks installations, without increasing considerably the annual wind energy rejection. Finally, a parametric calculation of the annual wind energy rejection percentage is presented in terms of the installed wind power, the power demand and the maximum allowed wind power instant penetration percentage. An overall diagram, providing the annual wind energy rejection percentage in isolated power systems in terms of the abovementioned parameters is constructed and presented.

Methodology and Data

Outline

The annual wind energy rejection percentage calculation is based on a methodology introduced by the Greek Regulatory Authority of Energy (R.A.E.)¹¹ and is applied for the years 2004 and 2007.

The methodology takes into account:

1. the wind power penetration probability, restricted by the thermal generators technical minima and the maximum allowed wind power instant penetration percentage.
2. the wind power production probability, based on the wind potential of the islands and the power curves of the installed wind turbines.

The necessary data for the application of the methodology are:

1. the annual power demand probability density functions of the two islands. The probability density functions for the year 2007 are based on the assumption of an annual power demand increasing rate of 7% in both islands.²
2. the synthesis of the power production systems. The characteristics of the thermal generators and the renewable production ones are taken into account, such as their power curves, the thermal generators technical minima and nominal powers, and the on-duty sequence into the production procedure.
3. a prediction for the installed thermal generators in the islands by the year 2007.
4. the wind potential of the islands of Crete and Rhodes, in terms of the Weibull probability density function parameters C and k .^{12,13}

The abovementioned R.A.E. methodology is applied in each investigated island and year for several scenarios, concerning the total installed wind power. For each installed wind power scenario, the annual wind energy rejection is calculated.

The Power Demand Curves

The local authorities of Power Production Corporation (P.P.C.) provided the data to model the annual mean hourly power demand time series for the islands of Crete and Rhodes in 2004. The power demand time series for the year 2007 are based on the assumption of an annual power demand increasing rate of 7% in both islands.²

The power demand curve for Crete for the year 2004 is presented in Figure 1. In the same figure, the on-duty thermal generators total technical minima are presented. Figure 2 presents the power demand duration

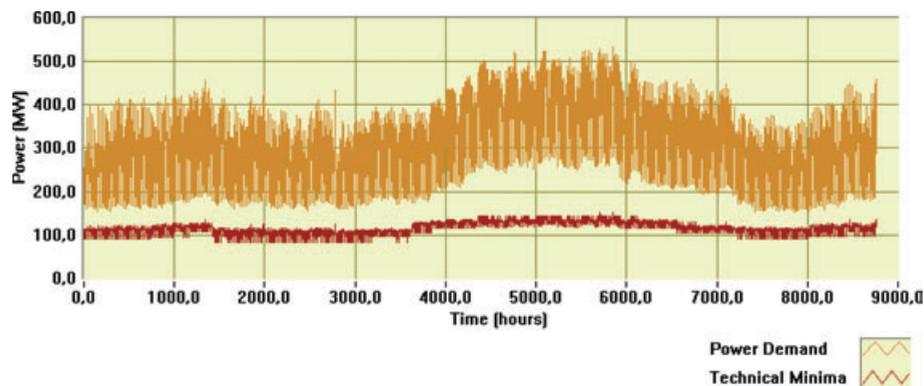


Figure 1. Annual power demand curve and technical minima of the on-duty thermal generators of Crete in 2004

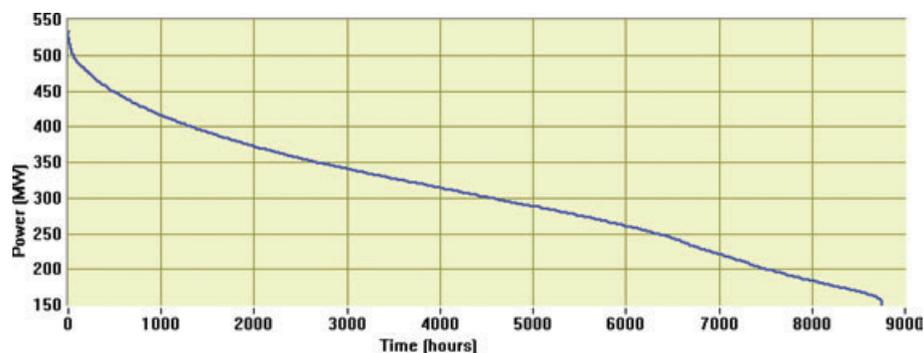


Figure 2. Crete annual power demand duration curve of 2004

curve. Each point on the curve presents the duration that the power demand was below a certain level for Crete.

The corresponding figures for the island of Rhodes and for the year 2004 are presented in Figures 3 and 4. The figures for the year 2007 exhibit similar trends.

A summary of the time series statistics is observed in Table I. Although there are considerable similarities to the nature of the systems, there are also noticeable differences in the size of the systems, such as:

- The power demand statistics (i.e. maximum or average power demand, annual energy consumption) in Crete are approximately three times higher than that of Rhodes.

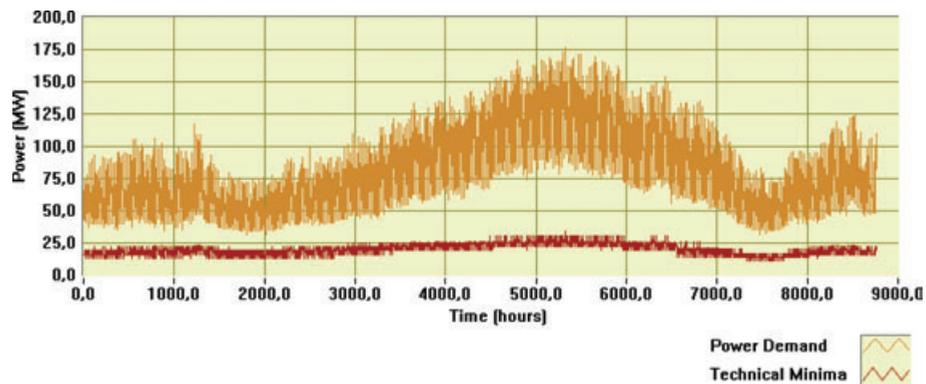


Figure 3. Annual power demand curve and technical minima of the on-duty thermal generators of Rhodes in 2004

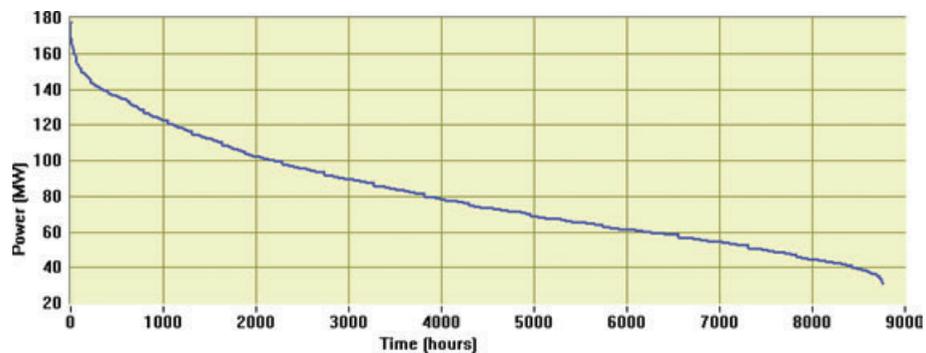


Figure 4. Rhodes annual power demand duration curve of 2004

Table I. Crete and Rhodes annual power demand characteristic values

Years	Rhodes		Crete	
	2004	2007	2004	2007
Maximum annual mean-hour power demand (MW)	165.00	202.13	498.64	610.86
Minimum annual mean-hour power demand (MW)	29.38	35.99	141.05	172.79
Mean power demand (MW)	75.62	92.59	285.77	350.07
Standard deviation of power demand (MW)	29.55	36.20	84.90	104.00
Coefficient of variance of power demand	0.367	0.367	0.278	0.278
Total energy consumed (MWh)	660,514.36	809,158.49	2,503,255.92	3,066,596.14

- The power demand seasonal variations in Rhodes (coefficient of variance of power demand, COV = 0.39) are much more intensive than in Crete (COV = 0.30). Generally, the maximum power demands in the Greek islands appear in summer. This is attributed to the influence of tourism. Generally, the intensity of the seasonal variation is inversely proportional to the size of the islands. Larger islands support more diverse economies and the power demand is with less seasonal variation. In Crete, mainly due to a considerable agricultural industry, which is operative in winter (olive oil production) and in September–October (wine production), the differences in power demand are not so intensive. This is not the case for Rhodes, hence the power demand differences between summer and winter are more intensive.

The Power Production Systems

Both the islands of Crete and Rhodes constitute isolated power production systems. The main power demand features of these islands for 2004 and 2007 are presented in Table I. The energy production on both islands is mainly based on thermal power plants that burn heavy fuel oil or diesel oil.

Crete's thermal power production system consists of three power plants, located in Heraklion, Chania and Lasithi prefectures. Steam turbines, diesel engines, gas turbines and a combined cycle are installed in these power plants. The combined cycle consists of two parallel gas turbines and a steam turbine. Each gas turbine relieves hot gases in the steam turbine. Crete's power production system is complemented with 75 MW of installed wind power.

The thermal power production system in Rhodes consists of steam turbines, diesel engines and gas turbines, installed in one power plant. In Rhodes, 12 MW of wind power have been installed, but have not yet been connected to the utility network.

The two islands' installed power synthesis is presented in Table II.

The thermal generators on-duty sequence is imposed by the following criteria, for both islands:¹⁴

- the uninterrupted power production, the power production system stability and the power quality; and
- the power production system cost-effective operation.

The first criterion imposes the continuous operation of the thermal generators with low response to the power demand variations and slow switching on procedure, namely, the steam turbines and the combined cycle. These thermal generators operate continuously, even at their technical minima, in case of low power demands. They are switched off only for scheduled maintenance purposes.

Table III presents the on-duty sequence of the thermal generators, which is imposed by the second criterion. This on-duty sequence is kept when no other constraints are imposed due to system stability. The steam tur-

Table II. Crete and Rhodes power synthesis at the end of 2004

Island	Steam turbine power (MW)	Diesel engine power (MW)	Gas turbine power (MW)	Combined cycle power (MW)	Total thermal power (MW)	Wind park power (MW)
Crete	109.2	146.0	312.0	110.6	677.8	75.0
Rhodes	30.0	94.0	68.0	0.0	192.0	0.0

Table III. Thermal generators on-duty sequence in Crete and Rhodes power plants

Crete thermal generators on duty sequence	Rhodes thermal generators on duty sequence
1. Diesel engines	1. Diesel engines
2. Steam turbines	2. Steam turbines
3. Combined cycle	3. Gas turbines
4. Gas turbines	

bines and the combined cycle operate continuously, at least at their technical minima, due to their limitations on power up.

In both islands, an annual energy consumption increase rate of 6–8% is recorded for the past years^{1,2} and is assumed to remain constant in the calculations for the power demand in 2007.

In 2004, the annual wind energy rejection percentage was lower than 10% in Crete, due to the low total installed wind power, relatively to the power demand. In Rhodes, there was no wind power production, hence no wind power rejection. However, these features are expected to change considerably in the near future, since several MWs of wind power have been already licensed and are going to be installed in both islands.¹⁵

In order to apply the proposed methodology for the year 2007, according to current known planning, it is assumed that the thermal generators presented in Table IV will have been installed by that year in the two islands.

The new thermal generators are assumed to be put on-duty just before the existing ones of the same type. This is because the new thermal generators are expected to exhibit better efficiency and fuel consumption features, than the existing ones.

The Wind Potential

The wind potential of Crete and Rhodes was evaluated according to real wind velocity time series. For the implementation of the adopted probabilistic methodology, Weibull C and k parameters must be calculated for both islands and the corresponding Weibull probability density functions must be constructed.^{12,13} The Weibull probability density functions calculations are presented thoroughly for each island next.

The Crete Wind Potential

For the Crete wind potential evaluation, 11 annual wind velocity time series of mean hourly values, coming from the sites shown in Figure 5, were employed.

Table IV. Crete and Rhodes new installed thermal generators until 2007

Island	Type of thermal generator	Power per generator (MW)	
		Technical minimum	Nominal power
Crete	Two steam turbines in Lasithi Prefecture power plant	17.5	50.0
Rhodes	Four diesel engines	3.0	20.0

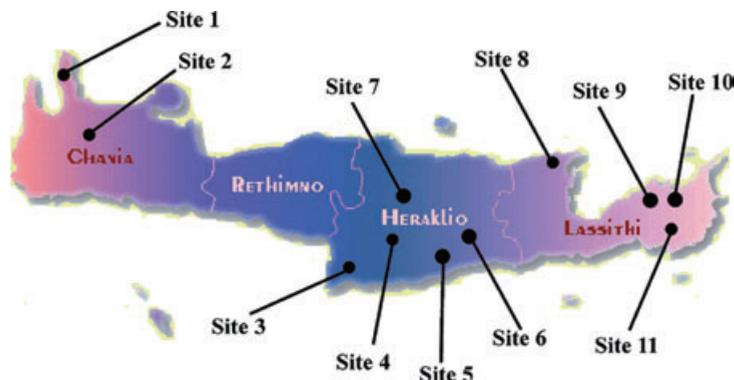


Figure 5. The site locations for the Crete wind potential evaluation

Four Weibull probability density functions were constructed, one for each prefecture of Crete. Table V presents the sites employed for each Weibull function calculation, as well as the Weibull C and k calculated parameters. Due to lack of data for Rethimno Prefecture, sites 7 and 3, the nearest ones to the abovementioned prefecture, were employed for the corresponding Weibull probability density function calculation.

A total averaged annual wind velocity time series was constructed for each Crete prefecture, by averaging the values of the initial wind velocity time series, employed for each prefecture. The Weibull parameters C and k calculations, based on the averaged wind velocity time series for each Crete prefecture, were implemented using a linear least squares approximation.¹⁶

The constructed Weibull probability density functions are presented in Figure 6.

The Rhodes Wind Potential

Implemented wind potential measurements in Rhodes indicate mean annual wind velocities of about 8.5 m s^{-1} , at the south region of the island (see Figure 7). Unfortunately, no completed annual wind velocity time series were available for the island of Rhodes. In order to proceed to the Weibull C and k parameters calculation and

Table V. Weibull C and k parameters for the Crete prefectures

Prefecture	Sites employed	Weibull parameters	
		C (m s^{-1})	k
Chania	1, 2	11.79	2.70
Rethimno	3, 7	9.14	2.05
Heraklion	3, 4, 5, 6, 7	9.73	2.60
Lasithi	8, 9, 10, 11	10.52	2.16

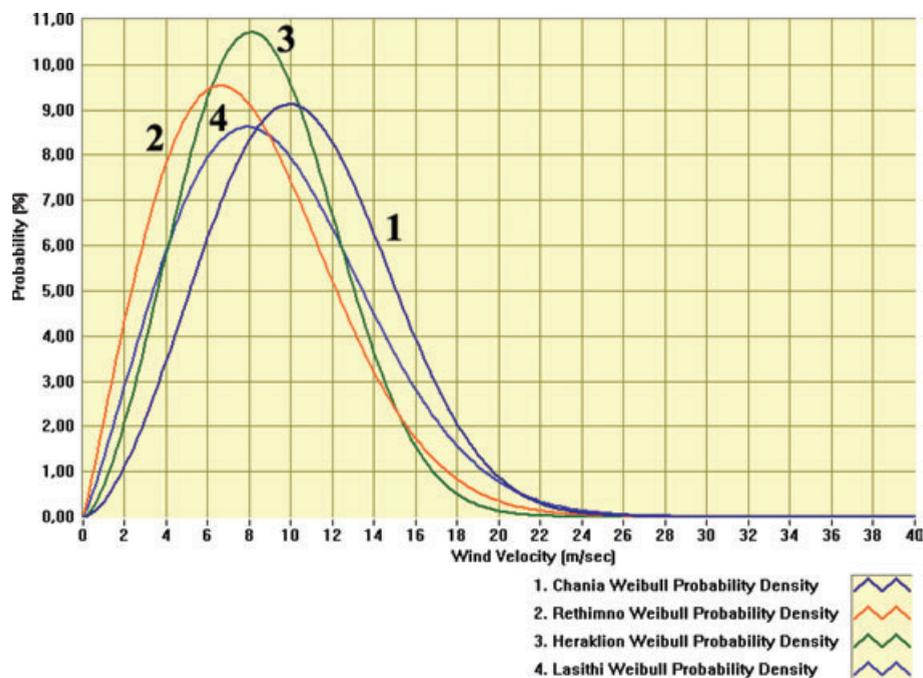


Figure 6. The Crete Prefectures Weibull probability density functions

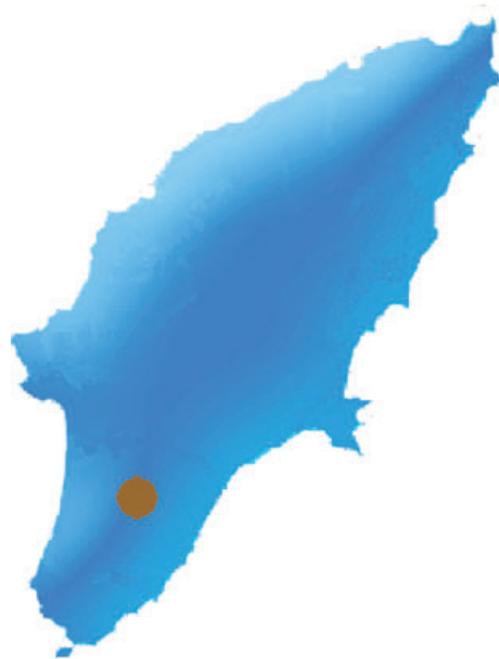


Figure 7. The assumed site locations for the Rhodes wind potential calculation

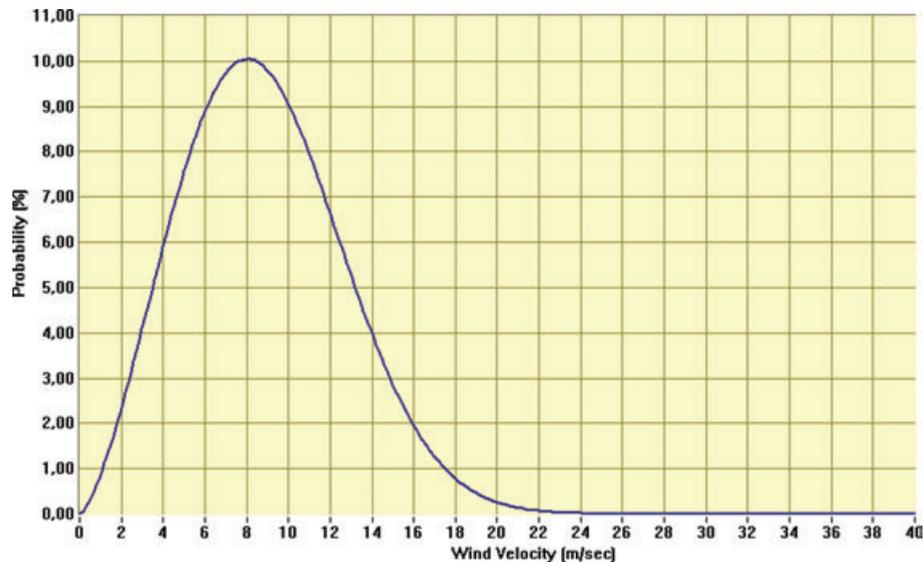


Figure 8. The Rhodes Weibull probability density function

to the corresponding probability density function construction, annual wind velocity time series from Crete, exhibiting mean annual wind velocities of about 8.5 m s^{-1} , were employed. Such wind velocity time series are the ones of sites 4 and 8 in Figure 5. Using these wind velocity time series, the Weibull parameters C and k for the island of Rhodes are calculated equal to $C = 9.93$ and $k = 2.46$, following similar methodology with the one presented previously. The constructed Weibull probability density function is presented in Figure 8.

Calculations

Wind Power Penetration Ability Probability Density

The wind power penetration ability for each power demand value is defined by:

- the total on-duty thermal generators technical minima; and
- the maximum allowed wind power instant penetration percentage.

As mentioned previously, a threshold for the wind power instant penetration is imposed in order to maintain the required levels of system stability and power quality. The 30% maximum wind power instant penetration percentage was explicitly defined until recently by the relevant Greek legislation framework. In recent law reforms the upper limit of wind power instant penetration percentage is not explicitly stated. Instead, it is the responsibility of the technical operators of each power production system to estimate the correct levels. In former studies,^{3–9} the maximum instant wind power penetration percentage has been calculated at the range of 30%, in order to ensure the isolated power production system stability and dynamic security. This value is not unique for all systems. For medium- and large-size isolated systems (such as the ones of Crete and Rhodes), the wind power instant penetration value may exceed 30%, while in smaller systems (small Aegean Sea islands), the corresponding value may be lower than 20%. It is noteworthy that the weather conditions and the power demand scale affect the upper safe limit of the wind power penetration. Taking into account the above-mentioned, for the purposes of the current study and the size of the power production systems of Crete and Rhodes, the maximum instant wind power penetration percentage is selected equal to the 30% of the instant power demand.

For each calculation year (2004 and 2007), the power demand range is discretized in steps of 1 MW. The power demand range for each year is defined between the power demand minimum and maximum value. After the discretization, *m* possible operation points of the power production system arise. For each one of these points, the following steps are executed:

1. The minimum thermal generators that must be put on-duty, in order to cover the total power demand, are determined (Figures 1 and 3).
2. The thermal generators provide power at least equal to the sum of the on-duty thermal generators technical minima.
3. The wind power penetration ability is equal to the difference between the power demand and the minimum power provided by the on-duty thermal generators, which actually, as mentioned above, is equal to the sum of the on-duty thermal generators technical minima.
4. If the above calculated wind power penetration ability is greater than the 30% of the power demand, the wind power penetration ability is restricted to this maximum allowed value of 30% of the power demand.

The wind power penetration ability versus time for the island of Crete and for the year 2004 is presented in Figure 9. The wind power penetration ability for the island of Rhodes is presented in Figure 10. In Figures 11

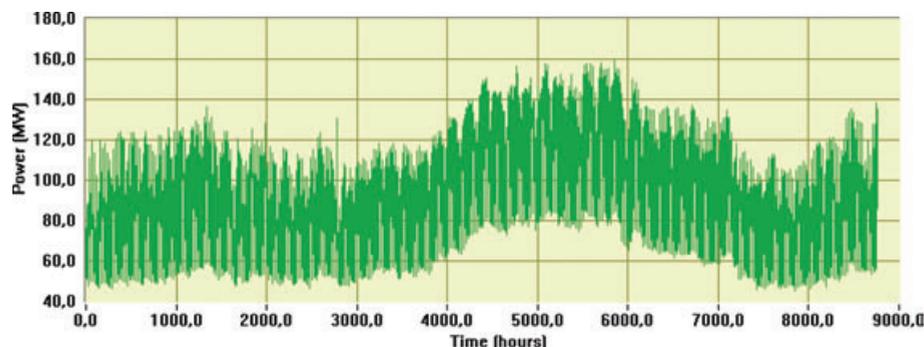


Figure 9. Wind power penetration ability of Crete in 2004

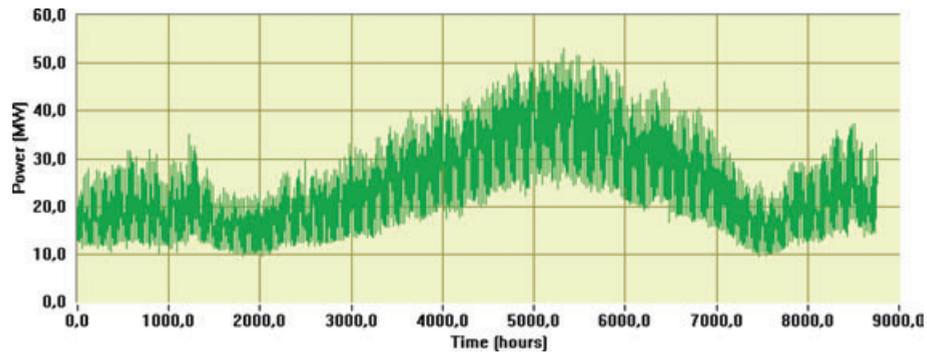


Figure 10. Wind power penetration ability of Rhodes in 2004

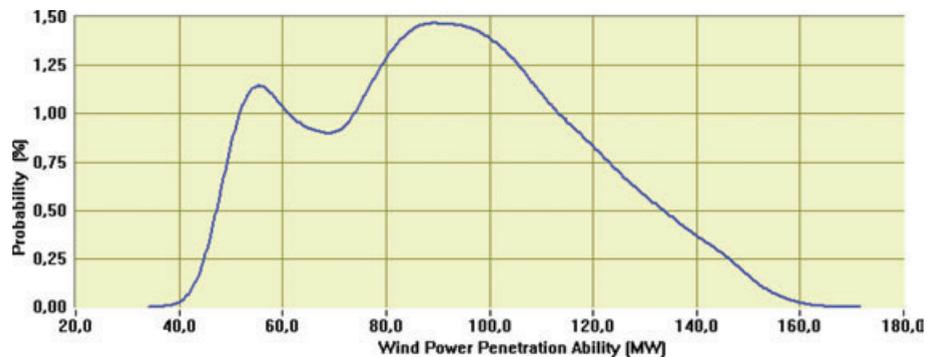


Figure 11. Wind power penetration ability probability density of Crete in 2004

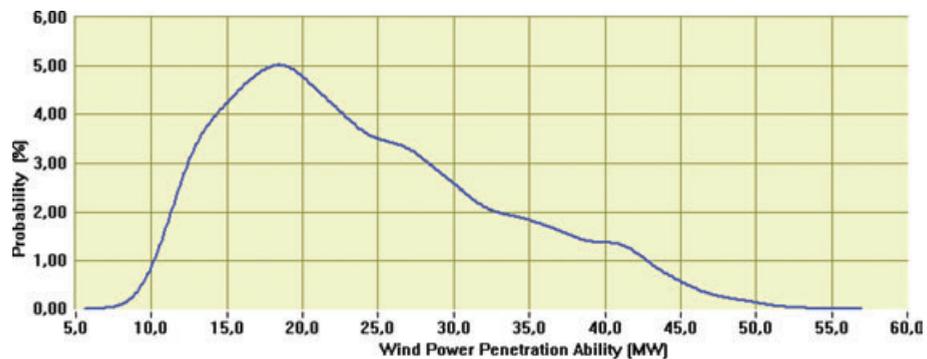


Figure 12. Wind power penetration ability probability density of Rhodes in 2004

and 12, the wind power penetration ability probability density functions are presented for the islands of Crete and Rhodes, respectively. Similar patterns exist for the corresponding 2007 time series.

Wind Power Production Ability Probability Density Function

The wind power production ability probability density is provided by the constructed wind speed Weibull functions. The Weibull probability density function provides the probability $P(V)$ of an existing wind velocity equal to V . By introducing a wind turbine power curve, the Weibull probability density function provides the prob-

ability $P(N)$ of produced wind power equal to N from the introduced wind turbine, given an existing wind velocity V .

The adopted calculation methodology requires one probability density function for the wind power production ability of each island. The benefit of this methodology is that the Weibull function can be sampled randomly (using the Monte Carlo method) and the autocorrelation structure of the actual time series is not required in order to obtain a wind power probability function.

For the island of Rhodes, one Weibull probability density function has been constructed. This function is assumed to describe the wind potential of all the island candidate sites for wind parks installation (presented in Figure 8). By introducing a wind turbine power curve and assuming that this model will be installed in all the island's wind parks, the Figure 8 Weibull function for the wind velocity is converted to the probability density function of the wind power production ability from all the Rhodes wind parks.

For the island of Crete, four Weibull probability density functions have been constructed. Each one of these functions is assumed to describe the wind potential of each Crete Prefecture candidate sites for wind parks installation. Since the adopted methodology requires one wind production probability density function, one probability density function must be constructed.

The probability density function for the island of Crete is constructed as described below:

- By introducing a wind turbine model and assuming that this model will be installed in all the island's wind parks, the four Weibull functions are converted to four probability density functions of wind power production ability for each Crete Prefecture.
- The installed wind power percentages at each Crete Prefecture, over the total installed wind power in the island, are calculated (see Table VI).
- The previously constructed probability density functions of the wind power production ability in each Crete prefecture, are multiplied with the corresponding installed power percentages.
- The products of the above calculations are summed, providing one probability density function of the wind power production ability for the whole island.

According to the already installed wind power at each prefecture¹ and the new licensed wind parks that are to be installed in the future,¹⁵ the Table VI wind power percentage allocation in Crete Prefectures was adopted.

Probability density functions for the wind power production ability of the whole island of Crete are constructed for 2004 and 2007, following the above described method. They are presented in Figure 13. These functions describe the wind power production ability probability from the installed wind parks in Crete for 2004 and 2007. Different wind power installation allocation in Crete prefectures in the examined years leads to different wind power production ability probability density functions.

Figure 14 presents the probability density function for the wind power production ability in Rhodes.

The introduced wind turbine power curve is presented in Figure 15. This wind turbine is assumed to be installed in all wind parks of both Crete and Rhodes. This is a simplification assumption that takes into account the proportion of different types of wind energy conversion systems installed on the islands.

The Annual Wind Energy Rejection Percentage Calculation

The annual wind energy rejection percentage is calculated, following the steps below:

1. For the year X ($X = 2004$ and 2007), adopting a discretization step of 1 MW for the power demand, there are m possible operation points of the power production system, derived by the annual power demand curve

Table VI. Wind power dispersion scenario in Crete prefectures

	Chania	Rethimno	Heraklion	Lasithi
Wind power allocation in 2004 (%)	0-0	0-0	15-0	85-0
Wind power allocation in 2007 (%)	15-0	15-0	30-0	40-0

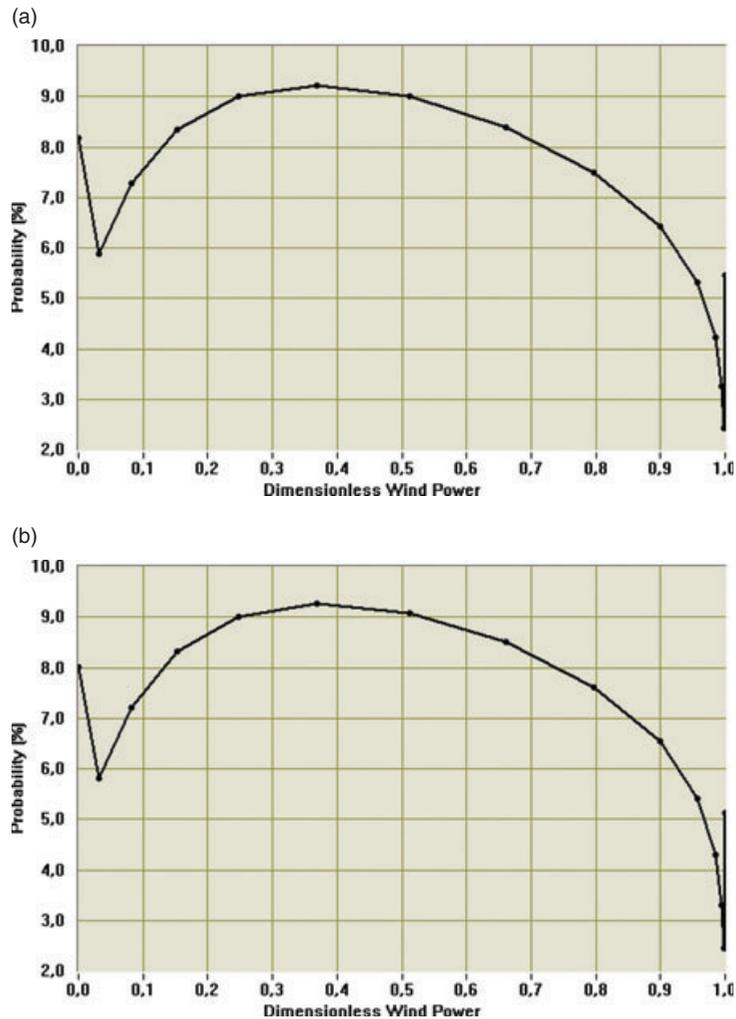


Figure 13. Probability density function for the wind power production ability of Crete in (a) 2004 and (b) 2007

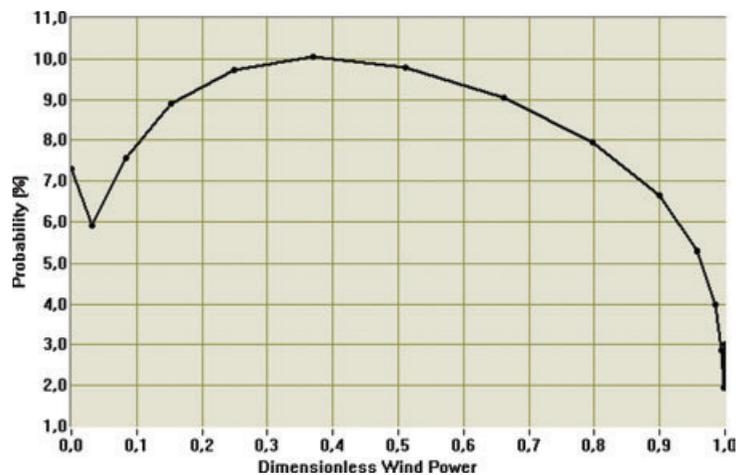


Figure 14. Probability density function for the wind power production ability of Rhodes in 2004 and 2007

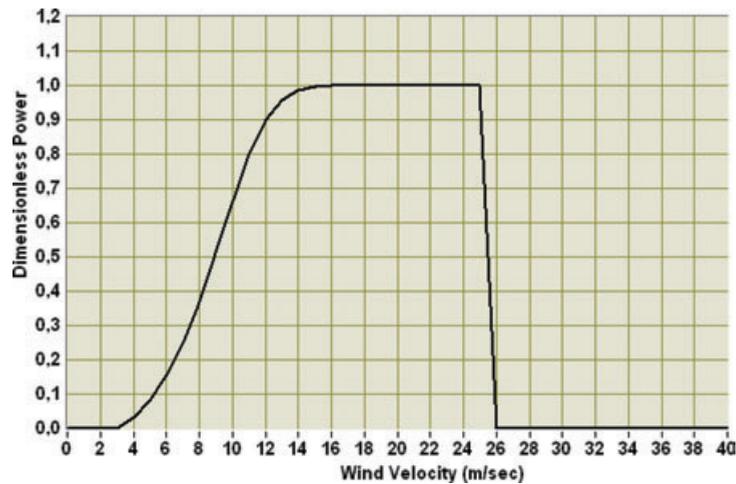


Figure 15. The introduced wind turbine power curve

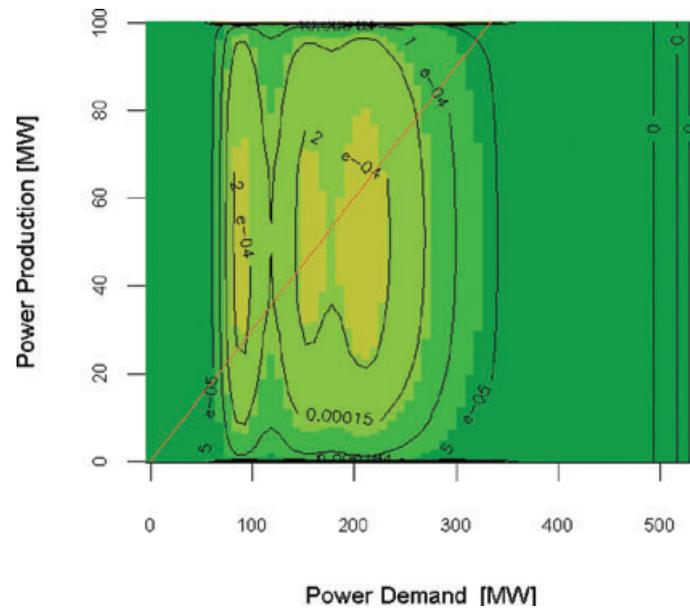


Figure 16. Bivariate joint distribution of power demand and wind power production, for a 100MW total installed wind power

(m = maximum power demand in [MW] – minimum power demand in [MW] + 1). Similarly, for the year X , adopting a discretization step of 1 m s^{-1} for the wind velocity, there are n possible discrete wind velocities. The power production system operation point defines the wind power penetration ability, while the discrete wind velocity defines the wind power production ability. In total, there are $m \times n$ discrete system operation points.

2. If the power production system operation point P_i , $i = 1, \dots, m$, has a probability $f(P_i)$ and the discrete wind velocity V_j , $j = 1, \dots, n$, has a probability $g(V_j)$, then the probability of the system operation point (P_i, V_j) is $f(P_i) \times g(V_j)$ since the power demand is independent of wind speed (see bullet point in the Introduction, ‘• the power demand exhibits . . .’ regarding Pearson’s correlation coefficient of actual wind speed and power demand time series) and therefore to wind power production. Every year, the system will be in a state i, j for $f(P_i) \times g(V_j) \times 8760 \text{ h}$. The probability $f(P_i) \times g(V_j)$ is presented in Figure 16. The joint probability that

is presented on the contour of Figure 16, represents the probability that the demand and the wind power production are at a certain level. For example, there is a 0.0002 probability that the power demand will be at 200 MW and the wind power production will be 50 MW. The diagram has been constructed for a 100 MW total installed wind power. The sum of all the probabilities is equal to 1. The line, starting from (0, 0) and ending at (300, 100), represents a maximum wind power penetration percentage of 30%. Values to the right and below of the curve are system states that no rejection occurs.

3. For each system operation point (P_i, V_j) , which annually occurs for $f(P_i) \times g(V_j) \times 8760$ h, the wind penetrated power equals with:

- the wind parks produced power, if the wind power penetration ability is greater than the wind parks produced; and
- the wind power penetration ability, if the wind parks produced power is greater than the wind power penetration ability.

The annual wind energy rejection percentage is the ratio of the annually rejected energy over the total annually wind parks produced energy.

The total annual wind parks produced energy is the quantity of energy produced from the installed wind parks and offered to the utility. It is equal to the summation of the total annual purchased and rejected energy.

Results

Figure 17 presents the annual wind energy rejection percentage in Crete for 2004 and 2007, in terms of the wind parks total installed power. Figure 18 presents the annual wind energy contribution percentage to the annual energy production in Crete for 2004 and 2007. The respective graphs for the island of Rhodes are presented in Figures 19 and 20.

Figures 17 and 19 present the annual wind energy rejection percentage with respect to the total installed wind power in Crete and Rhodes, for 2004 and 2007. In these diagrams, it is observed that:

- For a total installed wind power of 125 MW in Crete in 2007, the annual wind energy rejection percentage is estimated to remain lower than 10%. An increase of 20% of total installed wind power (to 150 MW) is estimated to increase the annual wind energy rejection percentage over 15% (over 50% increase). Taking into account the investment trends, both these scenarios are possible. The highly non-linear relationship between total installed wind energy and wind energy rejection is evident.
- The annual wind energy rejection percentage in Rhodes in 2007 is estimated to remain lower than 10%, if 25 MW of wind power are installed by 2007. If 50 MW of total wind power are installed in Rhodes by 2007, the estimation of the wind rejection increases to 25% (150% increase).

The above features indicate neither islands allows high wind power installation, without increasing significantly the annual wind energy rejection percentage. The annual wind energy rejection percentage remains in low levels until today, mainly due to the slow implementation rates of the licensed wind parks projects. If the rates change, several MW of wind power are expected to be installed in both islands. In such occasion, the annual wind energy rejection will increase considerably and the storage devices (pumped storage systems) introduction will be necessary for its limitation.

Parametric Calculation of Annual Wind Energy Rejection Percentage

Figure 21 summarizes the results presented in Figures 17 and 19. In this diagram, the four curves of Figures 17 and 19 are presented in terms of the installed wind power over mean annual power demand ratio. It is observed that the four curves in Figures 17 and 19 coincide in Figure 21.

At this point, the following are noteworthy:

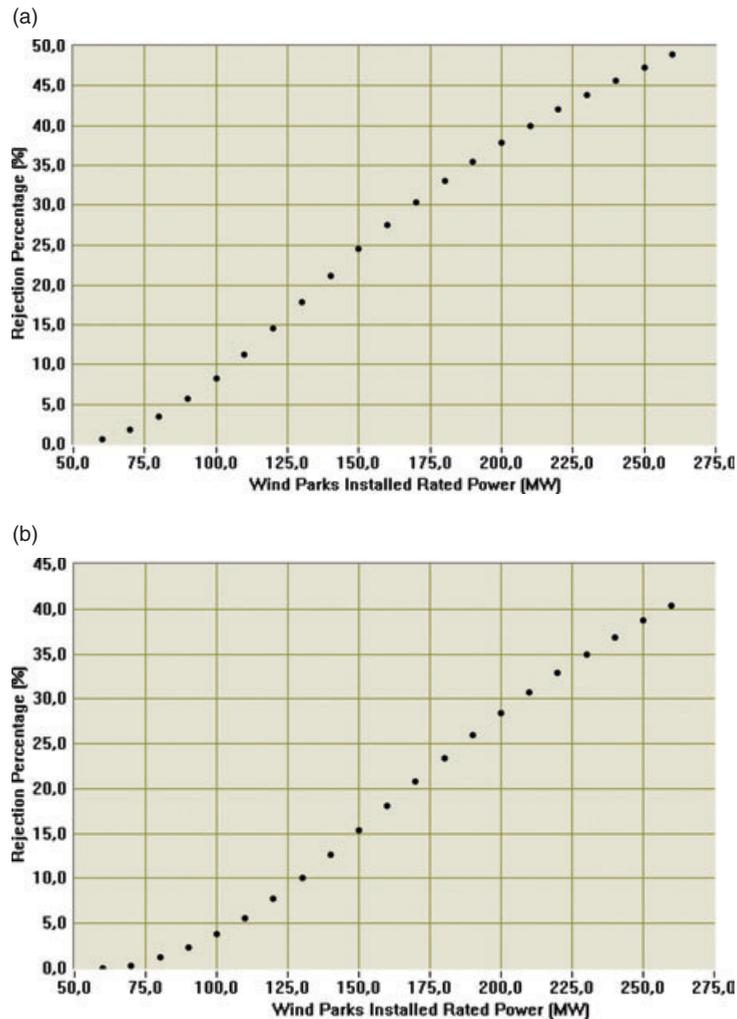


Figure 17. Crete annual wind energy rejection percentage in (a) 2004 and (b) 2007

- The curves in Figure 21 refer to two different isolated power systems, with different thermal power plants syntheses.
- The curves in Figure 21 refer to different years, during which the power plant syntheses have been changed, as well as the power demand.

The curve overlap in Figure 21 leads to the conclusion that the annual wind energy rejection percentage in an isolated power system, similar to the ones met in the Greek territory, depends exclusively on:

- the total installed wind power;
- the power demand;
- the maximum allowed instant wind power penetration percentage; and
- the installed thermal generators main features, particularly their technical minima.

A parametric study is undertaken with respect to (i) the maximum allowed instant wind power penetration percentage and (ii) the installed thermal generators main features, particularly their technical minima. Figure 22 presents the results of the parametric study. In this diagram, several annual wind energy rejection percent-

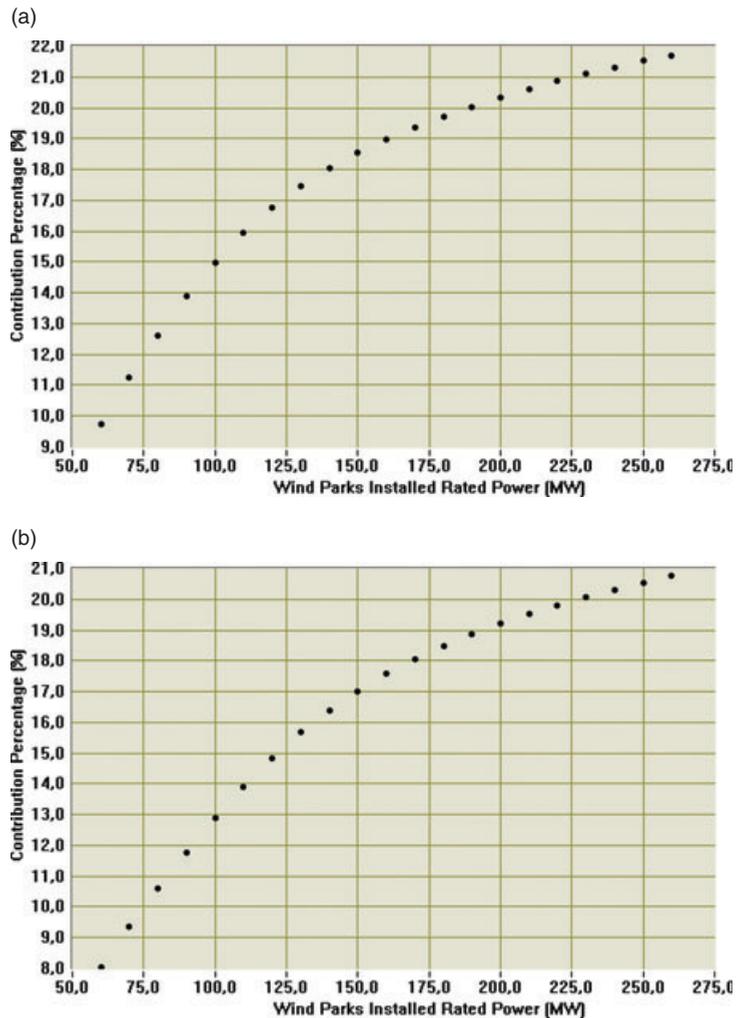


Figure 18. Crete annual wind energy contribution percentage in (a) 2004 and (b) 2007

age curves have been plotted for different maximum allowed wind power instant penetration percentages. The curves in Figure 22 were constructed using the 2004 Crete power demand and the existing thermal power plant synthesis of the island that year.

The functionality of Figure 22 presents several annual wind energy rejection percentage curves which are calculated for different maximum allowed wind power instant penetration percentages. The annual wind energy rejection percentage in an isolated power system can be estimated from the curves in Figure 22, in terms of the installed wind power over mean annual power demand ratio and the maximum allowed instant wind power penetration percentage.

The overlapping of the Figure 21 curves suggests that the results of Figure 22 are applicable to both islands and for 2004 and 2007. Therefore, the applicability of Figure 22 may be extended to any isolated power system with similar features to the ones of Crete and Rhodes, namely:

- The power production is based on thermal power plants.
- The power demand exhibits intensive seasonal variations.
- The mean annual power demand is greater than 10 MW.

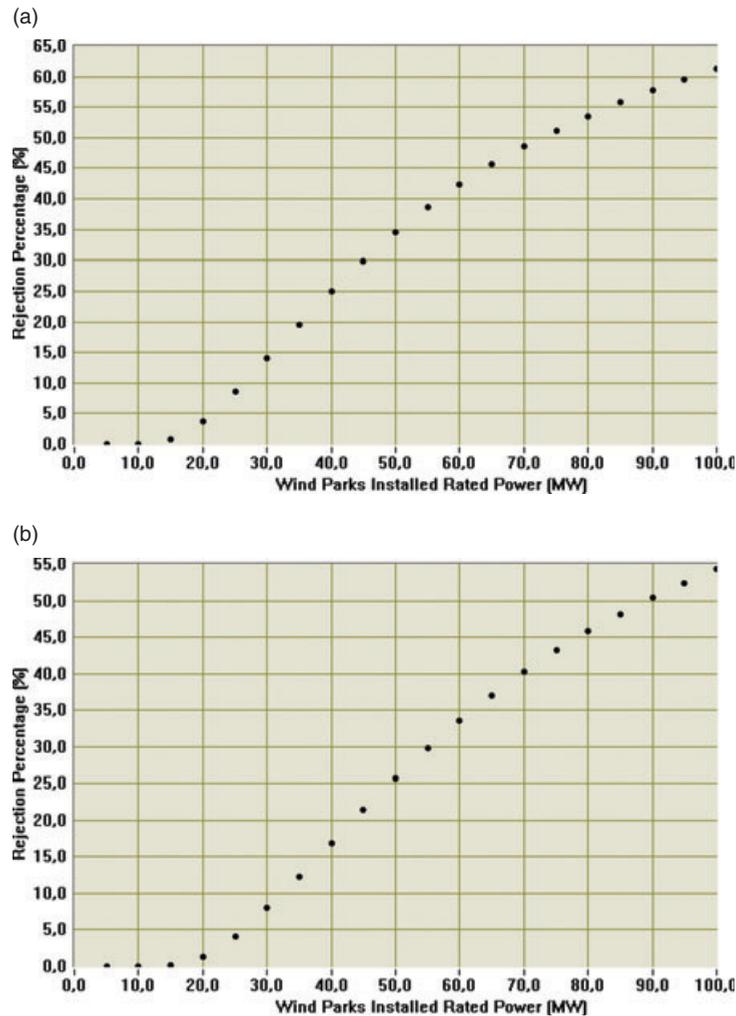


Figure 19. Rhodes annual wind energy rejection percentage in (a) 2004 and (b) 2007

- A high wind potential, presenting mean annual wind velocity values greater than 7.5 m s^{-1} is recorded.
- The power demand is independent of the wind power production.

The abovementioned features stand for the majority of the Greek islands and for plenty of isolated insular power systems worldwide. The results of Figure 22 are not applicable for very small isolated power systems, with mean annual power demand less than 10 MW, due to several peculiarities caused mainly by the weak power production systems. In such small and weak systems, the annual wind power rejection is expected to be higher.

From the curves in Figure 22 corresponding to 30% maximum wind power instant penetration percentage, it is estimated that in order to ensure annual wind energy rejection percentage less than 10%, the total installed wind power should not be greater than the 40% of the mean annual power demand.

The data in Figure 22 can be transformed to the contour that is presented in Figure 23. In the abscissa, the installed wind power as a percentage of annual mean power demand is presented. The ordinate presents the maximum allowed instant penetration percentage, and each of the contour lines represents a value of the annual wind energy rejection percentage. For example, it is easy to observe that for installed wind power percentage

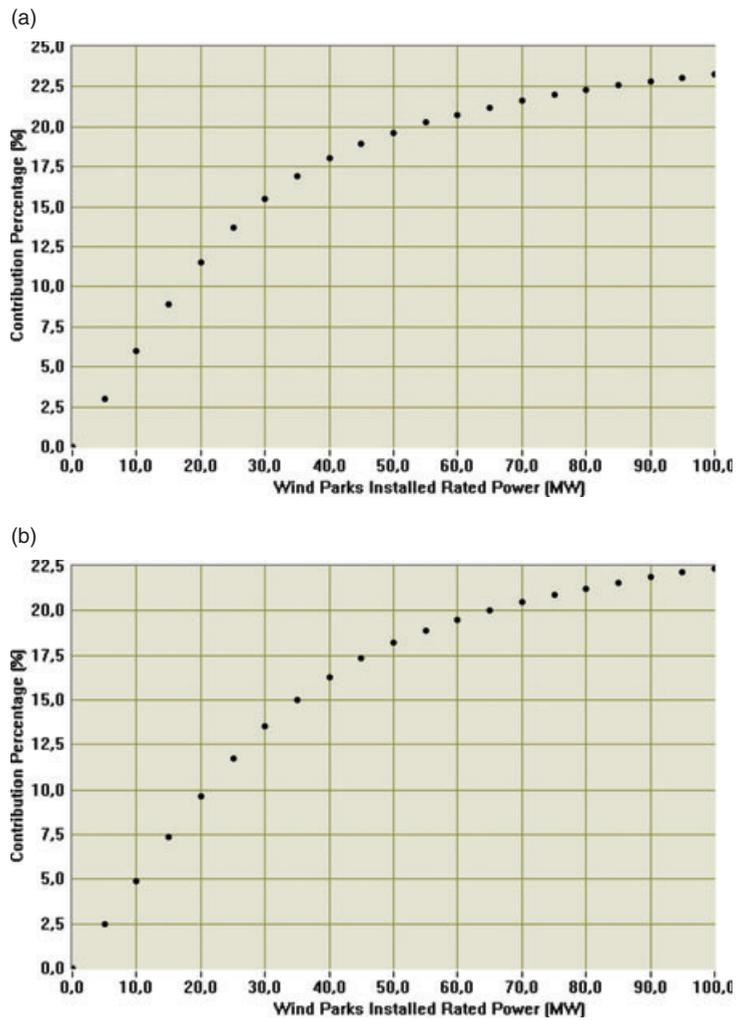


Figure 20. Rhodes annual wind energy contribution percentage in (a) 2004 (b) 2007

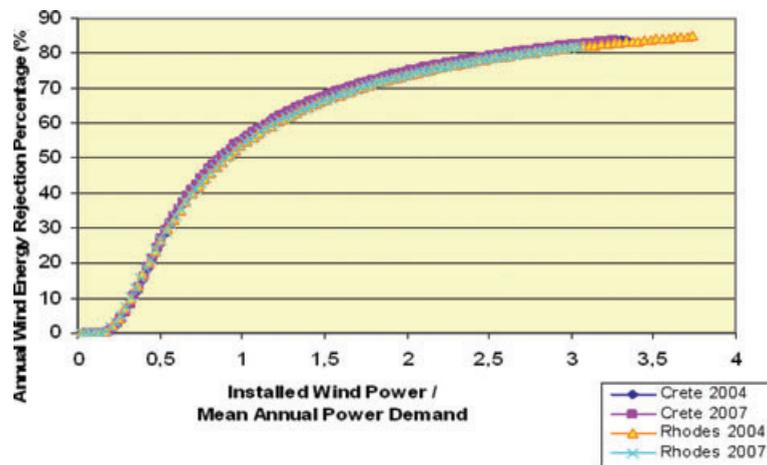


Figure 21. Annual wind energy rejection percentage curves of the investigated islands and years

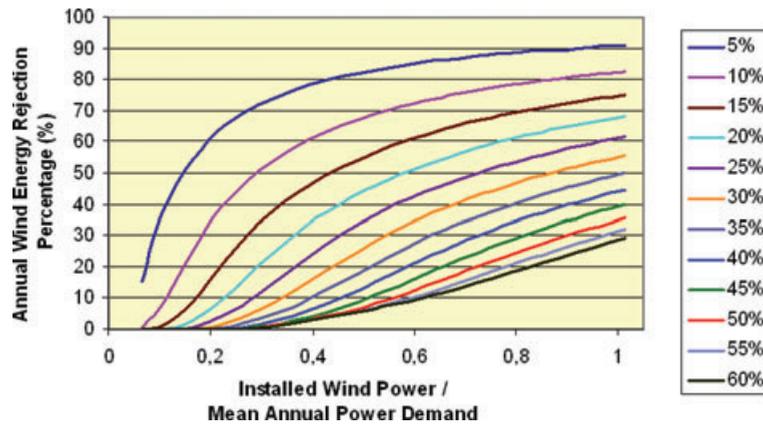


Figure 22. Annual wind energy rejection percentage curves in terms of different maximum allowed instant wind power penetration percentages

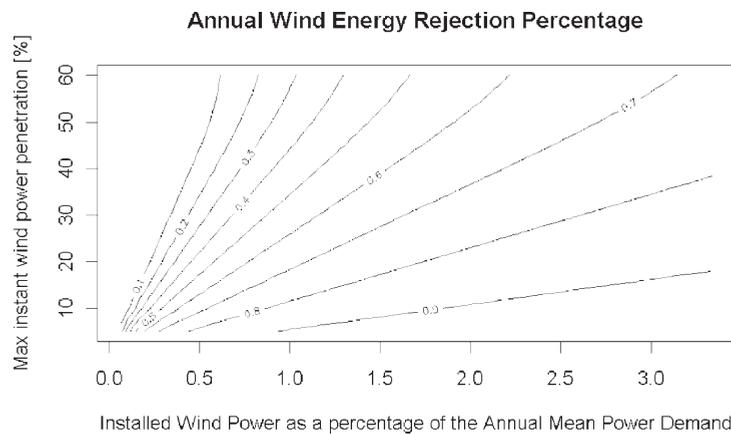


Figure 23. Annual wind energy rejection percentage curves in terms of different maximum allowed instant wind power penetration percentages

ratio equal to 1 and maximum allowed penetration percentage equal to 40%, the expected annual wind energy rejection percentage is just below 50%.

Conclusions

The annual wind energy penetration percentage was calculated in the present paper, for the islands of Crete and Rhodes and for the years 2004 and 2007, assuming several scenarios for the total installed wind power in each island. The calculations were based on a methodology introduced by the Greek Regulatory Authority of Energy.

The present paper proved the limited ability for high wind power penetration in isolated power systems, like the ones met in Greece. For a maximum wind power instant penetration percentage of 30%, in order to ensure an annual wind energy rejection percentage less than 10%, the total installed wind power should not exceed the 40% of the mean annual power demand.

Using the results of the wind energy rejection calculations in the examined islands of Crete and Rhodes, the diagram of Figure 22 was constructed. In this diagram, annual wind energy rejection percentage curves are

presented corresponding to different maximum allowed wind power instant penetration percentages. The curves are plotted in terms of the total installed wind power over mean power demand ratio. Using this diagram, the annual wind energy rejection percentage in a medium- or great-size isolated power system can be estimated, given the total installed wind power, the mean annual power demand and the maximum wind power instant penetration percentage.

The results of this paper stand for medium- and great-size isolated power systems, with particular features:

- The power production is based on thermal power plants.
- The power demand exhibits intensive seasonal variations.
- The mean annual power demand is greater than 10 MW.
- A high wind potential, presenting mean annual wind velocity values greater than 7.5 m s^{-1} is recorded.
- The power demand is independent of the wind power production.

In small-size isolated power systems, with mean annual power demand less than 10 MW, the wind penetration ability is expected to be further limited. Considerable wind power penetration increase in all isolated power system kinds can be achieved only with the cooperation of energy storage devices (pumped storage systems) in order to maintain a green attitude to energy.

References

1. Power Production Corporation. Annual bulletins for the power production systems of Crete and Rhodes, for the years 2001, 2002, 2003, 2004—P.P.C. S.A. (in Greek).
2. Skiadas C, Zopounides K, Christakis D. Forecasting for the energy consumption in Crete. *Colloquium for the Development of Energy Systems in Crete, Technical Chamber of Greece*, Chania, 12–14 May 1989.
3. Tande JOG. Exploitation of wind-energy resources in proximity to weak electric grids. *Applied Energy* 2000; **60**: 395–401.
4. Thiringer T, Petersson A. Grid integration of wind turbines. *Swedish-Polish Motion Control and Wind Energy Symposium*, Warszawa, Poland, 22 October 2003.
5. Boulaxis NG, Papathanasiou SA, Papadopoulos MP. Wind turbine effect on the voltage profile of distribution networks. *Renewable Energy* 2002; **25**: 401–405.
6. Hatzigiargyriou N, Tsikalakis A, Dimeas A, Georgiadis D, Stefanakis J, Gigantidou A, Thalassinakis E. Security and economic impacts of high wind power penetration in island systems. *40th CIGRÉ, Paper no 5*, Paris, France, August 2004.
7. Larson A. The power quality of wind turbines. PhD Thesis, Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 2003.
8. Thiringer T, Hesse W, Grauers A, Ottersten R, Petru T. Grid impact of a 20 kW variable speed wind turbine. *European Wind Energy Conference and Exhibition (EWEC 99)*, Nice, France, 1–5 March 1999.
9. Ehnberg JSG, Bollen MHJ. Reliability of a small isolated power system in remote areas based on wind power. *Nordic Wind Power Conference*, Chalmers University of Technology, Göteborg, Sweden, 1–2 March 2004.
10. Karalis G, Zervos A. Wind power penetration calculation in autonomous islands. *3rd Hellenic Conference "The RES Application, Perspectives and Priorities Towards the 2010 Target"*, Athens, Greece, 23–25 February 2005 (in Greek).
11. Regulatory Authority of Energy. A methodology for the renewable energy sources penetration estimation in isolated power production systems. February 2003 (in Greek).
12. European Wind Atlas. Riso National Laboratory, 1989.
13. Bergeles G. *Wind Turbines*, Symeon Editions: Athens, 1995 (in Greek).
14. Katsaprakakis D, Christakis DG. On the wind power penetration percentage in the island of Crete. *Hellenic Union Bulletin of Mechanical-Electrical Engineers*, December 2004; 50–54 (in Greek).
15. Regulatory Authority of Energy. Electricity Production Licenses from Renewable Energy Sources Projects Record. [Online]. Available: www.rae.gr. (Accessed February 2006).
16. Theodoropoulos P. Hybrid system simulation and dimensioning—Application in the island of Ikaria. Diploma Thesis, N.T.U.A., Department of Mechanical Engineers, 2001 (in Greek).