On the effect of spatial dispersion of wind power plants on the wind energy capacity credit in Greece

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Abstract
Wind energy is now a mature technology and can be considered as a significant contributor in reducing CO\textsubscript{2} emissions and protecting the environment. To meet the wind energy national targets, effective implementation of massive wind power installed capacity in the power supply system is required. Additionally, capacity credit is an important issue for an unstable power supply system as in Greece. To achieve high and reliable wind energy penetration levels into the system, the effect of spatial dispersion of wind energy installations within a very wide area (e.g. national level) on the power capacity credit should be accounted for.

In the present paper, a methodology for estimating the effect of spatial dispersion of wind farm installations on the capacity credit is presented and applied for the power supply system of Greece. The method is based on probability theory and makes use of wind forecasting models to represent the wind energy potential over any candidate area for future wind farm installations in the country. Representative wind power development scenarios are studied and evaluated. Results show that the spatial dispersion of wind power plants contributes beneficially to the wind capacity credit.

Keywords: wind power, capacity credit, spatial dispersion

1. Introduction
The national target of 29\% of electricity production from renewable energy sources by 2020 undoubtedly passes through the effective implementation of massive wind power capacity into the power supply system of Greece. Wind energy can be considered as the most significant contributor in substituting conventional fuels, reducing CO\textsubscript{2} emissions and protecting the environment. Moreover, it is now a mature technology and an economically competitive energy source. The higher the wind speed at a candidate area the more the benefits from a potential wind farm installation. At first sight, wind farm developments should take place in windy areas aiming at a sustainable energy planning and taking into account the development of local society and infrastructure along with the pure environmental character of the wind installations.

However, large scale implementation of wind power plants gives rise to technological issues regarding the variability of electricity production due to the stochastic nature of wind. In this connection, an effective power supply system management should have some kind of information on the mesoscale temporal and spatial wind variability. The former is associated with short term wind power forecasting whereas the latter with wind farm spatial dispersion strategies at a large scale (e.g. national level). In practical terms, ‘if wind drops somewhere, it is probably rising somewhere else’ should definitely be taken into account [1].

Consequently, an effective wind energy development plan at a national level is \textit{a priori} related to the spatial dispersion of wind farms along the power supply system. A holistic approach should encompass maximum possible yet reliable
potential substitution of conventional by wind power plants aiming at pollution savings (including CO₂ emissions) while ensuring reliable coverage of the system power demand (capacity credit). This is of crucial importance for the energy plan of Greece, characterized by a rather unstable power supply system, especially during the summer peak season. Moreover, study of the wind farm spatial dispersion effects could provide valuable information and support the system’s reliability.

In this connection, the present paper illustrates the basic principles of an up-to-date methodology developed to estimate at a large scale how the capacity credit is affected by the spatial dispersion of wind plants. The method is based on probability theory [2–6] and makes use of numerical weather forecasting models to represent the wind energy potential over candidate areas for future wind farm installations. Representative wind development scenarios for future wind energy developments in Greece are investigated and evaluated. Moreover, advantages of using specialized numerical methods (such as wind forecasting models) are revealed along with their application in wind energy strategic plans at a national level.

Finally, conclusions are drawn and suggestions are made on optimal wind energy development strategies in terms of spatial dispersion of wind farms in the national system in order to achieve high wind energy penetration levels.

2. Capacity credit estimation method

2.1. Definitions

In general, capacity credit of any power production unit is related to its capability to increase the reliability of the power supply system. In this connection, the question is why development of wind farms is needed in a system which is already reliable. The answer is that the demand is always increased; new power stations are needed to cover the additional demand and keep the reliability of the system at the same level. This is associated with the degree to which wind farms can effectively substitute the building of new conventional power units.

The reliability of the system can be measured by the probability of power loss occurrence (loss of load probability—LOLP) and corresponds to the percentage of time in which the system cannot respond to the power demand. Loss of load means that demand is higher than the capability of the available power supply units, merely resulting in disconnection of some consumers. LOLP depends among other factors on demand characteristics, availability, reliability and number of power production units etc. Certainly, the power supply systems are designed so as to keep LOLP at a very low level. When a new power unit is implemented into the system, its cost increases when LOLP decreases and reliability rises. Its effect on the system’s reliability varies depending on the unit character (stochastic, intermittent or steady) and its availability percentage.

Power production from wind farms is of stochastic nature since it depends on wind. Consequently, any reference to guaranteed wind power is treated with doubt and skepticism. On the other hand, a conventional power supply unit can always produce the power the system demands. In practice however, there is a probability for any unit to be off operation due to scheduled maintenance or casual malfunction at the time when the system needs its power production. Thus no unit type can operate with 100% capacity credit [7].

The loss of load probability of a system LOLPS without wind power plant installations is defined as

\[
\text{LOLPS} = \sum_{i=1}^{N} P(C_i < L_i),
\]

where \( P \) is the probability function, \( C_i \) the available load from the conventional power units at the \( i \)th hour, \( L_i \) the demand at the \( i \)th hour and \( N \) the hours within the time window of interest (e.g. \( N = 8760 \) for annual calculations).

Next, the loss of load probability of a system LOLPW with wind power plant installations is accordingly expressed as

\[
\text{LOLPW} = \sum_{i=1}^{N} P(C_i + W_i < L_i),
\]

where \( W_i \) is the wind power production at the \( i \)th hour.

Obviously, LOLPW < LOLPS, i.e. wind power installations enhance the system’s reliability. If the system’s reliability is already at high levels, the wind power effective load carrying capability (ELCC) is defined as ‘the increase in power demand, so as the system’s reliability is kept at the same level as before the wind power has been installed, i.e. the loss of load probability is LOLPS’.

ELCC can be calculated from the following equation via an iterative procedure:

\[
\text{LOLPW} = \sum_{i=1}^{N} P(C_i + W_i < L_i + \text{ELCC}).
\]

Finally, the capacity credit (CC) coefficient of wind power in the system is defined as

\[
\text{CC} = \frac{\text{ELCC}}{P_W},
\]

where \( P_W \) is the total installed wind capacity. The CC expresses the equivalent conventional capacity which can be effectively replaced by the wind installed capacity.

2.2. Input data required

The probability function is calculated through probability theory analysis for the following variables: the power demand, the available conventional power and the produced wind power. These variables are considered to be fully independent from each other. Data for the system’s power demand and availability figures of the conventional power plants as well as wind data are required.

- The demand figures are introduced via the annual power demand duration curve.
- The system might include a variety of types and sizes of conventional power production stations, the characteristics of which should be given (e.g. number of units, nominal
power, availability). Moreover, it is assumed that these stations either operate at 100% load (when required) or they are off due to scheduled maintenance or casual malfunction.

- Wind data are introduced via wind speed time series. For spatial dispersion studies, simultaneous wind data series have to be available for every area of interest. Next, for a desirable wind power installed capacity in each area and using a representative wind turbine power curve, time series of the total available wind power production can be reproduced on an annual basis.

2.3. Wind data

Simultaneous information on wind statistics over every potential area for wind farm development is required. Even if a large volume of wind measurements is available, it is practically very difficult for them to be simultaneous and cover every potential area. Installation of a mast network for this purpose could lead to rather prohibitive technical and economic restrictions. Additionally, existing wind monitoring networks are relatively large and can provide large spatial coverage but not necessarily high resolution [8]. On the other hand, use of wind atlases is not a solution since they only provide an estimate of the spatial distribution of the mean wind speed without any information on its temporal variation.

Application of a numerical weather prediction (NWP) model can effectively provide the information required. Appropriate adjustment of the numerical parameters, systematic application on a yearly (and beyond) basis and thorough analysis and processing of wind characteristics can provide simultaneous wind speed time series at the mesoscale over the whole territory of interest. In this connection, the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) developed at the US Naval Research Laboratory is used [9]. COAMPS is a three-dimensional non-hydrostatic model that has been used for operational forecasting since 1996 for a wide range of research purposes for both idealized as well as real data simulations. The model is driven by the US Navy Operational Global Atmospheric Prediction System (NOGAPS) (cold start) or the most recent COAMPS forecast as the first guess (warm start). Observations from aircraft, rawinsondes, ships and satellites are blended with the first guess fields to generate the current analysis fields (initial conditions). This input is freely available and updated every 6 h. Then, the forecast numerical module performs time integration of model numerics and physics. The atmospheric model uses any number of nested grids to achieve high resolution for a given area.

COAMPS is applied every 12 h at a high resolution of 3 km to simulate the wind field over Greece within a forecast window length of 24 h (figure 1). The model output is stored hourly and the parameters related to wind energy applications (temperature, wind velocity components, pressure) are analyzed and processed. Systematic application of the model since the end of 2005 together with wind predictions from operational weather forecast models used by national weather service organizations and wind measurements from meteorological masts resulted in a wind database development continuously updated and enriched.

The database is then addressed to extract the required wind speed time series simultaneously for every area within the wider territory of study. Moreover, this database can effectively be used to generate mesoscale aeolian maps of the wind energy potential on a monthly and/or yearly basis (figure 2). Although mesoscale models provide reasonable relative weather variation and wind change at different sites, they are incapable of predicting the local winds or wind speed-ups in complex terrain. However, for the purpose of the present paper, neglecting local winds and speed-ups is a rather conservative assumption, since wind at different sites is actually less correlated than NWP models show.

Figure 1. COAMPS computational domain showing topography and grid nests.
Figure 2. Mesoscale aeolian map of the wind energy potential in Greece (last week of April 2007) [14].

Figure 3. Wind acceleration observed in the microscale in complex terrain cases (indicative representation of wind flow, produced by the microscale model VANE) [19, 20].

Wind farms in Greece are mainly installed on top of mountain or hill chains to take advantage of the speed-up effect (figure 3). In complex terrain the wind profile is difficult to predict and use of a logarithmic or exponential law is not recommended [10]. Consequently, the calculated mesoscale wind potential given at 10 m a.g.l. (figure 2) is not representative in these areas. In the present study, a rather moderate value of 1.2 for the acceleration factor was adopted, so that any conclusions lay on the safe side.

The database is then addressed to extract the required wind speed time series simultaneously for every area within the wider territory of study. Moreover, this database can
is illustrated through the following steps: Mesoscale models do not predict the effect of local winds or wind speed-ups in complex terrain. The ignoring of local winds and speed-ups is considered as an assumption on the safe side. In reality wind between different sites will be less correlated than it is recorded to be by these models. Mesoscale models predict the relative variation of the weather and the relative reinforcement of the wind between different sites. However, a correction factor is usually applied to account for the wind acceleration observed in the microscale in complex terrain cases as in Greece (figure 2). Wind farms in Greece are installed mainly on top of mountain or hill chains to take advantage of this effect. Additionally, the mesoscale wind prediction is always referred to 10 m height. In complex terrain the wind profile is difficult to predict, and the use of a logarithmic or exponential law is not suggested [10]. Thus, although the mesoscale figure for the wind speed records the wind variation between different sites, the recorded wind potential is not representative in these areas. In the present study, a rather moderate value of 1.2 for the acceleration factor was adopted, so that any conclusions lay on the safe side. Application of the above procedure to forecast wind power production from the wind farms operating in the Lassithi region in the island of Crete [11] and in the island of Evia [12] gave promising results at a satisfactory agreement with available power production recordings.

2.4. Probability considerations

Based on the assumptions made and justified in the previous paragraphs, the wind power capacity credit estimation method is illustrated through the following steps:

- **M** different power load situations are identified. For each of them, *i*, the power load is \( P_{Li} \) and its duration is \( h_i \) hours annually. The corresponding probability of occurrence is \( f(P_{Li}) = h_i/8760 \), \( i = 1, M \). Calculations for all power load situations result in the power load probability distribution function and annual duration curve. It is noted that the availability of hydroelectric power stations is not a stochastic variable due to their inter-seasonal storage capabilities and their scheduled operation. Their power production is dependent on the power load itself and thus it is excluded from the load duration curve.

- **L** different situations of conventional power availability are identified. For each of them, \( k \), the available conventional power is \( P_{Ck} \) and its probability of occurrence is \( h(P_{Ck}) \), \( k = 1, L \). The corresponding discrete probability distribution and duration curve are derived similarly. For computational effort reasons, an average power capacity and availability is considered [5]. For instance, the number of different operational modes for 30 different power units is \( 2^{30} = 1073741824 \). Assuming that these units are identical, this figure reduces to 30.

- **N** different situations of wind power production are identified. For each of them, \( j \), the wind power production is \( P_{Wj} \) and its probability of occurrence is \( g(P_{Wj}) \), \( j = 1, N \). The corresponding probability distribution and duration curve are calculated.

Convoluted of \( f(P_{Li}), h(P_{Ck}) \) and \( g(P_{Wj}) \) results in a 3D matrix \( M \times L \times N \), whose elements correspond to the probability of occurrence of every possible operational mode:

\[
\Pi_{ijk}(P_{Li}, P_{Ck}, P_{Wj}) = f(P_{Li}) \cdot h(P_{Ck}) \cdot g(P_{Wj}),
\]

\( i = 1, M, k = 1, L, j = 1, N \).

Applying equations (1) and (2) to the matrix \( \Pi \), the total losses of load probability of the system with and without wind power plant installations, LOLPs, and LOLPW, are calculated. Next, according to equation (3), an iterative procedure calculates the increase in power demand (ELCC) so that the system’s reliability is kept at the same level as before the wind power was installed.

The above procedure is applied for various scenarios of wind power plant spatial dispersion along the system. For this purpose a computational tool AEFOR\_CC has been developed and applied for the power supply system of Greece.

3. Application in Greece

Initially, the regions of wind interest within the territory are identified. These include sites with operating wind plants and/or with a potential installation interest. The identification is based on the following:

- The current wind farm development situation in the territory (figure 4) [13].
- Mesoscale wind maps [14].
- Aeolian wind maps (figure 5) [15].
- Current national wind energy development plans (see section 3.1) [16].
- Available measurements representing the wind potential at a local level.
- Numerically generated wind speed time series (the method was outlined in section 2.3).

3.1. Wind power development plans in the mainland power system

The applications to follow emphasize the spatial dispersion associated with the mainland power system of Greece. Although Greek islands have rich wind energy potential, inter-connection reasons impose to a large extent prohibitive restrictions in studying scenarios in islands (ISL). However, for the sake of completeness, scenarios involving wind power plant implementations in islands were also included in the present analysis.

The national target for electricity production from renewable energy sources in Greece has been set to 29% by 2020. To meet this target, wind power plants of total capacity of at least 4500 MW should be installed in the mainland power supply system. Such a massive wind power implementation requires thorough study regarding its spatial distribution within the Greek territory in order to achieve effectively maximum wind energy penetration levels.
Figure 4. Current development of wind farms in Greece provided by the national information system for energy of the Ministry of Development [13].

Figure 5. Aeolian map of Greece [15].

According to the national Wind Energy Development Plan [16], there are three main regions of special interest for wind power plant developments in Greece named as Regions of Aeolian Priority (RAPs) illustrated in figure 6. More specifically, the wind power capacity planned to be installed in each of these regions is 960 MW (18.6%) in RAP1, 3237 MW (62.6%) in RAP2 and 876 MW (16.9%) in RAP3 as well as an additional capacity of 100 MW (1.9%) in the Attica region (AR). Moreover, Regions of Aeolian Suitability (RASs) have also been identified for potential wind power plant developments under favorable conditions (mainly areas with high wind energy potential).

Consequently, for compatibility reasons, the present analysis mainly includes development scenarios within the above concept while setting the limit of 5000 MW of total installed wind power capacity.

3.2. Case study assumptions

The mainland power supply system of Greece has a total installed conventional power capacity of 11 234.3 MW (including large hydro-electric plants) with a low wind power contribution (549.21 MW at the end of 2006) [14]. It consists of 22 lignite units (5288 MW), four diesel units (750 MW),
Figure 6. Regions of Aeolian Priority (RAPs), defined in the proposed land-planning for RES [16].

Figure 7. Annual duration curve of the power demand.

four combined cycle units (1630 MW), three natural gas units (507.8 MW) and a number of hydro-electric plants (3058.5 MW) [17].

For the test cases studied, a total net conventional power capacity of 7587.9 MW from the above 33 conventional units was considered (large hydro plants were excluded) with an average capacity of 230 MW and availability 89% each. Two scenarios were examined for the contribution of hydro plants: a ‘good’ and a ‘bad’ hydraulic year producing 5 and 2 TW h respectively distributed during the peak load hours with maximum production capacity of 3058.5 MW. Figure 7 presents the annual power demand duration curve with and without hydro contribution, which (as mentioned previously) can be assumed to be scheduled and fully predictable. These assumptions are considered conservative for wind power capacity credit calculations (any conclusions on the safe side).

Figures 8–10 illustrate information regarding wind power contributions to the mainland power system [18]. Indicatively, the annual wind energy contributions were 1.51%, 1.77% and 2.21%, while the average annual capacity factors were 30.44%, 29.27% and 27.38% for 2004, 2005 and 2006 respectively. Also, average wind power contributions to the peak load reach figures of 0.97%, 0.96% and 1.59% during these years.

Wind data of 2006 for which the database contains detailed information was used (see section 2.3). Data evaluation was performed through the following steps.

- Extract the time series corresponding to areas with operating wind farms.
- Assume a typical wind turbine power curve of 650 kW nominal power (which represents a reasonable average size of the wind turbines installed up to 2006).
- Calculate wind energy production for 2006.
- Calculate the corresponding average capacity factor.

An average capacity factor of 27.1% was derived. The excellent agreement with the recorded figure of 27.38% for 2006 confirms the reliability of the method and justifies the assumptions made.

For the wind turbines potentially to be installed in the regions of aeolian interest the size of 2 MW nominal power is used (according to the current state of technology) and a typical wind power curve was adjusted to that size.
3.3. The spatial dispersion scenarios

For the current situation (CS), a total wind power capacity of 1300 MW was assumed, including the operating wind farms (~550 MW) as well as those to be implemented in the very near future (an installation permit has already been provided). An upper limit of 5000 MW total wind power capacity development (including CS) was set. Cases of ‘good’ and ‘bad hydraulic year’ were also accounted for (see section 3.2).

To estimate the spatial dispersion effect of wind power plants on the wind power capacity credit, the following case study scenarios were investigated.

(A) Installation of additional wind farm capacity at 100% in RAPs and AR according to the development plan distribution percentages (18.6% in RAP1, 62.6% in RAP2, 16.9% in RAP3 and 1.9% in AR).

(B) Installation of additional wind farm capacity at 50% in RAPs and AR according to the development plan distribution percentages and at 50% in RASs (regions of high wind energy potential).

(C) Installation of additional wind farm capacity at 50% in RAPs and AR according to the development plan distribution percentages and at 50% in the islands.
For a complete evaluation, the contribution of each RAP was individually assessed through the following scenarios.

(A1) Installation of additional wind farm capacity at 100% in RAP1.

(A2) Installation of additional wind farm capacity at 100% in RAP2.

(A3) Installation of additional wind farm capacity at 100% in RAP3.

Detailed spatial dispersion scenarios are given in tables 1 and 2 and illustrated in figure 11.
Table 1. Spatial dispersion of wind installed capacity in the examined scenarios.

| Scenario | Total (GW) | Evros | Rodopi | Triakala | North Evia | South Evia | Evritania | Lakonia | Attiki | Kilkis | Pellas | Florina | Kastoria | Ioannina | Larisa | Kefallonia | Kerkira | Achaia | Argolida | Skyros | Chios | Lesvos | Lemnos | Naxos |
|----------|------------|-------|--------|----------|------------|------------|------------|----------|--------|--------|--------|--------|--------|----------|--------|--------|----------|--------|--------|--------|-------|-------|--------|-------|-------|--------|-------|
| RAP1     | 227        | 0     | 207    | 52       | 157       | 94         | 166        | 31       | 17     | 0      | 29     | 0      | 0      | 50       | 81     | 0      | 116      | 54     | 0      | 0      | 0     | 0     | 0      | 0     | 0     | 0      | 0     |
| RAP2     | 287        | 60    | 352    | 196      | 229       | 191        | 272        | 43       | 17     | 0      | 29     | 0      | 0      | 50       | 81     | 0      | 116      | 54     | 0      | 0      | 0     | 0     | 0      | 0     | 0     | 0      | 0     |
| RAP3     | 370        | 143   | 58     | 553      | 397       | 330        | 325        | 419      | 58     | 17     | 0      | 29     | 0      | 0      | 50       | 81     | 0      | 116      | 54     | 0      | 0      | 0     | 0     | 0      | 0     | 0     | 0      | 0     |
| AR       | 453        | 226   | 91     | 754      | 599       | 430        | 459        | 567      | 74     | 17     | 0      | 29     | 0      | 0      | 50       | 81     | 0      | 116      | 54     | 0      | 0      | 0     | 0     | 0      | 0     | 0     | 0      | 0     |
| RAS      | 536        | 309   | 125    | 955      | 800       | 531        | 593        | 714      | 89     | 17     | 0      | 29     | 0      | 0      | 50       | 81     | 0      | 116      | 54     | 0      | 0      | 0     | 0     | 0      | 0     | 0     | 0      | 0     |
| ISL      | 536        | 309   | 125    | 955      | 800       | 531        | 593        | 714      | 89     | 17     | 0      | 29     | 0      | 0      | 50       | 81     | 0      | 116      | 54     | 0      | 0      | 0     | 0     | 0      | 0     | 0     | 0      | 0     |

Average wind speed (m s\(^{-1}\))

| Scenario | CS | A-2 | A-3 | A-4 | A-5 | B-2 | B-3 | B-4 | B-5 | C-2 | C-3 | C-4 | C-5 | D-2 | D-3 | D-4 | D-5 | A1-2 | A1-3 | A1-4 | A1-5 | A2-2 | A2-3 | A2-4 | A2-5 | A3-2 | A3-3 | A3-4 | A3-5 |
|----------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Total    | 6.5| 5.9 | 5.7 | 6.2 | 6.0 | 6.7 | 6.5 | 6.2 | 7.4 | 7.3 | 5.7 | 6.8 | 7.5 | 6.7 | 5.4 | 7.1 | 7.4 | 7.2 | 7.1 | 7.6 | 5.3 | 6.4 | 5.9 | 6.0 | 7.4 | 6.7 | 5.4 | 7.1 | 7.4 | 7.2 | 7.1 | 7.6 |
| RAP1     | 227| 0   | 207 | 52  | 157 | 94  | 166 | 31  | 17  | 0   | 29  | 0   | 0   | 50  | 81  | 0   | 116 | 54  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| RAP2     | 287| 60  | 352 | 196 | 229 | 191 | 272 | 43  | 17  | 0   | 29  | 0   | 0   | 50  | 81  | 0   | 116 | 54  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| RAP3     | 370| 143 | 58  | 553 | 397 | 330 | 325 | 419 | 58  | 17  | 0   | 29  | 0   | 0   | 50  | 81  | 0   | 116 | 54  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| AR       | 453| 226 | 91  | 754 | 599 | 430 | 459 | 567 | 74  | 17  | 0   | 29  | 0   | 0   | 50  | 81  | 0   | 116 | 54  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| RAS      | 536| 309 | 125 | 955 | 800 | 531 | 593 | 714 | 89  | 17  | 0   | 29  | 0   | 0   | 50  | 81  | 0   | 116 | 54  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| ISL      | 536| 309 | 125 | 955 | 800 | 531 | 593 | 714 | 89  | 17  | 0   | 29  | 0   | 0   | 50  | 81  | 0   | 116 | 54  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
Figure 12. Capacity credit for wind penetration up to 5000 MW in a ‘bad’ hydraulic year for the scenarios ‘A’, ‘B’, ‘C’ and ‘D’.

Table 2. Scenario nomenclature.

| First part of the scenario’s name | Second part of the scenario’s name |
|-----------------------------------|------------------------------------|
| CS Current situation              | 2 Total wind installed capacity 2000 MW |
| A CS + (RAP1 + RAP2 + RAP3 + AR) | 3 Total wind installed capacity 3000 MW |
| B CS + (RAP1 + RAP2 + RAP3 + AR) + RAS | 4 Total wind installed capacity 4000 MW |
| C CS + (RAP1 + RAP2 + RAP3 + AR) + ISL | 5 Total wind installed capacity 5000 MW |
| D CS + (RAP1 + RAP2 + RAP3 + AR) + RAS + ISL | 6 Total wind installed capacity 6000 MW |

4. Results

Results of the methodology are presented in figures 12–17. Clearly, the following general remarks can be made.

- The wind power capacity credit decreases as wind power penetration level rises.
- The wind power capacity credit is lower than the capacity factor.
- The broader the spatial dispersion of wind plants the higher the wind power capacity credit.
- For the ‘bad hydraulic year’ wind power capacity credit appears higher than that for the ‘good’ one, revealing the contribution of wind energy in supporting the system’s reliability in peak load conditions and when other sources are limited.

As regards the comparison of scenarios (figures 12–14), the following conclusions can be drawn:

- Scenario A (RAPs and AR) appears with the lowest wind power capacity credit.
- Comparison between scenarios A and B shows that the wind power capacity credit increases significantly when RASs (regions with high wind energy potential) are included. If islands are included instead of RASs (scenario C), the capacity credit remains at the same level but wind power plants operate at 3% higher capacity factor. If both RASs and islands are considered the capacity credit reaches maximum levels (scenario D).
- Scenario C (islands) appears to be preferable to B (RAPs) for low power penetration, whereas this trend changes for higher power levels. This behavior is more noticeable...
in the ‘bad hydraulic year’ case. This can be explained by the fact that wind energy potential (high in islands) predominates in capacity credit terms compared to the wind power dispersion for low power penetration levels. The higher the penetration levels the more important role the spatial dispersion plays.

- Capacity credit values in ‘bad hydraulic years’ can exceed the 15% figure for 5000 MW installed wind power capacity associated with a substitution of approximately 750 MW of conventional power.
- Adopting better spatial dispersion strategies could result in approximately 100 MW (2% of the total wind power installed capacity) additional substitution of conventional power.

Finally, analysis of results for the individual RAP assessments (figures 15–17) leads to the following conclusions:

- RAP2 appears with the major contribution to wind power capacity credit due to its large area, while potential wind power plant developments in this area would operate at high capacity factor since the island of Evia (very rich in wind potential) is included.
- Evidently, wind power plant developments in all RAPs provide maximum capacity credit values due to positive effects of their spatial dispersion.

5. Conclusions—discussion

Wind power capacity credit should definitely be quantified in any energy development plan involving RES for effective implementation of wind power in the power supply system and for overcoming any technical issues arising from the stochastic wind character. Apart from the environmental benefits (clean energy production and CO₂ emission reduction), a thorough study of the spatial dispersion of potential wind power plant developments at a national or higher level could also increase the percentage of reliable substitution of conventional power by wind power. The present study has demonstrated that effective implementation of 5000 aeolian MW can substitute 750 conventional MW in Greece without disturbing the current power system reliability.

The assumptions made regarding the use of representative wind speed time series for wide areas of interest resulted in rather conservative results and on-the-safe-side conclusions. Results showed that the spatial dispersion of wind power plants contributes beneficially to the capacity credit of wind energy. Consequently, hyper-accumulation of wind turbines, even in wider regions, is not always the best case scenario. Taking into account the positive effects of the production spatial dispersion on the power supply reliability, a wind energy development plan should definitely give priority to areas of high wind energy potential at the local level for wind farm installations. However, if this is not feasible, specialized optimization methods should be used to achieve optimal wind power dispersion solutions. Such a method based on probability theory considerations has been outlined and applied within the present paper.

Finally, for the wind power development in Greece on the basis set by the results of the present study, reconsideration of exploiting the islands’ wind energy potential is suggested via a cable connection with the mainland’s power supply system.

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