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Analyzing the Limitations of Vast Wind Energy Contribution in Remote Island Networks of the Aegean Sea Archipelagos

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Abstract

The Aegean Archipelagos is an island region possessing excellent wind potential, with areas where the long-term average wind speed even exceeds 9m/s. Despite the excellent wind and solar potential of the area, most of the inhabited islands cover their electricity needs by utilizing thermal power stations (mainly diesel or heavy oil based units). In this context, wind power contribution is limited due to the local grid stability constraints, with zero new wind parks installed across the Aegean Archipelago during the last years. To this end, and in an effort to establish the "Green Island" electrification model for the numerous remote islands of Europe, a theoretical model is currently presented for estimating wind energy curtailments of existing and new wind parks. The model is then applied to an existing wind park of 3.6MW, operated in the island of Kos, and results obtained are compared with actual wind energy curtailments faced during a representative year of operation.

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Keywords: Wind Energy Curtailments, Island Regions, Green Islands, Energy Storage

1. Introduction

The Aegean Archipelagos is an island region possessing excellent wind potential, with areas where the long-term average wind speed even exceeds 9m/s (Fig. 1a). Despite the excellent RES potential of the area, most of the

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inhabited islands still cover their electricity needs via thermal power stations (mainly diesel or heavy oil based units) [1]. In this context, the available power quality is rather poor, while several black outs are encountered, especially during the touristic (summer) period (Fig. 1b). Finally, due to the local grids' stability constraints, wind power contribution is limited, with zero new wind parks installed across the Aegean Archipelago during the last years, as a result of no additional potential for wind energy absorption from the local electrical networks. On the other hand, during the recent years, several small and medium scale PV parks have been installed in the majority of remote islands. Due to their small size and distributed character, the local grid operator is obliged to absorb their production, thus limiting the corresponding wind power absorbance.

To this end, and in an effort to establish the "Green Island" electrification model [2,3] for the numerous remote islands of Europe, one may estimate the maximum wind energy available from existing wind parks and then the respective curtailments imposed by the local grid operators. Accordingly, the annual income loss of the wind parks owners can be calculated and compared with the turnkey cost of an appropriate energy storage system that may recover the excess wind energy production. In this context, a theoretical model is devised for the estimation of wind power curtailments and is presented in the following section 2.

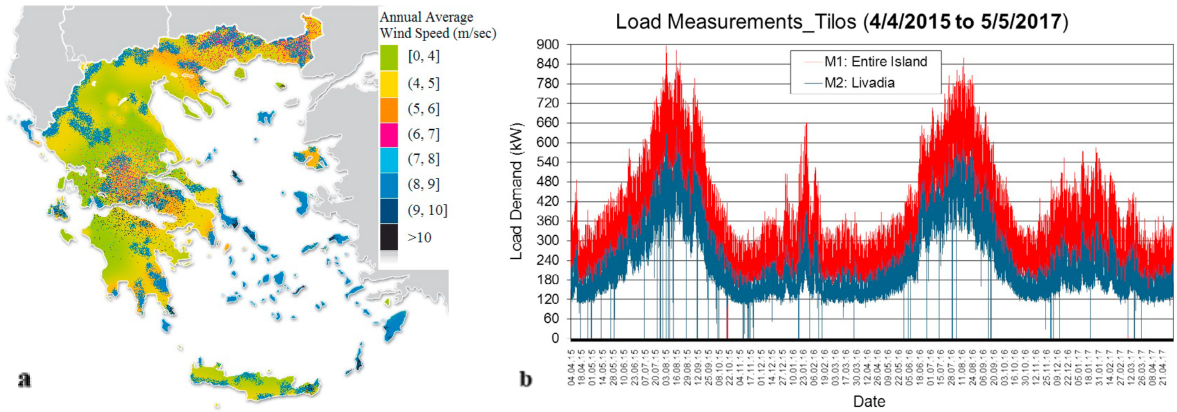

Fig. 1. (a) Wind potential in the Aegean Archipelagos; (b) Power cut events recorded for the island of Tilos (vertical lines to zero)

2. Wind Power Curtailments

2.1. Theoretical Model

One of the main problems of an autonomous electrical network is the constant estimation of the maximum wind power penetration, i.e. the wind power absorbed by the local grid without remarkable operational problems of the entire system. For this purpose, one should know the local grid load demand "$P_L(t)$" vs. time along with operational characteristics of the existing thermal units, while for bigger island regions, the topology of the local grid is also required. Furthermore, it should be noted that thermal units are not permitted to operate below a certain limit, to avoid increased wear and maintenance requirements [4]. This limit is mentioned as the "technical minimum" of each engine; hence the minimum output power of the "in operation" thermal units "P_{dmin}" is calculated as:

$$P_{d\,\min} = \sum_{i=1}^{i=i_{\max}} P_{d_i}^{\min} = \sum_{i=1}^{i=i_{\max}} k_i \cdot P_{d_i}^{*} \tag{1}$$

where the technical minimum of each engine is expressed via an appropriate factor "k_i" and the rated (or maximum) output power "P_{di}^{*}" of the unit. Typical values of "k_i" are 30–50% for heavy-oil units and 20–35% for diesel-fired engines (including gas turbines), depending much on the age and the overall condition of the engine. On top of this, the annual maintenance plan of the system, affecting the number (i_{max}) of engines "in operation" during the year, should also be considered. In addition, due to the stochastic nature of wind one cannot disregard the probability of an unexpected loss of a significant part of the "in operation" wind parks. To avoid (or to minimize) loss of load events [5,6] in similar situations, the system operator should maintain full spinning reserve, which suffices to cover the total load demand, i.e. the "in operation" thermal units should be able to cover "P_L", thus:

$$\sum_{i=1}^{i=i_{max}} P^*_{d_i} \geq P_L \tag{2}$$

However, in order for these units to come into operation at their minimum fuel consumption (maximum efficiency) point one should assume that:

$$P^*_w + \sum_{i=1}^{i=i_{max}} \xi_i \cdot P^*_{d_i} \geq P_L \tag{3}$$

where "ξ_i" takes values between approximately 65% and 80%, on the basis of the operational maps of the existing diesel engines. In an attempt to satisfy the "economic" operation of the existing internal combustion engines in view of the desired wind energy penetration, one should carefully plan the dispatch of thermal units. Hence, combining Eqs. 2 and 3 and assuming that one may use a single "ξ_i" value, one finally gets:

$$P^*_w \leq (1-\xi) \cdot P_L \tag{4}$$

For practical applications, Eq. 4 is written in the following simplified and widely used form, i.e.:

$$P^*_w \leq \lambda_1 \cdot P_L \tag{5}$$

where "P_w^*" is the maximum acceptable wind power by the local network and "λ_1" is the corresponding maximum instantaneous participation limit, based on the operational characteristics of the existing thermal power units. Finally, in order to avoid annoying system frequency excursions and increasing wear of the existing thermal power units, an additional penetration limit is also imposed, dictated by the instantaneous rate that the "in operation" units can compensate any power deficit of the system. This dynamic penetration limit [7] is characteristic of the network as well as of the spatial distribution and the type of the system's wind turbines. In general, this limit "λ_2" is selected by the system operator (also incorporating subjective/personal attitude) and is up to now empirically set in the range of 20–40%. In case of emergency, this value may drop down to 15% or even to zero [8]. In this context, the dynamic penetration constraint is expressed as:

$$P^*_w \leq \lambda_2 \cdot P_L \tag{6}$$

On the basis of the above analysis, the maximum absorbed wind energy "$P_w^*(t)$" by the local electrical system can be estimated according to the following equations, i.e.:

$$if \quad P_L(t) \leq P_{d\min}(t) = \sum_{i=1}^{i=i_{max}} k_i \cdot P^*_{d_i} \quad then \quad P^*_w(t) = 0 \tag{7}$$

In this case, there is no wind energy absorption by the local network; hence all the wind energy production is rejected.

$$if \quad P_{d\min}(t) \leq P_L(t) \leq (1+\lambda) \cdot P_{d\min}(t) \quad then \quad P^*_w(t) = P_L(t) - P_{d\min}(t) \tag{8}$$

where "λ" is the wind power upper participation limit depending on the optimum operation of the system thermal power units "λ_1" and the dynamic stability of the local network "λ_2", i.e.:

$$\lambda = \min\{\lambda_1, \lambda_2\} \tag{9}$$

Finally,

$$if \quad P_L(t) \geq (1+\lambda)\cdot P_{d\min}(t) \quad then \quad P_w^* \leq \min\{\lambda \cdot P_L(t), P_L(t) - P_{d\min}(t)\} \tag{10}$$

In this last case, the wind energy penetration is bounded by the upper wind power participation limit "λ" and the instantaneous load demand of the system. In most practical application cases the "λ" value is taken (as a thumb rule) less or equal to 30%. Applying Eqs. 1-10, one has the ability to estimate the maximum wind energy penetration in the local grid. However, in cases of low wind energy production the real wind energy contribution is quite lower (i.e. the maximum penetration limit is not approached), further reducing the contribution of clean energy to the balance of remote islands.

2.2. Real World Calculation Procedure

For the estimation of the instantaneous wind-power rejection "$\Delta P_{i(t)}$" of a specific "i" wind park in the course of time "t", the following information is needed: The instantaneous wind-power production "$P_{w(t)}$" of this specific "i" wind-park, assuming zero wind-energy rejection and corresponding to the sum of the electricity generation of all wind turbines "j_{max}" of the wind park under investigation, i.e.:

$$P_w(t) = \sum_{j=1}^{j=j_{\max}} P_{i,j}(t) \tag{11}$$

The wind power finally given to the local network (including wind rejections) by each wind park under operation is "P_{abs}". Hence, by definition, the wind power rejection "$\Delta P_i(t)$" is given by the following relation:

$$\Delta P_i(t) = P_i(t) - P_{abs}(t) \tag{12}$$

Thus, the main problem for the application of Eqs. 11 and 12 is the fact that the original wind-power output of each wind turbine "P_j" is not known, since the existing data (by the local operator) concern the final wind energy entering the grid "P_{abs}", thus they do not correspond to the wind energy rejected by the local network operator. An alternative and practical way to face this obstacle is to simulate the output of each wind-turbine based on the anemometer of the machine, taking also into consideration the central anemometer of the wind park along with meteorological conditions. In this context [9], one may write:

$$P_w(t) = {}^sP_i(t) \cdot \frac{\rho(t)}{1.2215} \cdot \delta_i(t) \tag{13}$$

where "^sP_j"' is the analytical function describing the power curve of the wind turbine "j", expressed as a function of the wind speed at hub height for standard day conditions, provided by the wind turbine manufacturer. More specifically "ρ" is the mean instantaneous air-density at the wind-turbine "j" location and "$\delta_j(t)$" is the well-known Kronecker's delta function taking values either equal to one (if the wind turbine is available for operation) or zero, in case that serious malfunctions appear in the specific machine. Finally, the air density at standard day conditions is 1.2215 kg/m^3. By comparing the expected and the finally absorbed wind power by the local grid (minus wind park self-consumption) one may estimate the corresponding wind power curtailments.

3. Application Results

The above-presented method is accordingly applied to estimate the wind-energy rejections, on a 10-min basis and for an entire year period (2013), in a 3.6MW wind park with 5 wind turbines, located in Kos island. Actually, the specific wind park has been licensed for only 3.6MW, although wind turbines employed have rated power of 0.9MW, thus the real power of the installation is 4.5MW. Unfortunately, the local network restrictions further limit the maximum power output of the installation and the existing wind turbines operate in down-rated mode, each one providing maximum power 0.72MW instead of 0.9MW. Moreover, the altitude of the specific wind park is 400m above sea and according to the long-term measurements of the meteorological parameters of the area, the corresponding air density mean value is 1.17kg/m^3. Besides air density, for this specific time period, the following historical data are also taken into account:

- the wind-speed values "$V_j(t)$" for every wind turbine of the installation; see for example Figs. 2a and 2b, describing the detailed wind speed data for selected wind turbines of the power station and the mean monthly wind speed values for all machines of the installation for an entire year respectively.
- The wind power finally given to the local network (including wind rejections) by each wind turbine "P_{abs}".
- The corresponding air-density, resulting from measurements of temperature "θ" and ambient pressure "p".
- The technical availability "δj(t)" of each wind turbine investigated in the course of time.

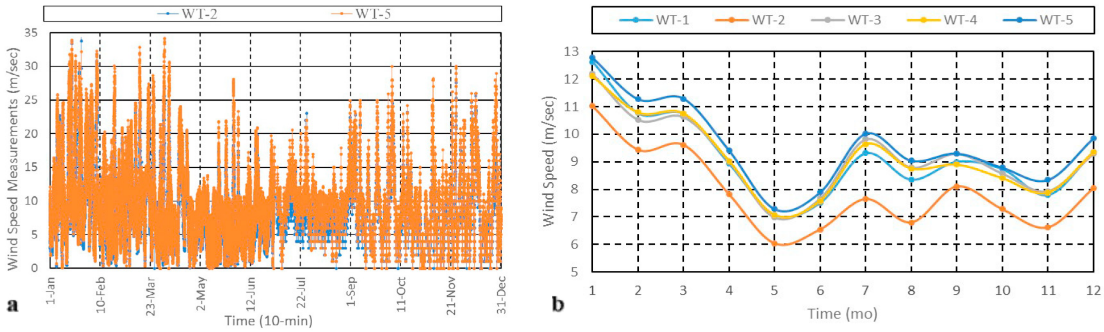

Fig. 2. (a) 10-min wind speed measurements; (b) monthly mean wind speed values;

Based on the above data, one may estimate the expected wind energy yield of the five wind turbines. In Fig. 3a the expected energy yield of all five wind turbines is given on a monthly basis, along with the expected capacity factor "CF" of the wind park, taking values between 40% and 60% (mean value ~44%). At the same time one may present the real CF of the wind park using the official data provided by the local network operator. According to those, the corresponding mean annual value is 23.2%, almost half of the expected CF value (Fig. 3a). Comparing the two CF distributions, we can see similar values only during summer (June to August) due to the increased load demand, while huge deviations appear between November and April. Another remarkable conclusion is the very high capacity factor of the island's PV plants. During 2013, the peak power of the existing PV installations was 7.1MW, with an average capacity factor equal to 20% on an annual basis, while from April to June, the CF of the PV installations is even higher than the corresponding value of the existing wind parks. This very unusual phenomenon occurs due to the fact that the grid operator cannot curtail the power output of PV plants, leading to CFs even at the level of 27%. Unfortunately, this is not the case for the "in operation" wind parks, where excessive curtailments are imposed due to the low load demand of the local network but also due to the presentation of the PV-based power plants. Finally, in order to obtain a clear quantitative picture of the wind power curtailments of the wind park under investigation, one may compare the expected and the finally absorbed wind power of the installation. More specifically the final absorbed wind power is (according to the official data by the local operator) equal to 9.74GWh (wind park self-consumption approximately 100MWh/year), while the expected wind energy yield is 14.13GWh (on the basis of the available wind potential), see also Fig. 3b. This means that almost 4GWh of clean electricity is curtailed, deteriorating the wind energy contribution of the existing 15.4MW wind parks of the island to only 8.9% on annual basis. On the other hand, the 7.1MW of PVs cover 4.5% of the local demand. Acknowledging the above, the annual income loss of the specific wind park owner (3.6MW) is almost 400k€, i.e. a considerable amount that strongly affects the financial performance of the entire investment.

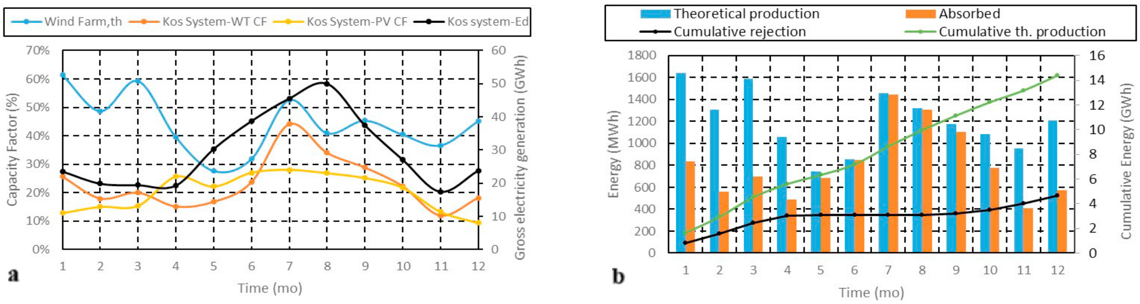

Fig. 3. (a) CF distributions for the Kos system; (b) theoretical wind energy production vs absorbed wind energy and wind energy rejections

4. Conclusions and Proposals

In order to address the major electrification problem of the numerous remote islands of Europe on the basis of considerable wind energy contribution, an integrated methodology has been developed. According to the proposed analysis, one has the ability to estimate the wind power curtailments of operating wind parks, necessary to properly evaluate the wind parks' financial performance and to explore the potential of using an energy storage device for the recovery of curtailments. Energy storage can support the increased contribution of wind energy by providing it to the grid in the form of guaranteed energy which is equivalent to the elimination of its stochastic character. In this context, energy storage provides grids operator with higher flexibility, while at the same time ameliorating the financial performance of wind parks operating in saturated environments.

Acknowledgements

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