The influence of technical availability on the energy performance of wind farms: Overview of critical factors and development of a proxy prediction model

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Nowadays wind energy comprises an established power generation solution that competes on equal terms with conventional thermal power generation technologies. On the other hand, the inherent characteristic of intermittent energy production, due to the stochastic nature of wind, still comprises the main drawback of wind power. In this regard, one of the most significant factors responsible for the reduction of the wind turbines’ energy yield is the machines’ technical unavailability. Realizing the important role of technical availability throughout the wind energy technology evolution, an overview of influencing factors and operational experience from wind farms around the globe are currently provided, while accordingly, a proxy prediction model is developed for the estimation of technical availability and the determination of its impact on the annual energy yield of a wind farm. Application results obtained for several case studies indicate the importance of the technical availability factor on the annual energy yield, while finally, the developed model is validated with the use of long-term real operation data from a wind farm installed on the island of Ikaria, Greece.

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1. Introduction

Wind energy is granted as a mature power generation technology (Kaldellis and Zafirakis, 2011; Sesto and Casale, 1998; Solari, 2007) that is nowadays found to compete on equal terms with conventional power generation. On the other hand, the inherent characteristic of intermittent energy production, due to the stochastic nature of wind, still comprises the main drawback of wind power (Albadi and El-Saadany, 2010; Bystryk and Sullivan, 2011). In this regard, one of the most significant factors responsible for the reduction of the wind turbines’ energy yield is the machines’ technical unavailability. In this context, it should be noted that although “regulation” of the local wind potential is not possible, improvement of the wind turbines’ energy performance through the increase of technical availability comprises one of the most important challenges for the increase of energy production. More precisely, by improving the technical availability of wind farms, reduction of the downtime period is the immediate result, which accordingly leads to the improvement of the overall energy and economic performance of the installation. To this end, a detailed description of the main factors influencing technical availability of wind farms and their impact on the latter energy yield is currently provided, followed by the presentation of a proxy prediction model for the estimation of a wind farm’s technical availability. The paper concludes with the application of the developed model, that sufficiently captures the impact of technical availability on the energy performance of wind farms.

The term of technical availability or reliability is used to express the ability of a given wind turbine or a wind park to operate safely (reliably) under a technical point of view. Note also that technical availability is not directly relevant to the local wind potential of the installation area, although strong winds appearing increase the possibility of faults and malfunctions and also hinder immediate repair. Realizing the importance of improving technical availability, significant progress has been noted during the last 25–30 years in the specific field (Kaldellis, 2002), corresponding to an increase in the order of 45%. In this context, it must be underlined that technical availability of 99% achieved in the recent years, implies that wind turbines are out of operation for less than 100 h per year (≈ 1% × 8760 h), or for less than the equivalent of 4 days per year.

At the same time, what should also be emphasized is the fact that safe operation of a wind turbine depends on the safe operation of several sub-components, as well as on the safe interaction between the different parts of the machine. On the other hand, one should acknowledge the fact that wind turbines are machines operating constantly (sometimes for several days...
without interruption), often in very unfavorable weather and site conditions (Botta et al., 1998; Christensen and Giebel, 2001), with their operation being difficult to regulate, since it is strongly dependent on uncontrolled parameters such as wind speed, ambient conditions, grid status, etc. Furthermore, as it may be easily realized, technical availability depends also on the reliability and the quality of equipment employed, as well as on the frequency of and the gravity attributed to maintenance services provided. Besides that, technical availability is also influenced by external factors such as weather conditions, the local electricity grid and infrastructure, as well as by the experience of the service staff of the wind farm. Moreover, what is also important to note is that a wind turbine’s reliability greatly depends on the design and construction of the model under consideration as well as on its material quality and class, while finally, a wind turbine’s reliability also varies with the operating environment, stressing the need for the careful selection of the appropriate turbine model for each specific location.

To this end, if taking into account the number of factors involved, a priori determination of technical availability is a hard task to achieve, considering at the same time however that its influential role in the energy production ability of a wind turbine/farm calls for the development of an estimation methodology. In this regard, as already mentioned, a prediction methodology is currently developed for the estimation of technical availability, with application results provided indicating the importance of each contributing factor as well as the validity of the proposed model. Prior to that, an overview of technical availability issues is undertaken by the authors, providing real life data from the operational experience of several wind farms around the globe and highlighting the main types of factors responsible for the decrease of technical availability.

2. Time evolution and status of wind farms’ technical availability

2.1. Time evolution of technical availability

According to Fig. 1, time evolution of technical availability presents remarkable increase during the last 30 years (i.e., from the values of 55%–65% for the first wind turbines of California (up
to 1985) to the values of 99% for contemporary wind turbines),
that also reflects the technological evolution met in the field, as
well as the introduction of considerably improved wind turbine
models, determined by minimum operation problems. In this
context, according to the latest official data (Tavner et al., 2007),
there is a substantial reduction recorded in the number of wind
turbine faults (failures) during the 15 year-period studied (Fig. 2),
this being in total agreement with the data of Fig. 1. On top of
that, in Fig. 2 one may also obtain a straightforward comparison
with the number of faults noted in other, thermal power genera-
tion technologies. According to the data provided, vast reduction
of wind turbines’ fault rate over the years has led to less faults per
machine and year in comparison with diesel generators and
combined cycle gas turbine (CCGT) units, expected at the same
time to drop near the levels of steam turbine units’ faults in the
near future.

As already seen, evolution of wind power technology during
the last 30 years has led to the substantial limitation of faults
responsible for the reduction of technical availability, which in
turn leads to the improvement of contemporary wind turbines' 
energy yield. In this regard, according to official data available
(Energy Information Administration (EIA), 2011), in Fig. 3 one also
presents the constant improvement of the mean annual global
and EU wind power capacity factor (CF) (being the product of the
mean power coefficient and the technical availability, see also
Section 4) in the course of time (1996–2007), underlining at the
same time that contribution of offshore wind parks for that time
period is rather restricted. Furthermore, taking into account the
fact that sites of high quality wind potential gradually diminish
(especially in Europe), improvement of energy efficiency of
contemporary wind turbines during this period cannot support
the substantial CF increase on its own, thus designating the
progress met in the field of technical availability.

Moreover, to further support actual contribution of improved
technical availability to the energy performance of wind parks, in
Fig. 4 one may obtain—as an example—the time evolution of the
average CF of all Greek wind parks during the period from 1990 to
2009. According to the data of the figure (Eurostat, 2012), the CF
value is found to even double during the second half of the period
examined, as a result of the remarkable technical availability
improvement. In the same context, what is worthwhile to note is
that currently the majority of wind parks is found on the main-
land part of Greece (Hellenic Wind Energy Association (HWEA),
2012), opposite to the first Greek wind parks installed almost
exclusively on island regions so as to exploit the local higher
quality wind potential, which also illustrates the level of

![Time Evolution of the Mean Annual CF on the EU & the Global Level](image1)

**Fig. 3.** Time evolution of CF for world and European wind farms (based on data from: Energy Information Administration (EIA), 2011).

![Time Evolution of Greek Wind Farms' CF (1990-2009)](image2)

**Fig. 4.** Time evolution of the mean annual CF for Greek wind farms (based on data from: Eurostat, 2012).
improvement encountered in technical availability issues during this 20-year period.

2.2. Presentation of up to date monitoring data

Owed to the importance of reliable operation, considerable efforts may be recorded during the recent years in respect of operation monitoring and dissemination of the data obtained by wind park operators (EMD International A/S, 2011; Harman et al., 2008; Hill et al., 2008; Vattenfall Power Consultant (VPC), 2011; VTT-TRCF, 2011). Based on these databases, evaluation of the various causes of technical unavailability may be better approached, using information from numerous wind farms around the entire globe. In this context, representative results are currently presented in order to provide some indication on the current status of reliability of contemporary wind turbines and also designate the detailed monitoring carried out in certain cases.

To this end, in Fig. 5, long-term monitoring of 14 GW of wind power, providing an aggregate of almost 750 wind farm-years for approximately 250 wind farms under study, produces a quite representative distribution of annual technical availability (Harman et al., 2008). Based on the results obtained, 50% of the aggregate 750 wind farm-years present technical availability values that are higher than 97.5% while on the other hand, it is only for 6% of the wind farm-years that technical availability drops below 90%. Besides, similar are also the results obtained from the Finnish and the Swedish databases of national wind drops below 90%. Besides, similar are also the results obtained in the German Wind Program, the majority of failures reported (Fig. 7a) are due to the electrical grid problems and problems of the electrical system of the machines, while no serious mechanical failures have been mentioned, excluding the brake problems representing less than 20% of the total problems.

Finally, of major interest is also the data concerning performance of a small wind farm operating in the island of Ikaria (Kalafatis et al., 2008), comprising 7 wind turbines of 55 kW each (2nd generation wind turbines) for the appreciable time period of 15 years (1991–2006). In this context, in Fig. 9, the impact of different types of faults on the energy production of the wind farm is presented for the entire time period of 15 years. According to the data presented, the greatest share of downtime hours derives from faults appearing in the electronic equipment of wind turbines, while following mechanical faults also hold an important percentage in the order of 36%, with the electrical equipment faults causing 8% of the downtime periods.

2.3. Technical availability data from different operation sites

Accordingly, one should also emphasize on the level of detailed monitoring currently achieved, allowing for the association of technical unavailability causes and effects. For example, in Fig. 7a one may obtain the downtime hours per machine component for approximately 21,000 wind turbines operating in Germany over the 3rd quarter of 2009, while in Fig. 7b, association of causes and effects is also presented (Carlsson et al., 2010). In this context, as one may see, rotor and air brakes comprise the most sensitive components and most frequent causes respectively for the given sample (Fig. 7a), while as it accrues from Fig. 7b, service of the rotor component is responsible for the highest number of downtime hours. As far as distribution of faults is considered for the under study wind turbines, it becomes evident that for German wind farms, the greatest share of faults concerns mechanical equipment (e.g. rotor, brakes, etc.), rather than other reasons such as poor quality of the local electricity grid.

On the contrary, in countries such as India, where the local infrastructure of the electricity network is not as developed, a significant proportion of faults is attributed to the local electricity grid. More specifically, according to the results reported (Iniyan et al., 1996) for the operation of a quite large—for the specific time period—(10 MW) wind park at Gujarat of India, the overall technical availability is estimated at 80%. The wind park includes 50 wind turbines of 200 kW rated power, while during the fault analysis almost 30 major failures have been encountered. Opposite to the German Wind Program, the majority of failures reported (Fig. 8) are due to the electrical grid problems and problems of the electrical system of the machines, while no serious mechanical failures have been mentioned, excluding the brake problems representing less than 20% of the total problems.

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Synopsizing, what may result from the analysis of data available is the fact that appearing faults are to a great extent site-specific, this resulting to the appearance of different types of faults among developed, under development and isolated island areas. Acknowledging the progress encountered in the area of monitoring, detection of the most sensitive components and the most frequent causes of failure in association with the characteristics of the installation area and the features of the machine each time investigated is believed to further evolve the efforts toward the maximization of technical availability and the increase of wind energy production reliability.

3. The main influencing factors of technical availability

A wind turbine is not considered to be technically available (Abderrazzaq and Hahn, 2006; Kalafatis et al., 2008; Kaldellis et al., 2003) (i.e., downtime period) in case of (see for example Fig. 10 concerning the operation of more than 21,000 wind turbines in Germany for a period of 3 months):

- Scheduled/regular maintenance
- Electrical grid problems
- Service problems
- Wrong/false fault announcement
- Component-material failure
- Extreme weather conditions
- Corrosion problems
- Force Majeure problems
- Various

Facing the specific problems (e.g. grid problems, normal service activities, false failure announcements), although not requiring additional expenses does—in most cases—imply an increase of the maintenance and operation cost (Kaldellis, 2002). On top of that, during the time that the wind turbine is out of operation, analogous wind energy production losses may be encountered—mainly dependent on the available wind potential during the specific time period—that as expected imply less or more considerable income losses to be considered (Kaldellis et al., 2004).

Scheduled/regular maintenance of a wind park, including normal service activities and depending on the schedule provided by the manufacturer is executed between two and four times per year. Moreover, scheduled/regular maintenance is normally combined with the repair of any appearing damage, lasts for a given time period (5–20 h, depending on the severity of the scheduled maintenance task) and is executed by a service crew of at least

Fig. 6. Probability distribution of downtime hours and technical availability for wind farms operating in Finland (a) and Sweden (b) (based on data from: EMD International, 2011; VTT-TRCF, 2011).
two engineers. To moderate wind energy production losses of the installation, it is preferable for the maintenance tasks to be executed during the calm spells' periods, while the opposite is valid for the windy periods of the year, i.e., when any maintenance tasks should be avoided in order to protect the maintenance crew from the risk of accident.
island networks (Kaldellis, 2008; Papathanassiou and Boulaxis, 2005; Tande, 2000; Weisser and Garcia, 2005). The most common problems include considerable voltage variation (voltage sags and swells), phase asymmetry due to faults appearing either in the operation of network transformers or in the respective of wind turbines’ compensation capacitors, phase discrepancy (normally following the network restoration), frequency deviations, as well as complete collapse of the local system (black out). In the majority of the above mentioned cases, the arising malfunctions are automatically repaired within a few minutes’ time (10 min up to 1 h), while during certain times, intervention of the machine operator through the use of a remote control system is necessary. To avoid similar problems during the past, the increase of the wind turbine tolerance limits in analogous fluctuations was attempted, involving however increased risk of seriously damaging the machine equipment. As already mentioned, the specific problems become more severe in small island networks where the fluctuations of operational parameters are by far greater than those encountered in strong mainland networks, due to both the limited inertia of the thermal power units’ operation and the small capacity of the electrical grid.

Besides that, another severe problem that is responsible for the restriction of the wind turbines’ technical availability in island networks, not however comprising a fault of either the equipment or the local electrical grid, is the curtailment-rejection of wind energy production owed to either low electricity demand encountered (Kaldellis et al., 2004) or the need to ensure grid stability (Papathanassiou and Boulaxis, 2005). More specifically, possible instability of the existing electrical grids and requirement for complete control over the quality of electrical energy provision set some serious obstacles in the dynamic exploitation of wind energy in autonomous electrical networks.

For this reason, an upper limit to the instantaneous wind power contribution to the local electricity demand is normally imposed by the operators of such electricity grids (e.g. 30%), which may both lead to insufficient exploitation of the local wind potential by the already existing machines and also limit any prospects of further wind energy integration. Note that it is these curtailments that stand as the main reason for the confined activity concerning the installation of new wind parks in several island areas, with annual wind energy participation in the Aegean Sea area (Greece) for example limited to a maximum of only 10% for most islands (Kaldellis and Zafirakis, 2007).

Moreover, as far as service problems are concerned, damages or unscheduled interruptions of operation, owed to the deficient maintenance of equipment should also be considered. In this category one may encounter the activation of aerodynamic brakes (due to the marginal adjustment of the respective mechanism) although there is no evidence showing an actual increase of the rotor’s speed, the activation of overheating protection sensors, the overheating of moving shafts-bearings due to deficient lubrication (yaw mechanism, gear box bearings), etc. The specific problems may be gradually constrained as the maintenance personnel become more experienced and as the technology of the corresponding sensors is improved.

Concerning wrong/false fault announcements, representing in many cases the majority of recorded problems for wind turbines during the past, they are usually dealt with the use of remote control systems, not requiring any considerable cost and not implying a significant reduction of the turbine’s energy production time. The cause of these problems may be ascribed to momentary fluctuations of the network parameters, to interruptions among different signals and to deficient coordination of the turbine’s operational parameters, as well as to deficient set-up of the controller algorithm (this meaning that unforeseen states of operation may appear for the wind turbine). To encounter the respective problems, the development of know-how regarding wind turbines as well as the use of the appropriate components that inhibit the appearance of these mock faults (e.g. cable shields, diodes’ placement, varistors, etc.), are critical.

Failure of materials and components comprises the most severe factor of unreliability for a wind turbine, while repair of these damages requires considerable time and additional expenses. Equipment failures may include the failure of small parts and the turbine’s operation interruption due to certain problems detected in the main components, i.e. blades, electrical generator, pitch mechanism, gearbox, yaw system, hydraulics, etc. Moreover, as far as service problems are concerned, damages or unscheduled interruptions of operation, owed to the deficient maintenance of equipment should also be considered. In this category one may encounter the activation of aerodynamic brakes (due to the marginal adjustment of the respective mechanism) although there is no evidence showing an actual increase of the rotor’s speed, the activation of overheating protection sensors, the overheating of moving shafts-bearings due to deficient lubrication (yaw mechanism, gear box bearings), etc. The specific problems may be gradually constrained as the maintenance personnel become more experienced and as the technology of the corresponding sensors is improved.

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direction systems, eventually leading to operation disruption. Additionally, both moisture and frost aggravate the operation of blades and other mechanical parts of a wind turbine, often causing increased loads (mainly fatigue) and leading to the acceleration of the equipment’s wear. Extreme wind speed phenomena and lightning strikes (Kwon et al., 2012; Peesapati, 2010), since classified in the category of “Force Majeure” problems are not currently examined. On the contrary, in the specific type of problems one may also encounter damages of the electrical and electronic equipment due to very high temperatures recorded in certain areas of the planet.

Moreover, despite the careful design and the special manufacturing of the equipment, there are always some parts or sections that appear to be more sensitive in the corrosion caused by the marine environment in island or coastal areas and offshore parks (Thick, 2004). In several cases, minor problems due to corrosion or rust may lead to more appreciable ones, like the blockade of the brake system and the electrical revolutions’ reducer, as well as the complete destruction of the corresponding motor.

Reliability problems owed to “Force Majeure” reasons include mainly destruction of equipment due to lightning strikes and extremely strong winds, while one should also consider destruction owed to fires, floods, and considerable disturbances of the local electricity network. Note for example that in the Greek territory, lightning is recorded as one of the most severe phenomena, leading the technical availability of the existing wind turbines. More specifically, lightning strikes may—according to the best case scenario—lead to the temporary interruption of the wind turbine operation. In more severe cases, destruction of certain electrical and electronic systems’ parts (mainly the controller’s) as well as complete destruction of the rotor or even of the entire wind turbine have also been encountered. Although contemporary systems of lightning protection ensure the equipment’s protection under high levels of reliability, they cannot—under no circumstances—ensure absolute protection from the most intense of natural phenomena. Similarly, the extremely strong winds considerably aggravate the strength of a wind turbine’s various sections, while in cases of gusty winds, destruction of both single turbines and entire wind parks have also been reported in several areas.

Finally, in the unclassified various problems one may include damages and problems owed to wrong handling and operation of machinery and control systems by the personnel as well as to destruction of cables and equipment parts caused by animals or third parties.

Recapitulating, it becomes clear that a series of problems may appear in a wind park operating in an isolated, mountainous or coastal area, these leading to both the inhibition of fair wind energy generation and the imposition of a remarkable replacement and re-establishment of safe operation cost.

4. Modeling technical availability and its impact on wind energy generation

As already seen, the exact value of technical availability of a wind farm is of primary importance with regards to its energy production and thus with regards to its economic performance, influenced by both revenues and expenses relating to maintenance and operation of the installation. To this end, estimation of technical availability a priori is critical in order to determine the energy and economic performance of a wind farm.

In this context, the annual (8760 h) energy yield of a wind park of “z” wind turbines, each of rated power “P_R”, is usually expressed as:

$$E_{wp} = CF(zP_R)8760$$  \hspace{1cm} (1)

where “CF” is the installation annual CF given as the product of the mean power coefficient “ω_C” and the technical availability “Δ” of the installation i.e.,:

$$CF = ω_C Δ$$  \hspace{1cm} (2)

where “ω_C” is defined as

$$ω_C = \int_0^\infty P_{ex}(V) f(V) dV = \int_0^V \frac{P_{ex}(V)}{P_R} f(V) dV$$ \hspace{1cm} (3)

According to Eq. 3, the exact value of the mean power coefficient depends on both the local wind energy resource characteristics (normally the probability density “f(V)”) curve of the local wind potential is used) and the operational non-dimensional power curve “P_{ex}(V)/P_R” of the wind turbine each time examined (with “P_{ex}(V)” being the power output in relation to wind speed “V”), with both curves expressed as a function of the wind speed “V” at the machine hub height. In this regard, it must be noted that the energy production of a wind turbine is
limited within the range of wind speeds from the cut-in “\( V_c \)" to the cut-out “\( V_F \)" wind speed.

Considering the above, importance of determining the mean technical availability in order to configure the energy yield of a wind turbine or a wind farm is reflected. In this context, technical availability of a wind turbine depends among others on the technological status, the age of the machine and the site of installation (Kaldellis, 2002, 2003), thus one may use the following expression:

\[ A(t) = \frac{A_0(t_0)}{D_w} \cdot A_n \cdot A_c \]

where “\( A_0 \)" describes the technological status (generation) of a wind turbine at time “\( t_0 \)" that the machine becomes commercial. In this context, one should note that in the early 80s, technical availability of the first wind parks was approximately 60%, while at the beginning of the next decade the value of “\( A_0 \)" outnumbered 90% mainly owed to the improvement of “\( A_c \)". Improvement of technical availability in the course of time may be clearly demonstrated in Figs. 1 and 2 (Kaldellis, 2002; Tavner et al., 2007), where reduction of the fault (failure) rate of wind turbines in the course of time may be obtained (in the order of 10 failures per year in the end of the 80s to approximately 0.2 failures per year in 2004). As a result, wind energy technology has nowadays achieved such a level of quality that contemporary wind turbines may even be determined by a technical availability of 99%.

The next term “\( A_w \)" takes into consideration the accessibility difficulties of the wind park under investigation. This parameter is of special interest for remote areas and offshore wind parks, especially during winter, due to bad weather conditions (high winds and huge waves suspend the ship departure, thus preventing maintenance and repair of the existing wind turbines). For this purpose, an adapted form of the analysis in (Van Bussel, 1999) may be used in order to simulate the “\( A_w \)" parameter of Eq. 4, see also Fig. 11.

Subsequently, in small autonomous grids one should take into account the actual upper limit of wind energy/power integration/penetration. In similar cases the period of time “\( A_G \)" that wind energy is absorbed by the local grid is strongly decreased (Kaldellis et al., 1993) as the wind power integration in the local grids is increased. To this end, in Fig. 12 one may find the variation of the technical availability integration factor “\( A_G \)" as a function of the existing upper limit of wind energy integration “\( l \)" extended up to 30%. However, detailed cost-benefit analyses...
and more recent calculations based on stochastic methods state that the actual wind energy contribution without any energy storage devices is quite low and rarely exceeds $\lambda \approx 10\%$ (Kaldellis, 2008).

Finally, the most relative to the current analysis term is the term "$A_o(\tau)/A_o^\tau$", which expresses the technical availability changes during a wind turbine's operational life "$t$". At this point it is important to mention that there are several “failure pattern distributions”, i.e., from the well known “bathtub curve” and the “slow aging” one up to the “traditional view”. Based on real data evaluation (Hahn, 1999), it can be assumed that most wind turbines' reliability is characterized by early failures until the third operational year. This phase is generally followed by a longer period (~10 years) of “random failures”, before the failure rate through wear and damage accumulation “wear-out failures” increases with operational age. In order to simulate the “$A_o(\tau)/A_o^\tau$” distribution the function "$d=\text{d}(\tau,z)$" is introduced, thus Eq. (4) may be equally well written as:

$$A(t) = A_o(t_o)A_o[A_o(1-\text{d}(\tau,z))]$$  \hspace{1cm} (5)

where "$\text{d}=\text{d}(\tau,z)$" is related to the wind turbine failure rate “$\text{FR}(\tau,z)$”, depending on the year of operation “$\tau$” and the number of wind turbines “$z$” of the wind park on the basis of the following relation:

$$\text{d}(\tau,z) = 1-e^{-\text{FR}(\tau,z)}$$  \hspace{1cm} (6)

Table 1
Variation of technical availability factors for the case studies examined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
<th>Mainland ($z=20$)</th>
<th>Island ($z=10$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_o$</td>
<td>Mean wind speed $V_m=5.2$ m/sec ($\omega=0.20$)</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>Mean wind speed $V_m=8.2$ m/sec ($\omega=0.39$)</td>
<td>0.973</td>
<td>0.913</td>
</tr>
<tr>
<td></td>
<td>Mean wind speed $V_m=10.8$ m/sec ($\omega=0.57$)</td>
<td>0.936</td>
<td>0.804</td>
</tr>
<tr>
<td>$A_o$</td>
<td>1st Generation-1982</td>
<td>0.600</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>2nd Generation-1992</td>
<td>0.959</td>
<td>0.905</td>
</tr>
<tr>
<td></td>
<td>3rd Generation-2002</td>
<td>0.580</td>
<td>0.580</td>
</tr>
<tr>
<td></td>
<td>4th Generation-2012</td>
<td>0.990</td>
<td>0.990</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Low integration ($\lambda=10%$)</td>
<td>1.000</td>
<td>0.938</td>
</tr>
<tr>
<td></td>
<td>High integration ($\lambda=30%$)</td>
<td>1.000</td>
<td>0.677</td>
</tr>
</tbody>
</table>

In this context, as it may be realized, in cases of numerous wind turbines (high “$\omega$” value) it is more possible for permanent service staff and for spare parts stock to exist. For this reason, the operational time-dependent technical availability diminution “$\text{d}(\tau,z)$” is lower for large wind parks ($z \approx 100$) than for individual wind converters (Hahn, 1999; Kaldellis and Kodossakis, 1999; Lemming et al., 1999) (Fig. 13).

5. Application results

5.1. The impact of technical availability on the annual energy yield

Acknowledging the fact that the annual energy yield of a wind farm is strongly dependent on both the power coefficient and the technical availability values, an attempt is undertaken in the current section so as to provide a direct estimation of the former in relation to the variation of the two aforementioned parameters. For this purpose, the annual energy yield of different wind potential areas under a given wind turbine power curve is studied. To this end, the wind turbine power curve presented in Fig. 14 is used in order to estimate, with the help of Weibull distribution, the mean annual power coefficient of different wind regimes (see also Eq. (3) and Table 1) representing low, medium and high wind potential areas (or in terms of Weibull scale and shape factor, $C=5.75$ and $k=1.41$, $C=9.36$ and $k=1.88$, and $C=12.56$ and $k=2.15$). In this context, results of technical availability variation on the annual energy yield (kWh/kW) are given in the nomogram of Fig. 15, where "4" is allowed to vary from 75% to 100% and “$\omega$” from 20% to 60%. As one may obtain from the figure, reduction of technical availability is as expected inducing a decrease of the annual energy yield. Furthermore, as it may be noted, the specific decrease is much more intense for the higher values of the power coefficient “$\omega$”, e.g. for a reduction of technical availability from 100% to 75% for $\omega=60\%$, the specific energy yield drops from 5300 kWh/kW to 3940 kWh/kW. On the other hand, reduction noted in the case of the lowest “$\omega$” value is much less significant, i.e., from 1750 kWh/kW to 1310 kWh/kW. Besides that, by also using the diagonal curves of the nomogram, one may also obtain the respective CF values, corresponding to each given combination of power coefficient and technical availability. More precisely, the CF value corresponds to the product of power coefficient and technical availability and can be obtained by reading the values of the right-hand axis, if combining a
specific "ω" curve and a specific technical availability value. Using the results of the respective graph, a first estimation of the energy yield per kW of installed wind power capacity may be provided, considering at the same time the possibility of either low or high levels of technical availability. In this regard, determination of a realistic technical availability value, being of primary importance in order to obtain a first estimation of the energy and economic performance of the installation, is analyzed in the following section.

5.2. The impact of technical availability factors on the annual energy yield

As already seen, determination of a realistic technical availability value is of primary importance for obtaining a first approximation on the expected energy performance of a wind farm installation. In this context, an analysis of the main problem parameters is currently undertaken in order to describe representative cases. More precisely, by capturing the parameter of technology (i.e., generation of the machines employed or start-time year), accessibility issues (i.e., area of interest and local wind potential), issues of grid integration, and finally the parameter of downtime hours due to appearing faults (depending on the operational year and the number of wind turbines), estimation of a realistic value for technical availability in the course of time may be obtained. In this context, based on the information of Table 1 and Fig. 13, the respective technical availability "Δ" time distribution for two different representative case studies, i.e., a mainland wind park of \( z = 20 \) wind turbines and an island wind park of \( z = 10 \) wind turbines, is currently estimated. For this purpose, the typical power curve of Fig. 14 is used in order to determine the mean annual power coefficient "ω" of the installation, with the respective distributions—in relation to wind speed—given in Fig. 16.

Taking into account each of the three wind potentials studied as well as the four different start-operation times and the low or high integration cases for the island region, results obtained are given in Figs. 17 and 18. More specifically, in Fig. 17, one may obtain the influence of technical availability on the long-term annual energy yield of the wind parks examined, on the basis of a fixed start-operation year, i.e., 1982 and 2002. In this regard, variation of the local wind potential is then applied, taking finally into account the area of examination, considering in the case of the island region a relatively low wind energy integration scenario (\( \lambda = 10\% \)) that can

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**Fig. 15.** Estimation of the annual energy yield and CF in relation to the technical availability and power coefficient variation.

**Fig. 16.** Power coefficient distribution for different mean average wind speeds.
be considered as representative of the current situation. According to the results provided in the figure, the period of the first 2–3 years implies a lower technical availability value which is then recovered to reach the optimum value in the time period between 3 and 5 years. From that point on, technical availability presents a gradual reduction in the course of time which is found to be more intense in the case of meeting a higher wind potential. Moreover, as far as the area factor is examined, both the number of wind turbines being higher and the fact that accessibility and integration issues are much improved in the case of mainland wind parks (see also Table 1), suggest that for the same wind potential encountered, the expected annual energy yield of the mainland wind park is much higher. At the same time, the improvement of wind potential quality, although implying a reduction of \( D_w \), is also inducing an increase of the power coefficient which outweighs the impact of the former and thus leads to the overall increase of the annual energy yield for the same type of wind park and area examined.

Next, the impact of the wind turbine technology is also reflected if comparing Fig. 17a and b, with the technological evolution impact being beneficial between the 1st (1982) and the 3rd (2002) generation wind machines. The opposite however is valid if comparing machines of the last decade (i.e., 2002–2012, see also Table 1), where difference noted is inconsiderable. This is clearly obtained in Fig. 18a–c, where the impact of technology for the two extreme wind potential cases and three scenarios of installation sites (including also the case of a high wind energy integration scenario for the island region, i.e., \( \lambda = 30\% \)) is provided. In this context, a mainland wind park, employing 20 4th generation wind turbines and operating in a high wind potential area, is expected to produce almost 4600 kWh/kW in the first year of operation, while the specific value for the island area and the 10-turbine wind farm reduces to almost 3700 kWh/kW and 2700 kWh/kW for \( \lambda = 10\% \) and \( \lambda = 30\% \) respectively, illustrating at the same time the importance of the wind energy integration factor (Kaldellis et al., 2004). On the other hand, in the case of encountering a low wind potential, difference noted between the mainland and the island area minimizes, although determined by considerable difference for \( \lambda = 30\% \).

5.3. Theoretical model validation

To examine the applicability of the proposed methodology for the theoretical estimation of the long-term technical availability

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**Fig. 17.** The impact of technical availability factors’ variation on the resulting annual energy yield for 1982 (a) and 2002 (b) wind turbines.
of a wind farm, real data deriving from the 15-year operation of the wind farm installed in the island of Ikaria (Greece) is used. More specifically, the Ikaria wind park—erected by the Greek Public Power Corporation (PPC) in 1991 and starting its operation in March of the same year—is one of the smallest Greek parks, consisting of seven old-fashioned (2nd generation) wind converters, i.e., 7 Windmatic 15S (or Aiolos-55) machines, rated power 7 × 55 kW. Ikaria is a medium-sized island of the East Aegean Sea, situated 240 km from Athens, nearby Samos, with the mean annual wind speed of the area exceeding 9 m/s. At the same time,
the wind park under investigation is a typical example of the first wind parks installed by the PPC in remote Greek islands, using 2nd generation wind turbines (see also Fig. 19).

In this regard, in Fig. 20, one may obtain the data of annual energy production against the respective downtime hours for two representative wind turbines of the Ikaria wind farm, i.e., wind turbine 4 (WT-4) and wind turbine 6 (WT-6). As one may see, energy production of both wind turbines is in almost total agreement with the appearing downtime hours, i.e., the reduction of downtime hours signals the increase of energy production and vice versa. On top of that, there is a similar pattern of operation for the two wind turbines, presenting rather low technical availability values for the first years of operation (in fact WT-6 is down during the entire year of 1993), followed by a period (1995–2000) that downtime hours are mostly kept below 1500, and being eventually determined by significant reduction of technical availability that is temporarily dealt with in 2004.

At the same time, in Fig. 21 one presents the time evolution of the two machines’ average power coefficient “ν” and average CF, with the latter being as already seen the product of power coefficient and technical availability. To this end, since the power coefficient of the machines is in most cases found to be higher than the respective CF value, the impact of the wind turbines’ technical unavailability is again demonstrated, in accordance with downtime hours provided in Fig. 20. Taking into account that the CF value comprises a measure of annual energy yield (i.e. kWh/ kW.a), difference between the CF and “ν” values is actually equivalent to the energy losses occurring due to technical unavailability reasons.

Furthermore, using the data available for the wind park of Ikaria, theoretical distributions of technical availability on the basis of Eq. (5) are produced for λ=5% and λ=10%, which based on the long-term experience concerning annual wind energy integration in island grids (Kaldellis, 2008) comprises an

Fig. 19. Aspect of the Ikaria wind park, comprising of 7 x 55 kW wind turbines.

Fig. 20. Time series of energy production and downtime hours for WT-4 and WT-6.
acceptable range of values, justified on the basis of poor wind energy absorption during the winter months of the year (owed to considerably lower energy demand in comparison with the summer months). Based on the results obtained (see also Fig. 22), the theoretical distribution is found to describe the average 15-year technical availability value of the wind farm.

Fig. 21. Time series of CF and power coefficient for WT-4 and WT-6.

Fig. 22. Validation of theoretical estimation using real data of operation (long-term average (a) and annual/period-averages (b)) from Ikaria wind park.
(i.e., $D = 71.2\%$) with acceptable for engineering purposes accuracy, with the respective average values of the theoretical estimation being $D = 70.5\%$ ($\lambda = 10\%$) and $D = 73.5\%$ ($\lambda = 5\%$), clearly demonstrating the ability of the proposed methodology to predict the long-term average value of technical availability (Fig. 22a).

Moreover, although as it results (Fig. 22b), the model is not able to effectively capture the annual variation of technical availability values, mainly because of the significant scattering noted, division of the 15 year period in early, mid-term and final stages of operation reflects the cycling trend of technical availability that is also produced by the model results, i.e. from low values of technical availability in the early stages of operation to higher ones during mid-term and back to low values during the last years of operation. To this end, to illustrate the ability of the model to perform fairly well, even under this extreme variation of technical availability from one year to another, comparison between the actual (based on actual technical availability values) and the theoretical (based on the model-derived values of technical availability) values of CF is obtained from Fig. 23, where a value of $\lambda = 7.5\%$ is used. More precisely, according to the results provided, correlation between actual and theoretical values on an annual basis approaches 60%, mainly owed to the stochastic variation of technical availability noted during certain years, e.g. 1992–93 and 2004, although as previously seen the model does manage to effectively eliminate such disturbances if long-term operation is taken into account.

Thus, as one may obtain, using the proposed proxy model of technical availability estimation one may obtain a fair approximation of the long-term average technical availability value that may allow for the determination of the wind farm energy performance. At the same time however, it must be noted that model validation requires the use of additional real data, deriving from different types of wind farms, in order to evaluate its former performance for all cases examined.

6. Conclusions

Acknowledging the important role of technical availability for the energy and economic performance of a wind farm, an overview of main issues and operational experience concerning the former is first undertaken by the authors. Accordingly, based on the development of a proxy prediction model for the estimation of technical availability of different characteristics wind farms, determination of the latter impact on the annual energy yield of a given wind farm may be obtained. To this end, application results provided by the variation of the main input parameters capture several scenarios of wind farm operation, including variation of the installation site, the wind turbine technology, the local wind potential, the number of wind turbines employed, etc. According to the results obtained, the role of technical availability becomes extremely important for small scale wind farms, operating in less accessible sites of high quality wind potential, that also deal with grid integration issues. At the same time, model validation achieved through the comparison of theoretical and actual technical availability values, deriving from the long-term operation of a wind farm installed on the island of Ikaria, Greece, is determined by fair levels of accuracy if the long-term average technical availability value is considered. On the other hand, exploitation of more real life time data from different types of wind farms is required in order to evaluate model performance, which however comprises the subject of a forthcoming research work to be prepared by the authors.

Reference


