

# Investigating the wind parks location impact on the failure rate of contemporary wind turbines

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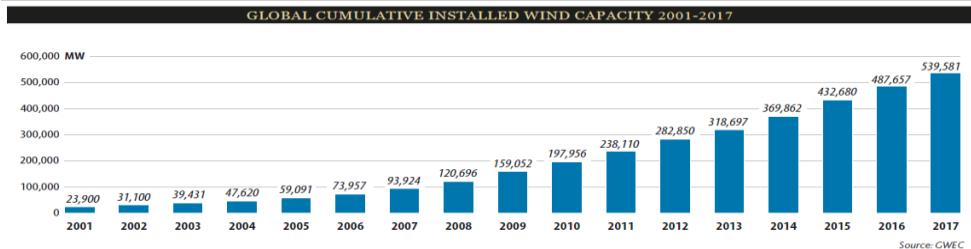
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**Abstract.** Wind energy is currently an established electricity production option worldwide, contributing to the reduction of environmental pollution and CO<sub>2</sub> emissions. Actually, during the last twenty years a considerable installed wind power increase has been encountered, thus the up to date installed wind power approaches 550GW<sub>e</sub>. The situation in Greece is fairly well since the current wind power in operation is approximately 2700MW<sub>e</sub>. As it is well established, the reliability of the wind turbines influences both the energy production and the maintenance and operation cost of commercial wind parks. As a result, the operational period of the machine is reduced, while additional expenses are needed in order to face the downtime causes. In the present work operational data of an important number of wind parks located in Greece have been analyzed. Moreover, emphasis is given on the impact that the wind parks' location has on the failures of commercial wind turbines. For this purpose real world data concerning similar wind parks, based on the same type of wind turbines, located on the mainland, on the islands or near the sea have been collected and analyzed. According to the data gathered one may compare the different failure patterns of contemporary commercial wind turbines operating for up to ten years all around Greece.

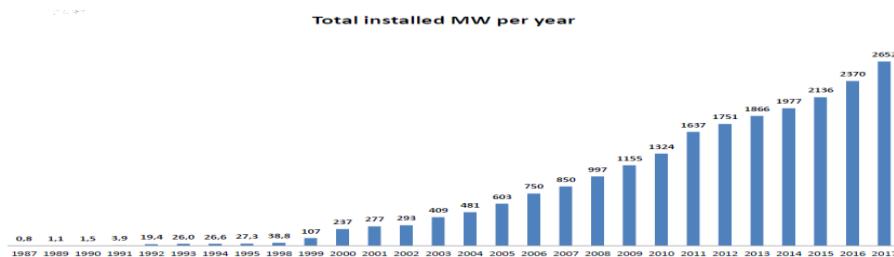
## 1. Introduction

Wind energy is currently an established electricity production option worldwide, contributing to the reduction of environmental pollution and CO<sub>2</sub> emissions generated by the existing thermal power units [1]. Actually, during the last twenty years a considerable installed wind power increase has been encountered, thus the up to date installed wind power (see figure (1), [2]) approaches or even exceeds 550GW<sub>e</sub>. The situation in Greece, taking also into consideration the excellent wind potential available, is fairly good since the current wind power in operation [3] is approximately 2700MW<sub>e</sub>.

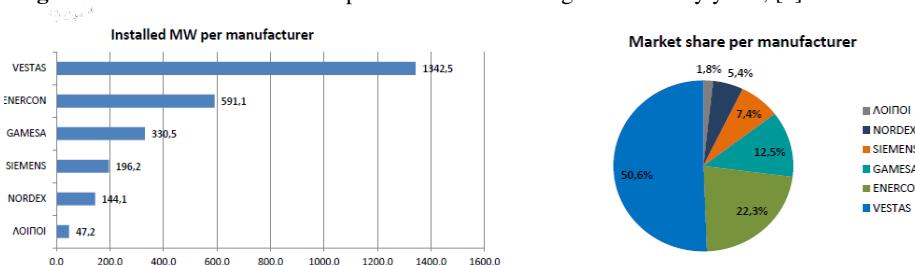


**Fig. 1:** Cumulative installed wind power of our planet (2001-2017), [2]

More specifically, with regards to Greece an almost linear annual increase may be noted, figure (2), thus the current wind power in operation is slightly less than 2750MW<sub>e</sub>. Another important issue concerning the local market is the fact that the vast majority of the existing wind turbines (WTs) have been manufactured mainly by Vestas (50%), Enercon (22%, gearless machines), Gamesa (12.5%) and Siemens (old Bonus, 7.5%), see also figure (3). To this end, one may support that roughly one out of four existing wind-MW use the gearless philosophy of the German company Enercon, while the other three out of four wind-MW are based on the well known Danish concept (i.e. Vestas, Bonus, Nordex and Gamesa).



**Fig. 2:** Cumulative installed wind power in Greece during the last thirty years, [3]



**Fig. 3:** Share of wind turbines manufacturers in Greece, [3]

The scope of the present piece of work is mainly concentrated on analyzing the main failure problems of contemporary commercial WTs, with special emphasis on the wind parks location impact. For this purpose real world data concerning similar wind parks, based on the same type of WTs, located on the mainland, on the islands or near the sea have been collected and analyzed. The results obtained are also compared with data gathered from various available sources, including published scientific papers, technical reports, etc., in order to determine the main reasons affecting the major failures of commercial WTs.

It is important to mention that the data collected cover the entire Greece and represent almost 1600 operational years of WTs, which for example is equivalent to the operation of almost 350 turbines for an average period of 5 years. Moreover, these (1MW and 2MW mainly) wind turbines studied represent almost the one fifth of the installed wind power in Greece, a quite significant percentage in order to obtain realistic conclusions for the entire country.

## 2. Problem Description

As it is well established [4] the reliability and the corresponding downtime period of the WTs influence both the energy production and the maintenance and operation (M&O) cost of commercial wind parks. This is reasonable, since the system reliability decreases as the downtime period of the machine increases. In most cases the reported downtime cases are

caused by both regular maintenance and unforeseen malfunctions. As a result the operational period of the machine is reduced, while additional expenses are needed in order to face the downtime causes [5].

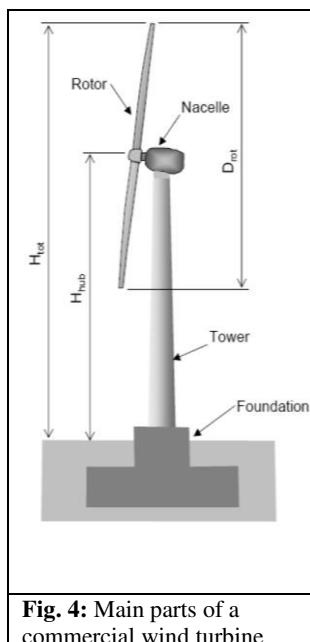
More specifically, the annual (8760hours) energy yield of a wind park of "z" wind turbines, each of rated power " $P_R$ ", is usually expressed as:

$$E_{wp} = CF \cdot (z \cdot P_R) \cdot 8760 \quad (1)$$

where "CF" is the installation annual capacity (or load/utilization) factor given as the product of the mean power coefficient " $\omega$ " and the technical availability " $\Delta$ " of the installation [4,5] i.e.:

$$CF = \omega \cdot \Delta \quad (2)$$

where the exact value of the mean power coefficient " $\omega$ " depends on both the local wind energy resource characteristics (normally the probability density curve of the local wind potential is used) and the operational non-dimensional power curve of the wind turbine each time examined, taking into account that the power output depends mainly on the wind speed of the area, i.e. at the machine hub height, figure (4).



**Fig. 4:** Main parts of a commercial wind turbine

Considering the above, the 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, the technical availability of a WT depends among others on the technological status, the age of the machine and the site of installation [6,7], thus one may use the following expression:

$$\Delta(t) = \Delta_o(t_o) \cdot \frac{\Delta_n(\tau)}{\Delta_o} \cdot \Delta_w \cdot \Delta_G \quad (3)$$

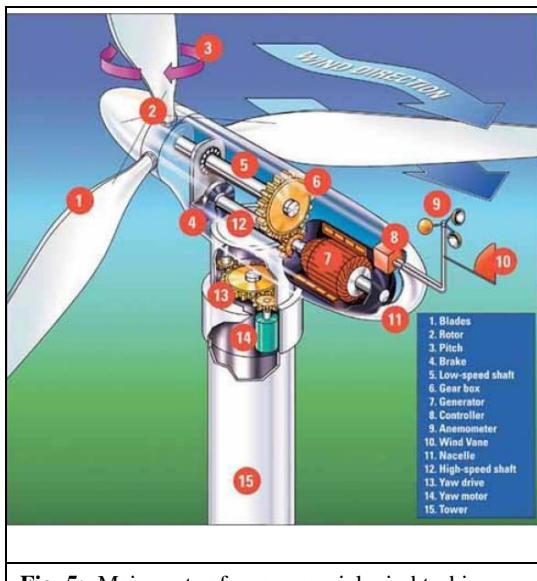
where " $\Delta_o$ " describes the technological status (generation) of a wind turbine at time " $t_o$ " that the machine becomes commercial, based however on the technology status during the initial design of the equipment. As a result, wind energy technology has nowadays achieved such a level of quality that contemporary wind turbines may even be determined by a technical availability of 99%. Moreover the wind park location and the existing climate conditions along with the available infrastructure should also be taken into consideration.

The next term " $\Delta_w$ ", takes into consideration the accessibility difficulties of the wind park under investigation. This parameter is of special interest for remote areas, islands 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 [8] may be used in order to simulate the " $\Delta_w$ " parameter see also [5]. 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 " $\Delta_G$ " that wind energy is absorbed by the local grid is strongly decreased [9] as the wind power integration in the local grids is increased [10].

Finally, the most relative to the current analysis term is the term " $\Delta_n(\tau)/\Delta_o$ ", which expresses the technical availability changes during a wind turbine's operational life " $\tau$ ". 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 [11], 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 " $\Delta_n(\tau)/\Delta_o$ " distribution the function " $d=d(\tau,z)$ " is introduced, thus Equation (3) may be equally well written as:

$$\Delta(t) = \Delta_o(t_o) \cdot \Delta_w \cdot \Delta_G \cdot [1 - d(\tau, z)] \quad (4)$$

where " $d=d(\tau,z)$ " is related to the wind turbine failure rate "FR( $\tau,z$ )", depending on the year of operation " $\tau$ " and the number of wind turbines "z" of the wind park.



**Fig. 5:** Main parts of a commercial wind turbine

In the context of the above described equations, one should detect -and finally minimize- the main reasons leading to low reliability of existing WTs in order to improve the energy yield of these installations. For this purpose several real world data concerning commercial wind parks in operation have been selected all around Greece and analyzed in order to determine the main failure reasons during the long service period of WTs provided from

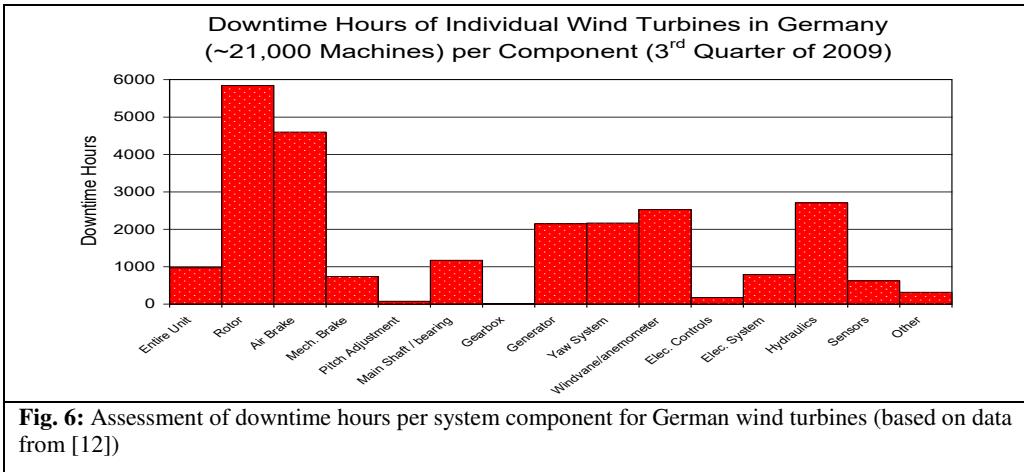
On the other hand, increased failures, especially concerning the main parts of a WT, affect strongly the maintenance and operation cost of a wind power station. Actually, the M&O cost of a wind park is expressed as a fraction of the initial capital invested, with values ranging between 1% and 3% for the first ten years. Gradually, as the operational period of a wind park increases, values up to 5%-10% may appear.

At this point it is important to mention the main components of a wind turbine presenting the majority of failures. Thus according to Figures (4) and (5) during the long-lasting operation of a wind turbine problems may appear on the rotor blades and on the power control mechanism (pitch control) of the

### 3. Data Analysis

In the context of the above described equations, one should detect -and finally minimize- the main reasons leading to low reliability of existing WTs in order to improve the energy yield of these installations. For this purpose several real world data concerning commercial wind parks in operation have been selected all around Greece and analyzed in order to determine the main failure reasons during the long service period of WTs provided from

various manufacturers. However, in order to separate the various reasons of WTs downtime one should first describe the main failures' causes.



**Fig. 6:** Assessment of downtime hours per system component for German wind turbines (based on data from [12])

### 3.1 Main failure causes

Using the experience gathered from various available sources, including published scientific papers, technical reports, on-field data and data based on personal communication with the appropriate service support stuff [13], the main reasons affecting the reliability of a WT include:

- i. Scheduled maintenance
- ii. Electrical grid problems
- iii. Service problems
- iv. Wrong/False failure announcement
- v. Material failure
- vi. Extreme weather conditions
- vii. Corrosion problems in island environment
- viii. Force Majeure problems
- ix. Various/Miscellaneous

Facing the specific problems may in some cases (e.g. grid problems, normal service activities and false failure announcements) require no additional expenses, although in most cases, increase of the M&O cost is induced. On top of this, during the time that the WT is out of operation, analogous wind energy production loss may be encountered, mainly depending on the available wind potential during the specific time period. Accordingly, extreme weather conditions, force majeure problems and others are out of the scope of the current analysis. To this end the present study is focused on material failure, including corrosion problems in island environment.

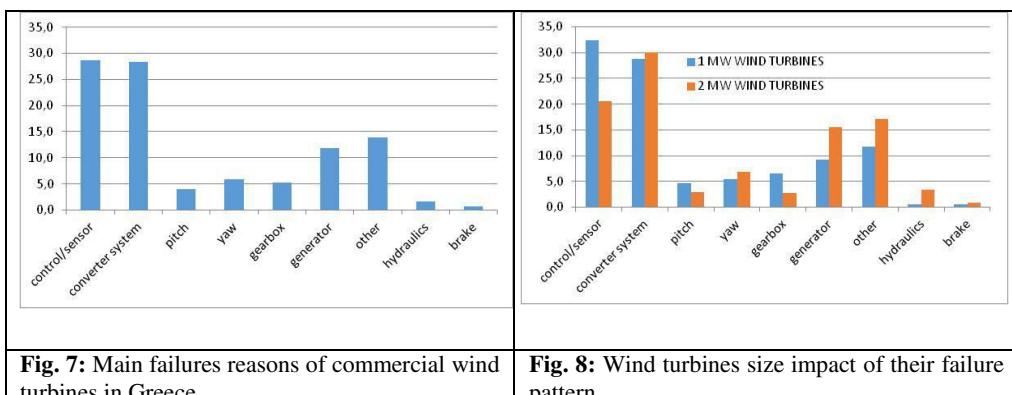
The failure of materials and components comprises the most severe factor of unreliability for a WT, while the repair of these damages requires considerable time and additional expenses. Equipment failures may include the failure of small parts and the turbine's stop due to certain problems of the main components, i.e. blades, electrical generator, pitch mechanism, gearbox, yaw system, hydraulics, etc. In several cases, it is almost certain that one of the pre-mentioned main parts of the turbine should be replaced at least once within the service period of the WT. As it is definitely expected, less time is required for repairing

the damage in case that permanent personnel is employed as well as in case that a stock of the appropriate spare parts is available (in respect of large scale wind parks) and the area of repair is easily accessed. On the other hand, the problem becomes more difficult to solve in isolated small island areas, due to the fact that the arrival of an experienced and trained crew for the damage repair is much affected by the existing weather conditions. More specifically, in the area of the Aegean, the appearance of strong winds along with the insufficient transport networks between the islands may postpone the repair of any damage even for several weeks, hence constraining the energy production ability of the WT as well. Besides, the replacement cost is also affected by the weather conditions and the size of the wind park. In many cases, the mobilization-transition and accommodation expenses for the maintenance crew may even correspond to 50% of the total maintenance cost. Finally, the availability or not of spare parts along with the time efficiency of the respective supply chain are also critical for the financial evaluation of each damage.

Moreover, in island environments or in coastal areas, 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 nearby marine atmosphere. In several cases, minor problems due to corrosion or rust may lead to more accountable problems, like the blockade of the brake system and the electrical revolutions' reducer, as well as the complete destruction of the corresponding electrical motor.

### 3.2 Data Analysis from the Local Market

Taking into consideration the above analysis of section 3.1, in the present research work operational data of an important number of wind parks located in Greece have been analyzed. Moreover, emphasis is given upon the wind parks location impact on the failures of commercial WTs encountered. For this purpose real world data concerning similar wind parks, based on the same type of WTs, located on the mainland, on the islands or near the sea have been collected and analyzed. In order to avoid problems with individual manufacturers and respect confidentiality issues, all the data presented are weight averaged values on the basis of the contribution of each manufacturer in the local market.

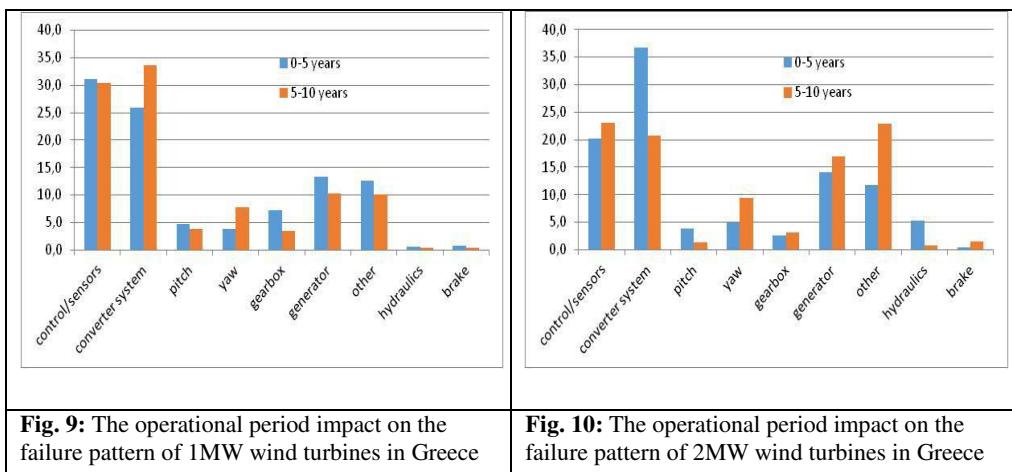


According to the total sample analyzed (figure (7)) the vast majority of wind turbine failures are related with problems in the machine sensors (e.g. wind vane, anemometer) and the entire control (protection) system as well as with the machine electronics (e.g. inverter, converter, etc.). Moreover remarkable share of failures have been attributed to the electric generator (11.5%), to the yaw system and to the gearbox, although a remarkable number of WTs investigated are gearless. Other causes of wind turbines' malfunction relate to the

pitch control system, the machine hydraulics, the mechanical brakes and the UPS included in the "other failures" category. In the next chapter one may discuss the impact of the main parameters on the failures pattern of the WTs analyzed.

## 4. Discussion of Results

Next, one may investigate the WT size impact on the failure pattern encountered, figure (8). It is important to mention that both types of WTs are already mature commercial machines since 2005, although the 2MW models are more recent ones. Moreover the size of these two categories is quite different since the rotor diameter of 1MW machines is between 50-55m while the 2MW turbines have normally a rotor diameter in the area of 80m. As we can see in figure (8), despite some differences concerning the control/sensor failures, where the 1MW machines are more vulnerable to problems (actually the 1/3 of failures is attributed to this category) than the 2MW ones, all the other failures encountered are almost similar for both categories. Of course the 2MW group presents slightly increased failures percentage for the electric generator, the turbine hydraulics and the yaw system, while the 1MW group has more problems with the pitch control system and the gearbox.



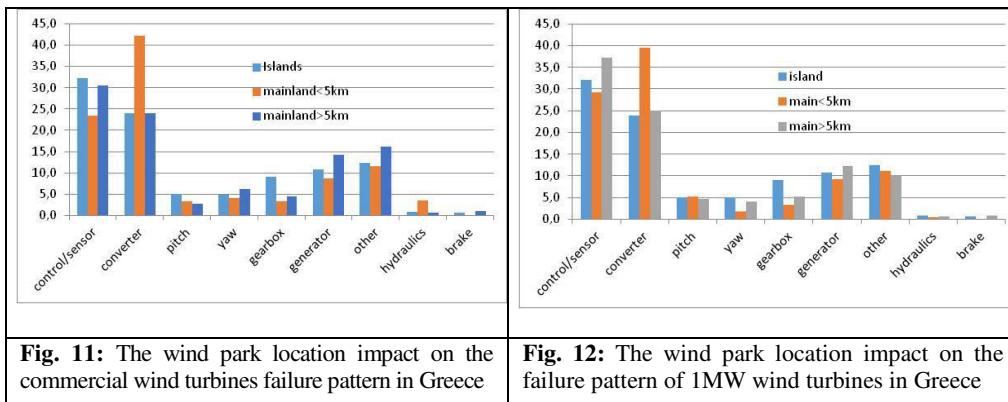
**Fig. 9:** The operational period impact on the failure pattern of 1MW wind turbines in Greece

**Fig. 10:** The operational period impact on the failure pattern of 2MW wind turbines in Greece

In order to check the age (or the operational period) impact on the failures pattern of commercial WTs, one may study separately two of the most common groups of contemporary machines, i.e. the 1MW and the 2MW group. Actually, as it is obvious from figure (9), the 1MW group presents high early failures at the pitch control mechanism, the gearbox and the electric generator, while after five years of operation, problems in the converter (electronics) and the yaw systems are more possible. On the other hand, a different pattern appears for the 2MW wind turbine failures' data, figure (10). Of course the number of 2MW WTs with operational age of more than five years is relatively small, however according to the data gathered during their first five years of operation 2MW turbines present significant percentage of electronic problems (almost 36% of all failures). Furthermore new WTs present increased problems at the pitch control system and at the machine hydraulics, while wind parks of 2MW operating for more than five years mention increased problems for the electric generator and the yaw system. Recapitulating, according to the data of both figures (9) and (10), one may conclude that for the first ten years of operation of commercial 1MW and 2MW WTs there is not a statistically validated different failures' pattern, although some small differences have been encountered. This is quite rational since the minimum service period of contemporary WTs is twenty years and thus

the first ten years of operation correspond to the minimum (random) failure rate of a typical bathtub curve.

Subsequently the current analysis is focused to analyze the wind park location impact on the failures pattern encountered. In this context in figure (11) one may find the failure data of wind parks located on islands, on the mainland (i.e. distance more than five km from the seashore) and near the seashore. It is quite interesting to note that wind parks on the islands and on the mainland present almost similar failures' pattern, with some small differences for the pitch control, the gearbox and the electrical generator statistically not validated. On the other hand, wind parks located near the seashore present quite different failures' pattern, see for example the control/sensor and the electronics percentage in comparison to the other two groups.



A similar picture is valid also for the 1MW (major) wind turbines' sample, figure (12). Note that this group is the most representative one, due to the period of operation of these machines (almost ten years on average), while bigger WTs cannot easily be installed (e.g. transportation problems and electrical grid constraints) in medium or small size islands. Thus the 2MW sample may not include WTs operating on islands. To this end one may validate again the similar failure pattern between wind parks on islands and on the mainland, while the WTs operating near the seashore present higher failures percentage concerning the machine electronics, which represent almost 40% of the problems reported.

One rational explanation for this situation is that since the wind park and equipment manufacturers implement their installations in accordance with the international standards for island and mainland regions, the failures' pattern should be the same for the same WT technology. Actually, using different wind turbine "class" and increased sea water protection for wind parks in islands seems to guarantee the same safe operation of contemporary WTs in island and mainland environments. On the other hand, using the standards of WTs operating on the mainland but near the seashore may lead to quite different failure pattern for these machines, being affected in a remarkable degree by their nearby sea environment. Summarizing, one may definitely support that according to the remarkable sample analyzed there is no serious failure pattern difference between wind parks operating on islands and on the mainland if the maintenance instructions by the WTs manufacturers are applied. Of course the utilization of higher quality machines on islands increases the installation cost, however at the same time keeps the M&O cost in rational values and encourages the exploitation of the excellent wind potential of the sea without problems, supporting the clean-green energy concept for all the Greek islands.

Finally, comparing the present data with the available data concerning a large number of WTs operating for four months in Germany (figure (6)), one may find several similarities as far as the electric generator, the yaw system and the control/sensor failures are concerned, while there are serious differences in the cases of the rotor and airbrakes (not mentioned at all separately in Greece) and the electronics (energy converter) system, its impact being much more severe in Greece than in Germany. Since the vast majority of wind turbines in Germany are gearless, the gearbox comparison is meaningless.

## 5. Conclusions

Summarizing and using the information gathered from various wind parks all around Greece, the main reasons of major failures for a wind turbine have been elaborated. Actually, in the present research work emphasis is given on several parameters, like the WT size and age, while special attention is given in order to investigate the wind parks' location impact on the failures of commercial WTs. For this purpose real world data concerning similar wind parks, based on the same type of wind turbines, located on the mainland, on the islands or near the sea have been collected and analyzed. According to the data collected, one cannot find different failure patterns between 1MW and 2MW commercial WTs, while even the age of the WTs is not a dominant factor characterizing the failures' pattern of similar machines. Finally, it is important to mention that failure patterns has been validated for wind parks located in between islands and mainland wind parks are quite similar. On the other hand, a quite different failures' profile is detected for the near seashore installations. Concluding, one may clearly state that on the basis of available data one cannot obtain different failures patterns that are statistically validated for the first ten years of operation for 1MW and 2MW commercial wind turbines. However using the data gathered one may -for the first time in our country- provide a representative picture of the operational problems of commercial wind turbines.

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