Early life failure modes and downtime analysis of onshore type-III wind turbines in Turkey

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ABSTRACT

Operations and maintenance costs, and unplanned downtime accounts for a significant proportion of the total expenditure of windfarms. Therefore, reduction of these costs is essential, which requires a better understanding of the wind turbines' reliability in terms of failure rates and downtime with operational lifetime. Failure rates and downtime are generally logged using condition monitoring systems, which mainly focus on Supervisory Control and Data Acquisition (SCADA) alarm signals. The aim of this paper is to use SCADA alarm statistics to provide a new failure rate and downtime survey and thus to evaluate reliability performance of the major wind turbine components and subsystems. The paper focuses on a modern onshore windfarm located in Turkey with Type-III wind turbines over the course of the first two years of operations, which is the first time reliability data from Turkey has been published in literature.

The presented data can help to provide a better understanding of early life operations, since all maintenance activities, as well as stoppages that caused the wind turbines not to generate electricity were considered in this paper. Furthermore, the evaluation and categorisation of the recorded SCADA alarms, their origins and whether they were associated with planned or unplanned downtime is presented. This analysis shows that early life modern wind turbines have the highest alarm rates and downtime associated with 'safety' factors, followed by the 'electrical systems', which was found to be the most critical (or unreliable) subsystem. The presented results therefore suggest that early life focus should be on the electrical systems of wind turbines for maximising their operating time and availability. Monthly distributions of both SCADA alarms and downtime rates are also presented to highlight the effects of environmental conditions.

HIGHLIGHTS

- Investigation of the SCADA alarm statistics of wind turbines contained within a modern windfarm located in Turkey over the first two years of commercial operations.
- Categorise wind turbine SCADA alarms into applicable subsystems and components.
- Present comprehensive early lifetime failure rate and downtime survey by utilising the data from a number of wind turbines within the windfarm and identify the most critical subsystems and components of Type III wind turbines.
- 'Safety' factors followed by 'electrical systems' were identified to cause the most failure rates and subsequent downtime.

KEYWORDS – Condition monitoring, downtime, failures, failure mode analysis, reliability, SCADA alarms, wind turbine.

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1. INTRODUCTION

Wind energy has increasingly become an important contributor to power generation over the past several decades due to the rising global energy demand and climate change awareness. Installed wind turbine (WT) power capacity reached approximately 743 GW worldwide in 2020 [1]. The future global targets are to increase the capacity of wind power generation even further; to provide approximately 18% of the world's electricity requirement by 2050 [2]. However, the fast expansion of the wind power market faces a number of issues such as lack of knowledge of new WT design failures and downtime rates, for example.

Turkey's cumulative installed wind power capacity increased from 59 MW in 2006 to 10.75 GW in 2021 [3]. The 10.75 GWs of capacity is equals to approximately 10% of the total electricity generation for the country [4]. Turkey is ranked among the top five European countries that invested the most money in wind energy with over €1 billion Euros ($1.19 billion) of land and wind energy investments in 2020. As a result, Turkey is the 6th country in Europe and the 13th in the world with the highest renewable energy installed capacity and this is only going to increase in the coming decades. Therefore, increasing the reliability and availability of WTs in Turkey is of significant importance to the country in helping to supply its growing energy needs and also contributing to reducing global carbon emissions targets.

1.1 Failure Rates of Wind Turbines

WTs are typically subject to high failure rates. A 'failure' is defined as the inability of a subassembly or component to perform its required function. Failures in WTs can be caused by a multitude of factors but can typically include manufacturing errors, irregular loading from extreme wind conditions, incorrect installation, fatigue, etc., [5, 6, 7]. Once a failure occurs in a WT, the Supervisory Control and Data Acquisition (SCADA) system produces an alarm, which subsequently and typically results in a stoppage, i.e. downtime. Experiencing high failure rates, therefore, makes maintenance issues important for the successful functioning and power generation capability of WTs. Furthermore, high failure rates increase the cost of electricity generation, as they increase operations & maintenance (O&M) costs, which can vary significantly amongst WT installations, locations, the type of topology used, age of equipment, etc., [7]. O&M costs are one of the biggest expenditures of windfarm projects, accounting for approximately 25% of their lifetime costs for onshore windfarms and 35% for offshore windfarms [8, 9, 10]. Unfortunately, failure statistics including failure rates and downtime, and the actual O&M costs of WTs are not typically publicly available. Scientific articles and reports also present limited information about the failure rates and downtime of WTs, as manufacturers are not inclined to reveal detailed data about the failures of their products. The currently available literature particularly depends on monitoring surveys conducted by scientific programmes such as the Scientific Measurement and Evaluation Programme (WMEP) [11] but they are generally not up-to-date studies, i.e. they present the data obtained from WTs comprising older technologies. Therefore, the aim of this paper is to present the failure trends of modern megawatt scale commercial variable-speed WTs and thus, provide pertinent information to help better understand how to improve their reliability.

1.2 Reliability and Availability of Wind Turbines

The reliability and availability of WTs can be enhanced by reducing downtime rates, optimising the design of WTs, and also improving the maintenance schedule [12]. All of these actions are dependent on a more comprehensive understanding of WTs and their operations, and in particular, their failure modes and mechanisms. Maintenance of WTs is generally either performed by the original WT manufacturer, a maintenance contractor or the windfarm operator. Preventive and predictive maintenance approaches are currently used in O&M practices for modern WTs, in order to minimise long downtime periods, unnecessary maintenance actions and high repair costs and therefore, provide high availability of WTs, which reduces the cost of the generated electric power [13, 14]. Preventive maintenance is the planned and periodical maintenance carried out at regular intervals to reduce the probability of failures or the significant short-term degradation of functioning components. Predictive maintenance on the other hand employs condition monitoring tools and techniques to monitor the performance of subassemblies and components of WTs during operation, in order to potentially identify and provide an alert of possible incipient defects so that the occurrence of failures can be minimised and potentially avoided altogether through undertaking reactive maintenance actions. Furthermore, identifying and correcting a fault before it leads to a catastrophic failure can save significant costs and downtime, as well as reducing Health and Safety risks. The main difference between these two approaches is that preventive maintenance is scheduled at regular intervals while predictive maintenance is scheduled as required. Predictive maintenance is gaining importance, as it can help windfarm owners to reduce their O&M costs by eliminating or minimising expensive maintenance actions [5]. Both preventive and predictive maintenance approaches are based on the correct estimation and identification of failures in the subassemblies and components of WTs, which can generally be successfully achieved with condition monitoring systems (CMS) [6].

1.3 Condition Monitoring Systems

CMS are primarily used to identify failures in WTs but the captured data could also be used as the foundation for the development in understanding of failure rates and modes. In addition to these functionalities, CMS also typically have the following benefits:

1. CMS are utilised to plan maintenance actions, as well as to identify and predict unexpected (sudden or developing) failures at the incipient fault stage in order to reduce downtime by providing information about the status of WT subassemblies and components [8];
2. CMS can alert and therefore cause relatively immediate repair action to be scheduled or taken and thus, minimise the damage to WT components and potentially avoid catastrophic failures to occur;
3. Addressing a fault before it leads to a potentially catastrophic failure can help to significantly reduce O&M costs;
4. CMS can help to reduce the degradation of WT components over their lifetime by analysing the severity of failures [15]. Consequently, CMS can increase the reliability of WTs, which is defined as the operational ability of WTs, as required without failure, for a given time interval [16];
5. CMS can help to optimise maintenance activities, i.e. enable repair or the replacement of components that have partially lost functionality or likely to fail during unfavourable seasons, so that downtime and economic losses can be kept to a minimum. Planning the optimal time for maintenance activities is critical especially for offshore WTs that operate in harsh environment such as offshore or in remote locations.

Overall, CMS help to ensure that WT systems can operate safely, profitably and cost-effectively.

1.4 SCADA Systems

Today, SCADA systems are the most commonly used CMS in WTs, and are used to capture extensive information about the state of critical components and operational signals from WTs [11]. SCADA systems are typically pre-installed in commercial WTs and therefore, no additional costs are required. They sample pre-programmed measurements at regular intervals or continuously, and perform analysis tasks on the captured data. Furthermore, they can subsequently automatically report analysis results and also create alarms and fault logs, for windfarm operators [15]. The origins and locations of a failure or component malfunction are identified using the SCADA alarms. Although SCADA systems typically operate as CMS in WTs, there is still a debate about their added value to failure data, as they are limited in providing the necessary resolution for diagnostics of failure modes due to their relatively low resolution data capture [13]. Furthermore, whilst SCADA alarms data has been previously investigated and presented in the literature, there is further need to understand the full correlation between particular SCADA alarms and failure modes observed in WT systems. Therefore, it is important to better understand the relationship between subsystem failures, their corresponding SCADA alarms and ideally their root causes. Categorisation of SCADA alarms in WTs is largely dependent on the turbine manufacturer, as sometimes alarms are separated into warnings and faults [12]. However, in this study, all the SCADA alarms, including both warnings and faults, are considered under the label of ‘failures’, as both can be a sign of a problem and cause downtime.

The purpose of this paper is to present an in-depth study that uses SCADA alarms to investigate the failure rate and downtime of commercial WT subsystems. Modern commercial WTs (less than five years old) are used for the analysis with the aim to help better understand and identify the most critical components and subsystems in the early life operation of modern Type III WTs. The outcome of this study can be used to help windfarm operators, as well other stakeholders, to monitor these critical components and subsystems more carefully and effectively, which could help to reduce electricity generation costs and to appropriately schedule maintenance activities and therefore, to improve the reliability and availability of WTs. In addition, this study will investigate the capability of SCADA systems and their usage as an online CMS by investigating the correlation between the observed WT stoppages and their respective SCADA alarms, which can potentially be used to improve WT alarm systems and their management.

1.5 Scope of the Paper

In this study, the SCADA alarms and consequential downtime rates of the main subassemblies of modern WTs operated by one of the principal operators of a windfarm in Turkey were analysed in detail, which has not been presented in the literature previously. The investigated WTs use the same generator technology, i.e. the doubly fed induction generator topology (geared-drive concept - Type III). The type III WT topology has long been and remains a strong contributor to both the Turkish and global wind power capacity [17, 18]. The exact location, specific total number of WTs within the investigated windfarm, the WTs nominal power ratings and rotor size, etc., are not provided in this paper to ensure confidentiality of the operator and WT manufacturer. Furthermore, in addition to the overall data collected from the investigated WTs, the SCADA alarms and consequential downtime rates of one randomly chosen individual WT within the population will be presented in detail, to provide an example of failure rate and downtime analysis of a single WT and also cross correlate the overall failure rate and downtime analysis results. The analysis does show differences between the reliability characteristics of the selected subassemblies such as gearboxes, generators and electrical system over the investigated time period, which is to be expected. However, the presented study identifies the specific reliability behaviours of the investigated components and subassemblies, with an underlying aim to strengthen the understanding of early life failures and downtime trends, along with reliability issues in modern Type III WTs. The findings provide new O&M related data and are pertinent not only to Turkish windfarm operators but also the wider wind power community. In addition, the SCADA alarms and downtime rates are also investigated in this paper using monthly data captured during the early lifetime operations for a number of WTs within the cluster of the examined windfarm, in order to enable the correlation between the SCADA alarms and downtime rates with month of operations, and also the external air temperature, internal nacelle temperature and external ambient air pressure.

The remainder of this paper is structured as follows: in Section 2, the motivation for this paper is explained. The description of the analysed system and used WT taxonomy are defined in Section 3. Section 4 provides detailed information about the SCADA alarms. The data obtained from a number of randomly selected WTs within the operational windfarm using the SCADA alarms are discussed in Section 5. In addition, the monthly occurrences of SCADA alarms and downtime rates in these selected WTs during the surveyed period (two years) are presented in this section. Finally, the conclusions drawn from the presented analyses are summarised in Section 6.

2. MOTIVATION

As a country Turkey is dependent on outside sources (other countries) for approximately 50% of its energy requirements, it is therefore of vital importance to diversify and strengthen the national capacity in this area by increased the utilisation of wind energy. Therefore, Turkey is aiming to reach 20 GW of installed WT capacity by the end of 2023, as part of the National Renewable Energy Action Plan [19]. This target does not contain any offshore development, and it is expected to go even higher once offshore projects start to be developed, as Turkey has not started to exploit its offshore capacity although there is potentially substantial wind energy availability [20]. The most suitable regions in Turkey for wind energy applications are Marmara, Aegean and the Southeast Mediterranean coastal regions due to their higher annual average wind speeds (typically exceeding 3 m/s in these coastal regions) [21]. Two cities (Çanakkale and Balikesir) located in the North Aegean and Marmara coasts, respectively, account for approximately 23.5% of the country's wind energy potential [22].

2.1 Failure Rate and Downtime Data from Wind Turbines

There is limited information about the failure rate and downtime data; i.e. failure rates and downtime, from commercial WTs due to the lack of available data since WT manufacturers do not typically divulge operational data about their products and subsequent stoppages or failures. Furthermore, retrieval of the data can also be expensive [5]. The available literature today [12] is mainly based on the published data and surveys conducted by scientific programmes and can have limitations in accurate and transparent representation of relevant failure rates and downtime, as well as the inclusivity of up-to-date commercial WT technology. For example, the publicly available failure rate and downtime data and surveys, which are the present sources of almost all the published failure rate and downtime studies in the literature, are presented in Table 1 [5], [8], [23, 24, 25, 26]; this data does not generally present the failure modes in detail. Furthermore, as Turkey is relatively new to the wind energy field, there is an even more limited amount of published studies related to WT establishments in Turkey [20, 21, 22]. Of these there is no published study related to the failure rate and downtime of WTs located in Turkish wind farms.

Table 1 presents data from seventeen failure rate and downtime surveys covering various WT sizes and topologies located in Europe, the U.S. and China. However, as can been seen from Table 1, Turkey is not included in this table, since no failure rate and downtime data was publicly available. One of the aims of this paper, therefore, is to present a novel investigation of the failure rate and downtime data and failure mode of WTs operating in Turkey.

Table 1: Specifications on the available failure rate and downtime data and surveys in the literature.

Data & Survey	Location	Year Span	Age	Capacity (MW)	Published Year	Technology	Speed Operation	Based on	Number
AWE	Europe	2013–2015	6	1-3	2016	Geared	Variable	Onshore	~2270
CWEA	China	2010–2012	<3	-	2016	All	All	-	-
CIRCE	Spain	2013–2016	-	0.3-1	2016	Geared	Variable	Onshore	4300
CARR	Europe	5 years	5	2-4	2015	Geared	Variable	Offshore	350

B&W	UK	Not known	3-6	2.3	2014	Geared	Variable	Onshore	-
CREW	US	< 1 year	-	1.3-1.4	2013	-	-	-	800-900
EPRI	US	1986-1987	-	0.04 - 0.6	1991	-	-	Onshore	290
EZ	Netherlands	3 years	5	3	2012	Geared	Variable	Offshore	36
Vindstat	Sweden	1989-2005	-	0.15-3	2012	-	-	Onshore	786
RELI	Europe	2008–2011	>2	>0.8	2011	Geared	Variable	Onshore	350
VTT	Finland	1996–2008	1-17	0.2-2.3	2010	-	-	Onshore	72
LWK	Germany	1993–2006	15	0.2-3	2008	All	All	Onshore	158-643
WSDK	Denmark	1994–2004	14	0.1-2.5	2007	All	All	Onshore	851-2345
WSD	Germany	1994–2004	<3	0.1-2.5	2007	All	All	Onshore	1295-4285
SW	Sweden	2000–2004	1-19	0.5-1.5	2007	All	-	Onshore	~624
WMEP	Germany	1989-2006	>10	-	2006	All	All	Onshore	>1500
ReliaWind	Europe	2008-2010	>2	>0.85	2011	All	Variable	Onshore	350
Windstats	Germany and Denmark	1994-2004	-	15	2006	All	All	Onshore	7000
SPARTA	UK	2015-2016	5-8	-	2018	-	-	Offshore	1045
Strathclyde	UK	2011-2016	3-5	2-4	2016	All	Variable	Offshore	350
WInD-Pool	Germany and Europe	2013 -	-	-	2017	All	All	All	456
MECAL	Netherlands	2010-2014	2-4	0.85-3	2015	All	All	Onshore	63

2.2 Lifespan of Wind Turbines

The average lifespan of WTs is estimated to be approximately 20 to 25 years, and a bathtub curve is used to model their reliability as a repairable system [23], [27], as illustrated in Fig. 1.

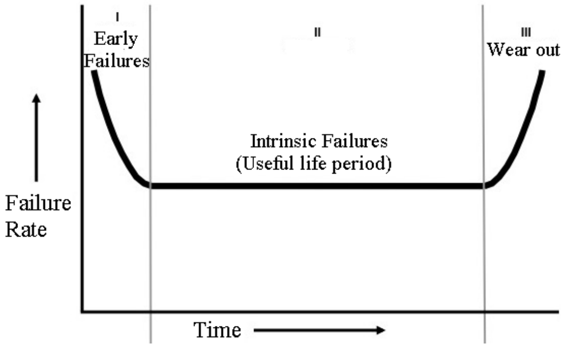

Fig. 1: Bathtub curve of failure rate vs. time of a repairable system.

The bathtub curve comprises three stages, as shown in Fig. 1: Stage One typically comprises ‘early failures’, Stage Two ‘intrinsic failures’, and Stage Three ‘wear-out failures’ (or deterioration/random failures). Fig. 1 shows that the failure rate is high both during Stages One and Three in the life of WTs. Stage One failures occur in the early years of operation when WTs can experience high failure rates not only for the whole WT but also for different WT subassemblies [28]. The high failure rates occur in the early years of operation progressively decreasing during the following years into and throughout Stage Two. The high failure rates in Stage One can be caused by manufacturing defects, inaccurate storage, incorrect transportation or poor assembly of the components [6]. Although early failures can be substantial for the operations and reliability of a WT [29], most published literature focuses on either the intrinsic failures or average failures including all failures detected during the lifetime of their respectively investigated WTs, as illustrated by the overview presented in Table 1. There are still a limited number of studies in the literature that consider early (Stage One) failures; in fact, the CWEA survey presented in Table 1 was the only study found in the literature that focused on early life failures (less than three years old).

The CWEA survey concluded that the investigated WTs in China had a very high early failure rate during their first year of operations [29]. The failure frequency of only seven components & subassemblies of the WTs were considered in the CWEA survey, and downtime rates were not included, limiting the value of this study. Furthermore, different types of WT technologies (or configurations), power capacities and also age were considered in the CWEA survey. It is therefore difficult to deduce if the design of the particular WTs was the main reason behind the high early failure rates observed. Consequently, it is beneficial to investigate early life failures in more detail and also in other global locations in order to understand the reasons for their occurrences and therefore potentially minimise them, to increase the reliability of WTs. Moreover, the CWEA survey presented the results from WTs operated during the years 2010-2012, and subsequently those WTs have relatively older topologies compared to contemporary WTs, as WT technology is continually improving/being updated. In this paper, early failures and their associated downtime rates of modern commercial WTs will be investigated, to provide a better understanding of potentially how to minimise downtime and economic losses, as well as to improve their reliability.

3. DESCRIPTION OF THE ANALYSED SYSTEM AND USED WIND TURBINE TAXONOMY

The presented failure rate and downtime analysis is based on the data collected from a cluster of WTs within a modern windfarm located in Turkey over a period of two years; performance data were continuously logged during the period between October 2017 and September 2019. The windfarm has been in operation for several years and it is located on the Aegean cost. The windfarm contains a number of horizontal axis, pitch regulated WTs with a three-blade configuration. The windfarm is located in a dry region with relatively low humidity, dust and sand. The ambient temperature was measured between the range of 0.8°C to 29.7 °C, and the ambient air pressure between the range of 94.8 to 98 kPa, which included seasonal variations, since climatic conditions are also believed to somewhat affect the reliability of WTs [28]. All the WTs in the windfarm are the same size and type, i.e. DFIG (Type III). This type of WT combines the blades, a multi-stage gearbox (high-speed ratio gearbox), a wound rotor induction machine (WRIM), two frequency converters and control units. In the DFIG topology, the stator windings of the WRIM are directly connected to the grid whilst the rotor windings are connected to the bi-directional AC-DC-AC converters. The converters are responsible for regulating the frequency, phase, amplitude and phase sequence of the rotor circuit and thus, the characteristics of the generator power output [29]. The WTs are in the order of modern megawatt scale WTs, i.e. a rotor diameter between 80–120 m and a nominal power between 2–4 MW [30].

Each WT in the investigated windfarm is equipped with a SCADA system, which is used for control, performance and condition monitoring [31]. Complex SCADA systems that are used in modern day WTs were not included in older WT set-ups and of the ones that did, they were only a basic system [13]. SCADA alarms are created when an incident occurs, which is potentially related to any stage of a failure. The failure rate and downtime analysis presented in this paper uses frequencies of SCADA alarm occurrences, as well as their downtime rates, which are obtained from conducting a wide-ranging review of monthly service reports, namely historical SCADA alarm databases. To conduct analysis of the SCADA alarm occurrences and downtime rates obtained from the SCADA systems of each WT, the data are collated by month, evaluated and subsequently presented in this paper. SCADA alarms with existing industrial guidelines during the evaluation of the collected data are used in this paper to provide a fuller understanding of modern commercial WT operations such as what operators encounter, and also a detailed analysis of their failure mechanisms.

3.1 SCADA Alarms Taxonomy

The SCADA alarms are classified into subsystems and components using pre-defined WT taxonomy. WT design has become more complex with technological developments, which has resulted in an increase in failure rates of WT subassemblies and components [28]. In order to better understand this effect and also to increase the readability of the data, each identified failure in WTs is classified by considering the affected component (or subassembly). As a result, the WT system is separated into subsystems, and this requires an accurate definition of subsystems under consideration, i.e. including physical location, details of component design, material specifications and after-treatment processes [32]. Subsequently, WT taxonomy is created by defining subsystems and components. It is important to state that there is unfortunately no uniform taxonomy in the literature [7, 13]. To create a precise taxonomy that is applicable to the available data, the WT's manufacturer's SCADA alarm data was cross-correlated with the most commonly used WT taxonomies in the literature, which was developed for the ReliaWind project [33], as well as for other well-known failure rate and downtime studies (Windstats in Denmark (WSDK) and in Germany (WSD) [7], [8], [13], [16]). The WT taxonomy used in this work is presented in Table 2.

Table 2: Wind turbine subsystems and components taxonomy.

Subsystem	**Components**	**Subsystem**	**Components**
Yaw System	Yaw bearings Yaw motor Wheels Shaft pinions Bedplate Yaw gear and gear reducer	*Hydraulic System*	Hydraulic pump Hydraulic pipes & hoses Pump motor Valves
Brake System	Mechanical brake Air brake Brake disk Brake pads Brake shoe Yaw brake Break rings	*Sensors*	Anemometer Wind direction indicator Blade angle sensor Vibration sensor Temperature sensor Oil pressure sensor Power sensor Revolution counter Pitch angle detection sensor
Generator	Generator windings Brushes Generator bearings	*Pitch System*	Pitch mechanism Pitch bearings Pitch converter
Structure	Foundation Tower Tower bolts Nacelle frame Nacelle cover Nacelle bed plate Ladder	*Electric System*	Grid Main converter Electrical components (fuses, switches, cables, connections) Transformer Contactor Power protection unit Soft starter Batteries
Control System	Control unit Relay Controllers Communication unit Data acquisition system	*Gearbox*	Bearings Wheels Gear shaft Sealings Grease & oil
Hub & Blades	Hub body Blade bolts Blade shells Bearings Rotor	*Other*	Auxiliary system Lift Heaters & Coolers
Safety	Electrical protection Human safety Lightning protection Fire-fighting system	*Drive Train*	Main (rotor) bearings High and low speed shaft Couplings

4. SCADA ALARMS

There are a number of potential root causes of a failure that can cause a WT to stop operating. However, it is beyond the scope of this paper to identify the root causes of these failures, as they have been explained in the literature previously (e.g. high wind, grid failure, lightning, icing, malfunction of control systems, component wear or failure, loosening of parts, etc., [16], [32]). The aim of this paper is to categorise the location within a WT of these failures, in order to identify the most critical subsystems and components and therefore their failure modes in early life Type III WTs. The SCADA data from monthly maintenance logbooks are used to categorise the failure alarms with respect to their locations (see Table 2).

All failures in some way create various changes in the operation and condition of WTs such as an increase in vibration, reduced speed, load noise, heat, etc., [16]. Information about the operational performance and conditions of subassemblies and components in a modern WT have been monitored by a SCADA system mounted in the controller, to enable local and remote control of basic functions [12]. This means that alarms requiring assessment or action are stored in the SCADA system. The stored information is remotely collected by an operator mostly through the internet or telephone lines. The current standards for data acquisition for SCADA signals on windfarms specify a sampling rate of approximately every 10 minutes, in order to decrease the transmitted data bandwidth and required data storage [14, 12]. However, the alarms data requires even less storage space than SCADA signals, since alarms occur much less frequently [12]. The time-sequence of the alarms can change from one incident to another. For example, the emergency control unit is sometimes required to be quickly activated under critical conditions when certain alarms are triggered, which uses faster communication channels than other less important alarms. In addition, the accuracy of these alarms significantly depends on the resolution of the data collection system, response time and constants of sensors [12].

SCADA alarms are generally classified as general alarms, system operational alarms, environmental alarms and communication/software alarms according to their function [12]. Depending on the alarm type, there are three options to clear an alarm and return a WT system back into operation:

1. 'Remote Reset (green alarms)'; can be remotely reset without following any rules or requiring any personnel to attend site and hence, the WT with the triggered failure alarm;
2. 'Reset by Rules (yellow alarms)'; which can be potentially reset if certain rules can be complied with; and
3. 'Never Reset (red alarms)', which requires the WT to be visited by maintenance personnel [12].

Some of these alarms and their respective locations observed during the first two years of operation of the examined WTs are provided in Table 3, as examples.

Table 3: Examples of observed alarms during the first two years of operation.

Subsystem	**Alarms**	**Subsystem**	**Alarms**
Yaw System	Yaw hydraulic break is not closed	*Hydraulic System*	Low level of oil in hydraulic tank
Rotor Brake System	Low rotor brake pressure	*Sensors*	A cable break in the temperature sensor
Generator	Generator slip ring brushes are worn	*Pitch System*	Internal faults in pitch converter
Structure	Vibration values in the tower's natural frequency range is too high	*Electric System*	Main converter disconnected from the grid
Control System	Controller executes a restart after grid outages	*Gearbox*	Low gearbox oil temperature
Hub & Blades	Temperature in hub is too high	*Other*	Wind speed too low
Safety	Fire alarm triggered	*Drive Train*	Main shaft direction vibration is too high

It is important to interpret and understand the SCADA alarms correctly, as Table 3 shows that alarms provide pertinent information to the operator about their causes, which can then potentially be useful to minimise their manifestation and thus, reduce the downtime of WTs and increase their availability.

Occasionally alarms are logged as, 'planned (scheduled and/or intended) stops' (i.e. the WT required disconnecting from the grid for maintenance actions or safety tests) in the SCADA system. These planned stops, however, still create downtime and consequently, reduce the availability of WTs. Therefore, those intended stops that occurred during the first two years of operation are also investigated in this paper, in addition to the alarms created due to failures identified in the WTs subassemblies and components.

5. FAILURE RATES AND DOWNTIME ANALYSIS - RESULTS AND DISCUSSION

The total incidents of SCADA alarms and consequential downtime of the investigated WTs for two years of operation are presented in this section. The combination of both the SCADA alarms and downtime rates of the WTs analysed is then used to identify the most critical WT subsystems in terms of reliability and the occurrence of their alarms on the operational hours of the investigated WTs. This information can potentially help the windfarm operator to appropriately update their maintenance schedules, and could benefit improved understanding of early life failure trends for other windfarms operators. The reason why both the SCADA alarms and downtime rates are analysed together is because their combination affects the availability of WTs [8]. For example, there may be a component that fails frequently but with a relatively small amount of downtime whereas there may be a component that fails only once in a few years but can cause a much longer period of downtime. The analysis presented in this paper will therefore use both the SCADA alarms and downtime rates together to help interpret and identify the most critical subsystems. Furthermore, for the purpose of this study, the SCADA alarms and downtime rates from one randomly chosen WT are also presented in this paper.

There are different ways that failure rates and downtime have been presented in the literature such as [8, 28]:

1. failures/turbines/year for failure rate calculation and downtime/turbines/year for the downtime calculation; or
2. normalised percentages, which is achieved by considering the total number of failure rates and downtime as 100% and proportionally calculating the contribution of each sub-system.

For both failure rates and downtime analyses, each failure is assigned to a specific subsystem of a WT whereas the downtime is considered as the period of time that a WT is not generating electricity. The normalised percentages both for SCADA alarms rates as failure rates and their consequential downtime are presented in this study, as this is considered to uniform the data and also simplify the identification of the most critical subsystem [8].

All the planned (scheduled) and unplanned (unscheduled) maintenance activities that cause downtime are considered for investigation in this paper. Unlike within the available literature, therefore, any WT stoppages are considered for the evaluation of downtime, for the completeness of this investigative study. Therefore, a large database of SCADA alarms from the cluster of investigated WTs is used to analyse the SCADA alarms and downtime rates using the previously defined taxonomy in Table 2. All the investigated maintenance activities are divided into categories in order to provide a better understanding of the reasons for downtime, as seen in Fig. 2. In total, 88 possible failure modes were identified, which are divided across 11 WT subsystems.

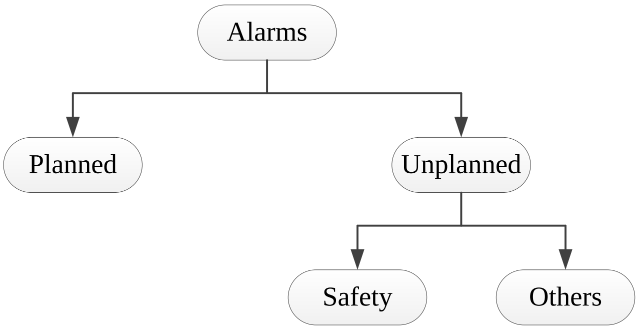

Fig. 2: Categorisation of wind turbine maintenance activities.

5.1 Data Evaluation

This subsection will explain how the SCADA alarms have been utilised to extract the failures and their associated downtime rates. A SCADA system uses a number of sensors inserted or mounted in critical places in WTs in order to monitor and inform the state of subsystems and components such as temperature, rotational speed, voltage, current, vibration, etc., [13]. Therefore, a SCADA system can detect when predefined thresholds are exceeded, register the cause or consequence of them directly and then send alarms to the windfarm operator/maintenance personnel, and at the same time, if required, shut down a failed WT. If the alarm is not critical, the WT can be restarted remotely. However, if the alarm indicates a failure, then either an operator or authorised personnel may have to attend site to perform a visual inspection/maintenance activities [5]. Furthermore, if the alarm indicates a major failure such as malfunction of a component, repair action or replacing the damaged part(s) of the WT must be performed by maintenance and repair personnel. The alarms generally indicate: *Changed WT running states*; *Component malfunction*; and, *Design defects* [12]. Categorisation of alarms in WTs is largely dependent on the turbine manufacturer, as sometimes alarms are separated into warnings and faults [12]. However, in this study, all the SCADA alarms, including both warnings and faults, are considered under the name of ‘failures’, as both can be a sign of a problem and cause downtime. Each SCADA alarm has a specific code, which is provided in the report to the windfarm operator and thus, denotes a specific meaning.

5.2 Total SCADA Alarms and Downtime Rates per Subsystem

In this sub-section, the SCADA alarms and downtime rates for all the investigated WTs with the randomly selected cluster are presented. The total SCADA alarms rates and average downtime per month per WT observed during the first two years of operational lifetime, are shown in Table 4. It can be seen in Table 4 that the studied WTs have exhibited a considerable amount of alarms over the observed time period, recording an average of approximately 33 events per turbine per month: these are followed by an average of approximately 23 hours of downtime per turbine per month, giving an average downtime of 0.7 hours per failure event. All the planned (i.e. simple remote resets or scheduled stoppages) and unplanned (i.e. unexpected or incipient faults in WT components) maintenance activities cause SCADA alarms and downtime and therefore, are also considered as failures in this paper.

The presented data for both the SCADA alarms and downtime rates are much higher in comparison to the available literature [13, 30, 5]. The potential reason for this is that existing studies generally focus on component failures, and do not include the SCADA alarms causing downtime events such as grid problems, windfarm tests or safety alarms. Therefore, the presented numbers in those studies are lower, as they only consider a small proportion of the total occurrences of real WTs stoppages. However, the methodology used in this study to analyse WT data is considered to enable a fully transparent view of the examined systems’ failures and downtime events, and allow a clearer understanding of their significance. In addition, the graphical location, age, turbine topology, and even ambient temperature can affect failure events and downtime rates [6]. The available literature generally presents failure rate and downtime data, which contains different topologies and lifespans [6, 13, 7] and thus, it is difficult to identify the failure and downtime rates more realistically. However, in this study the failure rate and downtime data belonging to the same age and type of WT topology from the same windfarm site is presented in order to achieve more consistency.

Table 4: Average total failure rates and downtime per WT per month.

SCADA alarm/WT/Month	**Downtime/WT/Month**	**Downtime/SCADA alarm**
32.88	23.04 hours	0.7 hours

A more detailed analysis of the total SCADA alarms and downtime rates from this study is presented in Fig. 3. In Fig. 3, the SCADA alarms and downtime data are classified into two categories: planned and unplanned, in line with Fig. 2, to clearly differentiate events associated with unplanned maintenance activities such as stoppages due to component breakdown or environmental conditions, from those arising from planned maintenance activities such as regular maintenance services, safety or visualisation tests, manual intervention, planned grid disconnection, external cut out due to farm functionality, etc. The reason why the planned and unplanned maintenance activities are shown separately is to highlight the contribution of planned events, which are usually not presented in the literature, to the total number of SCADA alarms and downtime rates.

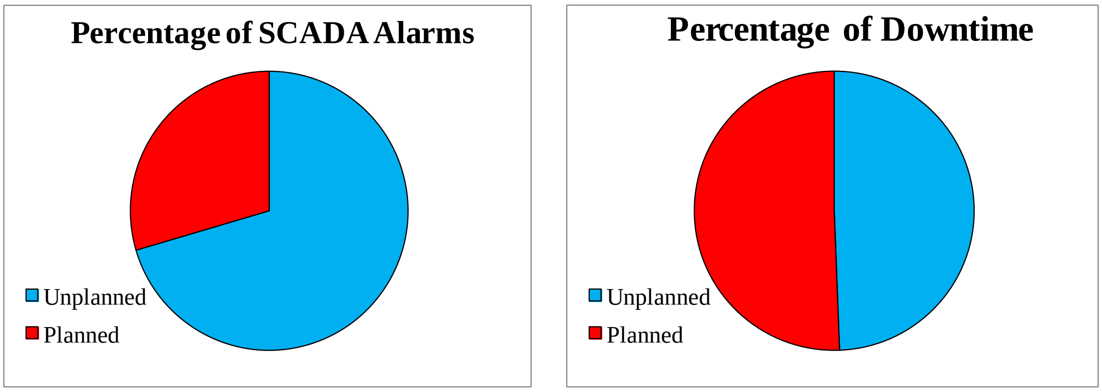

Fig. 3: Percentage of SCADA alarms (left) and downtime rates (right) across unplanned and planned maintenance activities.

The presented data in Fig. 3 is important, since it reports the relationship between all the unplanned and planned maintenance activities that caused downtime of the investigated cluster of WTs. This data provides a further insight into the relationship and scale of planned and unplanned maintenance activities on a functioning windfarm consisting of commercial MW scale systems. Although the presented data suggests that the total recorded downtime is almost equally shared between unplanned and planned maintenance activities, causing 49.4% and 50.6%, respectively, it also shows that the incidents of SCADA alarms for unplanned maintenance activities is approximately twice as much (nearly 70% versus 30%) as occurred for the planned activities. As a result, the unplanned maintenance activities will have a significant effect on both WT operations and availability when the SCADA alarms and downtime rates are considered. Therefore, the presented results in the remainder of the paper will focus only on unplanned maintenance activities, their failure modes and resultant downtime, which also aligns with the presented results in the literature.

The contribution of individual subsystems to the overall SCADA alarms and downtime rates is presented as subsystem related percentages in Figs. 4 and 5, respectively. The failure rate (SCADA alarm rate) of a given subsystem is calculated by dividing the total number of alarms identified for that subsystem with the total number of alarms identified in the cluster of WTs during the studied period. Similarly, the downtime rate of a given subsystem is calculated by dividing the total days of downtime per subsystem with the number of turbines in the farm and the number of years in operation.

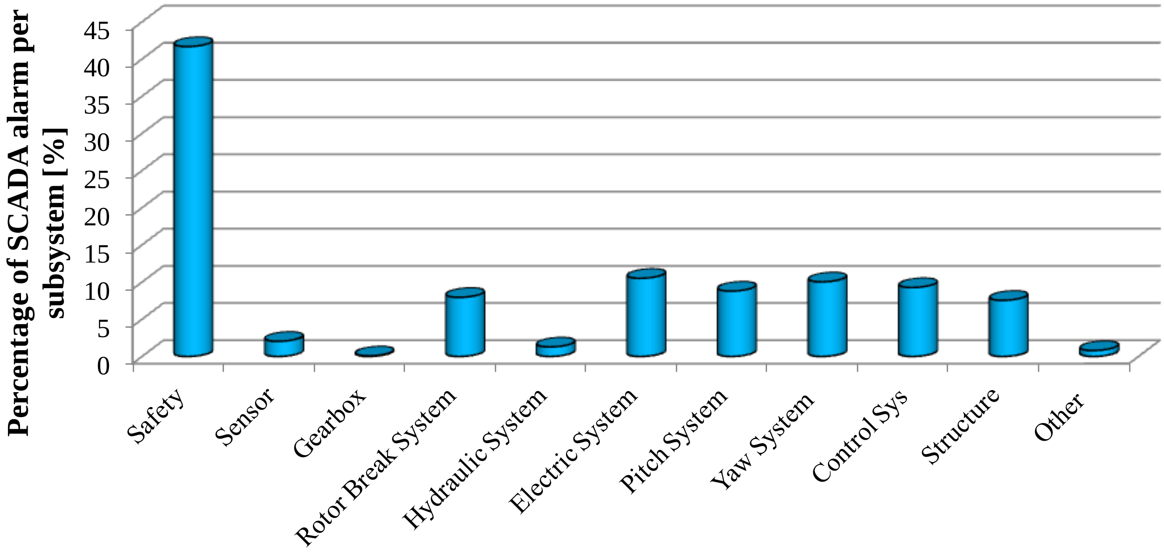

Fig. 4: Distribution of SCADA alarms per subsystem for the cluster of analysed wind turbines.

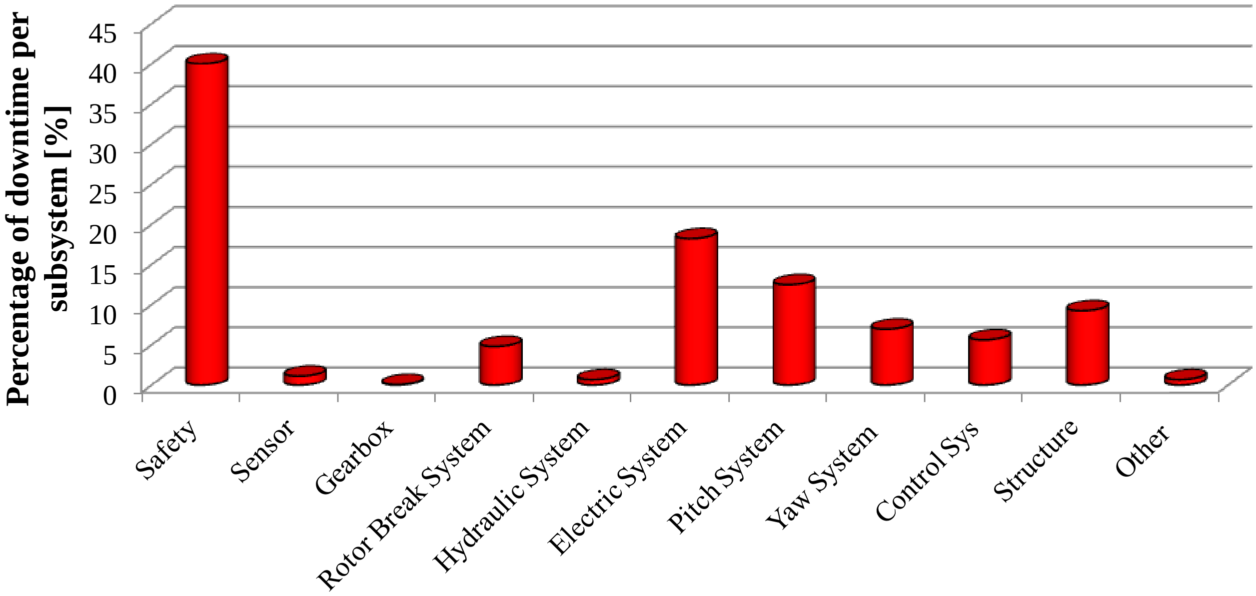

Fig. 5: Distribution of downtime per subsystem for the cluster of analysed wind turbines.

Figs. 4 and 5 show that the majority of WT subsystems contribute to the total number of SCADA alarms and downtime. Furthermore, it can be clearly seen that, based on the data evaluated for this study, early life modern WTs are more likely to suffer from ‘safety’ related alarms, which accounted for approximately 40% of the total number of SCADA alarms and downtime occurrences. Safety alarms can include anything related to WT components and operator/personnel safety such as alarms that occur when the wind direction or wind speed are not within parameterised limits, i.e. when there is high rotor speeds due to extreme gusts, when the generator and the rotor speeds indicate a difference that exceeds the maximum permissible difference over a defined period of time; when the angle between the nacelle and wind direction has exceeded predefined limits; when the fire alarm system in the tower indicates a fault, etc. Most of the time, however, safety alarms automatically reset themselves when monitored parameters such as wind speed drops below the predefined threshold limit again.

After safety, the ‘electric system’ subsystem category is typically responsible for the second highest incidents of WT failure rate occurrences and downtime. Therefore, it is possible to say that the most troublesome subsystem in the studied WTs is the electrical system. Faults in the measurement systems, grid, battery and charging system, main and subsystem converters, line contactors, over and under voltage relays, switches and transformer are examples of electrical system failure events. The presented early life WTs' results in Figs. 4 and 5 can be seen to align with the previously published studies taking into account long term WT operation [8, 28, 7, 5], which considers the electrical system components as the most critical WT components in terms of failures. In order to provide a clearer understanding of the correlation between subsystems and the SCADA alarm and downtime rates the data from Figs. 4 and 5 is put into pie chart form, as illustrated in Fig. 6. The analyse data in Fig. 6 does not contain safety related stoppages and therefore provides a clearer insight into the contribution of individual subsystems to the overall SCADA alarms and downtime rates.

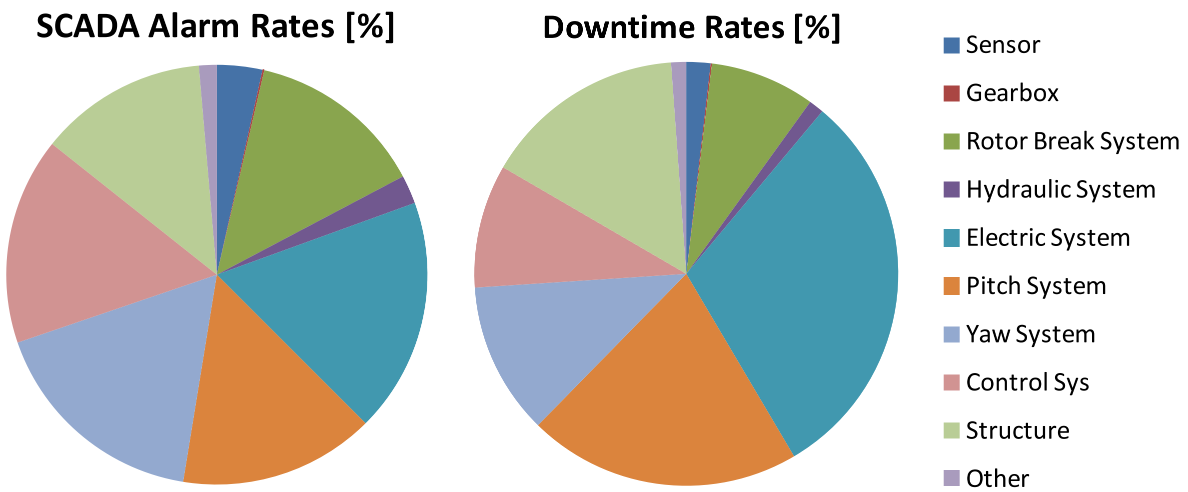

Fig. 6: Percentage of SCADA alarm and downtime per subsystem for the cluster of analysed wind turbines.

As seen in Figs. 4 to 6, following the ‘electric system’, the ‘pitch system’, ‘yaw system’, ‘control system’, ‘rotor break system’ and ‘structure’ based alarms can also been seen to be consistent major contributors to the observed SCADA alarms and downtime rates. The subsystems that have the least amount of contributions to both the SCADA alarms and downtime rates are found to be ‘sensor’, ‘hydraulic system’, ‘gearbox’ and ‘other’ during the investigated early lifetime operations. Heating and cooling systems, communication systems and lightning protection systems are some of the systems that are considered under 'other' for the purposes of this study. It is important to highlight that ‘gearbox’ has marginal effects on both the SCADA alarms and downtime rates observed during the early years of operations, which is in contrast to the claimed fact that it is one of the biggest failure contributors in Type-III concept WT in the literature [13, 32, 5]. In addition to ‘gearbox’, there is no ‘generator’, ‘drive train’ and ‘hub & blades’ related SCADA alarms and downtime that were identified during the studied period. Therefore, these subsystems are not presented in Figs. 4 to 6. In addition, it is important to state that there was no failure identified in the investigated windfarm during the studied time period that required major component replacement (which is a costly intervention due to the nature and sometimes location of WTs).

5.3 Failure Rates and Downtime per Subsystem for an Individual Wind Turbine

To illustrate the typical manifestation of the observed effects on an individual WT, in addition to the presented windfarm level average statistics, this subsection presents the results for the SCADA alarms and downtime per subsystem for one randomly chosen WT from within the investigated cluster of WTs. Both SCADA alarms and downtime data for the individual WT is also presented as normalised percentages (considering the total number of failure rates and downtime as 100% and proportionally calculating the contribution of each sub-system), in order to ensure consistency of the presented results in this paper.

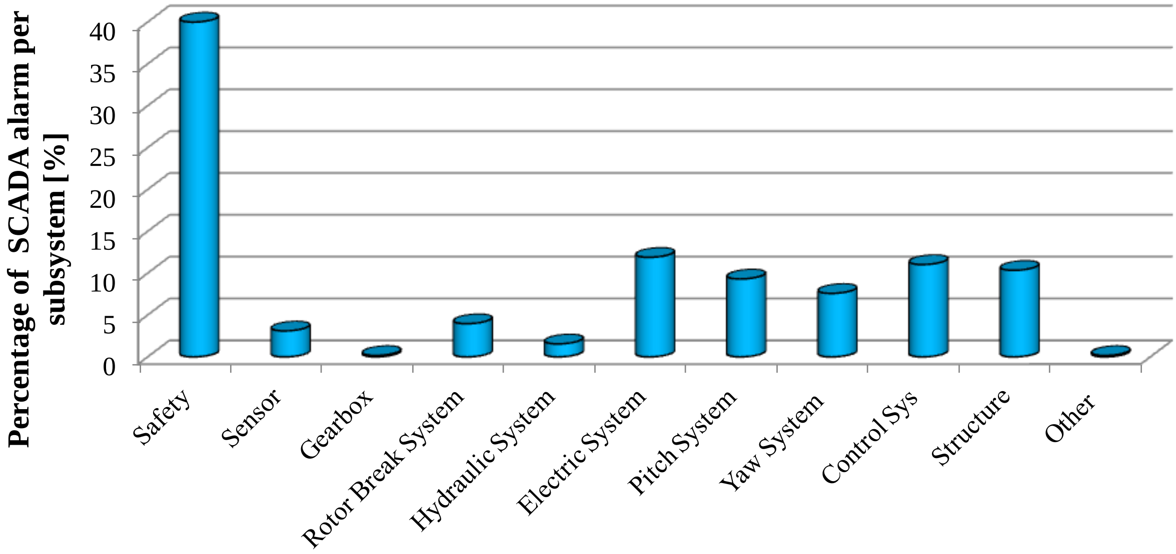

Fig. 7: Distribution of SCADA alarms per subsystem for the investigated individual wind turbine.

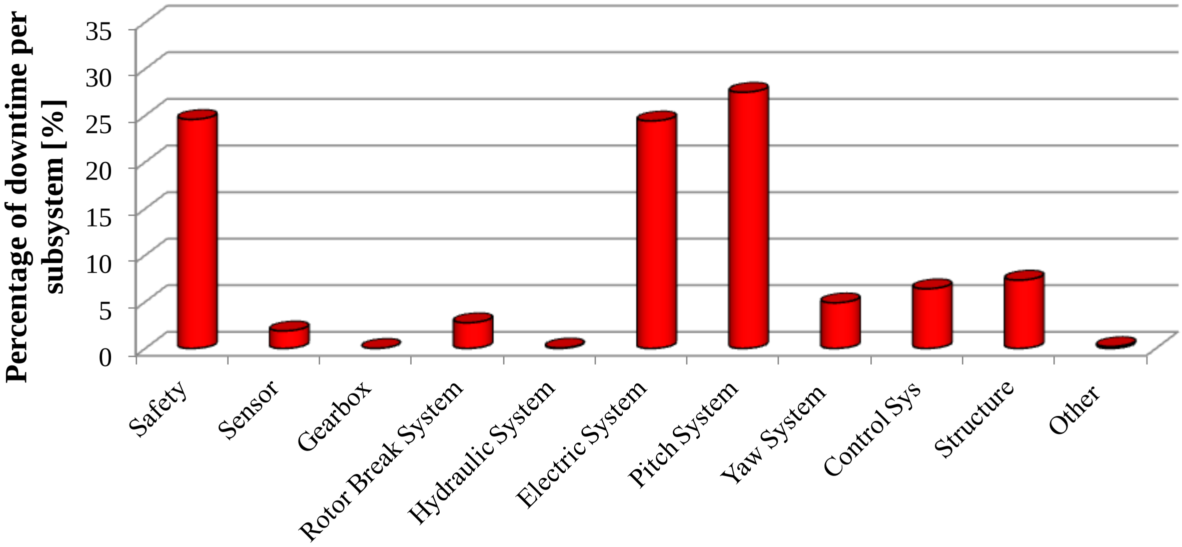

Fig. 8: Distribution of downtime per subsystem for the investigated individual wind turbine.

Fig. 7 shows that the most significant occurrence of SCADA alarms for the selected individual WT are also associated with ‘safety’ accounting for approximately 40% of the total number of SCADA alarms, which is consistent with the overall results of the cluster presented in Fig. 4. The ‘electrical system’, ‘control system’, ‘structure’, ‘pitch system’ and ‘yaw system’; respectively, are the subsystems with the next highest occurrences of SCADA alarms. These result show a similar trend in comparison to the results obtained from the cluster of WTs, as presented in Fig. 4. However, the downtime analysis result for the individual WT shows some differences to the analysed WT cluster, which is obviously to be expected, since each individual WT will have its own issues. For example, although 'safety' is the highest contributor to the total downtime rate in the investigated WT cluster, 'pitch system' failures caused the highest amount of downtime for the selected individual WT, followed by the 'electrical system' and then 'safety'.

Overall, the results show that the most troublesome subsystems are associated with the 'electric system', 'pitch system' and 'safety' both for the overall results and the individual WT when both SCADA alarms and downtime rates are considered. It is important to highlight that each WT has slightly unique operational practices and therefore, their SCADA alarms and downtime rates can be different from each other.

5.4 Total SCADA Alarms and Downtime Rates per Month

In this section, the percentage of SCADA alarms and downtime rates are presented according to the month of occurrence for the wind farm in Figs. 9 and 10, and for the individual wind turbine analysed in Sub-section 5.3 in Figs. 11 and 12, respectively. The percentage of SCADA alarms and downtime rates that occurred in each month of operation are calculated as contribution to the overall number of SCADA alarms and downtime that occurred during the entire period surveyed. In addition, the averaged external ambient temperature, internal nacelle temperature and external ambient pressure of the cluster of WTs selected from the windfarm are also presented in Figs, 13-15, respectively.

The percentage of SCADA alarms and downtime rates that occurred in each month of operation are calculated as contribution to the overall number of SCADA alarms and downtime that occurred during the entire period surveyed. Figs. 9 to 12 provide a clearer understanding of the SCADA alarm development trends throughout the early years of operational lifetime of the investigated cluster of WTs, as well as the analysed individual wind turbine.

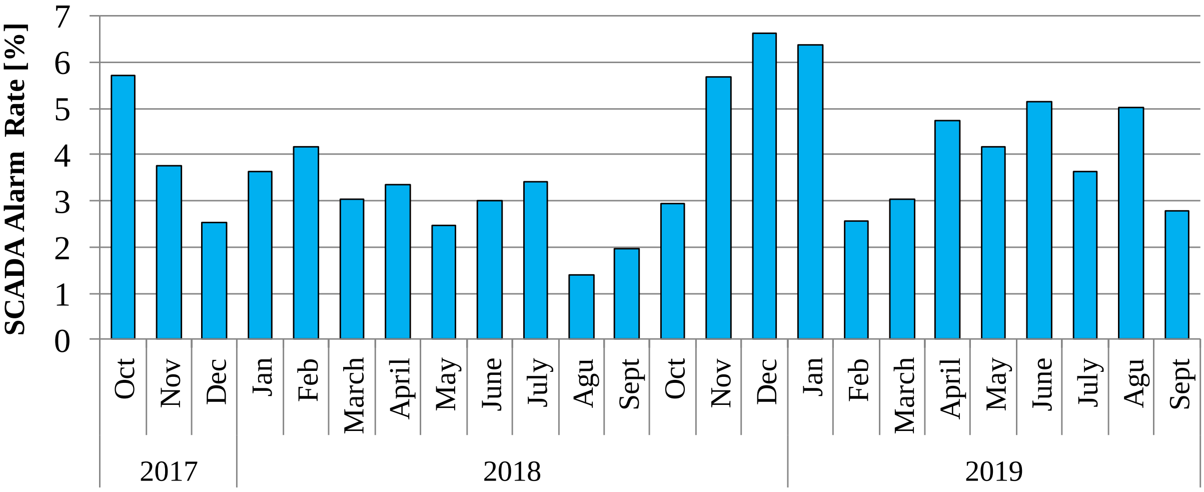

Fig. 9: Percentage of total SCADA alarm rate per operational month for the wind farm.

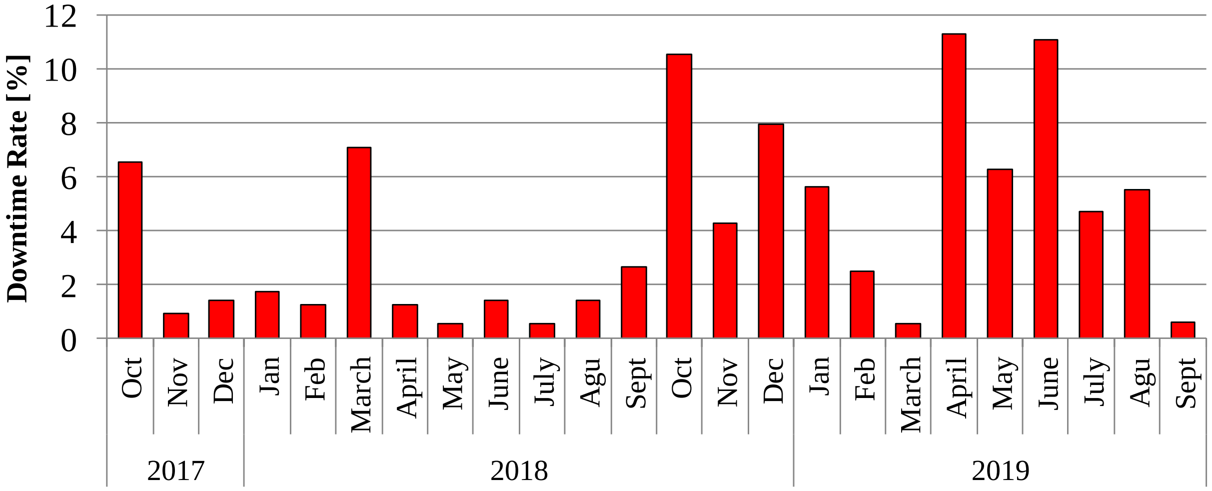

Fig. 10: Percentage of total downtime per operational month for the wind farm.

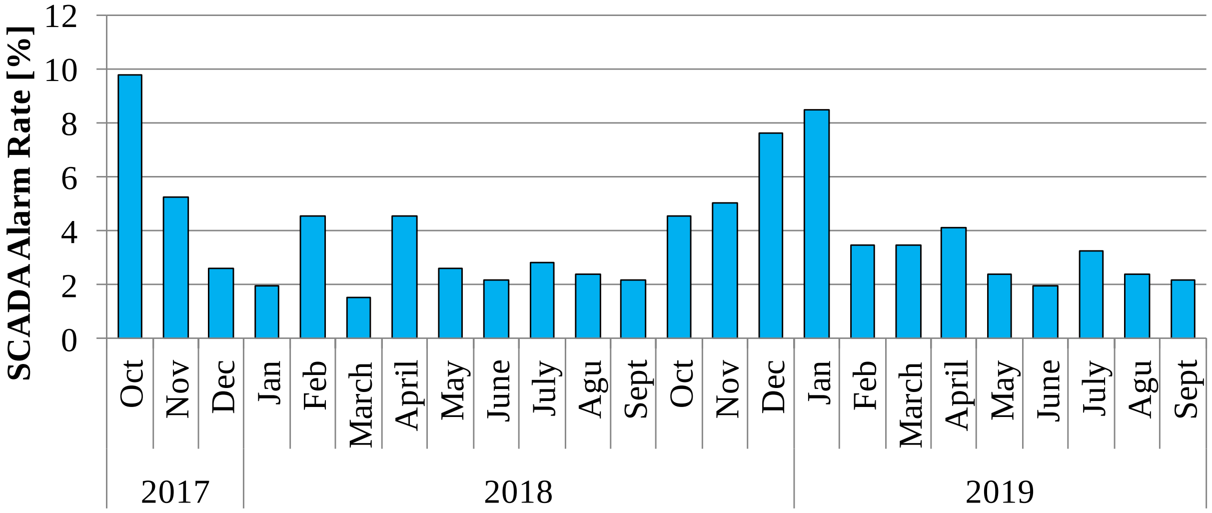

Fig. 11: Percentage of total SCADA alarm rate per operational month for the investigated individual wind turbine.

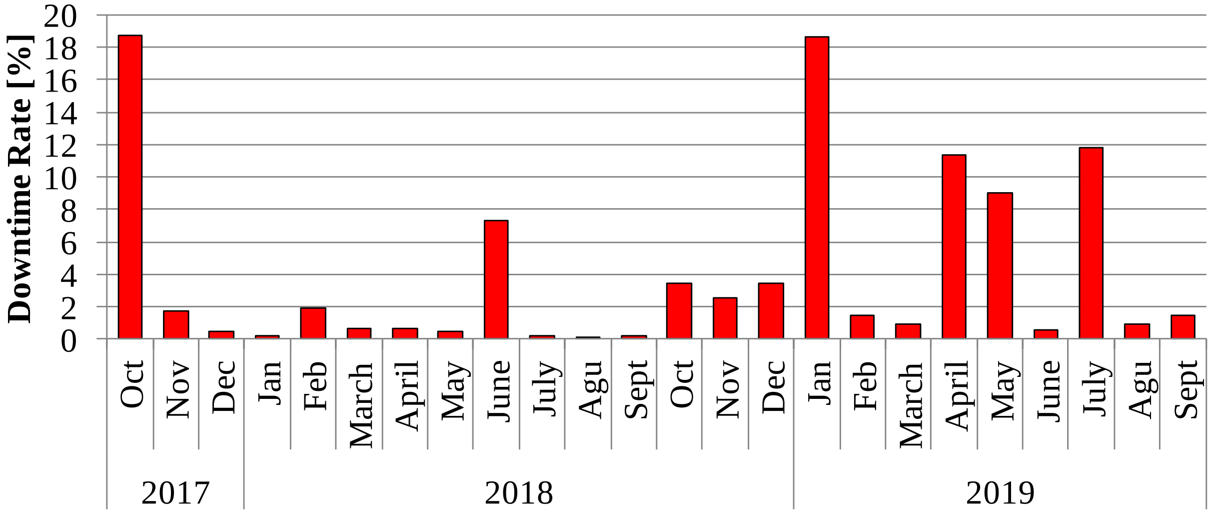

Fig. 12: Percentage of total downtime per operational month for the investigated individual wind turbine.

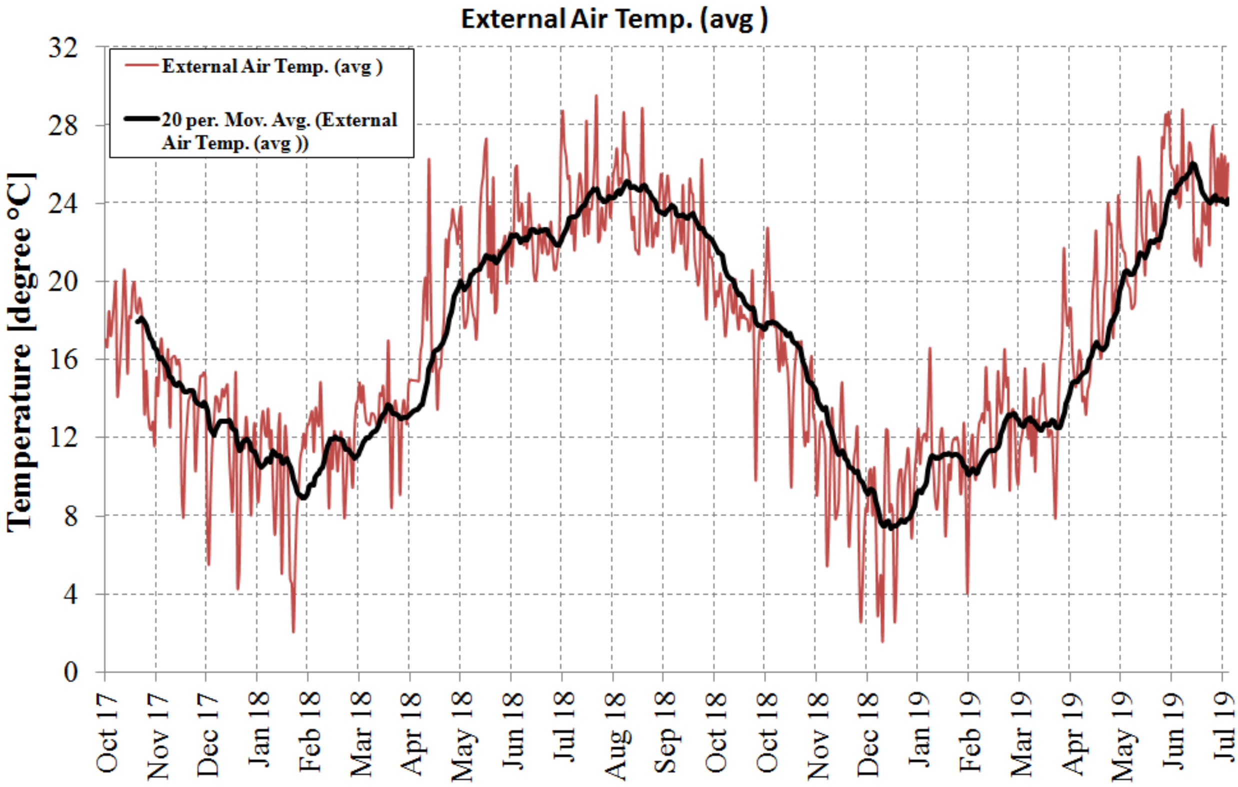

Fig. 13: The averaged external ambient temperature per operational month.

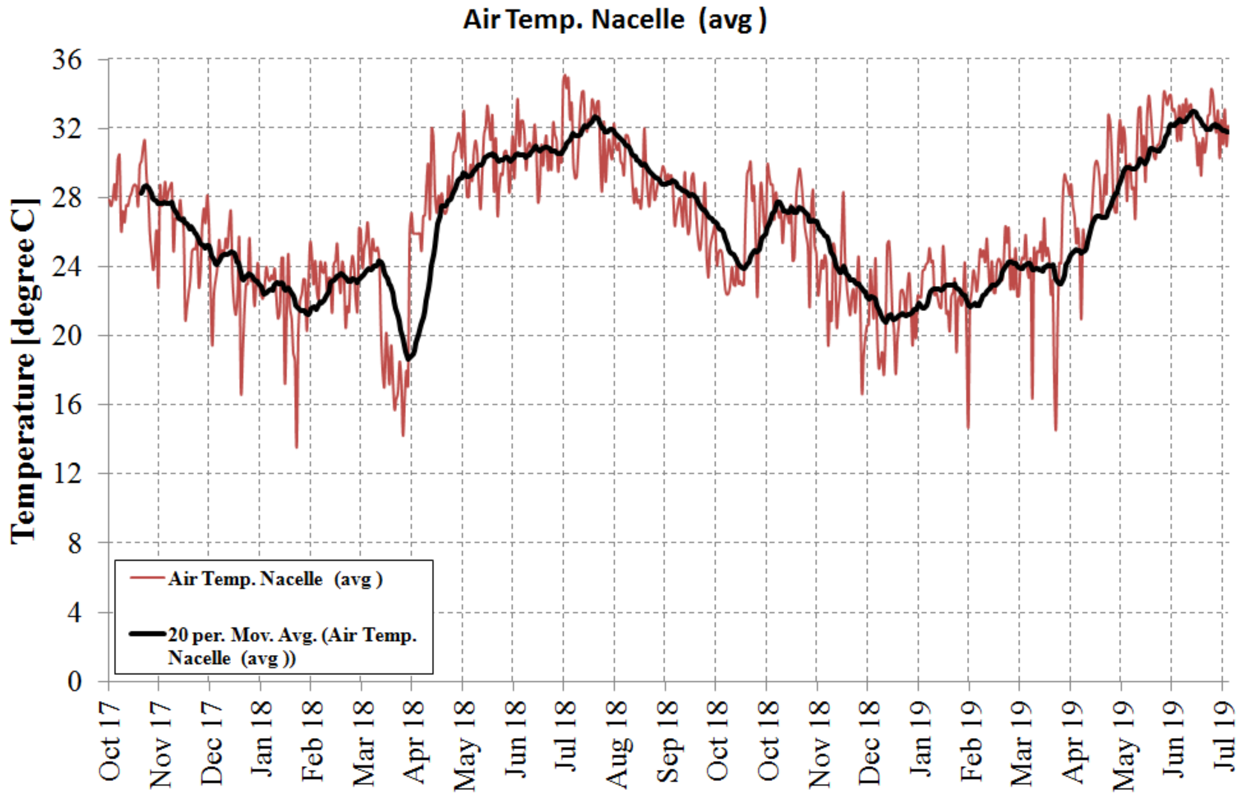

Fig. 14: The averaged internal nacelle temperature per operational month.

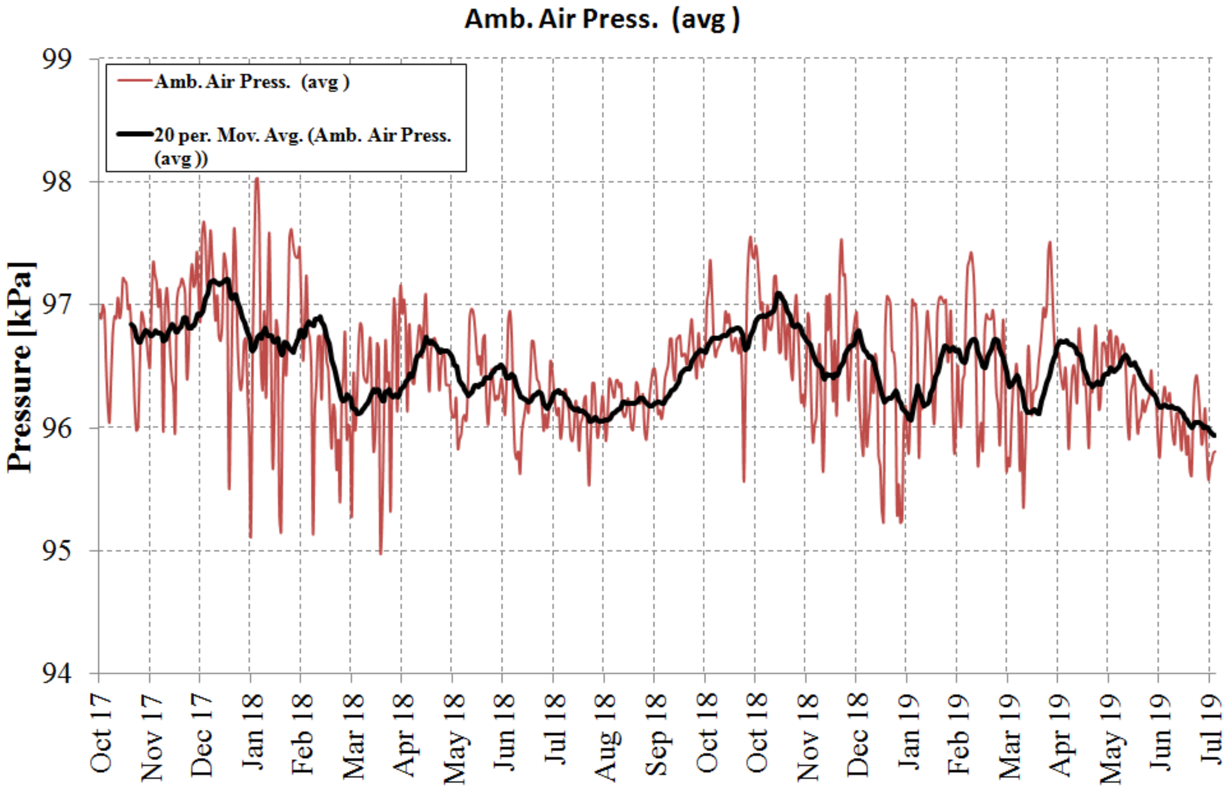

Fig. 15: The averaged external ambient pressure per operational month.

Figs. 9 and 11 show that there is no consistency between the SCADA alarms rates and operational month, which is also the case for downtime, as seen in Figs. 10 and 12, respectively. Furthermore, Fig. 9 shows that the number of SCADA alarms in the first operational year (~44% of the total number of alarms) is similar to the second operational year (~56% of the total number of alarms) on the studied systems. It is possible to observe a similar behaviour when the individual wind turbine is considered, which has ~46% of the total number of alarms in the first year and ~54% of the total number of alarms in the second year. This is in contrast to previously presented data in older studies [5]. A possible reason for this contradiction is that the older studies did not present all the failure events causing downtime, which are reported during the run-in period of a new WT. Therefore, it is considered that the data presented in this paper provides a more accurate presentation of results related to the early operational years of modern Type III WTs in general but also more specifically in Turkey.

Figs. 9 to 12 also show that it is not possible to conclude direct correlation of the number of SCADA alarms and downtime that occurred during the entire period surveyed with month of operation, as the trend differentiates for the wind farm and the individual wind turbine selected for analysis from the cluster. For example, the highest number of SCADA alarms occurred in Dec 2018 for the wind farm whereas for the individual wind turbine from the cluster Oct 2018 was the month that had the highest SCADA alarm rates. In addition, the highest downtime occurred in April 2019 for the wind farm and Jan 2019 for the individual wind turbine from the cluster, respectively.

The averaged external ambient temperatures measured across the cluster of WTs was between the range of 0.8°C to 29.7°C, as shown in Fig. 13. Furthermore, the internal nacelle temperatures was measured to be between the range of 13.2°C to 35.7°C, as presented in Fig. 14. This data highlights that the WTs experienced fairly normal and no excessive temperatures during their first two years of operation. Finally, the ambient air pressure was measured, as shown in Fig. 15, and was between the range of 94.8 kPa to 98 kPa.

Analysing and comparing the data presented in Figs. 13-15 with the data in Figs. 9 and 10 does not suggest any significant correlation between the percentage of SCADA alarms and downtime rates, and the ambient temperature, nacelle temperature and ambient pressure of the WTs according to the month of occurrence. For example, approximately 18.5% of the SCARDA alarms occurred between November 2018 to January 2019 but not for the same time period the year previously although the temperatures and air pressure were approximately consistent. This is also consistent with the longest duration of downtime, which occurred between April 2019 and August 2019, accounting for approximately 28.5% of the overall downtime experienced during the first two years of operation. Therefore, the presented figures in this sub-section show that there is no direct correlation between outside air temperature, internal nacelle temperature and outside air pressure, with the majority of the SCADA alarms and downtime rates, which occurred during the first two years of investigated and analysed operational lifetime of the selected WT cluster.

6. CONCLUSIONS

This paper presents SCADA alarms and downtime data for reliability analysis of modern Type III wind turbines (WT) from an onshore windfarm located in Turkey. The reliability of modern Turkish WTs has not been investigated in the literature previously and thus, this paper is the first time failure rate and downtime data has been published from Turkey. The presented data can be used to better understand the performance and operation of Type III WTs located in Turkey. The presented results can also help to understand unexpected failures modes in WTs during early lifetime operation, as there is a limitation on presenting reliability analysis results in the literature due to the lack of quantitative data and experience in the field, confidentiality of technical data and economic project performance, and therefore, define appropriate maintenance programs to reduce the downtime periods. Supervisory Control and Data Acquisition (SCADA) alarms are used to categorise and analyse the failure events and downtime for the identified WT subsystems. The combination of alarm occurrences and their related downtime periods was used to identify the most critical subsystems for the operation of WTs during their early lifetime (first two years).

The presented data shows that planned (scheduled) maintenance activities have significant effects on both SCADA alarms and downtime. When unplanned (unscheduled) maintenance activities were investigated, ‘safety’ was the highest contributor to the total SCADA alarms and downtime rate in the investigated windfarm, which was followed by the ‘electrical system’. Furthermore, no major component replacement was identified during the studied two year time period. Therefore, targeting these subassemblies through advanced condition monitoring systems can potential reduce failure rates and hence, downtime, which can improve overall reliability and availability of WTs and therefore, achieve lifetime extension of windfarm assets and availability, as well as reduce operations costs resulting in cheaper electricity. Furthermore, this paper presented individual WT failure rate and downtime analysis results, which can help the reader to understand in more detail the SCADA alarms and downtime rate of an individual WT, as an example, and how these closely correlate across the investigated cluster of WTs from within the windfarm. In addition, in the paper SCADA alarms and downtime rates for each subsystem were investigated using monthly data captured during the early lifetime operation of a number of WTs within the cluster of the investigated windfarm, and the results showed that there was no direct correlation between the SCADA alarms and downtime rate with month of operation or the external air temperature, internal nacelle temperature or external ambient air pressure.

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