

## Article

# Impact of the Air Filtration in the Nacelle on the Wind Turbine Performance

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**Abstract:** Wind turbine farms require efficient operation and maintenance strategies to ensure long-term profitability and cost-effectiveness. However, temperatures and dust accumulation can significantly affect turbine performance and increase maintenance costs. This study investigates the impact of air filter clogging on wind turbine nacelle temperature and performance by collecting data from the Supervisory Control and Data Acquisition (SCADA) system of wind farms in southern Jordan, including temperature, wind speed, and power generation. The findings demonstrate that uncleaned air filters can lead to inefficient heat dissipation, higher nacelle temperatures, and reduced power production. Turbines with uncleaned filters experienced an average nacelle temperature increase of 15.44 °C compared to 13.30 °C for turbines with clean filters, resulting in a difference in the power production of 66.54 kW.

**Keywords:** wind turbine performance; dust accumulation; nacelle temperature; wind turbine filters



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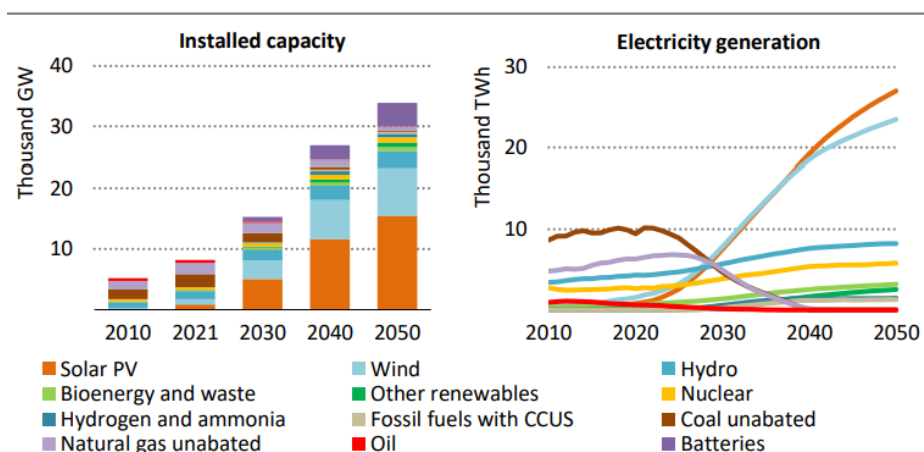


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## 1. Introduction

Renewable sources are the fastest-growing energy source on the planet, expected to make up 15% of all electricity by 2040 compared to 7% in 2015 [1–3]. Figure 1 shows the annual electricity generation growth from renewable energy sources from 2010 to 2050 [4]. Jordan has abundant renewable energy resources, particularly solar energy, with annual average insolation on a horizontal surface of about 5.4 kWh/m<sup>2</sup>.day and wind power with typical wind speeds exceeding 7 m/s [5,6]. The Jordanian government invested \$1.4 billion in the energy sector to achieve its goal of having 10% of its total energy mix from renewable sources by 2020. Currently, 20% of the country's electricity is generated from renewable energy sources, with a total installed capacity of about 2063.3 MW, with solar and wind contributing around 1339.7 MW [1].

Due to the development of wind turbine technology, the increased rated power of wind turbines has posed significant challenges in achieving these units' long-term stability and efficiency [7,8]. One such challenge is the increased heat load on components inside the nacelle, including the gearbox, generator, and control inverter [9,10]. As temperatures rise, the turbine performance slightly deviates from the manufacturer's guaranteed curve [11]. The higher winding temperatures can decrease generator efficiency, and control inverter life may be halved (normal operating range about −40 °C to +55 °C) [12].



**Figure 1.** Annual growth for renewable electricity generation by source, 2010–2050.

There are various reasons for an increase in temperatures in wind turbines. One such factor is dust accumulation on both the external and internal components. Al-Khayat et al. [11] found that the dust accumulated inside the nacelle hinders the effectiveness of the ventilating system, causing a temperature rise in essential components, such as the gearbox, generator, and control inverter, and may potentially limit turbine production. Additionally, dust accumulation on the blades affects the turbine's aerodynamic efficiency and reduces power output [13,14]. Accordingly, proper maintenance and cleaning of wind turbines are essential in minimizing the adverse effects of dust accumulation on turbine performance. These highlight the limitations of current cooling and ventilation technologies used in wind turbines [15].

The design and arrangement of components in the cooling system of wind turbines are complex concepts that pose significant challenges in the wind turbine industry. About 95% of wind turbines use liquid and air cooling methods to keep components inside the nacelle operating normally [16]. The literature indicates that considerable studies have been conducted on different cooling technologies to increase cooling efficiency and overcome the impact of heat increase in the nacelle [9,17]. These combined techniques include utilizing this unwanted heat to supply the required energy cooling/heating applications, which are still not prevalent [18–20]. On the other hand, CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> emissions will be reduced. In addition, the heat in the conventional wind turbine design can be dissipated by the air circulation and ventilation system installed inside the nacelle. Therefore, studies have also focused on developing various aspects of air filtration systems used in the ventilation and cooling system [21–23]. In recent years, the developments of air filtration involve lower cost, expansion of applications, improved temperature resistance, lower pressure drop at a fixed efficiency, and global usage [24]. According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), several air filters are commonly used in industry, including fiberglass, Polyester and pleated, carbon, High-Efficiency Particulate Air (HEPA) filters, and Washable air filters. The air filtering performance can be measured by pressure drop and capture efficiency [25]. Most filters cause pressure loss as air flows across the filter media. Generally, if the filter operates in dusty conditions for a long time, it affects filtration performance. This will lead to more dust particles adhesive on the filter media, leading to pressure drop and reducing airflow pathways [26]. According to the studies above, many investigated the technologies for designing these filters and the manufacturing materials [27–30]. However, according to the authors' knowledge, no recent research contained a real test to demonstrate the effect of unclean filters on wind turbine power generation.

There have been a few studies on the impact of dust on wind turbines in the literature, but the number of investigations remains limited. The motivation for this current work is to observe that the wind turbine farm around Ma'an City (Southern Jordan) was exposed to dusty storms that caused clogging in the primary air filter, leading to increased nacelle temperature

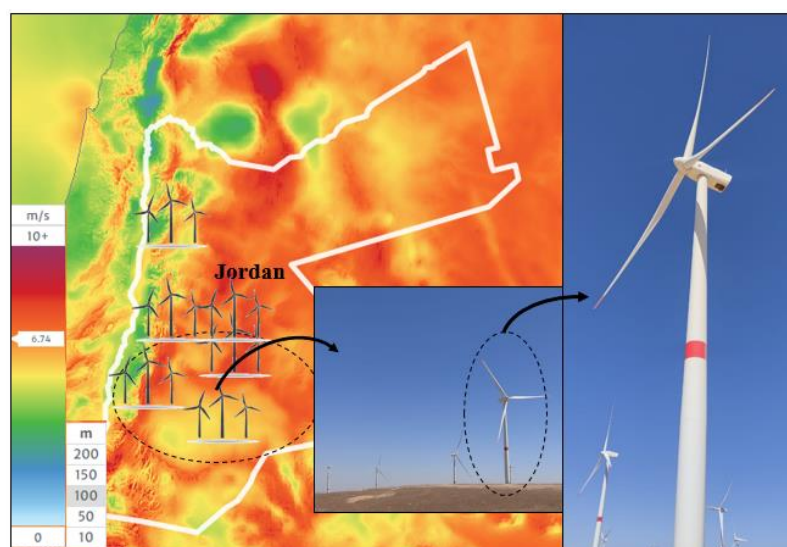
reported recently. This increase is a critical issue that yields turbine power reduction and increases wind turbine shutdown (about 10 times yearly, including two preventive shutdowns). This paper highlighted the effect of the increasing temperature inside the wind turbine nacelle on the productivity of the wind farm. While previous research has shown that dust accumulation can decrease turbine efficiency, this study provides detailed insights into how dust affects heat rejection, a critical factor in turbine performance.

## 2. Wind Power Plants in Jordan

According to a study by Marar [31], Jordan has vast desert lands highly suitable for wind turbines, with around 16% of the country's land possessing a total potential of 3.6 GW for wind energy generation. The south governorates of Ma'an, Tafilah, and Aqaba have been identified as the most promising locations for wind energy investment, as indicated in Table 1 [1]. Moreover, Figure 2 illustrates the wind speed distribution at 100 m height and the location of some wind energy farms in Jordan based on the brand-new wind measurements conducted by the Ministry of Energy and Mineral Resources (MEMR) for several years [32]. In 2016, the country signed a significant investment deal for wind farms with an installed capacity of 145 MW, which was implemented into operation in 2020. As per the National Electric Power Company (NEPCO), the contribution of wind-generated power to the peak load in 2020 was approximately 2%. These findings highlighted the significant potential for wind energy in Jordan, which could contribute to the country's efforts toward achieving a sustainable future.

**Table 1.** The wind energy projects in Jordan.

No.	Wind Energy Farms	Location	Database Capacity (MW)
1.	Hofa Wind Farm	Irbid	0.225
2.	Ibrahimiya Wind Farm	Irbid	0.32
3.	Tafila Wind Farm	Tafila	117
4.	Ma'an Wind Farm	Ma'an	80
5.	Fujeij Wind Farm	Ma'an/Fujeij	89.1
6.	Rajef Wind Farm	Ma'an/Rajef	86.1
7.	Shobak Wind Farm	Ma'an/Shobak	45
8.	Abur Wind Farm	Tafila/Abur	51.75
9.	Air Force Wind Farm	Mafraq	10

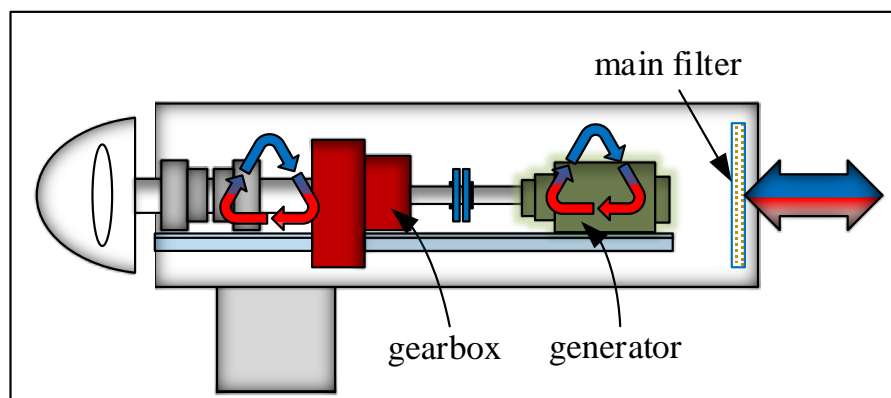


**Figure 2.** Wind map and locations of some wind power plants in Jordan.

### 3. Problem Background

Generally, wind turbines have been designed to operate under different environments, so the equipment that supports wind turbines must perform efficiently and reliably under extreme conditions. Dust, rain, and salt fog are significant concerns for wind turbine equipment, as these contaminants can cause system failure and decrease power production, as in Section 1.

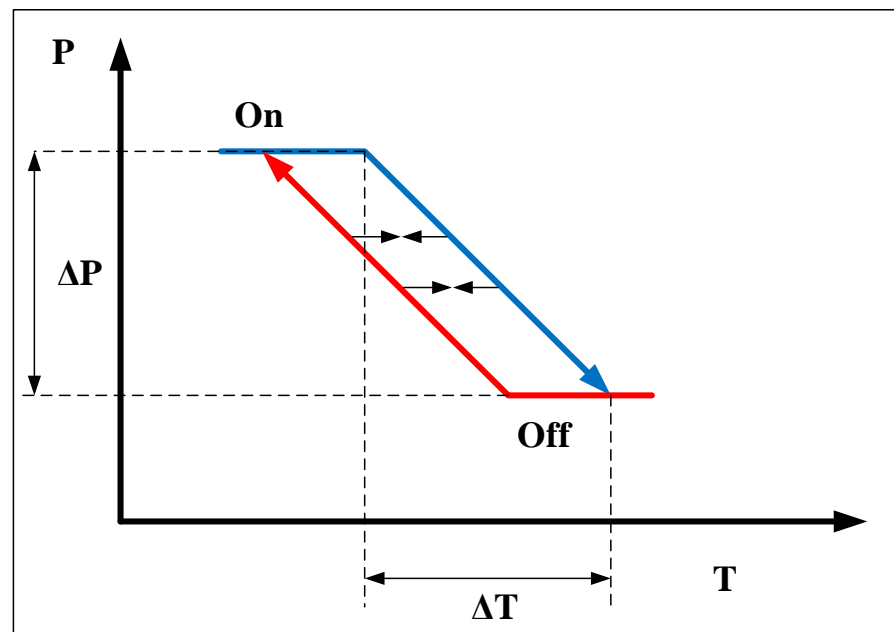
Cooling and ventilation systems are crucial systems to protect electronic and control equipment supporting wind turbines. There are various designs and technologies of wind turbines available in the market. Among these technologies, Gamesa and Vestas manufacture most of the wind turbines deployed in Jordan wind farms [33]. These use a multistage gearbox to increase the rotational speed of the generator more than 100 times. This turbine technology uses a cooling and ventilation system (heat exchanger –oil/air). A gearbox oil and generator heat exchanger are arranged into the nacelle in the cooling air duct. The same air that cools the nacelle environment also cools the engine and generator oil. This circuit operates sequentially when the temperature reaches a specific range to protect the main parts in the wind turbine nacelle. The air needed for the cooling system enters via the filter shown in Figure 3. The air filter is considered one of the main elements in the wind turbine cooling and ventilation system used to encounter dust and other contaminants. It is utilized to capture the dust particles from the air stream to keep the low dust particles inside the nacelle. Therefore, failure to appropriately filter intake (cooling) air can result in harmful dust ingress, which can cause electronic parts to overheat and mechanical controls and fans to fail. In addition, this will lead to energy production loss and additional maintenance costs. In addition to the cooling system, many openings in the nacelle body can allow the air to enter and exhaust from the nacelle. In emergency conditions (at a high oil temperature or in an engine shut-off condition), the nacelle vent doors open to provide airflow from the atmosphere.



**Figure 3.** A schematic side of wind turbine nacelle (front view), fresh air circulation.

Although filter technologies have been improved recently, the existing filter in such wind farms is a Polyester Fiber filter (synthetic fiber with gradual density). However, the pressure drop is relatively high (35–250 Pa), with low air velocity (1–2 m/s) [21,34]. As filter technology improves, wind turbine farm operators can select efficient filters that capture dust particles efficiently and reduce pressure loss. The essential filter technology improvements involve placing more folds in the filter media and creating valleys. This improvement will increase the filter's surface area and allow air to flow more effectively. The electrostatic air filter is a newer technology that uses static electricity to give dust particles a positive charge upon entering the filter. The charge is released as the air flows through subsequent filter layers, and the dust particle is ultimately trapped. Compared to fiberglass filters, the pressure drop across electrostatic filters is negligible [35]. A further filtration technology combines an electric field and a fibrous filter, resulting in better performance [36,37].

Most of the wind turbine components are typically enclosed inside a not-so-spacious nacelle. Indeed, as the power production for a wind turbine increases, the heat produced by the generator and gearbox increases significantly. Therefore, these parts need adequate ventilation to keep them cool and function correctly [38]. Insufficient ventilation might lead to higher gear and generator temperatures, reducing the service life of those parts. When the temperature of any wind turbine component reaches an excessively high value, a specific control system is applied to reduce the output power to the value necessary to keep from halting the wind turbine due to a component at a high temperature. Thus, the variation limit will decrease. As a result, this leads to a hysteresis cycle to prevent abrupt variations in the power set point, as shown in Figure 4.



**Figure 4.** Power hysteresis by temperature.

#### 4. Methodology and the Experimental Work

The investigation in this study was based on data collected from two turbines installed in the same wind farm in southern Jordan, as illustrated in Figure 5. One turbine was equipped with a clean air filter, while the other operated with an uncleaned filter. This approach enabled the experiment to be conducted under the same weather conditions, allowing for a direct comparison of the results. Data were recorded every 15 min over 90 days, covering different months and seasons. The period was divided into four periods: the first and third periods, each separated into seven units, each with three days, while the second and fourth periods, each divided into eight units, each with three days. Although conducting such an investigation in a lab or actual case is costly and challenging, the wind farm's Supervisory Control and Data Acquisition (SCADA) system provided the necessary data, including ambient temperature ( $T_{atm}$ ), nacelle temperature ( $T_n$ ), wind speed ( $U_\infty$ ), and power generation. The study's period covers different seasons when nacelle temperatures were observed to increase due to clogged primary air filters. In previous work, Shalby et al. [39] investigated and classified the dust collected from the filter in the wind turbine nacelle.

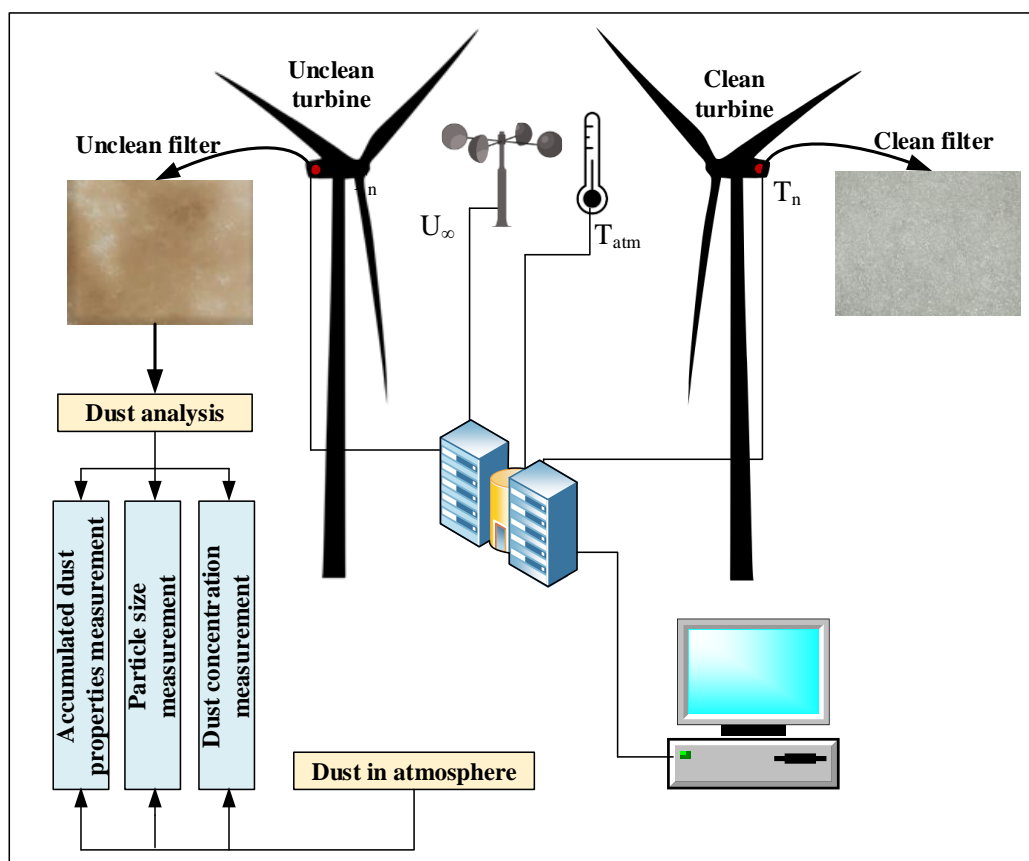


Figure 5. Data collection approach.

## 5. Results and Discussion

### 5.1. Dust Analysis

Dust accumulation on the filter can reduce airflow, leading to increased nacelle temperature and decreased wind turbine production. Shalby et al. collected dust from wind turbine nacelle filters and analyzed by using X-Ray Diffraction (XRD), sieves, and X-Ray Fluorescence (XRF) at Al-Hussein Bin Talal University and Asia Center in Amman laboratory [39]. The results of the analysis showed that it was primarily composed of Calcium (85.83%), Silicon (7.89%), Iron (3.20%), Potassium (0.66%), and Titanium (0.39%). The analysis of the same work also revealed a wide range of particle sizes, with 43.7% of the sample having a size of 149  $\mu\text{m}$ , 21.7% having a size of 74  $\mu\text{m}$ , and 19.9% having a size of 177  $\mu\text{m}$ . Dust sizes of 590  $\mu\text{m}$ , 420  $\mu\text{m}$ , and 297  $\mu\text{m}$  were found in the sample's lowest percentages (less than 10%). These results have been compared with the dust sample collected from the earth's surface (height < 1 m). Table 2 summarizes this comparison. This table demonstrates that the percentage of high levels of Calcium (Ca) in both samples (57.33%, 89.83%) was high compared to the other chemical compositions (Si and Fe). In addition, these results showed that the concentration of Calcium increased by about 49.71% at the height of 100 m (the level of the wind turbine nacelle). That is due to most wind turbines installed in the Ma'an area (Arid desert), located in the Khamsin winds' pathway [40]. These dry and warm winds from the Sahara wilderness, loaded with many heaps of sand, reached Egypt, the Levant, and the Arabian Peninsula [41]. In addition, wind farms around Ma'an City are located near stone crushers that produce limestone ( $\text{CaCO}_3$ ) and Gypsum ( $\text{CaSO}_4$ ). This soil type allows more effortless dust transfer [42]. The analysis showed that the filter's efficiency could gradually decline due to the considerable amount of Calcium (85.83%) present in the dust collected on the air filter, particularly in regions with hot and dry climates such as southern Jordan, in which the wind farm was situated. The filter type used in this wind farm was Polyester Fiber (synthetic fiber with gradual density), which

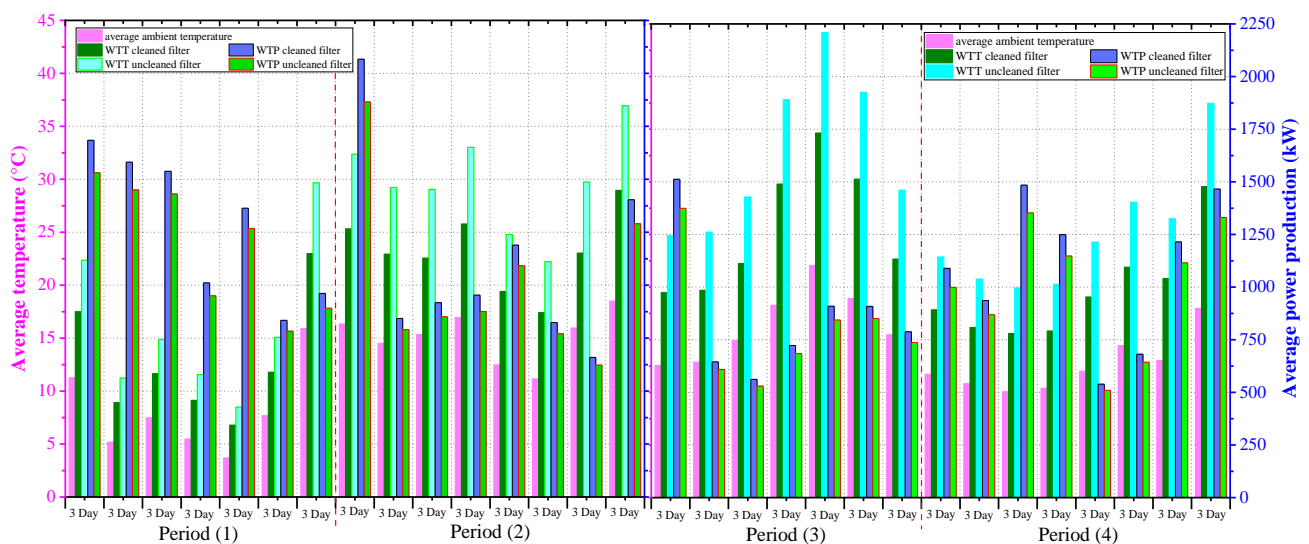
could trap most dust size ranges, including the range of particles found in the dust analysis results. However, the filter had a relatively low dust holding capacity of about 400 g/m<sup>2</sup>, which may require more frequent filter replacement in dusty environments.

**Table 2.** The chemical composition of the dust sample at ground level and the wind turbine filter.

Chemical Element	Height < 1 m at Ground Level	Height > 100 m at Wind Turbine Nacelle Level
Calcium (Ca)	57.33%	85.83%
Silicon (Si)	20.63%	6.11%
Iron (Fe)	11.17%	2.20%

### 5.2. The Impact of Temperature on Wind Turbine Productivity

As demonstrated in the introductory section, in the literature, a limited number of studies have highlighted dust effects on wind turbine performance. Therefore, this section aims to provide further research on this matter. The results of this work indicated that as the ambient temperature increased, the nacelle temperature in the turbine with an un-cleaned filter (WTT uncleaned filter) rose more than the turbine with a clean filter (WTT cleaned filter) during all investigation periods, as shown in Figure 6. This was attributed to reduced cooling and ventilation system efficiency due to clogged filters. As a result, the average power production (WTP) decreased in the wind turbine operating with an uncleaned filter in all investigated periods, as shown in Figure 6. For example, during the second unit of the period (1), the average ambient temperature was 5 °C. The wind turbine with a clean filter (WTT) had an average temperature of 8.5 °C, while the wind turbine with an uncleaned filter had an average temperature of 12 °C, an increase of 41.18% compared to the turbine with a clean filter. The average power production of the turbine with a clean filter (WTP) was approximately 1560 kW, while the WTP for the wind turbine with an uncleaned filter dropped to 1400 kW, a decrease of 10.26% compared to the turbine with a clean filter. The results in Figure 6 highlighted the impact of dust accumulation in the air filter on increased nacelle temperatures and reduced wind turbine productivity.



**Figure 6.** The relation between wind turbine temperature and average power production of the wind turbine that used a clean and unclean air filter.

To place more emphasis on the impact of temperature on wind turbine productivity, Table 3 was created from the collected data. The average power production and temperature for the two wind turbines utilized in this study throughout the four periods representing 90 days are illustrated in this table. In addition, the average wind speed,

ambient temperature, and dust concentration rate in the atmosphere were recorded during this period and added to the table. The average wind speed was 7.82 m/s, and the average ambient temperature was 13 °C. During the test, wind turbines with clean filters had an average power production of 1.1 MW, while those with unclean filters produced only 1 MW, as illustrated in Table 3. In the third test period, the wind speed averaged 7.06 m/s, and the ambient temperature averaged 16.69 °C. At these conditions, the wind turbines with clean filters generated 931.17 KW of power, while those with unclean filters produced only 864.63 KW, resulting in a 7.2% reduction in power generation. The increased nacelle temperature of the wind turbines with uncleaned filters during the test period, which reached 30.15 °C, contributed to this reduction. The decreased performance of the turbines is attributed to the clogging of the air filter, which impaired the efficiency of the cooling and ventilation systems. This situation could be more detrimental when the dust concentration rate in the atmosphere is higher.

**Table 3.** Average ambient temperature, wind speed, wind turbine temperature, and power production for four periods.

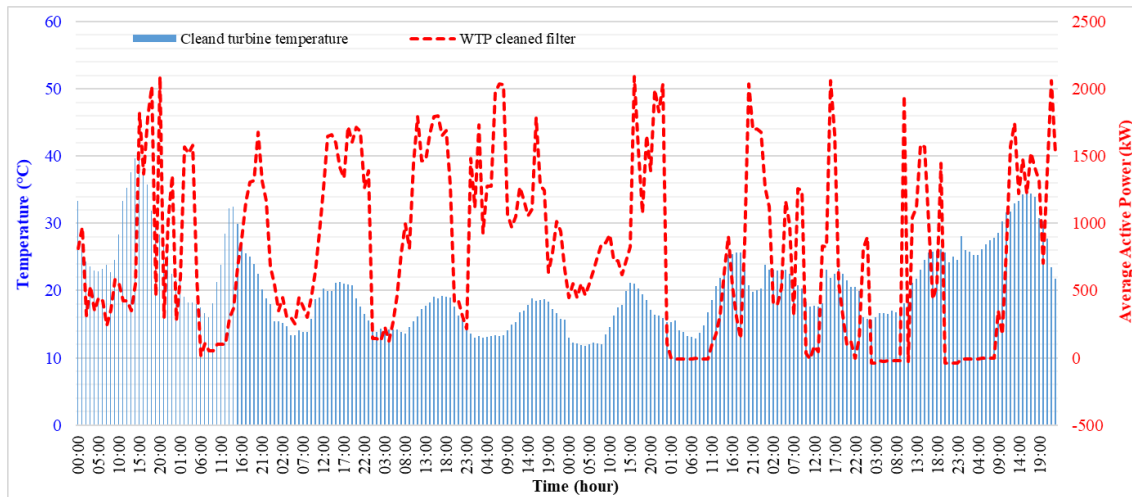
Weeks	Average Ambient Temperature (°C)	Average Wind Speed (m/s)	Cleaned Turbine		Uncleaned Turbine		Concentration Rate (µg/m <sup>3</sup> )
			Average Turbine Temperature (°C)	Average Power Production (kW)	Average Turbine Temperature (°C)	Average Power Production (kW)	
1st period	8.09	8.37	12.67	1281.6	14.71	1186.17	22.5
2nd period	14.67	7.72	22.34	1064.35	26.03	980.89	33.5
3rd period	16.69	7.06	25.96	931.17	30.15	864.63	73
4th period	12.55	8.11	19.59	1082.27	22.74	995.67	14

On the other hand, during the first period, wind turbines with clean or unclean filters produced 1281.6 kW (an increase of 37.63% more than the third period) and 1186.17 kW (an increase of 37.19% more than the third period) of average power, respectively. Although, the average wind speed rose about 18.56% more than in the third period. This could be attributed to a lower nacelle temperature for both turbines (a decrease of approximately 51.20%) than in the third period. These results confirmed that wind turbine production is closely related to the nacelle temperature, which, in turn, depends on the effectiveness of the cooling and ventilation system within the wind turbine nacelle.

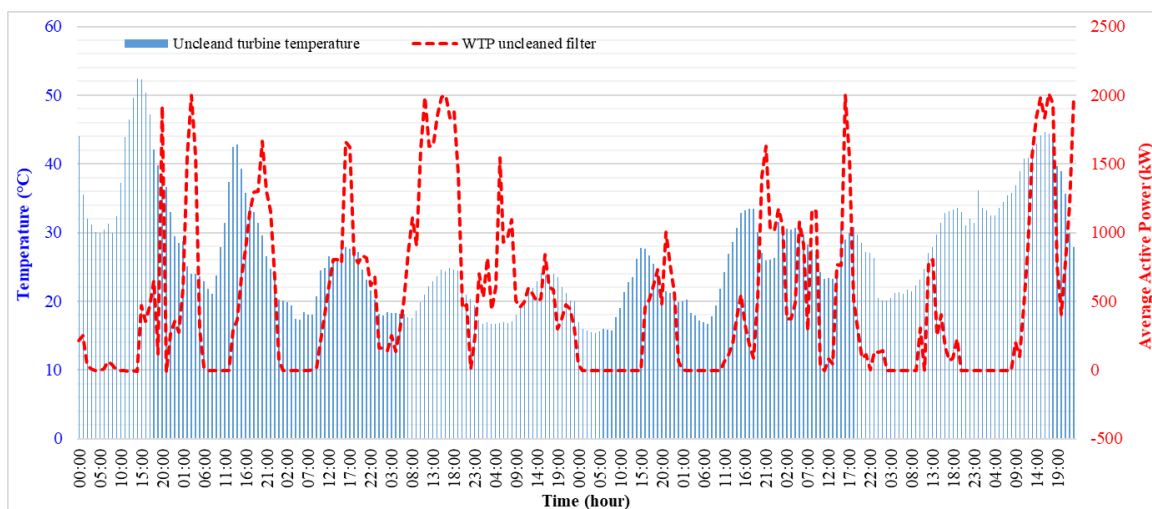
To accentuate the impact of nacelle temperature on wind turbine performance, the data collected from the SCADA system was represented in a time-series plot, focusing on a specific period (ten days in period four), as shown in Figures 7 and 8. As observed from the graphs, wind turbine production (WTP, red line) increased as the nacelle temperature decreased (blue line), except during periods of low wind speed (e.g., in Figure 7 on day 7 at time 6:00, where the temperature and production are low). Additionally, it can be inferred from these figures that the nacelle temperature in the wind turbine with an uncleaned filter (Figure 8) was higher than that in the turbine with a cleaned filter (Figure 7). Consequently, the turbine with an uncleaned filter had a lower average active power output than the turbine with a cleaned filter. This finding highlights the significance of this study.

Wind turbine system reliability is a critical factor in the success of a wind energy project. It depends on many factors; one crucial factor is the operating environment. Maintaining the wind turbine running for an extended period under different environmental conditions will allow the project's revenue stream through decreased operation and maintenance costs and increased generated power. Although the wind plant operator may be mainly interested in replacing an air filter and other failed components and getting their turbine running again, frequently replacing the air filter represents an opportunity to improve this system and prevent catastrophic temperature increases. Evaluating the root cause of replacing the air filter is essential to determine if the failure is due to filter quality or the

incorrect selection of the proper type of filter for this environment. This information, in turn, will assist the manufacturer in determining the type of filter that may be used in such wind plants.



**Figure 7.** Relationship between wind turbine productivity and nacelle temperature for a wind turbine with clean filter during the 10 days of the fourth period.



**Figure 8.** Relationship between wind turbine productivity and nacelle temperature for a wind turbine with unclean filter during the 10 days of the fourth period.

On the other hand, the annual energy production of the wind plant (kWh/year) is affected by turbine downtime associated with scheduled and unscheduled maintenance. Indeed, the operations and maintenance costs can account for 10–20% of the total energy cost for a wind project. This has been verified by many researchers that provided an estimated cost of energy produced by new turbines is approximately \$0.005 to \$0.006/kWh, escalating to roughly \$0.018 to \$0.022/kWh after 20 years of operation. This represents 75–90% of a turbine's investment cost, estimated based on a 20-year life cycle [43–45]. Thus, this type of work sustains the general trend toward reducing operations and maintenance costs for wind plants by highlighting the impact of the environment on energy production and encouraging manufacturers to improve air filter reliability.

## 6. Conclusions

Wind energy holds many promises for the future. This study has demonstrated that air filter clogging impacts the efficiency and productivity of wind turbines. The collected data indicated that uncleaned air filters could lead to inefficient heat dissipation, higher nacelle temperatures, and reduced power production. Moreover, the study has confirmed that wind turbine production is closely related to nacelle temperature, which, in turn, depends on the effectiveness of the cooling and ventilation system within the wind turbine nacelle. At the final stage before maintenance (at the end of the fourth period), the average power production from cleaned and uncleaned wind turbines reached 1082.27 kW and 995.67 kW.

In contrast, the average nacelle temperature reached 19.59 °C, and 25.01 °C, respectively. The power reduction in the final stage of the maintenance period, which is approximately six months, can receive 10% of the farm production in cold weather, and this percentage can be increased in hot climates. Therefore, the only way to enhance the device's operating environment is to maintain the airflow into the nacelle to remove the heat yielded by the machines and reduce the device's temperature to a reasonably acceptable range. These results also emphasize the importance of ongoing research and development in wind energy to ensure this vital industry's continued growth and success in the transition toward a sustainable future. In the next step of this research, further study will be conducted on the wind turbine filter to enhance its dust capturing and decrease the wind turbine shutdown to replace the filter.

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