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Lessons learned from 10 years of wind tunnel tests on small wind turbines designed by students

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Abstract.

This article discusses results from an international contest, open for university student teams (bachelor and master), involving the design, construction, and testing of small wind turbines in a large wind tunnel. The wind tunnel has an outlet of 2.85 x 2.85 m allowing a maximum rotor swept area of 2 m^2 without significant tunnel effects. Both horizontal and vertical axis wind turbines are part of the competition. The turbines are evaluated by an external jury of industry experts based on criteria such as Annual Energy Production, cut-in wind speed, innovations, design, and sustainability. Although the contest has been initiated in 2013 with an educational focus, it has also evolved into a valuable database for scientific purposes by providing a decade worth of performance measurements for roughly 9-10 various turbine concepts each year. The collected data may serve as a unique validation resource for assessing the accuracy of design codes in modelling diverse turbine concepts thanks to detailed design reports with model descriptions accompanying each turbine (such turbine descriptions are often considered confidential for field measurements). The paper aims to explore the scientific value of this database by comparing calculations with measurements, offering explanations where possible, and reporting intriguing findings on unconventional concepts' performance. Even though not all observations could be explained fully they provide food for thought. Recommendations are provided for both students to enhance their designs and for contest organizers to elevate the scientific value of the measurements in future contests.

1. Introduction, organisation of contest, goal of the paper

Since 2013, the International Student Wind Turbine Contest (ISWTC) has been organized annually where student teams design, build, and test a small wind turbine. From 2013 until 2018 the contest was organized by the University of Applied Sciences Leeuwarden, the Netherlands after which the organization was taken over by the Hanze University of Applied Sciences in Groningen, the Netherlands. This contest is open to student teams from universities (bachelor and master) from all around the globe. Both Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbine Axis Wind Turbine (VAWTs) are participating.
It consists of two phases: an in-house phase (generally from January to June) where students design and manufacture their turbine, and make a design report, followed by an on-site testing phase (typically end of June/beginning of July) at the Open Jet Facility (OJF) of the TU Delft. This second phase is a 5-day program with the first 4 days dedicated to wind tunnel measurements. The contest concludes with a technical symposium and an award ceremony where a jury of industry and academia experts assess the designs based on weighted criteria.

1.1. Goal of contest

The main reason behind organizing the contest lies in its educational significance because small-scale wind turbine design exhibits several similarities to large-scale wind turbine design. These similarities are particularly evident in the multi-disciplinary aspects involved. Students from diverse fields e.g. aerodynamics, electrical/mechanical engineering, controls, mechatronics and material sciences should collaborate to make their designs successful. Some teams even have non-technical members dealing with sustainability, finances, marketing, sponsorship etc. These multi-disciplinary aspects form a paradigm shift for many students (and their supervisors) who typically operate within their respective disciplines. Sparking enthusiasm amongst students is another extremely important objective of the contest.

1.2. Aim and structure of paper

Although the main objective of the contest is educational the question arises whether the ISWTC measurements can also yield scientific (or technological) benefits. This is inspired by other examples in the research community where wind tunnel measurements on wind turbines served a scientific goal. A nice example are the measurements from the Mexico project in which a model rotor of 4.5 meter was measured extensively (through pressure sensors along the blade complemented with PIV flow field measurements) in the large German Dutch Wind Tunnel. These measurements were analyzed by a large research team in the Mexnext project, which led to several scientific and technological breakthroughs [1]). Even though the measurements carried out within ISWTC are less extensive there is scientific potential through the vast volume and thorough documentation of the measurement database: a decade of annual performance measurements conducted on 9-10 very different (and often unconventional) turbine concepts within a renowned wind tunnel. For each turbine, a comprehensive design report must be submitted, ensuring a detailed and reliable model description that serves as input for calculations and facilitates the interpretation of results (such model descriptions are typically considered confidential for field measurements on commercial wind turbines).
Some experimental model validation using the ISWTC wind tunnel measurements has already been published by participants [2,3] but generally speaking the number of scientific analyses remained limited. The main aim of the present paper is then to explore the scientific or technological value of the ISWTC measurement database in a comprehensive way where recommendations are formulated to both future student teams and the organizers to enhance the value of future contests.

The paper is structured as follows: Section 2 describes the contest in terms of wind tunnel characteristics, regulations, test procedure and assessment. Section 3 describes the evolution of the contest "in a bird's-eye view" for both HAWTs and VAWTs where it will be described that the designs from the first years exhibited a relatively low performance. Since then the performance of

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VAWTs saw modest improvements but HAWTs experienced a substantial improvement reaching an apparent maximum a few years ago. This inspired the addition of an extra assessment criterion in the form of sustainability to discern between designs. Also some teams tried to go beyond this maximum through unconventional rotor designs or they aimed on a lower cut in wind speed e.g. through a special generator design. Section 4 then provides a more detailed exploration of these sustainability aspects and unconventional design approaches. The section is complemented with a consideration of tunnel effects, and a comparison between calculations and measurements. Finally section 5 describes conclusions, lessons learned, and recommendations to enhance the benefits of ISWTC even more.

2.Description of contest

2.1. Contest regulations

The wind turbines are tested in the OJF at the TU Delft, a closed-circuit open jet tunnel with an octagonal outlet of 2.85x2.85 m, see figure 1. An important constraint is formed by the maximum rotor swept area of 2 m^2 which is considered sufficiently small to prevent significant tunnel and flow blockage effects, see section 4.1 Moreover, a wind climate is prescribed through Weibull parameters which has changed slightly over the years. Since 2020 it has been based loosely on a few rural regions in Sub-Saharan Africa to align with the criterion on sustainability as described in section 2.3. For the last contest this gave Weibull parameters of A = 6 m/s and k = 2.8.

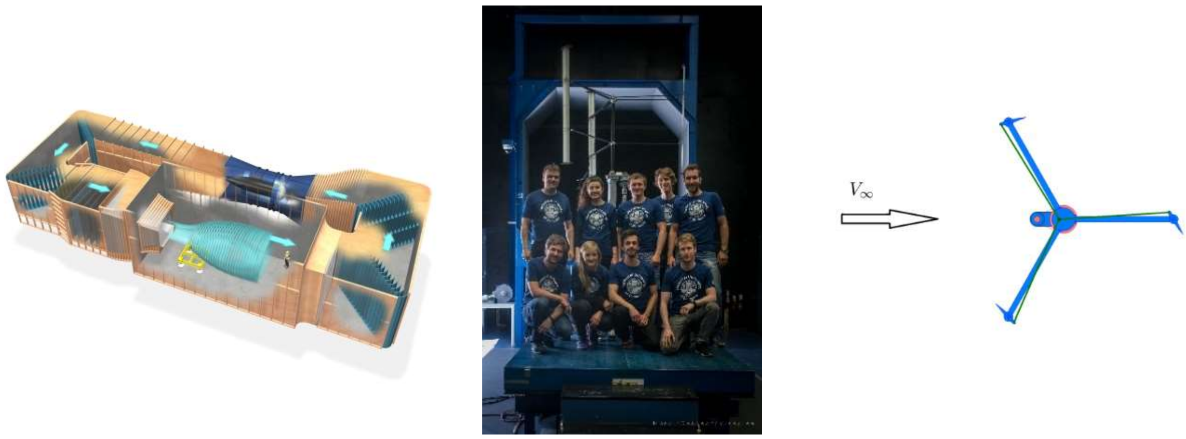

Figure 1: ***Left:*** *A schematic of the OJP,* ***Middle****: DTU team with a VAWT in the OJF.* ***Right:*** *DTU's cyclic pitch system.*

Identical electrical and mechanical interfaces to the tunnel equipment are provided. A frame is placed in the tunnel onto which the turbines are mounted. In the first few contests the electrical power output was connected to a manual resistor bank but in the most recent contests an electronic load is used to measure the power of the turbines. Turbines should be designed for automatic operation and must provide a DC output between 0-60 V and a maximum current of 20 A (due to safety restrictions). As soon as these limits are exceeded the data will be cut off. Power electronics between the output of the rectifier and the load are allowed only if the power supply is subtracted from the turbine power. A Maximum PowerPoint Tracker (MPPT) is allowed if it is designed and made by the team itself. For safety reasons all turbines must have an emergency brake operable from inside the control room of the OJF.

2.2. Contest procedure

The wind speed is increased with 0.5 m/s increments by the contest test leader from around 2 m/s until the turbine self-starts (cut-in) and then upwards to the maximum speed which is usually around 13 m/s. This maximum depends on safety limits (such as high vibrations), the prescribed wind regime, and sometimes teams themselves do not wish to go to higher speeds. The electronic load will be increased at every wind speed until the moment of maximum power output is achieved or to the point the competing team wishes to proceed and increase the tunnel speed. Afterwards the power production at windspeeds below cut-in is measured (note that turbines, once they have started rotating, may generate power at wind speeds below cut-in). The measured power output is combined with the wind speed from the tunnel to obtain the power curve and the power coefficient (C_P). Then, with the prescribed wind climate, the Annual Energy Production (AEP) is determined.

2.3. Assessment

An independent jury, see appendix A, assesses the designs through a list of criteria on e.g., AEP, cut-in wind speed (the wind speed where the turbine starts to produce power from standstill, as explained in section 2.2 this is not necessarily the lowest wind speed where power is produced), technical innovations, build quality, the quality of the design report, and sustainability. The last criterion was added in recent years to distinguish between designs of almost similar performance and to stimulate innovation. It includes the choice of build materials, a life cycle assessment (LCA), embeddedness in developing rural communities (i.e., suitable for remote locations without relying on advanced workshops), and a business case for the wind turbine in those communities. At least one jury member is present during each measurement to ensure a fair and equal contest and to visually inspect the turbines. Prizes are awarded for the overall best performance, for the highest AEP, for the most sustainable design, and for the best VAWT in case two or more VAWTs are competing. The physical awards are different each year and they are designed and built by industrial product design students from Hanze UAS.

3. Design evolution

3.1. General

The participating teams are listed for every year in appendix B with their designs in global terms (HAWT/VAWT, number of blades, and distinctive features). A maximum of 10 teams per year are allowed considering each team's 3-hour tunnel slot and additional time for travel, setup, and unforeseen events within a 4-day period.
Most designs are based on an optimization strategy with engineering rules assuming an axial induction factor of 1/3 and maximum c_l/c_d along the blade. Other teams optimize with either publicly available tools such as QBlade (https://qblade.org) or in-house design tools based on the Blade Element Momentum Theory. More advanced design methods like Free Vortex Models and Computational Fluid Dynamics (CFD) have been used as well. Much progress has been made. In the first contest, only a single turbine was successful but in later contests nearly all produced power and eventually with many C_P's above 0.4, see section 3.2.

*Figure 2: **Left**: wind tunnel test stand for preparatory analysis at Lodz University of Technology (1, 3D-printed rotor model; 2, bearing unit; 3, torque meter; 4, motor/generator) [4]. **Right**: Full scale testing rig of the NHL UAS on a trailer.*

While aerodynamics played a significant role in the performance improvement, reduced drive train losses also contributed to the enhanced performance, although the exact extent of these losses is not quantified, see section 4.2. Improved performance was also a result of better preparation since several teams participate in subsequent years (Appendix B), enabling them to leverage the knowledge and insights gained from prior competitions. Some teams even optimize their designs by testing their turbine experimentally on a trailer or conducting preparatory wind tunnel tests on scaled-down models, see figure 2 and section 4.2.

3.2. HAWTs

For the HAWTs often low Reynolds number airfoils are selected (e.g., the ones from [5]) although there has also been a turbine equipped with curved plates for blades as a cheap and robust solution even though the aerodynamic performance was lower. The number of blades is usually 3, but 2 and 4 bladed turbines have been in the contest as well. In section 4.2 the performance of a turbine with a different number of (similar) blades is described. The overall performance steadily increased as is reflected by the C_P increasing from approximately 0.2 in the first contest to 0.41-0.42 in later contests, which turns out to be an effective maximum for turbines of this size as it increased only very slightly over the last 5 years. The lower C_P values compared to the values on large scale turbines (of say 0.45 or higher) are mainly attributed to Reynolds effects although a lower generator efficiency at lower power will play a role too. In section 4.2 a clear example of Reynolds number dependency on performance is shown. The progress of the HAWTs is not only reflected in a higher C_P value but also by the fact that teams often achieve a power output over 1kW (which is about the maximum within the regulations) and by a lower cut-in wind speed. Nowadays cut-in wind speeds of 2.5-3 m/s are no exception anymore where it was around 4-5 m/s in the early days. As explained in section 4.4 this is partly a result of an active pitch control system which is now applied in many turbines while the earlier turbines had fixed pitch where also some teams designed and built their own generator with a low cogging torque. Some interesting new concepts and technologies have been applied over the years. Amongst others a shrouded HAWT rotor and a dual HAWT rotor were applied which both aimed to enhance AEP while keeping the same swept area. For the shrouded rotor a maximum C_P of 0.38 was measured which is higher than the C_P of 0.3 measured for the unshrouded situation, where AEP was higher too. Still the C_P is lower than 0.62 which was calculated with CFD for the shrouded rotor, but this is most likely due to the application of axial flux surface mounted permanent magnet synchronous generator. The observations on the dual rotor are described in section 4.3.

3.3. VAWTs

Various forms of VAWTs, such as drag driven Savonius or lift driven Darrieus and H-type, have been applied in the contest. The airfoils were often symmetric but also cambered airfoils were used to counteract the virtual camber effects on VAWTs. In none of the cases a VAWTs ever produced a C_P of more than 0.2, which is less than half of the best HAWTs. Also, the start-up of many VAWTs was found to be problematic, which is a major issue due to the low wind speeds in the rural areas (section 3.1). Still there was progress in the performance of VAWTs, amongst others through increased blade solidity combined with innovations like the passive cyclic pitching system from DTU. In this system each of the blades are connected to a controllable stationary common tab which is off-centered with respect to the rotation axis, forcing the blades passively to change their pitch cyclically, as the distance from each blade to the tab changes as the turbine rotates, see figure 1. The position of the stationary tab sets the amplitude and phase of the blade pitching. This approach allows bypassing conventional VAWT design rules for rotor solidity to solve start-up issues while also increasing C_P. Design of the setup was done with vortex-based methods, but despite significant efforts, the gap between measured and predicted performance is still significantly higher than for the HAWT turbines.

3.4. Sustainability

Many ideas have been applied which vary between material choice, modular/simple designs for easy maintenance in rural areas with lower level of maintenance facilities, and innovative business cases for rural developing communities. A more detailed analysis is presented in section 4.5. It must not go unmentioned that sustainability aspects are often well received and seen as both challenging and inspiring by students. Sustainable design ideas resulting from ISWTC are also published in [6].

3.5. Safety

Over the years some turbine failures have occurred and thereto safety has become paramount. On multiple occasions an electrical failure led to loss of the electronic load, causing a brief period of overspeed before the emergency brake is activated and the wind tunnel turned off. Once this resulted in the disintegration of all 3 blades. Learning from these experiences some teams built automatic emergency brakes coupled to an RPM sensor. Moreover, a battery inside the nose cone of a turbine, powering the pitch mechanism, came loose during operation and dealt significant damage. Also, a complete rotor flew off as a result from a set screw loosening amid small vibrations (see section 4.3). Safety-induced test stoppages happen as a precaution when rotor imbalances or nacelle construction issues already lead to excessive vibrations at low wind speeds. The applied safety measures, including the emergency brake and the exclusion of people in the tunnel during operation, have prevented injuries and significant wind tunnel damage.

4.Detailed analysis

4.1. Wind tunnel effects

To utilize wind tunnel measurements for scientific purposes it is important to have insight into tunnel effects. The OJF is a closed-circuit open jet tunnel with an octagonal outlet of 2.85 x 2.85 m. The test section is 6.0 meter wide, has a height of 6.5 m, and a length of 13.5 m. The maximum speed at the outlet is in the order of 35 m/s. Several devices (e.g., screens) are added to the settling chamber to improve flow quality in terms of homogeneity and turbulence. This results in velocity deviations smaller than 0.5% in the vertical plane at two meters from the outlet with a longitudinal turbulence intensity level smaller than 0.24%. As mentioned in section 2.1 a maximum swept area of 2 m^2 is allowed for which the nozzle and solid blockage leads to a deviation in tunnel speed of less than 0.5% [7]. Moreover, the "collector effect" which encountered challenges in e.g. the wind tunnel measurements from [1] where the collector was closed with a nozzle of identical size, causing a non-representative acceleration of the wake to keep mass conservation, is alleviated in the current set-up by the large collector size. Nevertheless, quantifying effects arising from the jet expansion i.e. the turbulent mixing between the tunnel and outer flow would require dedicated CFD simulations [8]. It should then be known that these tunnel effects become more pronounced at a high thrust coefficient with associated high axial induction factor, in particular near turbulent wake conditions (see [1]). The fact that the present measurements aim for maximum C_P i.e. a relatively low axial induction of 1/3 gives reason to believe that tunnel effects are limited.

4.2. Comparison between calculated and measured performance: 3- and 4-bladed rotors

In this section the analysis from the GUST Team from Lodz University of Technology is presented [9]. Figure 3 shows calculated (QBlade) and measured C_P-TSR (Tip speed ratio) curves at 2 different wind speeds (5 and 7 m/s) from a 4-bladed wind turbine rotor from the 2022 contest using a S826 airfoil. At the same TSR, a lower wind speed is equivalent to lower rotational speed and therefore a lower Reynolds number. Lower C_P values at 5 m/s were qualitatively confirmed by the ISWTC wind tunnel measurements. However, quantitative differences between calculated and measured results exist, which may suggest that the employed numerical model cannot accurately represent the complex phenomena associated with the considered flow case. It must also be noted that the airfoil data from

QBlade rely on XFOIL which is known to underpredict the values of c_d and so overpredict the performance.

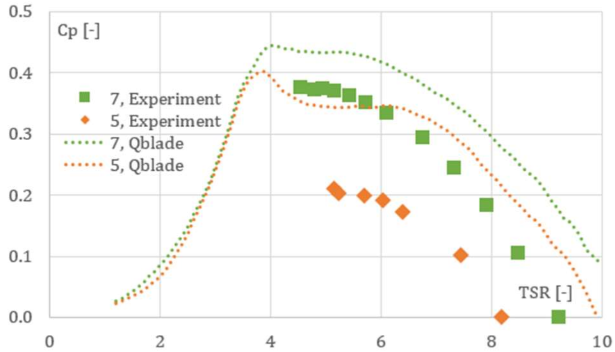

Figure 3: CP-TSR for a 4-bladed rotor at windspeeds 5 m/s and 7 m/s: ISWTC experiment vs QBlade simulation [9].

It is also important to mention that the measured C_P is based on the electrical power whereas the calculated C_P relies on purely aerodynamic power which by definition is higher than the electrical power. Noteworthy is that the gap between calculated and measured power is most prominent at low wind speed which might be attributed to the fact electrical losses are largest at lower power levels. A valuable recommendation for future contests is to quantify the electrical losses, e.g. in a lab environment to enhance the accuracy of power assessments at preliminary design phases.
Taking advantage of the fact that students of the GUST team have access to a subsonic wind tunnel facility (figure 2), a comparison was performed at various design stages for 1:4 scaled 3D-manufactured rotors. This also included an investigation on the influence of rotor solidity. Figure 4 shows calculated and measured results for both a 3- and 4-bladed rotor using blades with the exact same geometry so that the solidity of the 4-bladed rotor is 4/3 higher. It is found, that in both the 3- and 4-bladed cases, the simulation predicts a higher C_P than the experiment shows. Furthermore, the simulations indicate an optimal TSR value of 3.8 while the wind tunnel test finds an optimal TSR of 4.5. The overpredicted C_P values are in line with the observations given above. Moreover, during the wind tunnel tests, the actual level of turbulence intensity (estimated to be more than 1%) is higher than assumed in the simulations (overall corresponding to low to moderate turbulence intensity, according to the QBlade setup parameters). This higher turbulence may decrease the C_P.

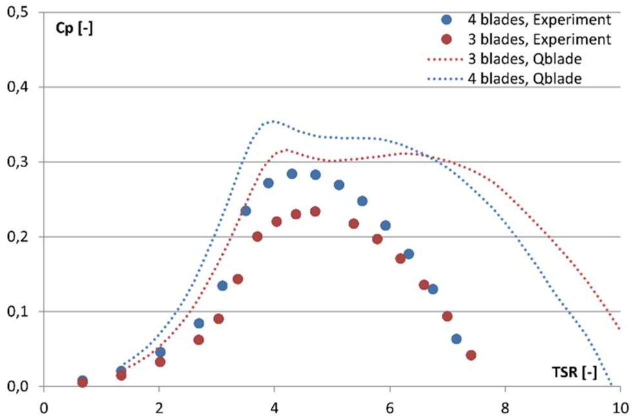

Figure 4: CP-TSR for different number of blades at 15.6 m/s of a 1:4 scaled rotor [9].

The fact that the performance of the 4-bladed rotor is higher than the performance of the 3-bladed version indicates room for a further optimisation of the blade geometry of the 3-bladed rotor. In this respect it is worth to mention that GUST is currently comparing 3- and 4-bladed rotors in a wind tunnel where the chord of the 3-bladed version is increased with a factor of 4/3 so that both rotors have the same solidity. Another observation is that the 4-bladed rotors yield a lower cut-in wind speed. On one hand the starting torque from a 4-bladed rotor is expected to be higher as more blades contribute to it, but the mass moment of inertia is higher as well, leading to a slower startup.

4.3. Dual Rotor Wind Turbine

Hanze UAS designed a dual rotor wind turbine (DRWT), i.e. 2 rotors of similar diameter upstream and downstream of the tower see figure 5 and [10]. The blades rotate in opposite directions at the same rpm with mirrored blade designs. The shaft of the generator is oriented downwards, i.e., perpendicular to the horizontal rotor shafts. The shafts are connected through a gearbox which consists of three bevel gears. Two of which are attached to the rotor shafts and one to the generator shaft.

DRWT's, not only in wind energy but for example also in ship applications, have been the subject of research in several references. In [11] the 1D Betz theory for a single Actuator Disc model is extended to multiple Actuator Discs. This results in a maximum C_P of $8n(n+1)/[3(2n+1)^2]$ for a system with n discs where the axial induction factor for the r^{th} disc in a row of n discs = (2r-1)/(2n+1) and the outflow axial induction factor far downstream in the outer streamtube as released from the r^{th} disc which just touches the next $(r+1)^{th}$ disc = 2r/(2n+1). For a dual rotor with n =2 this gives a C_P of 8/75 = 0.64 where the induction factor at the second rotor is 3/5 (compared to 0.59 and 1/3 respectively for a single rotor).

Based on smoke wind tunnel measurements with porous discs at different mutual distances a minimum distance between the discs of 0.5D is recommended to avoid flow curvature and non-uniformity and so preventing the violation of the 1D assumption. Even though the Hanze UAS turbine has a distance of 0.39D between the rotors falling short of this recommendation, and while it is acknowledged that a DRWT may increase loads and costs, the employed concept is still anticipated to enhance performance within the contest regulations since the swept rotor area remains unchanged. Enhanced performance from DRWT's is confirmed from CFD-RANS calculations in [12]. Thereto it should be realized that in the absence of measurements, CFD calculations alone can accurately model the complex DRWT flow field with the second rotor always in the very near wake of the first rotor. In [12] a diverse range of DRWT systems is calculated featuring co- and counter-rotating rotors of different sizes, including configurations with equally but also non-equally sized rotors using CFD-RANS. An increase in performance is found for all DRWT systems compared to a single rotor system. The benefit in performance from a counter-rotating system compared to a co-rotating system is less conclusive possibly because the main aerodynamic impact from a counter-rotating system may lie in reduced rotational losses where these losses may be low anyhow.

The front rotor of the Hanze UAS DRWT had an active electrical pitch mechanism while the second rotor had a manual pitch mechanism. Only a single pitch setting for the second rotor could be tested as it flew off after adjusting the pitch before all the planned measurements were finished. After this accident, an opportunity arose for a measurement with only the front rotor. The measurements showed a consistent higher performance for the single rotor, see figure 5, indicating that the second rotor adds a negative torque. This negative torque is not fully understood since the abovementioned literature indicates a positive torque. Possibly the manual adjustment of the pitch angle led to a very poor performing second rotor or the short distance between the Hanze rotors (0.39D) plays a role since this is smaller than the 0.5D which is needed to obey the assumptions in [12]. Also, some non-understood observations on the cut-in wind speeds were found. In the initial run the cut-in of the dual rotor was 4.8m/s. After adjusting the pitch angle of the second rotor the turbine started at 3.5m/s (just before the second rotor flew off) where the minimum cut-in speed for the single rotor turned out to be 4.5m/s. This lower cut-in speed from the DRWT is not fully understood since the inertia which the starting torque should overcome increases almost linearly with the number of blades (note that the inertia of the drive trains will not double). Although the start-up torque from a DRWT can be higher since it is generated by more blades it is not expected that the second rotor in the near wake with a manually set pitch angle will more than double the starting torque. Possibly the front rotor deflects the streamlines in such a way that it effectively leads to a more optimal angle of attack distribution along the second rotor. Further understanding of the negative torque from the second rotor and the lower cut-in speed anyhow requires the pitch angles to be known. These are not measured yet, but planned for the next ISWTC after which a CFD analysis may shed more light on the non-understood phenomena.

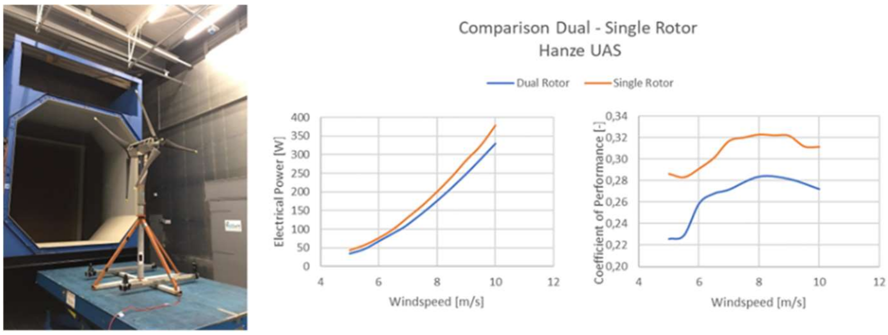

Figure 5: ***Left:*** *The DRWT from the Hanze UAS in the OJF.* ***Right:*** *Performance graphs of the DRWT.*

4.4. Start-up wind speed & Generator

One of the teams which paid significant attention to a low start-up wind speed was Ain Shams University. They achieved this through several measures: (1) pitch control of the blades at low wind speeds, (2) reducing the inertia of the rotor by using materials with high specific strength (carbon fibre for the blades and aluminum alloys for the generator rotor), and (3) reducing the cogging torque of the generator. The reduction of the cogging torque was achieved through skewing of the stator lamina with respect to radial flux magnetic field with 27 magnetic slots. Combining all those factors resulted in the lowest cut-in wind speed within the contest of less than 2.5 m/s and allowed the turbine to achieve the highest AEP in the competitions of 2019 and 2022.

4.5. Sustainability

The design from the University of Toronto (UTWind) [11] showed the highest sustainability in the latest contest in 2023. The blades were made primarily from 3D printed PETG with a steel bar serving as the inner structure of the blade. The 3D printed nature of the blades enabled them to be rapidly produced at a low cost utilizing readily accessible means. The nacelle and nose cone were made from wooden panels and the hub material was aluminum. Where possible, wood was used because it is accessible, cost effective, biodegradable, renewable, and easy to machine. Wood is a more sustainable material–particularly during the end-of-life phase of the turbine–when compared to industry standard composite materials. If higher strength was needed, aluminum was selected as the preferred material as it is also a cost effective, lightweight, corrosion resistant, highly recyclable material that can be manufactured using a variety of methods. During material selection and sustainability analysis, the impact indicator profiles for different materials were compared. These indicators include Environmental, Human Health, and Resource Impacts. The final materials were chosen based on an LCA to achieve a balance between cost and sustainability, ensuring social responsibility, minimal environmental impact, and long-term economic viability.
For 3D printed materials or biodegradable materials such as flax fibre reinforced composites (with bio resins), the surface quality is typically lower, especially the leading and trailing edge, than the conventional composite materials, resulting in a lower performance. To offset this lower performance, a greater degree of surface treatment is required than for traditional composite materials. An example can be seen in figure 6 where the DTU made identical blades from bio-based material and carbon fibre [14]. The highest decrease in power observed was about 17% at the highest wind speed, highlighting that special care in manufacturing or post-processing may be needed to counter drawbacks in terms of performance.

UTWind also paid attention to a business model [11] for a private company in rural Nigeria. This is a country with continuous and rapid growth in energy demand, but energy production capacity is not developing at the same rate. Multiple studies have concluded that wind speeds in northern and north-eastern Nigeria are strong enough to promote power generation through wind turbines in particular small wind turbines. The proposed business model consists of manufacturing small-scale wind turbines and

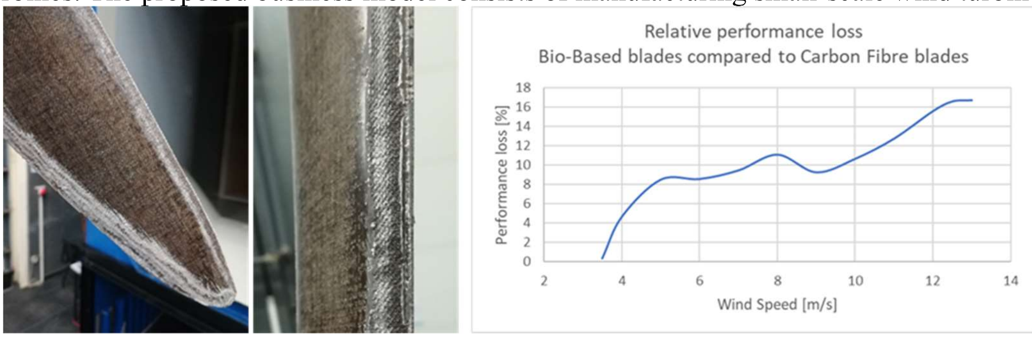

*Figure 6: **Left**: Bio-based blades tip and roughness on the leading edge. **Right**: Relative performance loss of the bio-based blades compared to carbon fibre blades.*

using them to generate electricity. The majority of the revenue generated follows an energy-as-a-service business model with a secondary source of revenue from customers purchasing wind turbines at a fixed price. This supports SDGs 7.1, 8, 9 and 11 (https://www.undp.org/sustainable-development-goals)) while leveraging local resources to reduce manufacturing costs. In [11] partnerships with educational institutions and trade schools are suggested to promote the social development of the community while creating a local skilled workforce which could then be hired, resulting in further economic growth for the community. The components manufactured by the aforementioned institutions could be purchased at a minimal price. These components would undergo extensive quality assurance. Those that meet requirements would be implemented and those that do not would be recycled as the components are made of entirely recyclable materials.

5. Conclusions and recommendations

The present paper describes results from the ISWTC, an international student competition where teams design, build, and test a small wind turbine (swept area < 2 m^2) in a large wind tunnel. Special focus is paid to the scientific and technological impact of the measurements.

- In terms of performance much progress has been made in particular for HAWTs which eventually reached C_P's of 0.41-0.42. This progress was partly aerodynamic driven but reduced drive train losses and better preparations play a role too. The performance of VAWTs was also enhanced e.g. through active/passive pitch but the maximum C_P of VAWTs remained smaller than 0.2.
- The C_P value of 0.41-0.42 turns out to be an asymptotic maximum for this size of turbines, as it increased hardly over the last 5 years. The lower C_P values compared to the values on large scale turbines (of say 0.45 or higher) are partly a result of higher drive train losses at low power but also due to Reynolds effects which were found to be significant for this size.
- The progress of turbines in the contest is not only reflected in a higher C_P value but also in a lower start-up wind speed. For HAWTs start-up wind speeds as low as 2.5 m/s have been accomplished partly due to dedicated generator design and the application of active pitch. Start-up of VAWTs remained challenging.
- Comparison between calculations and measurements showed qualitative consistency but quantitative comparisons are still challenging due to often unknown electrical losses.
- The performance of several unconventional concepts like shrouded rotors or dual rotors did not always give the desired outcomes, but they sparked inspiration and generated valuable insights.

- Several ideas for sustainable design of small wind turbines have been applied and tested which range from material choice, production techniques to business models. Surface quality of 'sustainable' blades is still lower which was reflected in a poorer aerodynamic performance.

The most important technical recommendations emphasize the need to monitor rpm and pitch angle alongside power and tunnel speed for more accurate power assessments where high-fidelity methods are needed for the modelling of unconventional concepts. Moreover, the electrical losses need to be determined as will be done by some participants before the next contest. Airfoil data from airfoil design codes were found to suffer from uncertainties at the appropriate (low) Reynolds numbers so dedicated measurements at these Reynolds numbers are recommended.

6. References

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Appendix A List of all jury members of the ISWTC throughout the years

Member	*Affiliation*
J. Beurskens	Former head of Unit Wind Energy at ECN
C.S. Fereira	Professor at TU Delft
Z. Parker	NREL, US Collegiate Wind Competition, Senior Technical Analyst RWE
E. de Vries	Journalist, Technology Watcher
J. Kuikman	Former CEO of Fortis Wind Enery
M. Schubert	Former CTO of Repower
L. Machielse	Former Unit Wind Energy at ECN
L. Fingersch	NREL, USA Key member of US Collegiate Wind Competition
L. de Vries / M. Colon	Epomat
B. LeBlanc	PhD TU Delft, Siemens Gamesa Renewable Energy
R. Kamerling	Delft Global Initiative
J. Holierhoek*	JEHO B.V.
R. Rudolf*	Vestas Wind Systems A/S
D. Wood*	University of Calgary
J.J.E. Teuwen*	Associate Professor at TU Delft

Note: jury members during the last competition*.

Appendix B Participating teams with global characterisation of turbines in terms of HAWT / VAWT, number of blades, and distinctive features.

Year	*Teams*								
2013	UAS NHL 3B HAWT	TU Delft VAWT	UAS Flensburg 3B HAWT						
2014	UAS NHL 3B HAWT	DTU VAWT	UAS Flensburg 4B HAWT	UAS Bremerhaven 2B HAWT	University of Sheffield 3B HAWT				
2015	UAS NHL 3B HAWT	DTU VAWT + 3B HAWT	UAS Flensburg 4B HAWT	UAS Bremerhaven 2B HAWT	University of Sheffield 3B HAWT	-			
2016	UAS NHL 3B HAWT	DTU VAWT + 3B HAWT	UAS Flensburg 4B HAWT	Lodz University 3B HAWT	University of Sheffield 3B HAWT				
2017	UAS NHL 3B HAWT	DTU VAWT + 3B HAWT	Ain Shams University 3B HAWT	Lodz University VAWT + 3B HAWT	UAS InHolland VAWT				
2018	UAS NHL Stenden 3B HAWT	DTU VAWT + 3B HAWT Design reports missing	Ain Shams University 3B HAWT Design reports missing	Lodz University VAWT + 3B HAWT	University of Manitoba 3B HAWT (D =0.5 m)				
2019	UAS NHL Stenden 3B HAWT	DTU VAWT+ 3B HAWT	Ain Shams University 3B HAWT	Lodz University VAWT + 3B HAWT	University of Manitoba 3B HAWT	Zewail City of Science 3B HAWT	TU Delft VAWT	Hanze UAS 6B HAWT Dual rotor (No WT test)	
2020*	UAS Emden Leer 3B HAWT	DTU VAWT + 3B HAWT	Ain Shams University 3B HAWT	Lodz University 3B-4B HAWT	University of Manitoba 3B HAWT	Zewail City of Science 3B HAWT	TU Delft 3B HAWT	Hanze UAS 6B HAWT Dual rotor	
2021*	UAS Emden Leer 3B HAWT	DTU VAWT + 3B HAWT	Ain Shams University 3B HAWT	Lodz University 3B-4B HAWT	University of Manitoba 3B HAWT			Hanze UAS 6B HAWT Dual rotor	
2022	UAS Emden Leer 3B HAWT	DTU VAWT + 3B Shrouded HAWT	Ain Shams University 3B HAWT	Lodz University 3B-4B HAWT	University of Manitoba 3B HAWT	Zewail City of Science 3B HAWT	TU Delft 3B HAWT	Hanze UAS 6B HAWT Dual rotor	University of Toronto 3B HAWT
2023	UAS Emden Leer 3B HAWT	DTU VAWT + 3B Shrouded HAWT	Ain Shams University 3B HAWT (No WT test)	Lodz University 3B-4B HAWT	University of Manitoba 3B HAWT (No WT test)	Zewail City of Science 3B HAWT		Hanze UAS 6B HAWT Dual rotor	University of Toronto 3B HAWT

Notes during the Covid-19 pandemic*:

- The ISWTC 2020 was held remotely, no tests were conducted in the OJF.
- The ISWTC 2021 was held part remote and only 3 teams were able to come to the OJF due to travel restrictions.