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Utilizing Low-Level Jets with Airborne Wind Energy Systems for Mobile Missions at Research Station Neumayer III in Antarctica

Dirk Heutelbeck[1], Vera Schorbach[1], Roland Schmehl[2], Dirk Heinen[3], Christopher Wiebusch[3], Simon Zierke[3], Clemens Espe[4], Marco Feldmann[4], Gero Francke[4], Fabian Schoettler[4]

[1]Competence Center for Energy Transition (CC4E), University of Applied Sciences Hamburg (HAW Hamburg), Hamburg, Germany

[2]Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands

[3]III. Physics Institute B, RWTH Aachen, Aachen, Germany

[4]GSI GmbH, Aachen, Germany

E-mail: dirk.heutelbeck@haw-hamburg.de

Abstract. Airborne wind energy systems (AWES) are particularly suitable for remote applications where mobility is important. The present study investigates the use for mobile research missions at the Neumayer Station III in Antarctica. Light Detection and Ranging (LiDAR) wind data up to 500 m height are analyzed, with focus on the occurrence of low-level jets, whose high energy potential can be used by AWES. The energy yield of a 30 kW AWES is compared with a conventional wind turbine of the same rated power. The comparison is based on wind speed time series on respective heights and the power curves of both systems. The following assumptions are used: The AWES harvests energy at an average height of 300 m, the conventional wind turbine has a hub height of 18 m, the power generation of both systems is determined by a combination of wind speed measurement time series and the respective power curves. Two scenarios are analyzed: In Scenario A, a full Antarctic summer mission period (between November 2024 and February 2025) is considered. Over the entire period, the AWES produces about 10% more energy than the conventional wind turbine. During low wind conditions, the AWES shows a substantially increased energy output. However, due to strong winds at higher altitudes and a lower cut-out wind speed regarding the utilized power curve, the AWES is more often shut down. This comparison is a very conservative view on the AWES, because lower harvesting heights with lower wind speeds would be possible. In Scenario B only periods with wind speeds below 12 m/s are considered, in which field work is possible. In this case, the AWES produces about 40% more energy.

1. Introduction

The most remote places are often those of the highest interest for scientific discoveries [1][2]. In Antarctica, many research missions try to find answers to some of the most fundamental questions of the world, as demonstrated by numerous studies, such as [3] and [4]. As part of the

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Explorer Initiative of the German Space Agency at DLR (German: Deutsche Raumfahrtagentur im DLR), the project Technologies for Rapid Ice Penetration and subglacial Lake Exploration (TRIPLE) explores technologies for future space missions to the icy moons of the solar system at Neumayer Station III. A sonde equipped with an autonomous nano underwater vehicle melts through approximately 100 m of ice to enable the subsequent exploration of subglacial lakes [5] [6]. This melting process requires a substantial amount of energy. The expedition at Neumayer Station is a pre-mission for upcoming projects in the Dome C region, located in the interior of Antarctica on a high plateau with ice thicknesses of up to 3000 m. The preparation for the search for extraterrestrial life is combined with the goal of covering energy needs with renewables, which is contractually stipulated in the Antarctic Treaty [7].

Interestingly, renewables in Antarctica have been rather neglected for a long time. [8] have shown that of 29 research stations in Antarctica, only five use renewables with a share of at least 50 %. Instead, the main energy sources are diesel generators, which is also the case for the German Neumayer Station III with an annual consumption of approximately 300,000 liters [9]. A recent study from [10] has shown that the use of a renewable energy concept of wind, PV, and energy storage at the South Pole station has massive cost-saving opportunities with a time to payback of the whole energy system of only two years. The extreme environments place special demands on logistics and material costs. Especially at these remote places, where the costs of one liter of diesel reach up to 11 USD.

The compactness and possible exploitation of higher-altitude winds have triggered the question of whether airborne wind energy, which uses tethered kites for wind energy harvesting, could be a cost-effective option for mobile Antarctic missions. The objective of this study is the description of wind speed profiles at Neumayer Station III. Furthermore, the energy potential of a ground-based turbine and an AWES using high altitude winds will be compared.

This paper is structured as follows. Section 2 presents the methods used and the main sources this research is based on. Section 3 describes the underlying measurement infrastructure as well as the datasets used for the analysis. Section 4 illustrates and analyzes the wind speed profiles including low-level jets. In addition, the performance of an AWES and a ground-based turbine are compared using wind speed measurements at different altitudes for the time period of one Antarctic field season from November to February. Section 5 discusses the results followed by a concluding summary of main findings in Section 6.

2. Methodology - State of the Art

For most atmospheric conditions, the wind speed increases with height. A frequently used model to extrapolate the wind speed profile from a single measurement height is the logarithmic height formula, also known as the Log-Law, which is valid for the surface boundary layer typically up to 100 m [11]. Another regularly used model is the power-law [12]. In [13], long-term LiDAR data of the North Sea are evaluated, showing more complex behavior of wind speed profiles, proposing more accurate models "for obtaining wind statistics for an extended height range". Phenomena like Low Level Jets (LLJ) among other reasons are responsible for these more complex high altitude winds. By definition, a LLJ is a strong increase in wind speed in the lowest hundred meters of the troposphere. In most cases, LLJ are related to a near-surface inversion of temperature. [14] grouped them to non-polar land (LLLJ), polar land (PLLJ) and coastal (CLLJ) LLJs, where the strongest and lowest LLJs are observed in Antarctica. In [15], measurements and evaluation methods of radiosonde and Doppler LiDAR data of Neumayer Station III are presented and discussed, covering altitudes up to 5000 m.

3. Surroundings and Measurement Setup at Neumayer Station III

The wind conditions at Neumayer Station III are mainly influenced by two large-scale weather patterns. On the one hand, there are katabatic winds from south/south-west coming from the mountains. On the other hand, much more influential are the strong easterly winds, driven by low-pressure systems north of the Antarctic coast and their cyclonic circulations [16]. The wind measurement setup at Neumayer Station III consists of two anemometers measuring wind speed at 2 and 10 m height, respectively. The measurements are taken at intervals of 6 s and are aggregated in minute-by-minute averages [17]. The meteorological mast is located 300 m south-east of the main station building, to minimize the influence of unwanted flow disturbances or wake effects, compare figure 1.

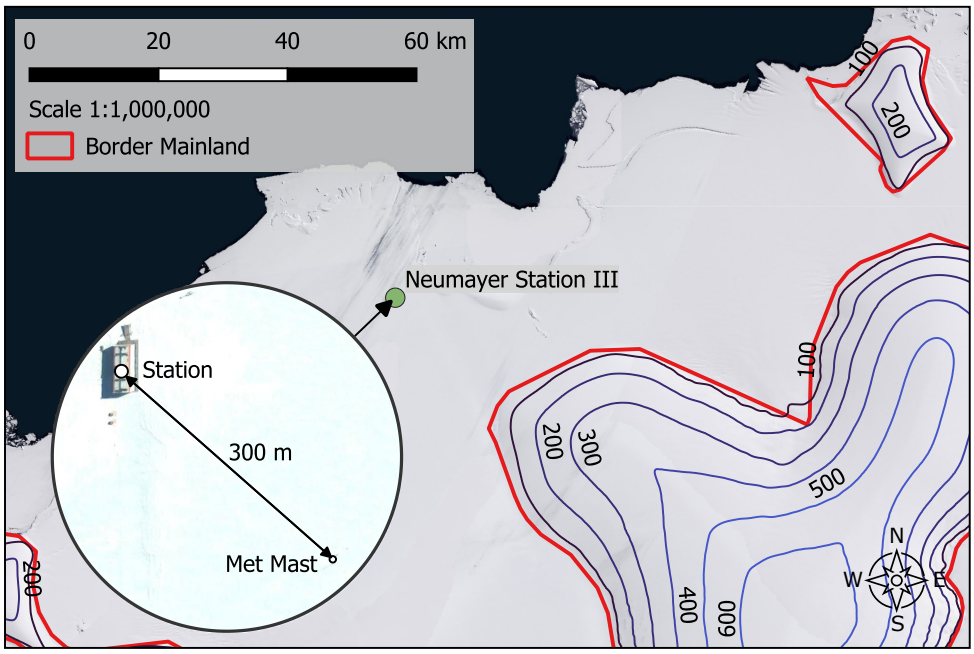


Figure 1. Position of Neumayer Station III on the Antarctic ice shelf and position of meteorological mast

The meteorological observatory of Neumayer Station also launches one radiosonde per day around 12UTC. Wind speed and direction are determined based on the continuously tracked GPS signal [18]. Additionally, the Continuous Observations of Aerosol-cLoud interAction (COALA) installed a Doppler LiDAR system at Neumayer Station. From 50 m up to one kilometer above ground, it is possible to retrieve wind speed profiles [19]. Figure 1 illustrates the location of Neumayer Station. For this scenario, it is important that Neumayer Station is located approximately 50 km away from the surrounding hills. This provides an ideal setting for measuring wind speed profiles, as no significant local disturbances need to be taken into account.



Figure 2. Meteorological mast with anemometers at 2 and 10 m height



Figure 3. Start of radiosonde measurement with GPS and height tracking

4. Results

Figure 4 shows wind speed profiles for wind speed bins ranging from 0-1 m/s up to 22-23 m/s. For clarity, only every second wind speed bin is displayed. The measurement gap between the ground-based anemometer at 10 m height and the lowest LiDAR measurement height is indicated by a dashed line. A distinct difference can be observed between the wind speed measured at 10 m height and the lowest LiDAR measurement. This difference increases with rising wind speed bin. On the basis of the Log-Law, one would assume that the wind speed increases continuously with height. Instead a peak is observed, after which the wind speed decreases again with height. The height and the strength of this maximum also increase with rising wind speed bins. In the lower wind speed bins, this maximum is not visible. The first wind speed bin, depicting this maximum is wind speed bin 4-5 m/s, compared to figure 5. For this bin, the maximum occurs at a height of approximately 250 m. In the highest wind speed bin of 22-23 m/s, the maximum shifts to a height of around 400 m. The profiles represent mean values derived from up to 4000 individual profiles. Bin 2-3 m/s contains the maximum number of profiles, while bin 22-23 m/s contains the minimum of 200 individual profiles. The widest 95 % confidence interval is 1.7 m/s. The average confidence interval is 0.45 m/s. This guarantees a stable shape of the vertical wind speed profiles and confirms their statistical robustness. Figure 5 presents two exemplary wind speed profiles. LiDAR and radiosonde measurements are compared. A difference between LiDAR and radiosonde measurements can be observed. This is consistent with the findings of [20], where deviations below 500 m height are also reported, where in radiosonde measurements a pendulum-like motion is documented, but it acknowledges the general trend of the wind speed profile. A strong increase in wind speed is observed above 100 m compared to the near-surface measurements. For comparison, the vertical wind profile based on the Log-Law is also shown in Figure 5. For the application of the Log-Law to standardized profiles, only wind directions between 55°–90° and 155°–240°, unaffected by coastal or orographic influences, are considered,

assuming a constant roughness length [21].

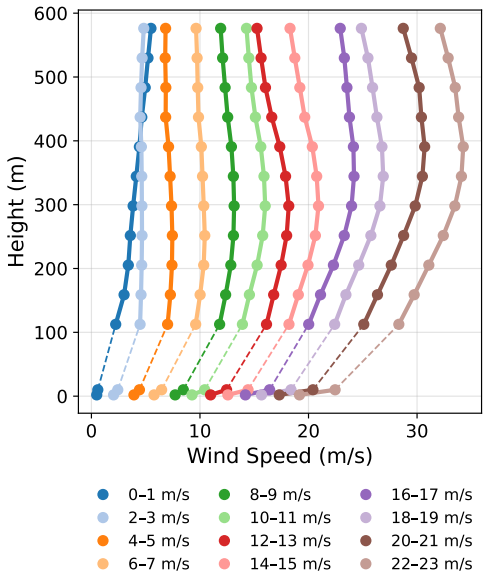


Figure 4. Wind speed profiles, determined by LiDAR measurement, combined with ground-based anemometer in 2 and 10 m height. Averaged measurements of the Antarctic summer months Jan, Feb, Nov, Dec 24 and Jan, Feb 25 are represented. The bins refer to the corresponding wind speed at 10 m height.

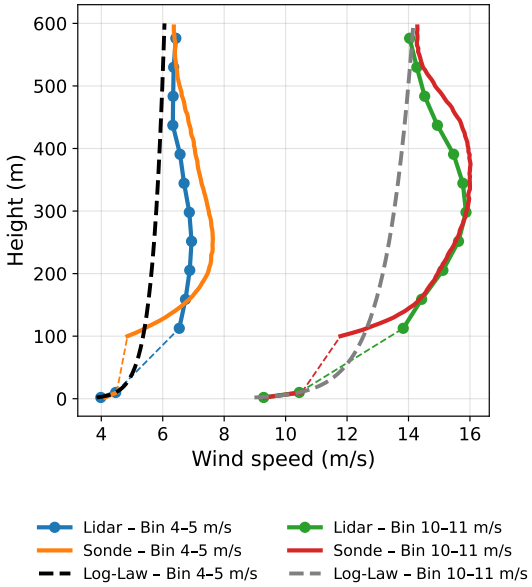


Figure 5. Comparison of radiosonde-, LiDAR measurement, and Log-Law of exemplary wind speed profiles. Underlying roughness-length of Log-Law: z= 0.0001 m, as recommended in [22] for ice surfaces. Only directions without orographical or coastal influence are considered

The large difference can be explained by the fact that the Log-Law is only valid within the surface boundary layer. In the Antarctic coastal region, this layer is extremely shallow compared to other locations [14]. Therefore, the Log-Law is included only as a reference for sites where it may extend to higher altitudes. This serves only as a first indication of how PLLJs may compare to vertical wind speed profiles at other locations. This is further addressed in the Discussion.

Figure 6 shows the probability density function of wind speeds at heights of 18 m and around 300 m. The wind speed at 18 m is extrapolated from measurements at a height of 10 m using the Log-Law and a roughness length of 0.0001 m, as recommended in [22] for ice surfaces. 298 m is one measurement height of the LiDAR system. These heights have been chosen because the representative ground-based turbine works at 18 m. For power production of the AWES a simplified harvesting altitude of 300 m is assumed. The high altitude wind speeds, represented by the orange curve, are clearly shifted towards higher wind speeds compared to the wind speeds at 18 m height. It can be seen that at higher altitude the probability of higher wind speeds rises significantly.

Figure 7 shows the cumulative distribution function (CDF) of the considered heights and relates them to the cut-in and cut-out wind speed limits of the ground-based wind turbine and the AWES. At an altitude of around 300 m, the wind speed exceeds the cut-out wind speed for approximately 15 % of the time and falls below cut-in wind speed for about 25 % of the time. With regard to the cut-out wind speed, it should be noted, that this point of view is a conservative assumption, because the share of time above this threshold can be reduced by operating the kite at lower altitudes. In contrast, a ground-based turbine does not have to

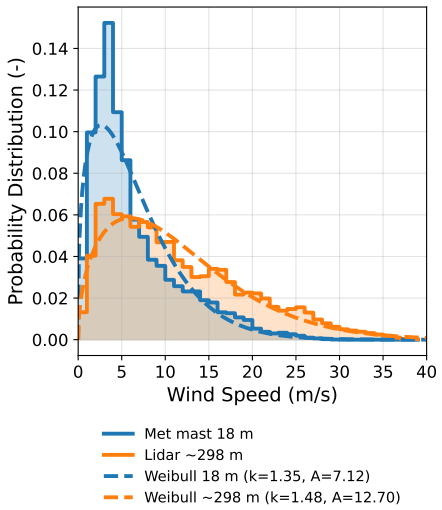


Figure 6. Probability density function of wind speed and corresponding weibull fit for 18 m and 298 m height at Neumayer Station

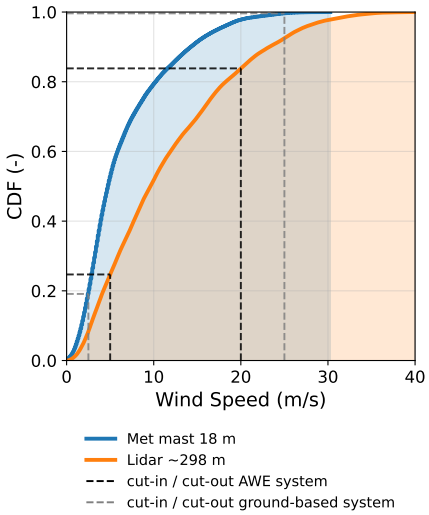


Figure 7. Cumulative distribution function of wind speed for 18 m and 298 m height and corresponding cut-in and cut-out rates

address cut-out wind speed, as the wind speed exceeds the cut-out threshold only for a negligible amount of time. It is important to note, that the summer months of 2024 and 2025 represent only a limited sample of wind conditions for the considered mission periods.

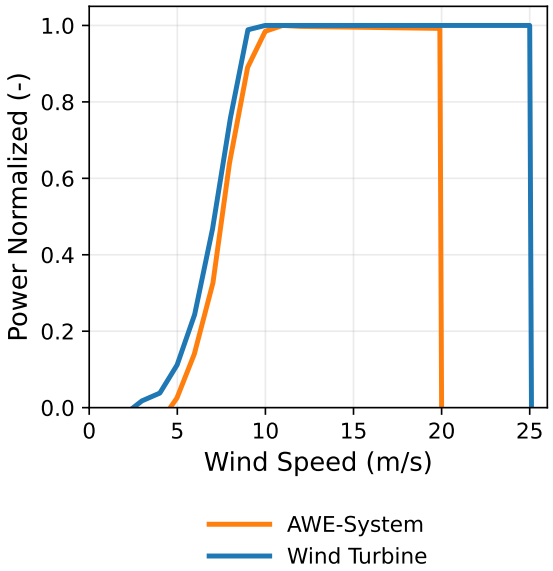


Figure 8. Power curves of a wind turbine and an AWES of equal rated power, normalized by the maximum power according to manufacturer information

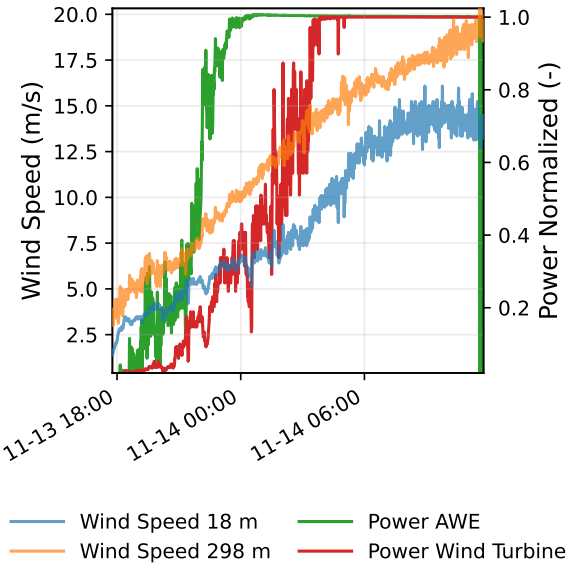


Figure 9. Exemplary detailed view of time series of wind speed measurements in different heights and the associated power production based on the corresponding power curve

Figure 8 compares the power curve of a representative ground-based wind turbine with the power curve of a market-ready AWES with same rated power. The main differences between

the two power curves are the cut-in wind speed and the cut-out wind speed. The cut-out wind speed is of special importance and will be covered additionally in Chapter 5. Figure 9 shows an exemplary section of wind speed and power time series, in which three different comparison states of the two systems can be clearly identified. At the beginning of the time series, it is evident that the AWES benefits from stronger winds at higher altitudes and therefore produces more power at lower wind speeds than the ground-based turbine. This advantage continues until a wind speed range is reached, where both systems operate in rated power. This status continues until the cut-out wind speed of the AWES is reached, while the ground-based system is still in power production mode.

Figures 10 and 11 show the total energy yield of both systems during one mission season, in this case in Antarctic summer 2024/25. As already indicated in Figure 9, at high wind speeds the AWES does not provide an energy-related advantage, because wind speeds above the cut-out limit of the AWES occur frequently. This can be observed sporadically in Figure 10 until the beginning of December 2024. During periods with lower wind speeds, the AWES delivers higher power again. As a result, when considering the total energy produced over the entire season, the AWES achieves about a 10 % higher energy yield than the ground-based system. An important additional operational constraint must be considered for missions of this type. Based on experience, field work is not conducted at wind speeds above 12 m/s. Therefore, figure 11 shows the total energy for the considered period after excluding time intervals with wind speeds above 12 m/s. Under these conditions, the AWES exceeds the total energy yield of the ground-based systems by more than 40 % over the mission period. This is because the advantages of the AWES at low wind speeds are particularly effective during these time intervals.

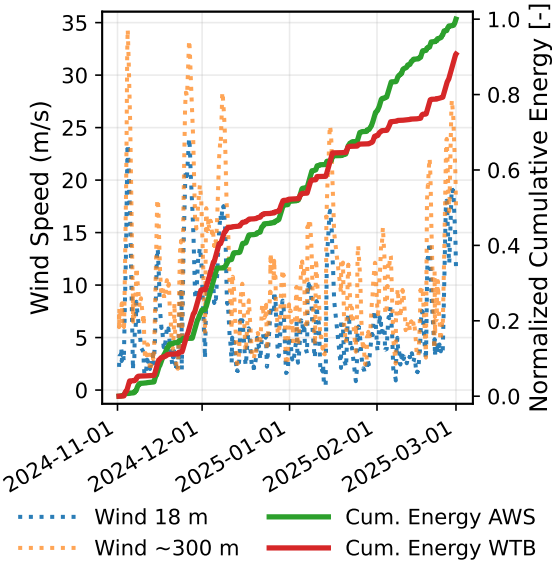


Figure 10. Cumulative energy beneath related wind speeds. Wind speeds are represented as rolling daily means for a more clear visualization

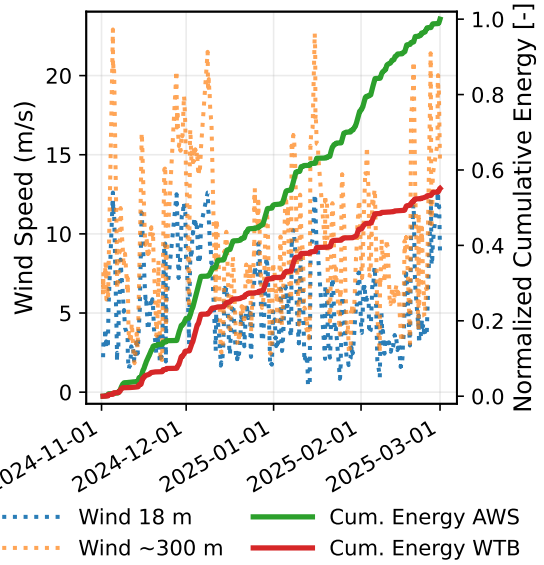


Figure 11. Cumulative energy, where only periods under 12 m/s wind speeds are considered to represent times, where field work is possible

5. Discussion

The underlying LiDAR data cover only a period of one and a half years. Therefore, the result of this study should be regarded as an exemplary case study rather than a long-term assessment. Future work could include measurement campaigns or the application of Measure Correlate

Predict methods. These methods could be used to extrapolate near-ground measurements to higher altitudes and thus allow statements for longer time periods. The wind direction will also be decisive for the different vertical wind speed profiles. In particular, the coastline located about 20 km from the site could be of significant importance. This aspect could also be considered as a possible extension of the analyses presented in this work. The cut-out wind speed of the AWES is a key factor for power performance. It should be noted that AWES are a relatively new technology. Therefore, it is expected that the allowable range of operating wind speeds will increase in the coming years. For simplification, an abrupt drop of the power curve to zero at the cut-out wind speed has been assumed, based on Figure 10. Consequently, in the model the turbine output switches abruptly between rated operation and zero when wind speeds fluctuate around this threshold. This behavior also represents a simplified assumption and does not fully reflect real system behavior. The combination of the AWES power curve with wind speed at a single height provides only an estimation of power output. In reality, power generation is significantly more complex and should be investigated in more detail in future studies. Further potential lies in a deeper understanding of LLJ. A more detailed analysis of LLJ could help to better assess and optimize their use for AWES applications. A more comprehensive assessment of how polar wind profiles compare to those at other locations would require additional measurements and the inclusion of a broader range of reference sites.

6. Conclusions

This study investigates wind speed profiles at the Neumayer Station III in Antarctica. The profiles were derived using a combination of LiDAR, near-surface anemometer and radiosonde measurements. The results clearly show the occurrence of low-level jets. Both the strength and the height of the low-level jets increase with increasing reference wind speed. The jet maxima are found at heights between 250 and 400 m. These strong winds at higher altitudes provide significant potential for energy generation, particularly for AWES. In an exemplary application case representing a research season with fieldwork during the Antarctic summer, the analysis of the complete time series shows an increase in available power of about 10 % compared to conventional ground-based turbines. Assuming that fieldwork is only possible when near-surface wind speeds are below 12 m/s, an increase in power output of about 40 % was observed. With respect to pure energy yield, AWES therefore offer considerable potential, despite the technology still being at a relatively early stage of development.

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References

[1] Schorbach V and Weiland T 2022 Wind as a back-up energy source for Mars missions *Acta Astronautica* **191** 472–478
[2] Schmehl R, Rodriguez M, Ouroumova L and Gaunaa M 2024 Airborne wind energy for Martian habitats *Adaptive on- and off-Earth Environments* Adaptive Environments ed Cervone A, Bier H and Makaya A (Cham: Springer Nature) chap 7, pp 145–197

[3] Säwström C, Lisle J, Anesio A M, Priscu J C and Laybourn-Parry J 2008 Bacteriophage in polar inland waters *Extremophiles* **12** 167–175
[4] Bulat S A, Alekhina I A, Blot M, Petit J R, De Angelis M, Wagenbach D, Lipenkov V Y, Vasilyeva L P, Wloch D M, Raynaud D *et al.* 2004 Dna signature of thermophilic bacteria from the aged accretion ice of lake vostok, antarctica: implications for searching for life in extreme icy environments *International Journal of Astrobiology* **3** 1–12
[5] Heinen D, Audehm J, Becker F, Boeck G, Espe C, Feldmann M, Francke G, Friend P, Haberberger N, Helbin K *et al.* 2021 The triple melting probe-an electro-thermal drill with a forefield reconnaissance system to access subglacial lakes and oceans *OCEANS 2021: San Diego–Porto* (IEEE) pp 1–7
[6] Audehm J, Bachmayer R, Bande M, Bannasch R, Becker F, Bestmann U, Bhattacharya D, Böck G, Clemens J, Do M *et al.* 2025 Triple-technologies for rapid ice penetration and subglacial lake exploration: Whitepaper by the triple project within the german space agency explorer initiative at dlr *Authorea Preprints*
[7] Treaty A 1992 *Protocol on environmental protection to the Antarctic treaty* (Ministry of External Relations and Trade)
[8] Lucci J J, Alegre M and Vigna L 2022 Renewables in Antarctica: an assessment of progress to decarbonize the energy matrix of research facilities *Antarctic Science* **34** 374–388
[9] Umweltbundesamt 2005 Zusammenfassende Darstellung und Bewertung der Umweltauswirkungen der geplanten Tätigkeiten: Neubau der Station Neumayer III, Betrieb der Station Neumayer III, Abbau der bestehenden Station Neumayer II, i 2.4 – 94003-2/43
[10] Babinec S, Baring-Gould I, Bender A N, Blair N, Li X, Muehleisen R T, Olis D and Ovaitt S 2024 Techno-economic analysis of renewable energy generation at the South Pole *Renewable and Sustainable Energy Reviews* **193** 114274
[11] Hau E and Von Renouard H 2006 *Wind turbines: fundamentals, technologies, application, economics* (Springer)
[12] Emeis S 2018 *Wind energy meteorology: atmospheric physics for wind power generation* (Springer)
[13] Schelbergen M, Kalverla P C, Schmehl R and Watson S J 2020 Clustering wind profile shapes to estimate airborne wind energy production *Wind Energy Science* **5** 1097–1120
[14] Luiz E and Fiedler S 2024 Global climatology of low-level-jets: Occurrence, characteristics, and meteorological drivers *Journal of Geophysical Research: Atmospheres* **129** e2023JD040262
[15] Erdmann A and Gasch P 2024 A modular wind profile retrieval software for heterogeneous doppler lidar measurements *Geoscientific Model Development Discussions* **2024** 1–43
[16] Bagheri Dastgerdi S, Behrens M, Bonne J L, Hörhold M, Lohmann G, Schlosser E and Werner M 2021 Continuous monitoring of surface water vapour isotopic compositions at Neumayer Station III, East Antarctica *The Cryosphere* **15** 4745–4767
[17] Schmithuesen H and Koch M 2020 Continuous meteorological observations at neumayer station https://doi.pangaea.de/10.1594/PANGAEA.921529 dataset, published via PANGAEA
[18] König-Langlo G and Loose B 2007 The meteorological observatory at Neumayer stations (GvN and NM-II) Antarctica *Polarforschung2006* **76** 25–38
[19] Radenz M, Engelmann R, Henning S, Schmithüsen H, Baars H, Frey M M, Weller R, Bühl J, Jimenez C, Roschke J *et al.* 2024 Ground-based remote sensing of aerosol, clouds, dynamics, and precipitation in Antarctica: First results from the 1-year COALA campaign at Neumayer Station III in 2023 *Bulletin of the American Meteorological Society* **105** E1438–E1457
[20] Kumer V M, Reuder J and Furevik B R 2014 A comparison of lidar and radiosonde wind measurements *Energy Procedia* **53** 214–220
[21] Atlas W 2012 European wind atlas
[22] König-Langlo G 1985 Roughness length of an Antarctic ice shelf *Polarforschung* **55** 27–32